Ontario

Groundwater Resources Study 13

Early Silurian Sequence Stratigraphy and Geological Controls on Karstic Bedrock Groundwater-Flow Zones, Niagara Escarpment Region and the Subsurface of Southwestern Ontario

2020

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Early Silurian Sequence Stratigraphy and Geological Controls on Karstic Bedrock Groundwater-Flow Zones, Niagara Escarpment Region and the Subsurface of Southwestern Ontario

Ontario Geological Survey
Groundwater Resources Study 13

by

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OBJECTIVE

The *Groundwater Resources Study* (GRS) series seeks to better the understanding of Ontario's groundwater resources through the collection, evaluation and distribution of geoscience data. The main objective of the series is to provide accurate information on a range of groundwater-related themes, including local- to watershed-scale aquifer characterization and delineation; geologic controls and influences on groundwater quantity and quality; and methods development. Products of the groundwater program include geoscience reports, data sets and protocols for information collection and handling. Geoscience information generated through the series will find application in the protection and sustainable management of the province's groundwater resources.

DISCLAIMER

CITATION

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

Brunton, F.R. and Brintnell, C. 2020. Early Silurian sequence stratigraphy and geological controls on karstic bedrock groundwater-flow zones, Niagara Escarpment region and the subsurface of southwestern Ontario; report [PDF document] *in* Ontario Geological Survey, Groundwater Resources Study 13.

NOTE

Abstract

More than 3 million Ontarians rely on groundwater resources. This Ontario Geological Survey (OGS) study forms part of an integrated, field-based initiative to map bedrock groundwater resources within the Paleozoic succession of southern Ontario. The main objective of this study is to delineate potable groundwater resources within the upper few hundred metres of stacked cuesta-forming carbonates of the Niagara Escarpment. The establishment of the OGS groundwater mapping initiative in 2007, in part a response to the Walkerton tragedy in May 2000, is an outgrowth of geoscience activities that have been ongoing for more than half a century. This OGS initiative represents an expanded geoscience mandate comprising three-dimensional (3-D) surficial and Paleozoic bedrock mapping, and ambient groundwater geochemistry.

Sedimentary strata of early Silurian age form the caprock of the Niagara Escarpment cuesta. This succession was selected as the first multiyear and multicomponent bedrock groundwater mapping project because many of the larger cities on the cuesta are experiencing substantial growth, in part as a response to recently introduced provincial policies, and the regional hydrogeology and geologic controls on groundwater-flow zones of the Niagara Escarpment were poorly understood.

Field- and laboratory-based protocols have been established to both undertake lithostratigraphic and sequence stratigraphic studies and integrate rock and water geochemistry to demonstrate the geological controls on the groundwater-flow systems. These studies have facilitated communities to explore for new groundwater resources in a cost-effective manner, to address questions related to human health issues (i.e., natural occurrences of elevated arsenic, fluoride, lead-zinc), and to serve public good.

Phase 1 of the study involved collaboration with 3 municipal governments to drill 35 deep bedrock cored holes in the City of Guelph, Region of Waterloo (Cambridge) and Hamilton corridors (2006 to 2008). Phase II involved regional-scale drilling of 19 cored boreholes down to regional aquitards (up to 350 m deep) within and away from key growth areas (e.g., city of Hamilton–Cambridge–Guelph–Region of Waterloo, Orangeville, Town of Shelburne), and on Manitoulin Island (2009 to 2011). Phase II also involved the compilation of more than 100 cores across the Niagara Escarpment outcrop–subcrop region. It included BSc and MSc theses by Candace Brintnell on parts of the Clinton and Lockport group strata (this research extended into Michigan), and MSc and PhD studies by Alyssa Bancroft on conodont biostratigraphy. Cores were logged, photographed, slabbed and sampled at the formation- and member-scale for lithogeochemistry and carbon, oxygen and strontium isotopes. Borehole studies included camera and video logging, optical and acoustic televiewer logging, geophysical logging (gamma, caliper, resistivity), heat pulse and flow-meter profiling, pumping tests, dye tracer tests, FLUTe™ K-profiling, and installation of Water FLUTe™ multilevel systems for sampling discrete flow zones in selected wells.

The 3-D subsurface mapping involved the integration of existing water well and oil and gas well logs and from collaborative drilling programs with select communities and conservation authorities, resulting in the logging of more than 200 medium- to high-quality boreholes and hundreds of data points from literature. More than 40 000 water wells and oil and gas wells were vetted to delineate the positions of shallow and deeper bedrock groundwater flow zones within the early Silurian, escarpment-forming stacked carbonate succession, and assess the regional geologic controls on the groundwater-flow systems (2010 to 2017).

This report summarizes the regional lithostratigraphic and sequence stratigraphic character of subsurface and outcrop strata and provides new paleogeographic, paleoenvironmental and biostratigraphic interpretations of the early Silurian succession. It also summarizes the main geologic controls on the hydrologic setting and positions of groundwater-flow zones. The final phase of this multiyear and multi-component study, which involves characterization of hydraulic conductivity at the formation scale and integration of water and rock geochemistry to delineate local and regional bedrock aquifers, is currently underway with OGS colleague Elizabeth Priebe and colleagues in academia and the consulting industry.

Executive Summary

Mapping and predicting the present-day potable Paleozoic bedrock groundwater resources in southern Ontario, and their relation to the varied spatial and temporal geological controls, is only possible by understanding the tectonic, paleogeographic and depositional history of Laurentia and North America. Paleozoic-age sedimentary strata in southern Ontario are under a regional, horizontal compressive stress field (Lo 1978; Lo and Hori 1979; Lee 1981; Zoback 1992) as a result of the westward movement of North America since the Atlantic Ocean began to open and the supercontinent Pangaea broke up more than 200 million years ago. The present-day Niagara Escarpment cuesta landform exposes part of the Paleozoic succession that has been subjected to differential erosion and karstification for at least the past 300 million years. This arcuate scarp consists of early Silurian-age carbonate-dominated strata and extends from western New York State through southern Ontario and Manitoulin Island to the Upper Peninsula of Michigan and ending in central Wisconsin (approximately 1500 km long).

Regional bedrock, potable groundwater-flow-zone mapping by the Ontario Geological Survey across the Niagara Escarpment region of southern Ontario and Manitoulin Island has revealed the existence of preferred pathways that have, and are taking advantage of, predictable and karstic sequence-stratigraphic boundaries. Building upon revisions to the early Silurian stratigraphy in southwestern Ontario by other researchers (Brunton and Brintnell 2011; Cramer et al. 2011; Brunton et al. 2012; Brett et al. 1995), this study highlights the implications of a new paleogeographic and paleoenvironmental perspective. The new perspective provides important insights into the geological controls on, and predictability of finding, carbonate-bedrock potable-water pathways. It highlights the importance of characterizing forebulge-tectonic zones on the far-field side of foreland basins, and the value of geologic mapping and acquisition of regional-scale field data, to successfully explore, characterize, correlate and name bedrock potable-water flow zones in a cost-effective manner.

The study area straddles what has traditionally been described as the boundary between the Michigan intracratonic basin and Appalachian foreland basin – a northeast-southwest–trending feature known as the Algonquin Arch. This study supports the hypothesis that the structural feature known as the “Algonquin Arch” can better be referred to as a flexural forebulge region that migrated both spatially and temporally from north to south in southwestern Ontario, spanning more than 10 million years of early Silurian time. Intermittent responses to far-field tectonics—now referred to as “Taconic and Salinic tectophases”—along the Appalachian foreland basin influenced carbonate ramp geometries and relative sea-level fluctuations and resulted in the complex sequence-stratigraphic architecture preserved on the Laurentia craton.

The sedimentary rocks that comprise the caprock portion of the Niagara Escarpment are early Silurian in age and display a complex but predictable stratigraphic architecture that has been revealed through acquisition and detailed logging and sampling of cores and outcrops both within and away from the “Arch”, or forebulge, region. As a result of regional stress fields that developed prior to, during, and post-breakup of the supercontinent Pangaea, the Paleozoic strata of southwestern Ontario presently dip gently in a southwesterly direction away from the topographic high of the Niagara scarp face (forming a regional-scale cuesta that extends for more than 1500 km). The Lockport Group, which comprises stacked carbonates of highly variable thickness, porosity and permeability, forms the caprock of the Niagara Escarpment cuesta. Regional mapping has confirmed the following rock units for the Lockport Group in southwestern Ontario, from base to top: Gasport, Goat Island, Eramosa and Guelph formations (Brunton 2009). Differential erosion over hundreds of millions of years (prior to and development and breakup of Pangaea), including the most recent and atypical glacial-induced physical and chemical erosion over the past few million years, has resulted in the present-day bedrock surface topography. The underlying and regionally extensive Cabot Head Formation shales of the Clinton Group form a regional vertical barrier to the potable groundwater-flow zones in the overlying Lockport Group carbonates in an area extending from the Hamilton–Cambridge–Guelph region to Manitoulin Island. Between Hamilton and Niagara Falls (the Niagara Peninsula), the potable groundwaters of the Lockport Group strata are underlain by a younger subregional barrier: the Rochester Formation shales and mixed carbonates of the Clinton Group.

Delineation of preferred, potable bedrock groundwater-flow zones has required regional outcrop mapping, combined with examination of more than 200 bedrock and overburden cores and/or geophysically logged boreholes, selected oil and gas well records, and thousands of Ministry of Environment, Conservation and Parks (MECP) water well records. The cores were logged and sampled for whole rock, trace element, and selected rare earth element (REE) geochemistry and isotopes (carbon, oxygen and strontium), and conodont biostratigraphy over a five-year period (2009 to 2014). Key cored holes across the study area also had video and camera logs, variable duration packer-pumping tests, FLUTe™ hydraulic conductivity (K)-profiling in blank liners, Heat Pulse and optical-acoustic televiewer profiling, and dye-tracer tests between wells. Many of the key boreholes integrated in this study were drilled in collaboration with municipalities and other partners that rely on bedrock groundwaters and/or are exploring for new sources to meet future population and industry demands.

Following examination of the regional, up-dip, shallower potable water wells, in combination with the more than 16 000 deeper oil and gas wells, it became apparent that the sequence stratigraphic character of the early Silurian strata was more complex than previously reported. It was also discovered that similarities exist between the up-dip and more deeply buried three-dimensional structures referred to as Guelph “Pinnacle reefs” (up to 100 m thick by kilometres in width and length). The more deeply buried Guelph “Pinnacle” structures are not biogenic reefs of the Guelph Formation, but instead comprise older and variably paleokarsted Lockport Group strata dominated by the Gasport and Goat Island formations. Although similar to the transmissive three-dimensional structures described from the Cambridge and City of Guelph areas in the Niagara cuesta (Brunton and Brintnell 2011; Brunton et al. 2012), the up to 100 m of paleorelief of the Lockport Group strata observed in the subsurface wells represents an ancient (early Silurian), discontinuous, northwesterly facing and northeasterly trending set of scarps (cf. mesa and butte topography versus karstic landforms) enveloped by much younger Salina Group shallow marine microbialites and interbedded evaporites (salt and gypsum beds that are variably paleokarsted and brecciated) in the Sarnia through Kitchener–Waterloo areas. The Guelph Formation is a karst breccia unit (referred to in oil and gas literature as interreef Guelph) in what has been interpreted to be slope and deeper shelf facies near the Lake Huron shoreline in southwestern Ontario (*see* Carter, Trevail and Smith 1994). This karst breccia–paleosol–caliche unit is reinterpreted as a terrestrial terrain. Equivalent strata down ramp (in the Guelph–Cambridge and Elora–Fergus to Luther Lakes areas) display little paleokarstification and record a more open marine and reefal carbonate ramp environment that transitions both upward stratigraphically and laterally, from southwest to northeast, to restricted marine, nutrient-rich lagoonal facies and periodic exposure and karstification (Brintnell 2012; Brunton et al. 2012).

The regional changes in the stacking patterns of carbonate-dominated rock units of the Lockport Group have resulted in the development of preferred karstic, bedrock groundwater-flow zones. Between the Guelph–Cambridge through Hamilton and Niagara regions, confined bedrock groundwater-flow zones are preferentially developed in the Gasport Formation reef mound and interreef encrinites (well-cemented carbonates with greater than 50% crinoidal debris of gravel to sand size) and overlying Goat Island Formation wackestones and packstones. Both unconfined and confined, karstic, shallow bedrock groundwater-flow systems are present in both the Eramosa Formation Reformatory Quarry member lithofacies and overlying Guelph Formation lithofacies. Northward of the Lockport-time forebulge area (north of the City of Guelph), the deeper bedrock, confined groundwater-flow zones change from Gasport Formation-dominated flow zones to Goat Island, upper Eramosa and Guelph formational bedrock flow zones. The Gasport Formation becomes less reef mound-bearing and thins northward in the outcrop–subcrop belt of the Niagara cuesta, and the younger Goat Island and Guelph formations thicken and possess reef mound phases and distinctive karstic groundwater-flow zones. The Eramosa Formation displays a complex lithofacies mosaic in southwestern Ontario. Upper Goat Island Ancaster Member and basal Eramosa Formation Vinemount member lithofacies depict transgressive, deeper marine and cyclic deposition associated with a short-lived adjustment of the Appalachian foreland basin that resulted in mixed terrigenous-carbonate sedimentation, with cladoporid-bearing (finger-size digitate tabulate coral) facies, onto the structurally complex Laurentia cratonic ramp that formed on the far-field side of Appalachian foreland basin. From the Niagara region through City of Guelph areas, the overlying Reformatory Quarry member comprises open marine and higher-energy lithofacies. This paleoenvironmental setting changes northward to a more varied open to restricted marine, evaporitic lagoon to possibly estuarine conditions, based upon faunas and stratal packages. Seismite-bearing units are evident within this member from the central Bruce Peninsula region to Niagara region, supporting the interpretation of episodic disturbances of marine deposits during multiple, short-lived, Salinic II tectophases following the major Salinic I disturbance cut-downs (uplift and erosion) evident in underlying Clinton Group strata.

Regional lithofacies patterns support a revised interpretation for each of the Lockport Group formations across southwestern Ontario, whereby more open marine and higher energy lithofacies are found towards the present-day Niagara Escarpment margin, or scarp face, of southwestern Ontario and the most restricted marine and/or missing (paleokarsted) strata of the Lockport Group occur to the northwest in the Michigan structural basin. In contrast, previous papers have inferred deeper water conditions. We propose a revised depositional model for Lockport Group sedimentation, one that reflects a structurally complex carbonate ramp that dipped towards the Appalachian foreland basin (from Michigan and Lake Huron into New York and Ohio) throughout Lockport time. Differential block faulting, earthquake activity and episodic forebulge vertical and lateral migration influenced the relative preservation potential and stacking patterns of the early Silurian strata. Anomalously thick strata of the Goat Island and Guelph formations (both depositional and erosional in origin) under the Waterloo Moraine and which extend in a northwesterly direction from Lake Erie through west Cambridge, suggest the presence of a previously unrecognized and subparallel “sag” to the Chatham Sag. The length and width of this inferred sag region cannot be delineated based upon existing oil and gas and deeper water well records.

The hydrologic and hydrogeologic conditions of the bedrock in southwestern Ontario are largely controlled by a combination of the structural reconfiguration of Phanerozoic strata during the creation and break-up of the supercontinent Pangaea, and the subsequent millions of years of erosion that resulted in the cuesta geometries from Manitoulin and North Channel Islands in Lake Huron to Niagara Falls. The apparent circular shape and general concentric dip of Phanerozoic strata of the Michigan structural basin is not a depositional feature but rather a plate tectonic, or structural (mantle plume activity), response followed by differential erosion of once more regionally-extensive marine Paleozoic strata that have been eroded off the Precambrian shield to its present-day configuration. Manitoulin Island possesses regionally distinctive and well-developed cuesta steppes of Late Ordovician- and early Silurian-age stacked carbonates and mixed siliciclastics and carbonates, represented by an Upper Ordovician Coboconk–Gull River formation steppe, a Lower Silurian Manitoulin Formation, Fossil Hill Formation and Lockport Group (Niagara Escarpment) succession of dolostone alvars forming variably karstic carbonate cuesta steppes. These steppes are not as pronounced or evident across the thin-drift-covered karstic, dolostone plain of the Bruce Peninsula region, nor across the largely glacial sediment-covered stacked dolostones that subcrop and outcrop from the southern Bruce Peninsula to Niagara Falls, and to the west-southwest, where largely buried Upper Silurian to Middle Devonian stacked carbonate steppes of the Onondaga Escarpment subcrop. Prior to the glacial advances and retreats over the past few million years, St. Lawrence Lowland physiography was subjected to millions of years of physical and chemical weathering that resulted in development of a regional karstic drainage terrain characterized by sequence boundary-controlled, karstic bedrock groundwater-flow systems, maze-caves, sinkholes and karren.

The multiple advances and retreats of continental-scale ice sheets over this bedrock topography would have introduced large volumes of cold and chemically aggressive waters that would have accentuated and enhanced existing karst drainage networks. The current drainage basins and surficial watershed boundaries in the postglacial sediment regime have resulted in a more complex and, in part, disconnected surface water and groundwater drainage network on the various carbonate bedrock cuestas. Along much of the Niagara Escarpment and cuesta, the deeper bedrock groundwater-flow systems recharge in thin drift and exposed bedrock regions well up-dip of where municipal wells are drawing waters and do not correspond to the shallower, overburden-controlled watershed divides. These geological controls, which influence the separation of groundwater-flow systems across the Niagara Escarpment and cuesta region, were not generally recognized prior to this regional study of deeper, potable, bedrock groundwater-flow systems. Another key element of this regional assessment has been the recognition that the cuesta margins (within a few kilometres of cuesta edge), which represent areas of regional stress-field relaxation, display much more complex recharge conditions: precipitation infiltrates overburden and exposed bedrock areas and either flows off the escarpment or is directed by vertically connected and solution-enhanced, joint-controlled openings oriented in various directions. Those surface waters and groundwaters entering the bedrock further away from the cuesta scarp face penetrate the variably karsted joints and preglacially- and glacially-enhanced karstic bedding planes and sequence boundaries of the differentially eroded stacked carbonates, and generally follow the regional dip of the cuesta stratigraphic architecture.

Introduction

The Paleozoic Bedrock Groundwater Mapping Initiative of the Ontario Geological Survey (OGS) was officially established in 2007. It was preceded and overlapped by a three-year field- and GIS-based surface and subsurface karst mapping initiative (2005 to 2008; Brunton and Dodge 2008; Brunton 2013), a three-year GIS-based bedrock topography mapping project (2004 to 2007; Gao et al. 2006, 2007) and collaborative field-based projects with various conservation authorities (e.g., Ausable Bayfield, Maitland River, Grey–Saugeen–Bruce, Grand River, Halton–Hamilton, and Niagara Region) and municipalities (e.g., Region of Waterloo, City of Guelph, City of Hamilton, Halton, Acton, and Shelburne) to integrate bedrock geology with karstic groundwater-flow mapping and delineation.

The mapping of karst features across the Silurian-age dolostone plains and alvars of the Niagara Escarpment has revealed that the Cabot Head Formation shales represent a regional aquitard, or barrier, for potable bedrock groundwaters over an area extending from Cockburn–Manitoulin Islands through to the city of Hamilton. The slightly younger, early Silurian-age Rochester Formation shales that subcrop and outcrop between the city of Hamilton and Niagara Falls portions of the Niagara Escarpment cuesta form the regional aquitard in this region, commonly referred to as the Niagara Peninsula region.

The Silurian carbonate sedimentary rocks that comprise the Niagara Escarpment region of southwestern Ontario and Manitoulin Island were chosen as the first stratigraphic succession to establish the OGS bedrock groundwater mapping initiative and protocols because the largest population base reliant on deep bedrock groundwaters in southern Ontario occurs in this region. Additional motivations to begin subsurface bedrock groundwater mapping in this region include increased population pressures due to the introduction of provincial legislation. such as the *Places to Grow Act* (2005) and *Green Belt Act* (2005), and response to recommendations associated with the Walkerton Tragedy in the spring of 2000, and subsequent introduction of the *Nutrient Management Act* (2002), *Safe Drinking Act* (2002) and *Clean Water Act* (2006). Also, some of the larger cities (e.g., Guelph, Cambridge, and Hamilton) have enough water well fields that enable comparisons of hydrogeologic and stratigraphic characteristics, and the establishment of protocols for the OGS bedrock groundwater mapping initiative.

While mapping karst features across southern Ontario to produce the first provincial-scale, reconnaissance-level karst map (Brunton and Dodge 2008), the Ontario Geological Survey and the City of Guelph entered into 2 collaborative subsurface drilling programs (2006 and 2008) to drill 30 deep bedrock holes down to the regional Cabot Head Formation aquitard and acquire 23 cores to improve the understanding of bedrock geology and shallow to deep potable groundwater-flow conditions. Various hydrogeological and geological investigations were undertaken to evaluate the geological controls on deeper bedrock groundwater-flow systems in karstic and fractured stacked dolostone formations across the city (Brunton et al. 2007; Brunton 2009; Brunton and Piersol 2009; Brunton, Brintnell, Priebe and Bingham 2010; Brunton and Brintnell 2011; Priebe, Brunton and Lee 2012; Priebe, Neville and Brunton 2014). Subsurface mapping was carried out, in part, to assist the City of Guelph in establishing a fifty-year Water Supply Master Plan to provide a three-dimensional (3-D) geologic model to assist with Source Water Protection studies underway in various communities of the Grand River watershed, and to develop protocols for a regional groundwater mapping program across the Niagara Escarpment. The timing of the collaborative research with the City of Guelph Waterworks staff was strategic (initially proposed in the 2005 OGS Project Planning process) because it addressed the integration of high-quality stratigraphic–sedimentologic and sequence stratigraphic principles with hydrogeological investigations at the appropriate scale (i.e., well-field to municipal scales) for the City of Guelph to be used as a model community for studying fractured and karstic rock aquifer systems.

Over the course of this mapping program, examination of the Ministry of Environment, Conservation and Parks (MECP) water well database (2004 to 2017), and Provincial Groundwater Monitoring Network (PGMN) wells (Singer, Cheng and Scafe 1997, 2003) has revealed that many of the so-called bedrock water wells in Paleozoic sedimentary rocks are quite shallow into the upper fractured, weathered and karstic bedrock surface, representing interface aquifers. Therefore, this well database does not adequately reflect the potential, renewable, deeper bedrock groundwater resources (discrete karstic flow zones up to 250 m below the bedrock surface) and Great Lakes Basin hydrology that the OGS is currently mapping. Results of this study also reveal that the Quaternary sedimentary cover has altered the ancient karstic paleodrainage systems of the St. Lawrence Lowland region comprising Paleozoic sedimentary rock steppes. Therefore, the current delineation of watershed boundaries may require reconsideration (*see* discussion in Brunton et al. 2007; Banks and Brunton 2017), especially pertaining to the protection of deeper potable groundwaters, and an improved understanding of the hydrology of shallow to deeper bedrock groundwater-flow zones (aquifers) above regional aquitards.

The results of this study have been incorporated into an ongoing multiyear collaborative project with the Geological Survey of Canada (Natural Resources Canada) and Oil, Gas, Salt Resources Library and Ontario Ministry of Natural Resources and Forestry staff, to produce a 3-D Phanerozoic geological model that delineates key bedrock groundwater-flow zones across south-central and southwestern Ontario (Figures 1, 2a, b), and to support the development of a proof of concept groundwater model for the Paleozoic succession and overlying Quaternary sediments (Carter et al. 2017, 2019).

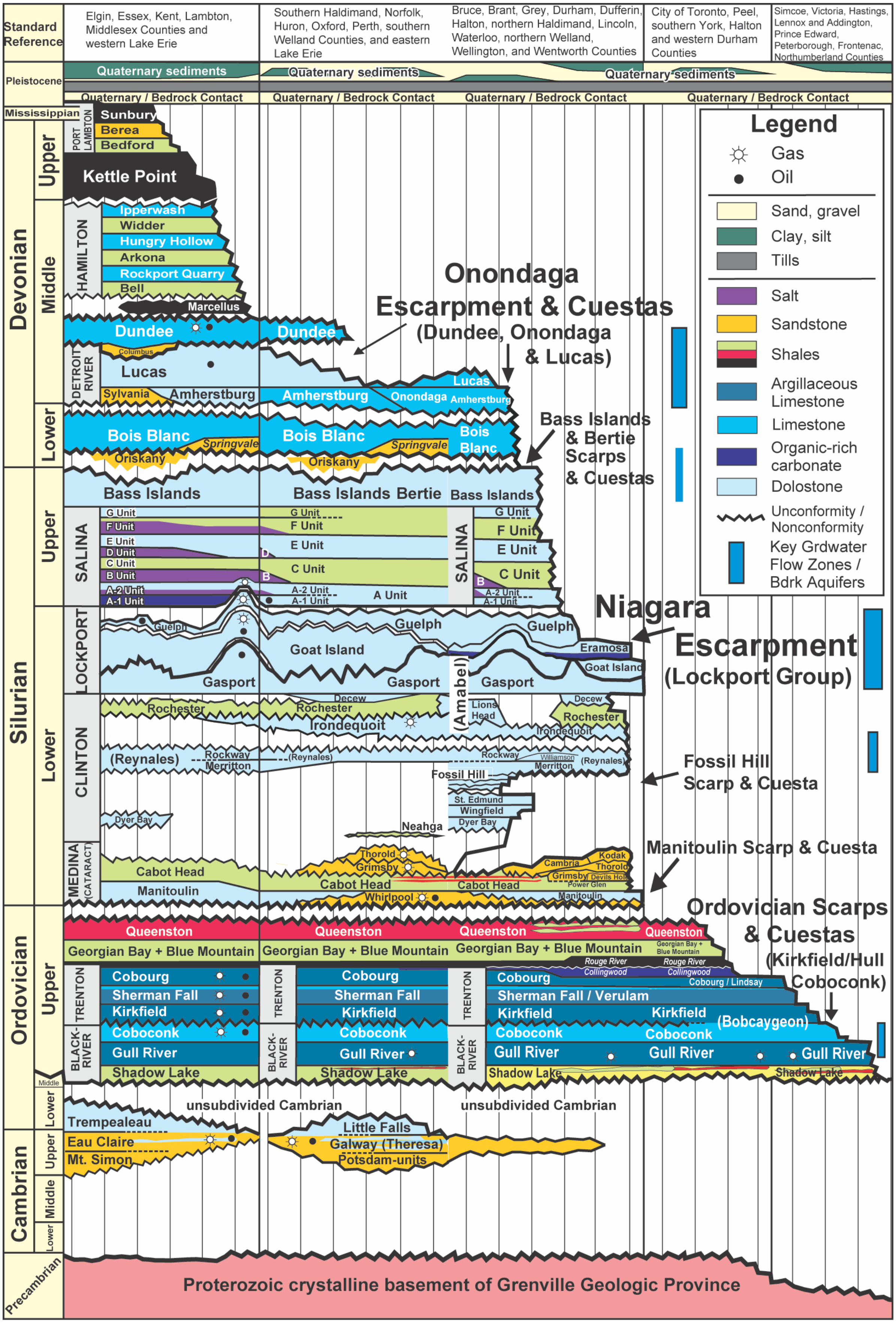
Standard Reference
Elgin, Essex, Kent, Lambton, Middlesex Counties and western Lake Erie
Southern Haldimand, Norfolk, Huron, Oxford, Perth, southern Welland Counties, and eastern Lake Erie
Bruce, Brant, Grey, Durham, Dufferin, Halton, northern Haldimand, Lincoln, Waterloo, northern Welland, Wellington, and Wentworth Counties
City of Toronto, Peel, southern York, Halton and western Durham Counties
Simcoe, Victoria, Hastings, Lennox and Addington, Prince Edward, Peterborough, Frontenac, Northumberland Counties
Pleistocene
Quaternary sediments
Quaternary / Bedrock Contact
Mississippian
Devonian
Upper
Middle
Lower
PORT LAMBTON
Sunbury
Berea
Bedford
Kettle Point
HAMILTON
Ipperwash
Widder
Hungry Hollow
Arkona
Rockport Quarry
Bell
Marcellus
Dundee
Columbus
DETROIT RIVER
Lucas
Sylvania
Amherstburg
Onondaga
Bois Blanc
Springvale
Oriskany
Onondaga Escarpment & Cuestas (Dundee, Onondaga & Lucas)
Bass Islands & Bertie Scarps & Cuestas
Silurian
Bass Islands
Bass Islands Bertie
SALINA
G Unit
F Unit
E Unit
D Unit
C Unit
B Unit
A-2 Unit
A-1 Unit
A Unit
D
B
LOCKPORT
Guelph
Goat Island
Gasport
Eramosa
(Amabel)
Niagara Escarpment (Lockport Group)
CLINTON
Rochester
Decew
Irondequoit
Lions Head
(Reynales)
Rockway
Merritton
Williamson
Fossil Hill
St. Edmund
Wingfield
Dyer Bay
Neahga
Fossil Hill Scarp & Cuesta
MEDINA (CATARACT)
Cabot Head
Manitoulin
Thorold
Grimsby
Whirlpool
Cambria
Kodak
Devils Hole
Power Glen
Manitoulin Scarp & Cuesta
Ordovician
Queenston
Georgian Bay + Blue Mountain
Rouge River
Collingwood
Ordovician Scarps & Cuestas (Kirkfield/Hull Coboconk)
TRENTON
Cobourg
Sherman Fall
Sherman Fall / Verulam
Kirkfield
Cobourg / Lindsay
(Bobcaygeon)
BLACK-RIVER
Coboconk
Gull River
Shadow Lake
Middle
Cambrian
unsubdivided Cambrian
Trempealeau
Eau Claire
Mt. Simon
Little Falls
Galway (Theresa)
Potsdam-units
Precambrian
Proterozoic crystalline basement of Grenville Geologic Province
Legend
☼ Gas
● Oil
Sand, gravel
Clay, silt
Tills
Salt
Sandstone
Shales
Argillaceous Limestone
Limestone
Organic-rich carbonate
Dolostone
Unconformity / Nonconformity
Key Grdwater Flow Zones / Bdrk Aquifers

Figure 1. Revised terminology of Paleozoic strata for south-central and southwestern Ontario (*modified after* Winder 1961; Beards 1967; Winder and Sanford 1972; Armstrong and Carter 2010; Brunton et al. 2017; Carter et al. 2017). The A-0 Carbonate of the basal Salina Group is not shown because of its localized distribution and thickness in southwestern Ontario and southeastern Michigan and the fact that it has been placed within the Salina Group A-1 Unit (*see* discussion in Gill 1973, p.41, p.133). Group names are in capital letters, members in italics, and abandoned formation names (e.g., Amabel) or regionally restricted but valid names (e.g., Reynales) that have been miscorrelated in past studies are in parentheses (e.g., Amabel Formation has been shown to comprise the Irondequoit and Rochester–Lions Head formations of the Clinton Group and Gasport Formation and lower member of the Goat Island Formation of the Lockport Group; Brunton and Brintnell 2011; Brunton et al. 2012). The ephemeral salt- and sulphate-bearing successions are purple, sandstones are yellow-orange, and the shale-bearing intervals depict organic-rich shales (black) and variably reduced and oxidized (green and red) shale intervals within mixed siliciclastic and carbonate successions. The thick carbonate successions are varied: organic-rich units (e.g., Collingwood, parts of Eramosa, A-1 carbonate) are dark blue, mixed limestone and shale units are medium blue, limestones are lighter blue, and dolostones are lightest blue. Ordovician and Devonian carbonates are largely limestones and Silurian carbonates are predominantly dolostones. The Phanerozoic bedrock topography is depicted by the erosional line (thickened black zig-zag line), from lower right to upper left, of stepped karstic cuestas (key escarpments labelled; *see also* Figure 2) that reside above the Grenville geologic province crystalline rocks, from Lake Simcoe–Frontenac Arch area to Windsor area (northeast to southwest; see geographic regions at top of figure). The remaining horizontal black zigzag lines reflect unconformities, or sequence boundaries. The line thicknesses signify inferred missing time interval (note Cambrian, Lower to Middle Ordovician and Lower Silurian gaps in sedimentation). Oil- and gas-bearing units (deeper subsurface) and the main potable-water zones (upper 250 m) in carbonate cuesta successions are highlighted: the blue vertical boxes depict main stratigraphic intervals of potable-water zones, with the relative widths and sizes of boxes graphically depicting the significance of regional to subregional groundwater-flow zones (aquifers). The Niagara Escarpment stacked dolostone succession represents the most significant regional bedrock groundwater-flow zone system in southern Ontario. The Middle Devonian Onondaga Escarpment stacked carbonates represent the second most significant groundwater resource and will be the focus of future studies by the OGS. The relative thicknesses of rock units are not to scale.

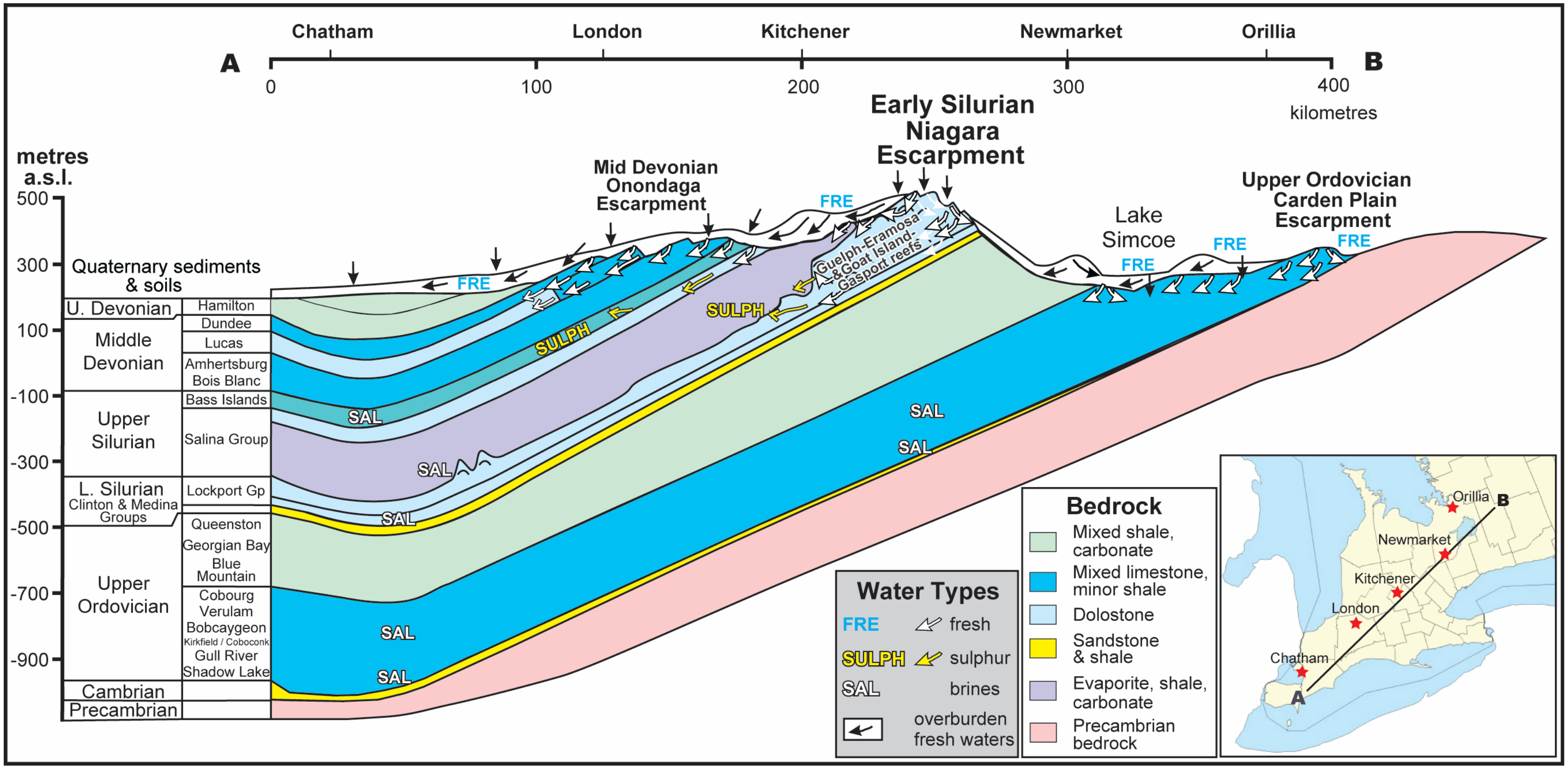

Figure 2a. Generalized northeast to southwest cross-section of Phanerozoic strata across southern Ontario, extending from Upper Cambrian–Upper Ordovician strata of the Carden Plain cuesta, north of Lake Simcoe, through younger Early Silurian strata of the Niagara Escarpment to the Late Silurian through Middle Devonian cuestas in the Nanticoke through Ingersoll to Windsor areas (*modified after* Brunton et al. 2017, and Carter et al. 2014). The cross-section highlights the bedrock topography and erosional modification during the numerous Quaternary glacial advances and retreats that have produced the resultant geomorphology. Note that the regional hydrology across southwestern and south-central Ontario is strongly influenced by the physiography of the various Phanerozoic bedrock cuestas and overlying Quaternary sedimentary cover. The black arrows depict rain and snow melt waters into Quaternary sediments and shallow bedrock (interface aquifer zone) and the white arrows are shallow to deeper, potable, bedrock groundwater-flow zones, extending down to 250 m depth. The potable, bedrock groundwater-flow zones of the Lockport Group of Niagara Escarpment cuesta, which are the focus of this report, reflect substantive recharge into bedrock and/or thinner drift areas where elevations are highest (up dip) along the escarpment and regional flow is variable but generally in a southerly to southwesterly direction through the shallow, karstic Lockport Group dolostones. The deeper bedrock pore- and formational-waters are either sulphur or sulphate waters or NaCl brines and are shown in yellow and white text. The yellow arrows do not reflect flow directions at depth. These fluids are under variable pressure and are at or below sea level, and in some places, upward gradients and/or artesian conditions may prevail (data from deep wells at the Deep Geological Repository (DGR) at Bruce nuclear power generating facility in Tiverton/Kincardine, Ontario). Results of studies carried out at the DGR, in conjunction with a review of hydrogeological data from other areas, indicate that there are 3 hydrogeological domains in southwestern Ontario: 1) a shallow zone extending from the Middle Devonian carbonates of Dundee and Detroit River Group to Late Silurian Bass Islands Formation; 2) an intermediate zone that extends from the basal Bertie and Bass Islands formations to Manitoulin Formation, possessing carbonate successions of highly variable porosity and permeability; and 3) a deep sulphur and brine fluid-bearing succession extending down to Proterozoic-age crystalline basement rocks. The basal Cambrian to Lower Ordovician siliciclastic artesian aquifer system is the most significant at the DGR site (Hobbs et al. 2011; Sykes, Normani and Yin 2011).

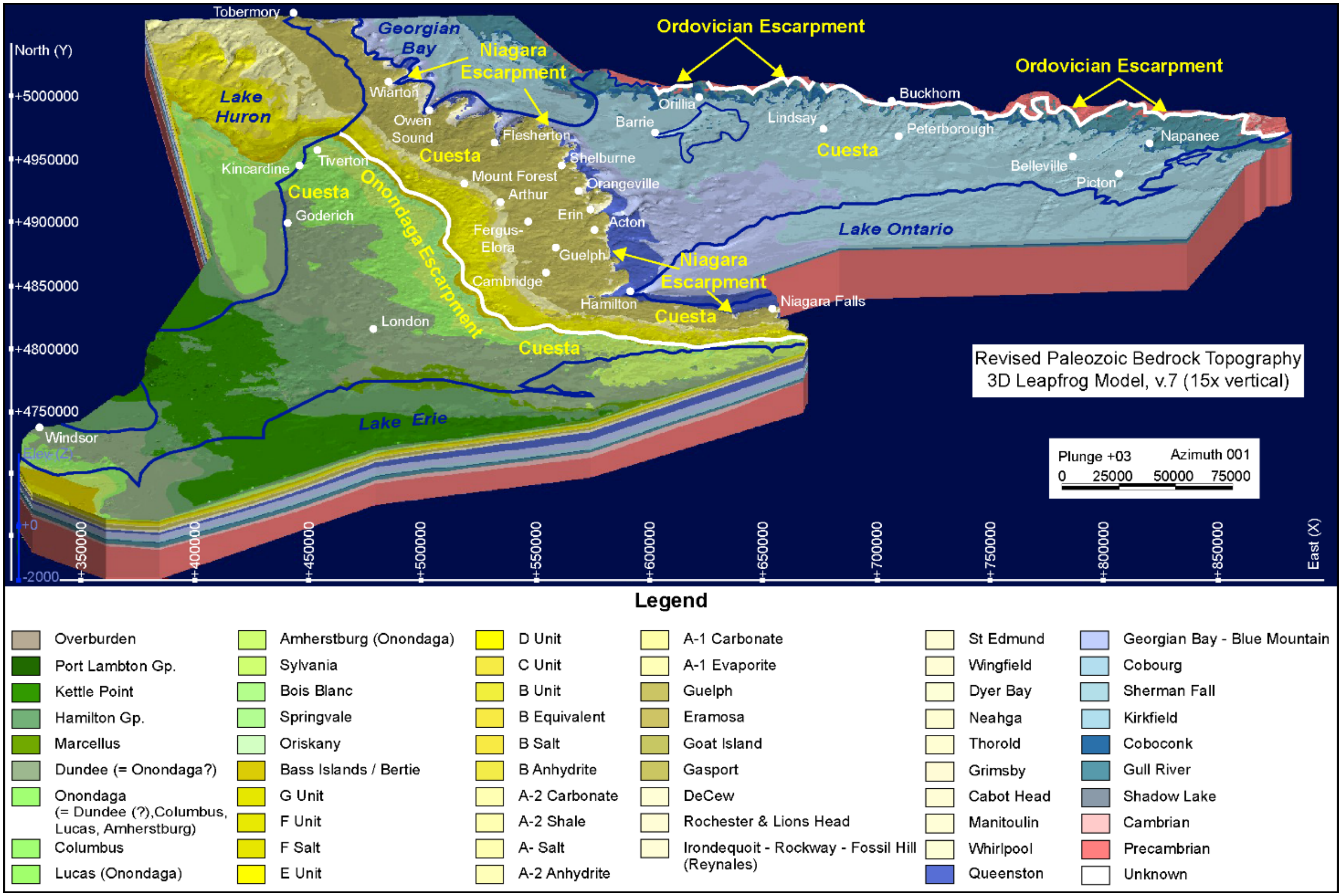

Figure 2b. The 3-D Leapfrog® Works model of Paleozoic bedrock geology and topography for southcentral and southwestern Ontario (Carter et al. 2019). The study area is greater than 110 000 km^2. In this version of the model, the Quaternary sedimentary cover is removed to show the regional locations of the key carbonate-capped cuestas and escarpment margins (stepped scarp faces). The model is based upon the lithostratigraphy chart shown in Figure 1 (*modified from* Brunton et al. 2017; Carter et al. 2019) and represents a five-year collaborative initiative between the Ontario Geological Survey, Geological Survey of Canada, Ontario Oil, Gas, Salt Resources Library and the Ontario Ministry of Natural Resources and Forestry. Significant karst landforms and karstic groundwater flow systems occur within these carbonate-dominated landforms: 1) upper Gull River, Coboconk and Kirkfield formations of Ordovician age; 2) Gasport, Goat Island, Eramosa and Guelph formations of Early Silurian age, and Bertie and Bass Island formations of Late Silurian age; and 3) Lucas, Onondaga and Dundee formations of Middle Devonian age.

Field Methods

Field and laboratory protocols were established to undertake the regional-scale, bedrock groundwater-flow system mapping within the early Silurian (Wenlockian) Lockport Group of the Niagara Escarpment. This mapping involved the development of a testable, early Silurian sequence stratigraphic framework for southwestern Ontario that builds upon the tectonostratigraphic work of Carl Brett and colleagues in New York and Ohio beginning in the 1980s (e.g., Brett, Goodman and LoDuca 1990; Brett, Boucot and Jones 1993; Ettensohn 1994; Brett 1995, 1998; Brett et al. 1995; Ettensohn and Brett 2002; Brunton et al. 2009; Brunton et al. 2012; Brett, Brunton and Calkin 2018), an improved technique for sampling conodonts, and the application of chemostratigraphy.

The general approach to regional-scale bedrock mapping and groundwater-flow zone delineation involved 3 main components, or phases: 1) mapping and sampling of key outcrops, quarry sections and cores; 2) hydrogeological investigations of selected deep bedrock wells; and 3) instrumentation of selected deep bedrock wells.

PHASE 1 – MAPPING OF KEY OUTCROPS AND QUARRY SECTIONS

Phase 1 involved the mapping of key outcrops within select quarry, roadside, railway and cliff sections (Figure 3A). Stratigraphic sections were measured and used to establish and/or update reference and type sections for the various formations of the Lockport Group (*see* Brunton 2009; Brunton et al. 2009; Brunton, Turner and Armstrong 2009; Brunton and Brintnell 2011; Cramer et al. 2011; Brunton et al. 2012; Bancroft, Kleffner and Brunton 2016). While regional karst mapping was underway between 2005 through 2007, partnerships between the OGS and City of Guelph, Region of Waterloo, and City of Hamilton waterworks staff, and collaboration with chemical stone and aggregate companies and land owners were established to drill deep, cored holes to the regional Cabot Head Formation aquitard through this part of the Niagara Escarpment (Figure 3B, C, D).

The geologic data gathered from these cores were combined with regional outcrop mapping to produce a 3-D geologic model for the City of Guelph and Region of Waterloo Source Water Protection Tier II and Tier III studies and groundwater exploration programs underway by the 3 jurisdictions (Figures 3, 4). This information formed a testable 3-D geologic model for undertaking a regional, bedrock groundwater exploration drilling program from 2009 to 2011, predominantly to the north of Guelph, to investigate the lithofacies character of the stacked dolostones of the early Silurian Lockport Group and the geologic controls on bedrock groundwater-flow zones (key borehole locations are shown in Figure 4). The HQ- and PQ-diameter deep-bedrock cores were logged, photographed and sampled for whole rock and select trace element geochemistry, and isotopes (carbon, oxygen and strontium). Select outcrops and cores were also sampled for conodont biostratigraphy purposes and samples were processed using formic acid to improve conodont element yields in the dolostones (see brief description of chemostratigraphy and biostratigraphy methodologies below; Bancroft 2008, 2014; Bancroft, Kleffner and Brunton 2016; data concerning key stratigraphic logs are provided in Appendixes 1 to 5).

Figure 3. The main components involved in mapping bedrock groundwater-flow zones in relation to sequence stratigraphic and karst features along the Niagara Escarpment region and deeper in the subsurface of southwestern Ontario included Phase 1 – **A)** outcrop and quarry mapping; **B, C, D)** remote and regional drilling (Manitoulin and Fitzwilliam islands to Hamilton regions) and collection of HQ-diameter cores of early Silurian carbonate strata down to regional aquitards; **E)** core logging and sampling for lithogeochemical (whole rock and trace elements) and selected carbon, oxygen and strontium isotopes, and biostratigraphy; Phase 2 – **F)** the use of cameras, varied down-hole geophysical, heat-pulse, and packer tools to characterize aspects of bedrock hydrogeology relative to stratigraphy, sedimentology, sequence stratigraphy; and **G, H)** installation and sampling of multilevel FLUTe™ systems with ports at the identified and generally karstic, bedrock groundwater-flow zone intervals in order to characterize the flow zones and establish a conceptual model for the discrete flow systems to assess water quality, quantity and regional geological controls on potable groundwater distributions.

PHASE 2 – HYDROGEOLOGICAL INVESTIGATIONS

Phase 2 involved hydrogeological investigations of select OGS and municipal-partner bedrock boreholes. These select, deep bedrock holes extended to the regional Cabot Head Formation aquitard and were logged using a combination of well video cameras, spinner meter flow profiling, borehole geophysical (optical-acoustic televiewer, caliper, apparent conductivity, gamma, fluid temperature and conductivity) and heat pulse profiling, packer testing, aqueous geochemical sampling, and FLUTe™ blank liner installation and continuous hydraulic conductivity profiling (Figure 3F, G, H). This latter profiling provided additional hydraulic data to complement existing data and further characterize the stratigraphic position of bedrock hydrogeologic units and karstic groundwater-flow zones. Bedrock wells that possessed karstic groundwater-flow zones had FLUTe™ multilevel (referred to as Water FLUTe™) systems installed (see descriptions of systems: Keller, Cherry and Parker 2014; Keller 2015, 2017).

Prior to hydrogeologic testing and geophysical logging, each of the 30 key boreholes (*see* Figure 4) were inspected with a miniature camera and/or video-logged to evaluate the nature of karst, any potential blockages as a result of the drilling, and to look for physical evidence of groundwater flow from bedrock fractures (movement of particles in water or the observation of air bubbles is evidence of upward or downwards flow). All holes were logged geophysically, except for OGS-DDH7-09, which could not be logged due to strong artesian conditions at this hole.

FLUTe™ hydraulic conductivity profiling was completed at all holes except OGS-DDH7-09. The FLUTe™ hydraulic conductivity profiling method, which is patented, involves everting (opposite of inverting) a blank liner (water tight, nylon fabric) down the borehole, and the progress of the everting can be analyzed to estimate a hydraulic conductivity profile along the borehole (Cherry, Parker and Keller 2007; Keller, Cherry and Parker 2014). As the FLUTe™ liner is everted down the borehole, water is forced to exit into the bedrock formations and the liner covers any permeable intervals present in the rock (returning hole as close as possible to pre-drilling conditions). The descent rate is governed by the bulk transmissivity of remaining permeable bedrock features below the liner. The eversion process reduces the transmissivity of the borehole below the liner and therefore reducing flow of water out of the borehole (reducing the velocity of the liner). The velocity of eversion is measured with a roller, and the excess head pressure, which drives the liner down the borehole, is measured with a transducer. The tension on the liner is also measured during the profiling. As the liner descends and flow-producing zones are sealed, the velocity of the liner decreases, and this is directly proportional to the flow into the zone before it was sealed. A steady-state assumption is used to calculate a transmissivity of the borehole wall over the section traversed by the liner between recorded intervals (see more detailed discussion in Keller, Cherry and Parker 2014). The OGS 2009 and 2010 regional holes that did not have Water FLUTe™ multilevel systems installed have FLUTe™ blank liners so that pre-drilling conditions could be restored.

Flow profiling and high-quality video logging was completed by Lotowater Technical Services, Inc. The flow profiles used a spinner flow meter. The borehole was pumped at 1.5 L/s for 30 minutes prior to profiling to purge, or clear, the hole and attempt to establish steady-state conditions. Flow profiling was also conducted under nonpumping conditions but in many cases the flow was insufficient to activate the minimum threshold velocity of the tool of 0.02 m/s. The video logging included a down-looking scan on the way down and side view video on the way up the borehole. The borehole was pumped with a small pump during video logging to minimize turbidity and induce movement of small particles, so they could be seen moving into or out of bedrock karstic features. The geophysical logging included optical televiewer, acoustic televiewer in select holes, caliper, fluid temperature and conductivity (except at OGS-DDH10a-10), apparent conductivity, and gamma (*see* Figure 3F).

No regional-scale studies prior to this one had utilized the combination of above tools and methods, with FLUTe™ blank liner installation and hydraulic conductivity and transmissivity estimates, to

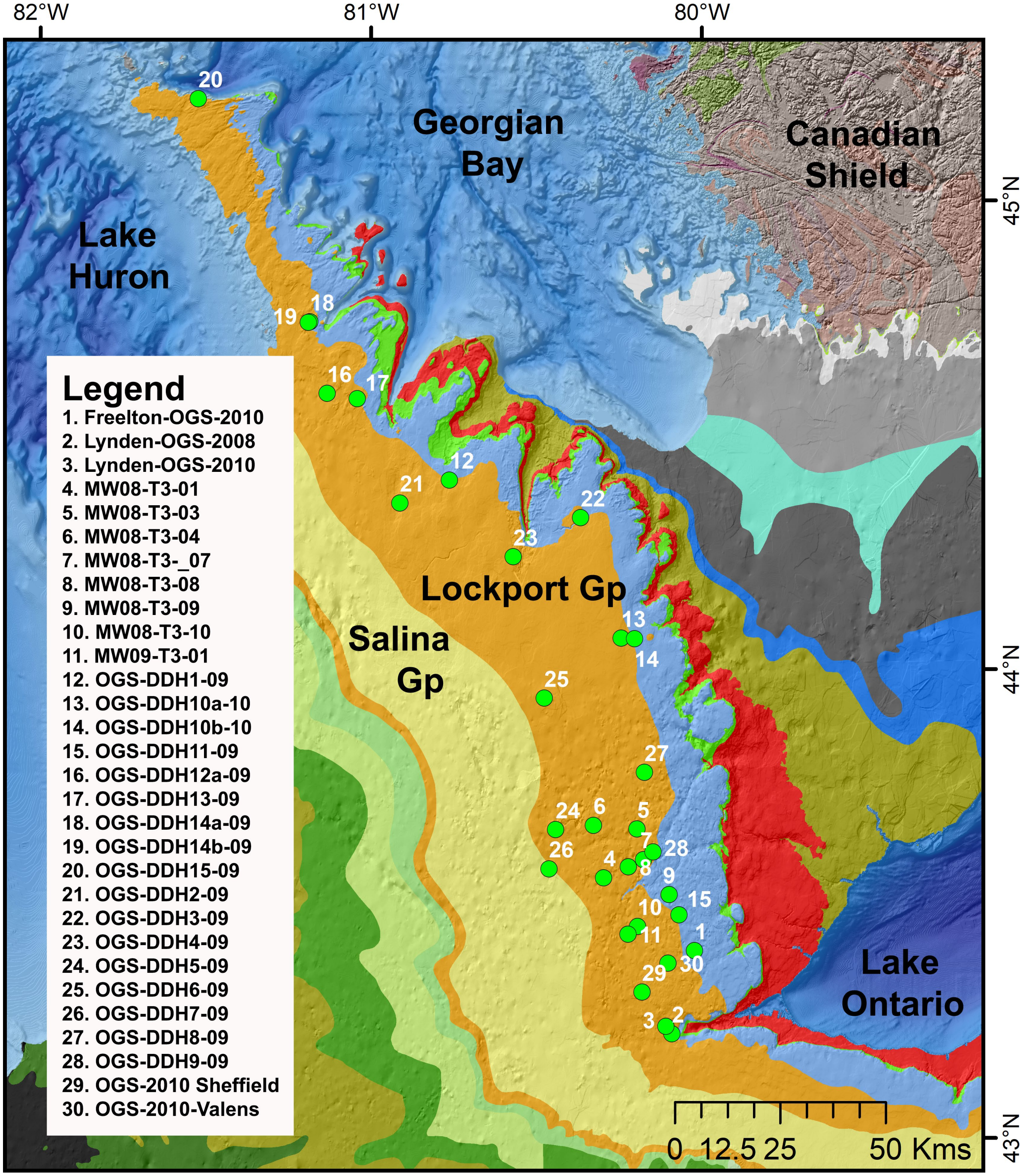

Figure 4. Location map of regional, deep bedrock holes (red dots) through Lockport Group strata of the Niagara Escarpment that have been instrumented with either FLUTe™ liners or Water FLUTe™, Solinst or WestBay multilevel systems. The Freelton, Lynden, Sheffield and Valens wells were investigated in partnership with the City of Hamilton. The MW08-T3 and MW09-T3 holes were instrumented and investigated in partnership with the City of Guelph and University of Guelph-G360 research group. The OGS-DDH-09 and 2010 exploration wells have FLUTe™ or Water FLUTe™ multilevel systems. These wells form the basis for assessing the relationships between hydrochemistry and whole rock and select trace element lithogeochemistry and isotopes to discern discrete flow zones and bedrock aquifers within the early Silurian stacked carbonates of the Lockport Group (*see* Priebe, Neville and Brunton 2014; Priebe and Lee 2016; Priebe, Neville and Brunton 2017). The legend for the OGS bedrock geology layer (*modified after* Armstrong and Carter 2010) that is draped on the OGS bedrock topography surface (Gao et al. 2006, 2007) can be found in Figure 7.

maximize success of delineating key groundwater-flow zones within variably-karstic bedrock formations. The integration of stratigraphic and hydrogeologic analyses helped eliminate uncertainty regarding the delineation and naming of carbonate bedrock groundwater-flow zones, whereby the regional sequence stratigraphic character of the succession may vary significantly and incorrect terms or names applied (e.g., Newburg groundwater zone in Ohio: Santini and Coogan 1982; Strobel and Bugliosi 1991; and numerous examples of southern Ontario bedrock aquifers that are largely interface aquifers, e.g., Singer, Cheng and Scafe 2003).

This field-based protocol for karstic-bedrock groundwater-flow zone mapping considered many of the techniques described from other areas (e.g., Quinlan 1989; Worthington and Ford 1997; Worthington 2002a, 2002b, 2005). This work was undertaken by various consultants and academic researchers (e.g., Lotowater Technical Services, Inc.; Golder Associates Ltd.; Banks Groundwater; FLUTe™ – Flexible Liner Underground Technologies, LLC; the University of Guelph – G360 research group; and Worthington Groundwater Inc.) and OGS staff (Brunton et al. 2010; Lee et al. 2011; Priebe, Brunton and Lee 2012; Priebe, Neville and Brunton 2014; Priebe and Brunton 2016; Priebe, Neville and Brunton 2014, 2017; Priebe et al. 2019; Banks and Brunton 2017).

PHASE 3 – INSTRUMENTATION OF SELECT DEEP BEDROCK HOLES

Phase 3 involved the instrumentation of select, regional, deep bedrock groundwater exploration holes drilled by the Ontario Geological Survey and select holes with municipal partners (*see* Figure 3, 4). FLUTe™ blank liners were initially installed to seal off the various flow zones encountered to undertake flow profiling (*see* Keller, Cherry and Parker 2014).

Subsequently, the blank liners were pulled and replaced by Water FLUTe™ multilevel systems, with ports constructed to sample all key karstic-bedrock flow zones (*see* Figure 3G, H; see field sampling and measurement description in Priebe and Lee 2016; Cherry, Parker and Keller 2007). FLUTe™ blank liners and Water FLUTe™ are predominantly used on contaminant sites and to eliminate cross-contamination while sampling (*see* Cherry, Parker and Keller 2007).

The decision to go forward with the installation of the Water FLUTe™ multilevel system over other multilevel groundwater sampling systems was based upon the findings from the camera and video logs, which revealed the presence of variable karst development within the Lockport Group stacked dolostones, and discussions with Jamie Kristjanson in 2008 (Program Manager, Environmental Monitoring, Waste Management Services, Public Works, Niagara Region) regarding his success with FLUTe™ technologies where karst conduit systems were prevalent in the Lockport Group in the Niagara region. The Water FLUTe™ MLS system was chosen because many of the karstic intervals were identified as flow zones and the other 2 main MLS systems (Solinst and WestBay) are not able to have ports within karstic intervals.

This is the first regional-scale bedrock groundwater mapping program to exclusively use FLUTe™ technologies to enable sampling of discrete, shallow to deep (>200 m), potable, karstic bedrock groundwater-flow zones. A more detailed overview of the FLUTe™ profiling method and Water FLUTe™ system is summarized in papers on the FLUTe™ website (http://www.flut.com/; *see also* Cherry, Parker and Keller 2007; Keller, Cherry and Parker 2014). The results of this work formed part of a PhD study undertaken by Elizabeth Priebe of the Ontario Geological Survey on the local to regional hydraulic conductivity and transmissivity of the Lockport Group stacked dolostones along part of the Niagara Escarpment, southern Ontario (*see* Priebe, Neville and Brunton 2014, 2017; Priebe et al. 2019; Priebe 2019).

Downhole Geophysical Survey Methodology

Natural gamma-ray logs provide a measure of the natural gamma-ray activity of a given sedimentary rock formation produced by the radioactive decay of naturally occurring isotopes of uranium, thorium and potassium. The measurements, which are often in counts per second or counts per minute, relate to differences in the abundance of radioactive elements in different minerals (usually phosphatic or clay minerals, and/or sulphides and other secondary diagenetic and basinal fluid Mississippi Valley Type (MVT) minerals, such as galena, sphalerite and pyrite). The radioisotopes tend to occur as exchange cations associated with those minerals.

Appendix 2 contains borehole logs for 15 of the key regional, deep bedrock cored holes across the Niagara Escarpment region that form part of the multiyear bedrock aquifer characterization mapping project by the OGS. These Water FLUTe™-instrumented wells provide the framework for the collection of hydrochemical and hydraulic head data that, in relation with the sequence stratigraphic model, has led to a better understanding of the geologic controls on groundwater flow and water quality and, ultimately, to supporting the delineation of local and subregional aquifers and aquitards across the study area.

The data displayed in the logs were compiled by a subcontractor (Golder Associates Ltd.) and provide continuous optical and acoustic televiewer images, natural gamma, caliper, apparent conductivity, flow profile (static), FLUTe™ hydraulic conductivity, FLUTe™ transmissivity, FLUTe™ Q/dh and the positions of the main FLUTe™ multilevel port positions that were designed after delineating where the main bedrock groundwater-flow zones were present. Details that relate the FLUTe™ profile data and spinner flow profile data are beyond the scope of this study and will be covered in more detail in future hydraulic conductivity-focused studies of some of the main, regional, bedrock groundwater-flow zones by the OGS under the direction of Elizabeth Priebe.

The design of each Water FLUTe™ system and selection of sampling port intervals was accomplished by evaluating all available borehole geological, geophysical and hydraulic testing data. Hydraulic conductivity testing, including flow profiling, packer testing and select dye tracer and pumping tests, are outlined in Brunton et al. (2010) and Lee et al. (2011). The final phase of hydraulic conductivity characterization work, completed in the winter of 2011, included hydraulic conductivity profiling (K-profiling) using FLUTe™ liners.

An example of the borehole geophysical work, completed at each of the key OGS regional boreholes in 2010, including video camera and spinner logger, optical and acoustic televiewer, natural gamma, conductivity, caliper and heat pulse flow meter at select locations, is shown in Figure 5. Water FLUTe™ sampling ports were designed to target discrete water-bearing zones. In general, ports were placed where discrete water-bearing zones were confirmed using as many lines of evidence as possible. Each Water FLUTe™-bearing well contains 3 to 5 ports with a total of 44 ports at all 12 sites. The installation of pressure transducers to measure hydraulic head, Water FLUTe™ multilevel systems, sampling of groundwaters, and establishment of precipitation monitoring stations is summarized in Lee et al. (2011). General methodologies and techniques that combine downhole geophysics, cross-formational flow measurements, and the use of FLUTe™ systems are discussed in Paillet (1993, 1998, 2000, 2001, 2013), Paillet and Crowder (1996), Cherry et al. (2007), Keller, Cherry and Parker (2014) and Keller (2015, 2017). The utility of gamma-ray logs for interpreting the regional variations in Silurian stratigraphy at the formation and member ranks are summarized in the interpretation sections of this report related to regional stratigraphy and sequence stratigraphy.

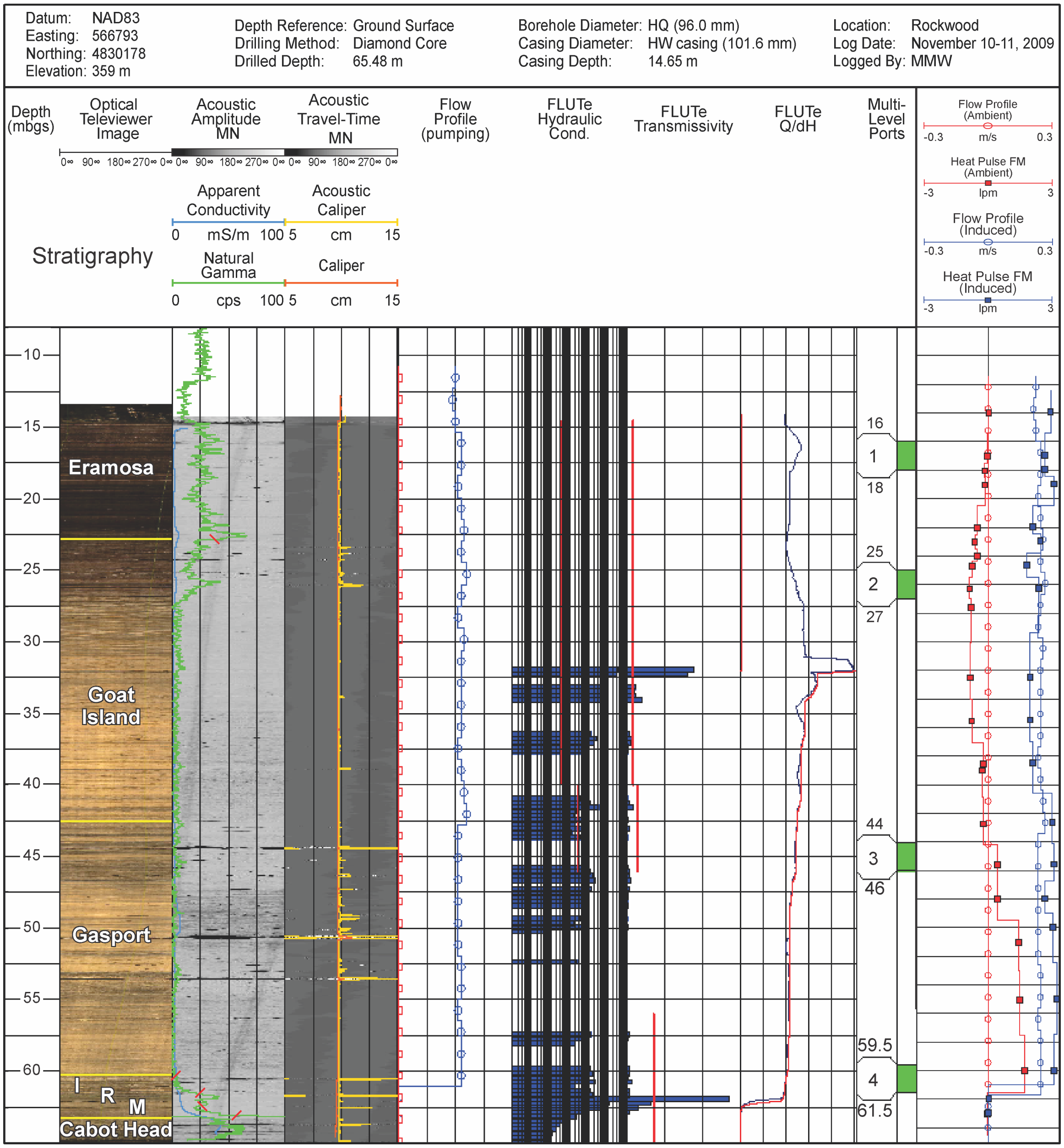

Figure 5. Graphic log of OGS-DDH-9-09 showing geologic (optical and acoustic televiewer profiles), geophysical (gamma, conductivity and caliper logs) and hydrogeological data (Water FLUTe™ profiling, heat pulse metre profiling; packer test data not shown) from a well in the Rockwood area, southern Ontario (stratigraphy updated from Lee et al. 2011). IRM = Irondequoit, Rockway and Merritton formations. The Merritton Formation is stratigraphically equivalent to the upper Fossil Hill Formation at type section on Manitoulin Island. The red lines on the green gamma log profile show positions of formation contacts. Note difficulty of simply relying on gamma logs (relatively flat gamma ray signature when encrinites are similar) to pick the Gasport and Goat Island contacts. Note how the acoustic televiewer log highlights the karstic fractures (black areas), which predominantly occur at and/or near formation contacts and within cycles of formations (e.g., at least 3 distinct zones in middle to upper Gasport, upper Goat Island and near Irondequoit–Gasport contacts). Video logs for each of the regional boreholes verify and support karstic origin of majority of key groundwater-flow zones and borehole integrity or fracture distributions. The heat pulse flow profile data shown on far right were collected at a different time and clearly shows a net upward flow in the borehole from a deep horizontal karstic fracture at base of the Gasport Formation to a key bedrock solution-enhanced fracture at port 3 (upper Gasport Formation) and a net downward flow in the well (from Reformatory Quarry member of Eramosa Formation and Ancaster Member of Goat Island Formation) to area delineated by port 3. Preliminary groundwater sampling at this well demonstrates a differentiation of the upper and lower water-bearing zones. The nature of this complex groundwater-flow system would be difficult to discern using more standard, nested piezometer installations and single packer tests.

Lithogeochemistry

Detailed sampling along selected intervals of approximately 40 cores and selected outcrops across the study area was undertaken between 2007 and 2012. The sampling was on a variable scale (10 cm to metre scale), depending upon the complexity and thickness variations of major lithofacies. Sampling also took place below and above major lithologic contacts representing sequence stratigraphic boundary surfaces. Much of the sampling undertaken between 2009 and 2012 also coincided with stratigraphic intervals where carbon and oxygen isotope and select strontium isotope samples were obtained in selected cores (see discussions below). The compilation of a regional lithogeochemical database of key early Silurian formations has been underway since 2004 and has multiple purposes, including 1) the geochemical characterization of dolostones for industrial minerals and aggregate applications; 2) the provision of formation-scale data in order to compare lithogeochemistry data to surface and groundwater geochemistry to help distinguish discrete and evolved, potable, bedrock groundwater-flow systems within the Paleozoic cuestas in southern Ontario; and 3) the systematic compilation of lithogeochemistry in combination with select chemostratigraphic isotopes analyses (C, O, and Sr) and biostratigraphy to improve our ability to distinguish various stratigraphic units across the study area.

The total number of sample analyses processed as part of this regional study was 5540, broken down as follows: 160 samples in 2007; 256 samples in 2008; 865 samples in 2010; 1925 samples in 2011; 1193 samples in 2013; 196 samples in 2015; 474 samples in 2017; and 471 samples in 2018. The test codes and descriptions for the sample analyses include IAC-100 ICP-AES with closed vessel multi-acid digestion; IMC-100 ICP-MS with closed vessel multi-acid digestion; IRC-100 carbon and sulphur; SAM-AGM agate mill sample preparation; SOL-CAIO closed vessel multi-acid digestion; SOL-PLN pre-leach digestion of Ca-rich samples; XRF-M01 XRF major elements; XRF-T02 XRF trace elements; and XRF-T03 XRF trace elements. The methodologies of the various sample preparation techniques are described in Burnham et al. (2002); Burnham and Schweyer (2004); Keating and Burnham (2012, 2013); and Amirault and Burnham (2013). The lab work is close to completion and the data will be published as an OGS Miscellaneous Release of Data or Open File Report within the next year.

Conodont Biostratigraphy Methodology

Improvements in the preparation of conodonts (consisting of carbonate fluorapatite-francolite) in dolostones, using formic acid to enable extraction of more intact conodont elements and higher element yields per sample, was initiated in the 1980s by Jeppsson (e.g., Jeppsson, Fredholm and Mattiasson 1985; Jeppsson 1987; Jeppsson and Anehus 1995, 1999). Prior to this approach the acetic acid residue method was employed to extract conodont elements from carbonate rocks (Graves and Ellison 1941). Jeppsson had determined through controlled experiments that many conodont elements were damaged or destroyed using the acetic acid processing method and that this was especially apparent in processing dolostone versus limestone samples. This, in part, is why there is generally poor conodont biostratigraphic control of the predominantly dolomitized Silurian carbonate succession in Ontario and the midcontinent region of North America (see discussion and data in Kleffner 1989; Kleffner et al. 2009; Barrick et al. 2010), with some exceptions for the Eramosa Formation (Stott et al. 2001; von Bitter and Purnell 2005; von Bitter et al. 2007; Jones, Purnell and von Bitter 2009).

In general, biostratigraphy is a robust method for chronostratigraphic correlation, but conodont biostratigraphic resolution is limited by the number of specimens that can be collected from a given stratigraphic interval and by endemism of the conodont faunas. Bancroft (2008, 2014) is among the first to have used a buffered formic acid approach to enhance conodont yields in the Silurian dolostones of Ontario and elsewhere in the midcontinent area. The combination of refined processing techniques and an increase in the number of studied stratigraphic sections globally over the past few decades, has resulted in significant revisions of Silurian conodont taxonomy and biostratigraphy (e.g., Jeppsson 1997; Jeppsson, Eriksson and Calner 2006; Männik 1998, 2007a, 2007b). Conodont samples processed (ranging in weight from 0.5 to 2 kg) as part of this southern Ontario regional bedrock groundwater study utilized the refined standard techniques of Jeppsson (e.g., Jeppsson, Fredholm and Mattiasson 1985; Jeppsson 1987; Jeppsson and Anehus 1995, 1999).

Ongoing chemostratigraphy and biostratigraphy studies of parts of the Lockport Group (Eramosa and Guelph formations) have demonstrated that the Eramosa Formation is of Wenlock (mid-Sheinwoodian) age and that the entire Lockport Group is most likely of Wenlock age (*see* Bancroft 2008, 2014; von Bitter, Bancroft and Purnell 2012; Bancroft, Kleffner and Brunton 2016).

Conodont biostratigraphy data, in combination with the regional sequence stratigraphic approach and chemostratigraphy, has improved our ability to map and predict the geological controls and positions of bedrock groundwater-flow zones.

Chemostratigraphy Methodology

Approximately 5200 carbon and oxygen isotope analyses were processed from 24 cores from Manitoulin Island, in the northern part of the study area, to Niagara Falls, in southern part of study area. The sampling was on a variable scale (10 cm to metre scale), depending upon the complexity and thickness variations of major lithofacies. Sampling also took place below and above major lithologic contacts representing sequence stratigraphic boundary surfaces.

All carbonate carbon ($\delta^{13}C_{carb}$) isotope samples collected for this project were drilled from micritic matrix, where possible, and sent to the University of Kansas W.M. Keck Paleoenvironmental and Environmental Stable Isotope Laboratory (KPESIL) for analysis. Samples were measured (20 µg to 80 µg) and heated under vacuum at 200°C for 1 hour to release any volatile organic compounds. To dissolve the carbon of calcite, carbonate powders were reacted under vacuum with 3 drops of prepared 100% phosphoric acid for 4 minutes (or reacted for 12 minutes to dissolve the carbon of dolomite) at 75°C using a Kiel Carbonate Device III, and the carbon dioxide (CO_2) released was trapped cryogenically and transferred to a Finnigan MAT253 isotope ratio mass spectrometer for analysis.

Data are reported using the per mil (‰) notation relative to the Vienna Pee Dee Belemnite (VPDB) standard (Craig 1957). Precision and calibration of data were monitored through routine analysis of National Bureau of Standards (NBS-18 and NBS-19) and an internally calibrated calcite standard. Reproducibility for values obtained was checked by replicate analysis of laboratory standards and typically yielded an R^2 value of 0.9995 or better.

CARBON ISOTOPES

The realization that the primary marine carbon isotopic $\delta^{13}C_{carb}$ signature is relatively well-preserved in marine carbonates (Munnecke, Samtleben and Bickert 2003; Bickert et al. 1997; Saltzman and Thomas 2012), the utility of carbonate carbon ($\delta^{13}C_{carb}$) isotope excursions (chemostratigraphy; Figure 6) has been demonstrated to be a valuable method for global chronostratigraphy correlation (Saltzman 2005; Saltzman and Thomas 2012), especially when combined with high-resolution biostratigraphy (e.g., Kaljo, Kiipli and Martma 1998; Kaljo et al. 2003; Munnecke, Samtleben and Bickert 2003; Calner, Jeppsson and Munnecke 2004; Cramer et al. 2011) and sequence stratigraphy. Seven major carbonate carbon ($\delta^{13}C_{carb}$)

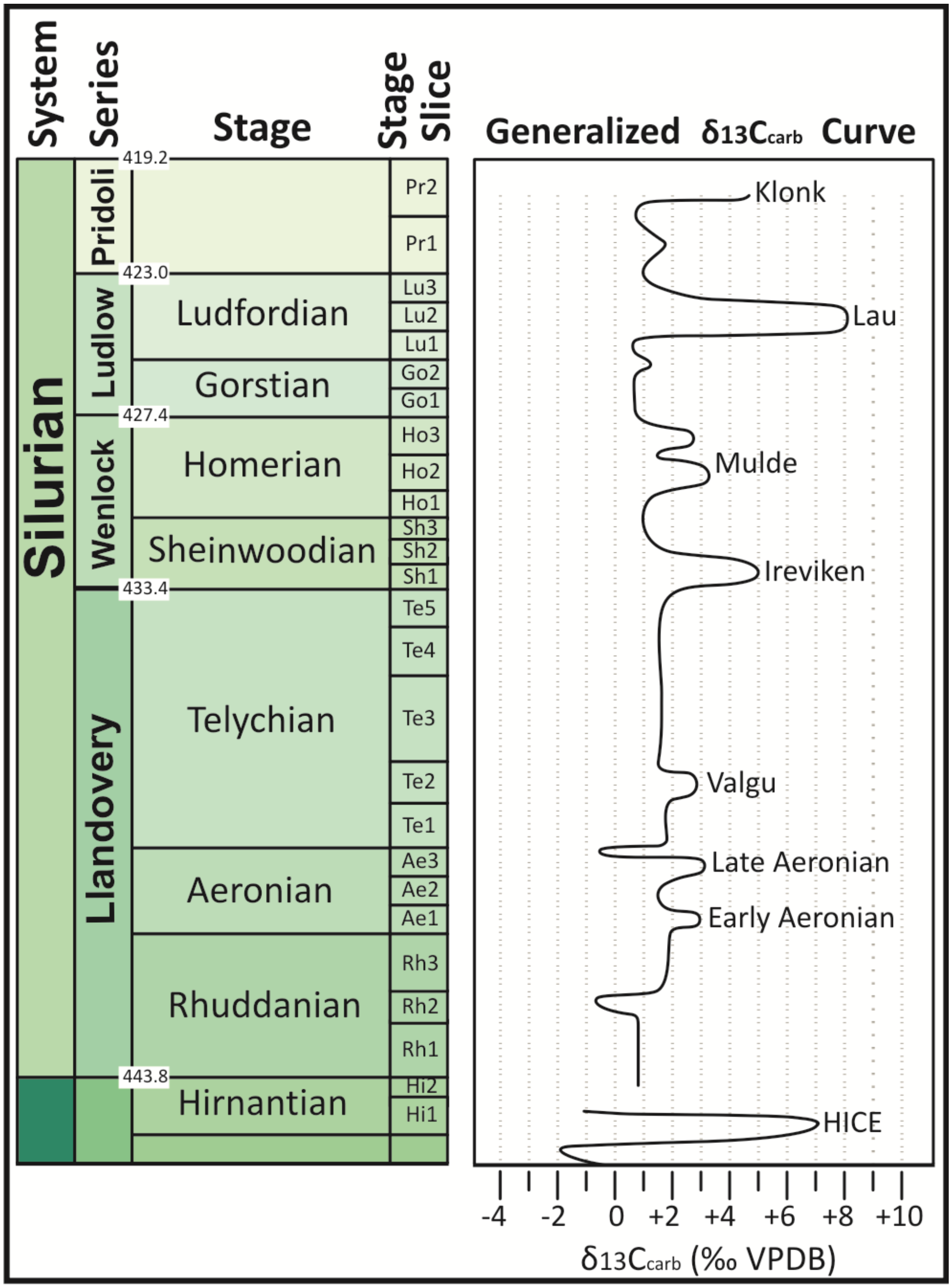

Figure 6. Carbonate carbon ($\delta^{13}C_{carb}$) isotope profile for the Late Ordovician and Silurian periods. The Late Ordovician and Silurian systems and series dates are from Gradstein et al. (2012). Stage slices and carbonate carbon ($\delta^{13}C_{carb}$) isotope data for the Ordovician part of section is from Bergström et al. (2009), and the Silurian from Cramer et al. (2011). The names and relative ages of 7 positive carbon isotopic excursions and bioevents have been recognized on a global scale and have been compiled by several researchers since the late 1980s and early 1990s (*see* Jeppsson 1990, 1997, 1998; Aldridge, Jeppsson and Dorning 1993; Jeppsson, Aldridge and Dorning 1995; Jeppsson and Aldridge 2000; Jeppsson and Calner 2003; Cramer et al. 2011; Melchin, Sadler and Cramer 2012).

excursions serve as chronostratigraphic markers for the Silurian Period (*see* Figure 6; *see* Cramer et al. 2011; Melchin, Sadler and Cramer 2012).

Carbon isotopic profiles from the regional cores reveal that the Llandovery (2 Aeronian, 1 Telychian) and Wenlock (Ireviken) carbon isotopic excursions are present in the northern parts and southernmost regions of the study area, where a greater thickness of Llandovery-age carbonates and mixed siliciclastics are preserved. In the central region of the Niagara Escarpment cuesta in southwestern Ontario, much of the early Silurian Aeronian and Telychian succession is missing as a result of intermittent tectophases and the dynamics between marine sedimentation and erosion resulting from forebulge migration onto the Laurentia craton on the far-field side of the Appalachian foreland basin in southwestern Ontario and New York State (*see* Brett, Goodman and LoDuca 1990; Brunton et al. 2012) and to the south, in Ohio and Kentucky (Ettensohn and Brett 1998, 2002; Ettensohn et al. 2013).

OXYGEN ISOTOPES

Although the oxygen isotope profiles for the regional boreholes are plotted adjacent to the carbon isotope cores, they were not used to assist in regional correlations and understanding of the tectonostratigraphic relationships of the early Silurian succession across the study area.

Study Area

The present study area includes southwestern Ontario (west of the Niagara Escarpment margin) and Manitoulin and Fitzwilliam islands in Lake Huron, parts of Lake Erie and select boreholes in the adjacent state of Michigan, USA (Figure 7).

Major outcrop sections of Lockport Group strata are concentrated in an arcuate belt that follows the Niagara Escarpment cuesta scarp, following a northwesterly direction from Niagara Falls to Cockburn Island, Ontario, and extending into the Upper Peninsula of Michigan. Key outcrops in this study include those located near Niagara Falls, city of Hamilton, Cambridge, City of Guelph, Elora, Fergus, Duntroon and the Bruce Peninsula. Work in Michigan was a part of Brintnell's BSc and MSc thesis studies, where selected cores were logged and sampled at Western Michigan University in Kalamazoo and quarries were visited in the Upper Peninsula of Michigan (Brintnell et al. 2009; Brintnell 2010, 2012).

Drill cores used to examine Lockport, Clinton and Medina Group strata in the subsurface of southwestern Ontario are from various sites located along the Niagara Escarpment but are more heavily concentrated in the Guelph–Cambridge–Waterloo area (*see* Figure 7; Brunton 2009; Brintnell et al. 2009; Brunton et al. 2010; Brintnell 2012; Brunton et al. 2012). Additional drill cores from the subsurface of southeastern and northwestern Michigan were used to evaluate the regional character of Lockport Group strata from some classic studies (*see* Figure 7; *see* Brintnell 2012; and historic papers of Sanford 1969a, 1969b; Gill 1973, 1977a, 1977b, 1979, 1985; Briggs and Briggs 1974; Mesolella et al. 1974; Huh, Briggs and Gill 1977; Briggs et al. 1980; and Friedman and Kopaska-Merkel 1991).

Geologic Setting

In a traditional sense, the study area straddles 2 sedimentary basins. The northwestern part of the study area includes the southeastern to north-central parts of the Michigan (intracratonic) structural basin, whereas the southeastern part of the study area lies along the distal northwestern margin of the Alleghany

Basin (sub-basin), which is part of the much larger Appalachian foreland basin (Figure 8). Between these 2 basins, and following the axis of southwestern Ontario, is a broadly linear northeast-southwest-trending zone that delineates the position of the Appalachian foreland basin forebulge zone (commonly referred to as the Algonquin Arch), separating the Laurentia intracratonic regions (e.g., Wisconsin–Michigan,

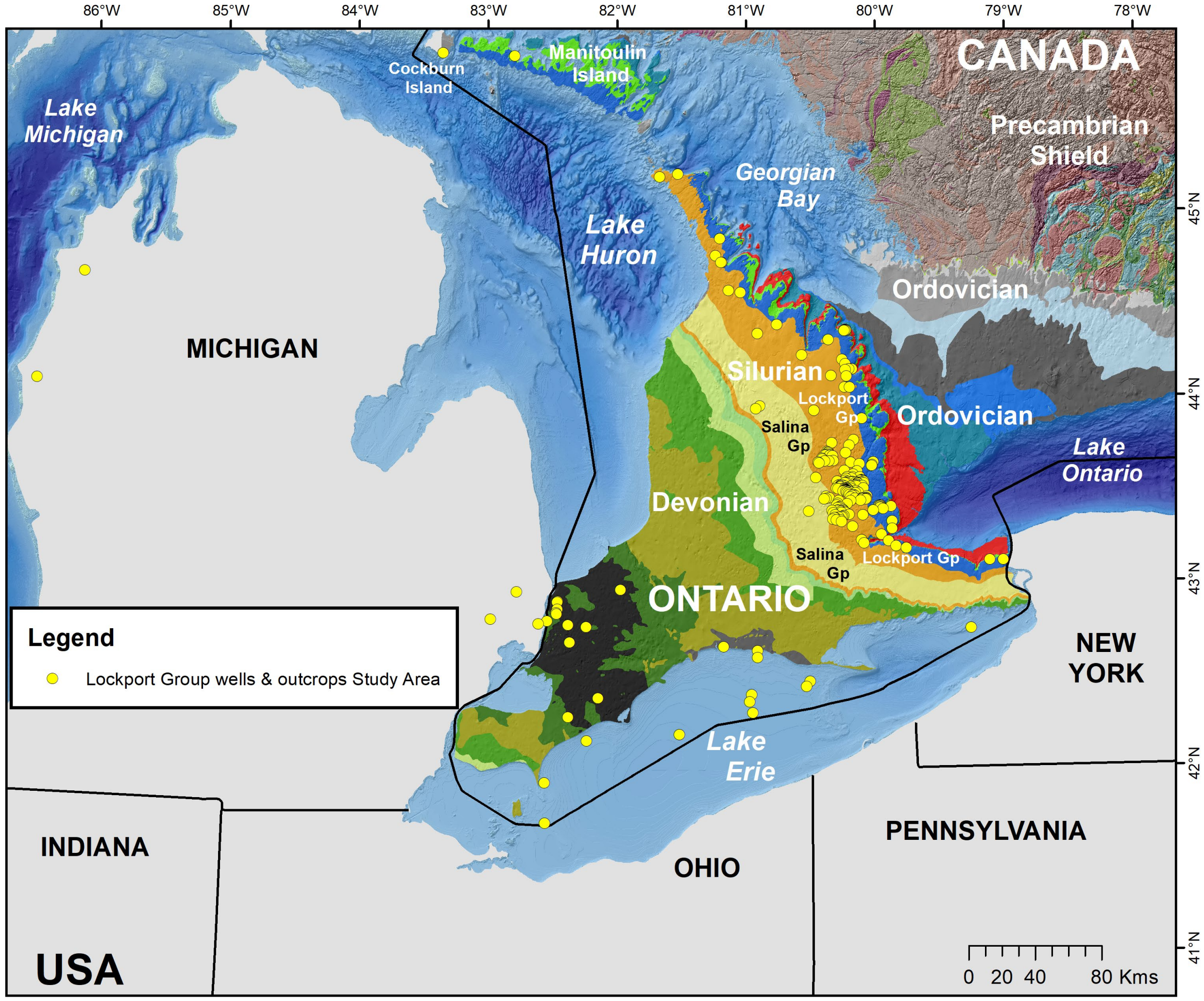

Figure 7. Location map showing Paleozoic bedrock geology and topography, and locations of key deep and shallow bedrock diamond-drill holes (DDHs) and test wells (exploration holes drilled by HudBay Resources for lead-zinc Mississippi Valley Type (MVT) ore deposits) that were examined to characterize the Lockport Group strata along the outcrop–subcrop belt of the Niagara Escarpment and extending into the deeper subsurface of southwestern Ontario and Michigan, USA (*see* GRS 13 and 19 appendixes for stratigraphic logs of boreholes).

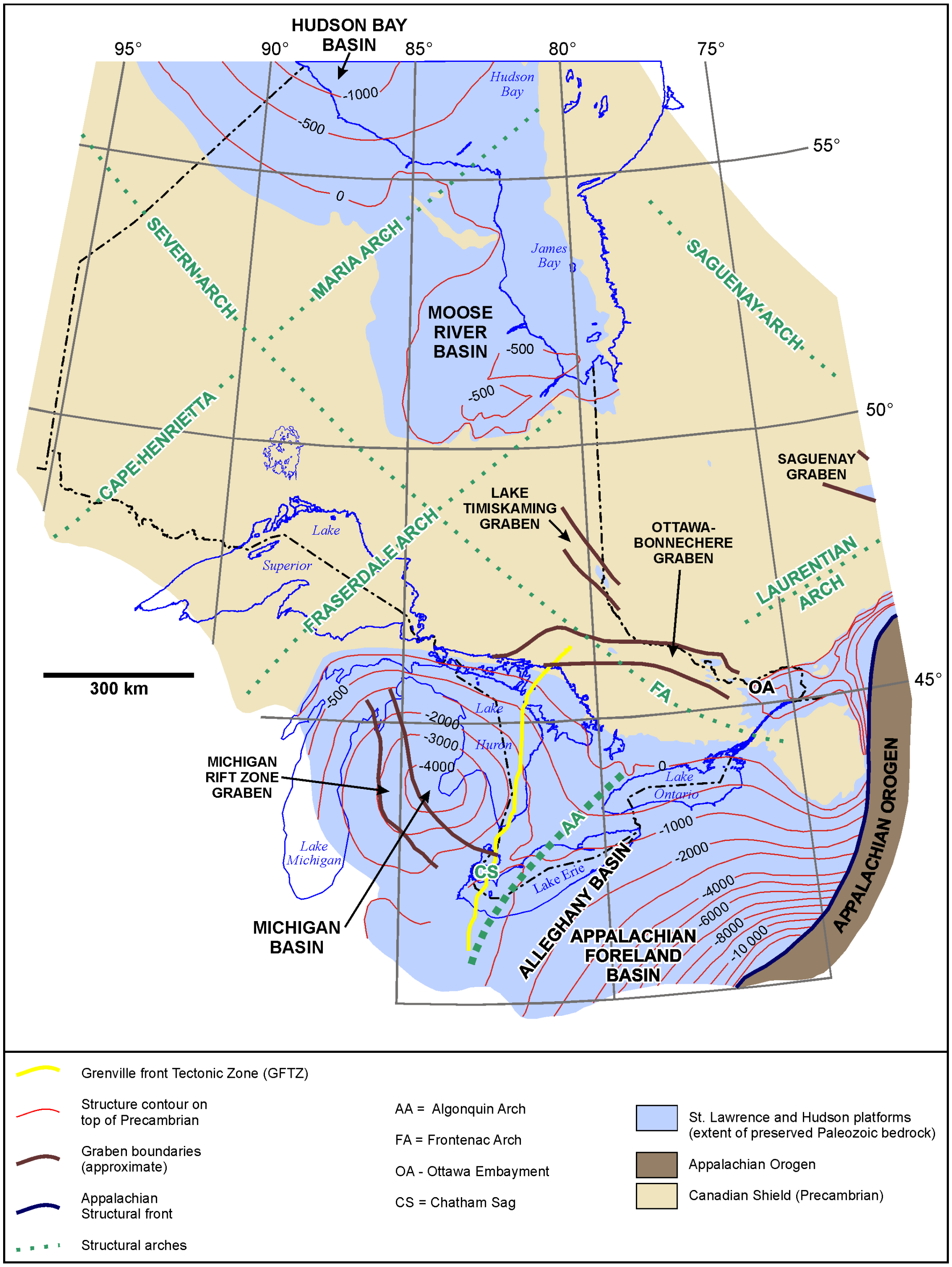

Figure 8. Tectonic and structural elements associated with Phanerozoic strata of the Michigan structural basin and adjacent Appalachian foreland basin in southern Ontario and adjacent US states (*modified from* Sanford, Thompson and McFall 1985). Contours show thicknesses of Phanerozoic rocks in metres. Also shown are the position of the Proterozoic-age midcontinent rift (Michigan Rift Zone) relative to the younger Grenville Front Tectonic Zone (yellow line) and the position and orientation (see contour trend) of the Chatham Sag (CS). The Algonquin Arch (AA), or forebulge, area is positioned further to the south than has been traditionally shown in other publications (e.g., Brett, Goodman and LoDuca 1990; Johnson et al. 1992; Armstrong and Carter 2010) to reflect the sequence stratigraphic characteristics of upper Clinton Group and Lockport Group strata. Regional drilling and integration of subsurface data between Hamilton and Cambridge–Guelph has enabled improved understanding of the changing positions of forebulge migration (Algonquin Arch) during deposition of Clinton and Lockport Group strata in southwestern Ontario (*modified from* Brunton and Piersol 2009; *see* Brunton et al. 2012).

Lake Huron region) from the intermittent intracratonic far-field downwarping and upwarping events associated with tectophases within the Appalachian foreland basin (*see* discussions and descriptions of forebulge tectonics and tectophase concept for this region in Jacobi 1981; Quinlan 1987; Quinlan and Beaumont 1984; Sanford, Thompson and McFall 1985; Jamieson and Beaumont 1988; Brett, Goodman and LoDuca 1990; Sanford 1993; Ettensohn and Brett 1998, 2002; Ettensohn 2008; Figure 9). Two structural highs, traditionally referred to as the Algonquin and Findlay arches, make up this complex tectonic zone, which is separated by a local, saddle-like structural low called the Chatham Sag (Kay 1942; Cohee 1948; labelled as CS in Figure 8).

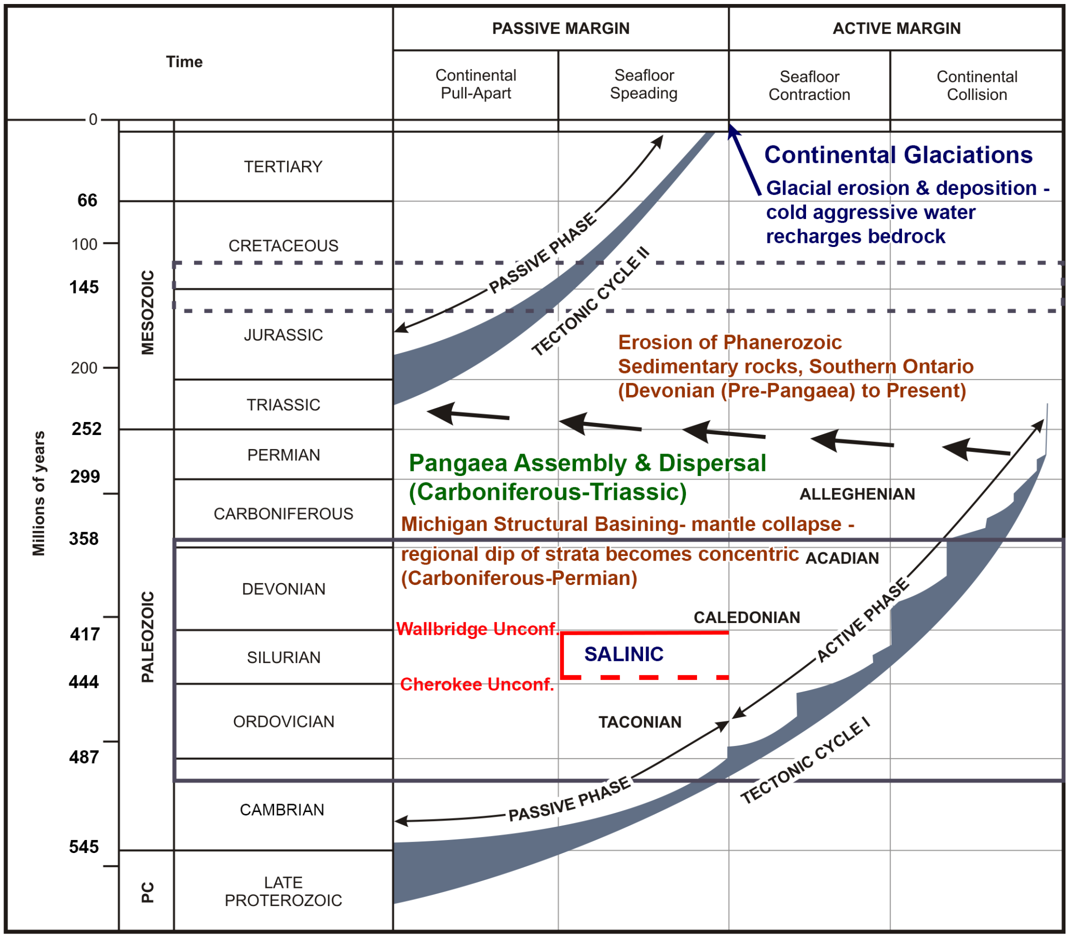

Figure 9. Tectophases for eastern margin of Laurentia during the Phanerozoic (pre-Pangaea and post-Pangaea; *modified from* Sanford, Thompson and McFall 1985) showing temporal range of Salinic Orogeny (*see* Boucot 1962; Johnson 1971; Dunning et al. 1990; Ettensohn and Brett 1998, 2002; Brand, Azmy and Veizer 2006) and associated spatial and temporal forebulge migration phases that influenced Silurian stratigraphic architecture in southwestern Ontario. The Salinic Orogeny time interval (red box) has a dashed lower boundary because orogenesis and forebulge migration phases most likely began in Late Ordovician and continued episodically through the Silurian Period. The grey band widths represent relative tectonic intensity during various tectophases, and far-field forebulge migration activity or responses along the western margin of the Appalachian foreland basin (*see* discussions in Boucot 1962; Jacobi 1981; Quinlan and Beaumont 1984; Jamieson and Beaumont 1988; Mitrovica, Beaumont and Jarvis 1989; Ettensohn 2008; and Ettensohn and Brett 2002). PC = Precambrian. Grey dotted lines highlight Mesozoic interval of kimberlite emplacement following breakup of Pangaea. The relative significance of tectophase activity and regional unconformities evident in the early Silurian stratigraphic succession in southwestern Ontario are not adequately reflected for the Silurian Period. Terrains along eastern Laurentia and regions on the far-field side of the Appalachian foreland basin within Laurentia (representing southern Ontario and Michigan today) record evidence of episodic volcanism with associated bentonites, regional-scale earthquakes with associated seismites, and regional unconformities related to forebulge migration and relaxation.

Based upon the nature of disconformities within the early Silurian Clinton Group and Lockport Group strata from Niagara Falls and Lake Erie into southwestern Ontario and Michigan (*see* Brett, Goodman and LoDuca 1990; Brett et al. 1995; Brunton 2009; Brintnell et al. 2009; Brunton and Brintnell 2011; Brunton et al. 2012; Brett, Brunton and Calkin 2018), it is apparent that this region was subjected to 1) short-lived tectophases and forebulge migration and relaxation phases (Brunton et al. 2012); 2) regionally extensive earthquakes and resultant seismite deposits over thousands of square kilometres (e.g., Brett, Goodman and LoDuca 1990; Kahle 2002; Onasch and Kahle 2002; Brunton, Dekeyser and Coniglio 2005; Brunton 2009; Brunton et al. 2012; McLaughlin and Brett 2006; Ettensohn et al. 2010; Wallace and Eyles 2015); and 3) ash falls from volcanoes in collisional terrains along eastern Laurentia, resulting in Silurian bentonite deposits on the far-field side of the Appalachian foreland basin (Brunton et al. 2012; this study; *see* temporal span of Late Taconic and Salinic tectophases in Figure 9).

MICHIGAN STRUCTURAL BASIN

The present-day, erosional outline of the Michigan structural basin is roughly circular and covers an area of 196 400 km^2. It is centred in the lower peninsula of the state of Michigan, where its basement attains a maximum depth of approximately 5 km (Figure 8; Telford 1978; Howell and van der Pluijm 1990). From Michigan, the margins of the Michigan structural basin extend into the neighbouring states of Wisconsin, Illinois, Indiana, Ohio, and the western part of southwestern Ontario. In Ontario, the Michigan structural basin is bounded by the Canadian Shield to the north and east and by the northeast-southwest-trending Algonquin Arch (more correctly referred to as a forebulge region that was reactivated during the final phases of Taconic and Salinic tectophases) to the south (*see* Figures 8, 9). The inferred boundary, or edge, of the Michigan Basin is a karstic, erosional scarp face and geomorphologic cuesta landform and is not defined by its depositional or tectonic character. The Algonquin Arch flexure or forebulge region affected the continuity of sedimentation from the Appalachian foreland basin through to the interior of Laurentia (Michigan structural basin) throughout Paleozoic time. Some authors suggest that the differential uplift and downwarping combined with sea level fluctuations in this forebulge region resulted in differential subsidence of individual fault-bounded megablocks: the Bruce megablock, north of the arch, relative to the Niagara megablock, located to the south of the arch (Sanford, Thompson and McFall 1985; see alternative explanations in Quinlan and Beaumont 1984; Jamieson and Beaumont 1988; Mitrovica, Beaumont and Jarvis 1989; Ettensohn and Brett 1998, 2002; and Ettensohn 2008).

The underlying factors that initiated the development of the Michigan structural basin remain controversial, although it is suspected that mantle plume activity may have played a significant role in determining its saucer-like form, either via localized lithospheric thinning (Mitrovica, Beaumont and Jarvis 1989) or lithospheric drawdown associated with the cooling of plume material (Howell and van der Pluijm 1990; Bond and Kominz 1991; Kominz and Bond 1991). Alternatively, others have attributed its early development to intraplate stresses reflecting the far-field compressional effects of craton-margin tectonics (Quinlan 1987; Beaumont, Quinlan and Hamilton 1988).

It is generally agreed upon, based on regional stratal patterns, that the Michigan structural basin began subsiding by at least the Late Cambrian, and thereafter experienced intermittent episodes of subsidence into the Early Jurassic (pre-Pangaean and post-Pangaean phases; Sloss 1988; Howell and van der Pluijm 1990). The nature of subsidence experienced in the Michigan structural basin during this time varied significantly. Perhaps most notably, Coakley and Gurnis (1995) demonstrated that during the Late Ordovician, the Michigan structural basin departed from its purported bull's eye pattern of subsidence to a more uniform, platform-like pattern, tilting unidirectionally toward the east. The authors attributed this phenomenon to regional-scale lithospheric deflection associated with subduction-related mantle flow that accompanied the Taconic Orogeny and associated tectophases, in a manner like that described for the Cretaceous Western Interior Basin (Beaumont, Quinlan and Stockmal 1993). Tectonic-induced subsidence of the Michigan structural basin was reactivated during the Silurian, coinciding with renewed tectonic loading in eastern Laurentia (now eastern North America), arguably associated with the Salinic I, and II orogenies, or disturbances, which were also responsible for increased rates of flexural subsidence (as recorded by accumulations of transgressive marine deposits) in the adjacent Appalachian Basin (*see* Ettensohn and Brett 2002; Brunton et al. 2012; Brett, Brunton and Calkin 2018).

Brintnell (2012) and Brunton et al. (2012) regional lithofacies mapping of the Lockport Group strata and older Silurian Cabot Head Formation to Fossil Hill Formation lithofacies of the underlying Clinton and Medina groups (Brintnell et al. 2009; Brintnell 2010) support a revised view of the early Silurian carbonate ramp, demonstrating that it also tilted towards the Appalachian foredeep in an easterly to southeasterly direction. The authors identified more marginal marine facies in the west-central part of the Michigan structural basin, becoming more open marine in fossil content and sedimentary fabrics and stratigraphic architecture from northwest to southeast into southwestern Ontario. Evidence of both temporal and spatial changes in the regional-scale erosional cut-downs, due to relatively short-lived tectophases, forebulge migration and associated sea level fluctuations, includes the presence of seismite beds in Clinton Group strata (specifically, in the DeCew Formation; Brett, Goodman and LoDuca 1990) and overlying Lockport Group strata (seismite beds in the Reformatory Quarry member of the Eramosa Formation in outcrops from Bruce Peninsula to Niagara Falls and into Ohio and southern Michigan: Kahle 2002; Onasch and Kahle 2002; Brunton, Dekeyser and Coniglio 2005; Brunton et al. 2009; Brunton et al. 2012; Wallace and Eyles 2015). A newly discovered bentonite bed at the DeCew–Gasport formational contact in the Hamilton area provides evidence for Wenlockian volcanism along eastern Laurentia during deposition and/or erosion of the Lockport Group strata. The significance of the cut-down of the Gasport Formation surface and onlap of Goat Island and Eramosa lithofacies on thickened Gasport composite reef mounds in Cambridge–Guelph areas has significant implications on the true nature of deeper subsurface Guelph "Pinnacle reefs". The relatively short-lived temporal and spatial constraints and regional extent of seismite beds in the DeCew and Eramosa formations supports the interpretation of a renewed active phase of tectonism along the eastern margin of Laurentia referred to as the Salinic I and II Disturbances or Salinic Orogeny (*see* Brand, Azmy and Veizer 2006; Brunton et al. 2012; *see* Figure 9).

APPALACHIAN FORELAND BASIN

In total, the Appalachian Basin is approximately 2050 km long, extending from southern Quebec and southeastern Ontario to northeastern Alabama, with a maximum width of 530 km, and covers an area of 536 000 km^2 (*see* Figures 8 and 10; Colton 1970). The Appalachian Basin is bounded by the Algonquin and Findlay and Cincinnati arches (forebulge regions) in and to the south of the study area (Ettensohn 2008; Lavoie 2008; Ettensohn et al. 2013; Figure 10). The total thickness of Paleozoic strata filling the foredeep ranges from 600 m in its western region to 13 700 m in the deepest part of the foredeep, in the east. During the formation of the Appalachian foreland basin, a time interval spanning approximately 220 million years, 4 major episodes of orogenic uplift—the Taconic (Middle Ordovician to early Silurian), Salinic/Caledonian (Silurian), Acadian (Devonian to Mississippian), and Alleghanian (Pennsylvanian to Permian) orogenies—took place, each corresponding to a major collisional event in eastern Laurentia (Ettensohn 2008; *see* Figure 9).

During the Silurian and Devonian periods, the Appalachian Basin most likely represented a retro-arc foreland basin resulting from failed subduction of the original peripheral foreland basin at the cratonic edge during Middle to Late Ordovician time (Ettensohn 2008). It likely formed by flexural lithospheric subsidence in response to events of orogenically induced loading that took place along the eastern margin of Laurentia from Middle Ordovician through Carboniferous to Permian time (Ettensohn 2008). Lithospheric loading associated with each of these orogenic episodes led to the asymmetric deepening of the trough-like foredeep of the Appalachian Basin proximal to the orogenic belt, and concomitant uplift and migration of an ephemeral distal forebulge on the Laurentian cratonic region (with smaller, higher frequency events; see evolution of ideas in Brett, Goodman and LoDuca 1990; Brett et al. 1995; Brett et al. 1998). The stratigraphic discontinuities associated with episodic forebulge migration and relaxation on the far-field side of the Appalachian foreland basin generally coincide with the positions of the arches shown on many tectonic maps (*see* Figure 8).

The elongate shape of the Appalachian Basin today reflects the most recent Alleghanian Orogeny (Lavoie 2008). Movement and changes to the shape of the Appalachian Basin occurred with alternating phases of orogenic loading and unloading throughout the Paleozoic (*see* Figure 9). It is believed that these plate tectonic processes influenced regions far removed from the foredeep, including the surrounding Illinois, and Michigan intracratonic basins (*see* Figure 8; Quinlan and Beaumont 1984; Sanford 1993; Ettensohn and Brett 2002).

Regional Tectonics and Michigan Basin Geometries – Was it a Basin During Wenlock?

It is generally agreed that subsidence of North American intracratonic basins was initiated by extensional breakup of supercontinents and that their circular shapes were responses to reactivation of tectonic structures that accompanied mantle flow instabilities (Allen and Armitage 2012). However, the apparent semicircular geometry of the Michigan Basin is defined by the millions of years of differential erosion of the Paleozoic strata off the older Precambrian shield bedrock, and the present-day outcrop margins are erosional cuesta steppes and do not reflect a depositional or structural margin or boundary to the Michigan structural basin. Despite the evidence that the Michigan Basin tilted eastward during the Late Ordovician (Coakley and Gurnis 1995) and through early Silurian time (Brunton et al. 2012), most researchers interpret the apparent circular shape of the Silurian Lockport carbonates (Niagara Escarpment cuesta) with Guelph “pinnacles” and overlying Salina Group evaporites as reflecting a syndepositional circular pattern of an intracratonic depositional basin.

Howell and van der Pluijm (1999) interpreted the Silurian strata of the Michigan Basin as a time of basin-centred subsidence because of the inferred “Pinnacle reef” geometries and apparent thickening and off-lap of overlying Salina Group microbial carbonates, evaporites and shales. However, examination of cores from the supposed centre of the Michigan Basin during Lockport Group deposition has revealed no Guelph or Eramosa formation lithofacies or slope or deeper basinal lithofacies, but instead the presence of marginal to shallow marine lithofacies of the Goat Island and Gasport formations (Brintnell 2012; Brunton et al. 2012).

The lithofacies observed in the few cores from the “central part of the Michigan structural basin” reflect shallow and restricted marine conditions and display extensive and multiple phases of karstification (Brintnell 2012; Brunton et al. 2012) and are overlain by microbial sabkha cycles of the basal Salina Group (Gill 1977a). Smith (2002) has shown that the “Salina A Basin” tilted from northwest to southeast and that the dissolution of salts has been ongoing since shortly after deposition took place. The apparent circular shape of the Michigan Basin during late Wenlock to Ludlow time appears to have formed after the accumulation of the Salina A-Unit, most likely as a result of the reactivation of basement tectonic structures and differential erosion of Salina sabkha sediments in a karstic terrain (possibly related to a Salinic II disturbance). Also, the presence of thick breccias and/or regional-scale unconformities that demarcate time intervals spanning late Silurian through Early Devonian time that occur across the midcontinent region of North America (e.g., Sloss Sequence boundary), supports the contention that the late Silurian evaporites and mixed carbonate-shale successions of the Salina Group once extended much farther across Laurentia than the present-day geomorphological erosional cuesta escarpments reflect.

EARLY SILURIAN PALEOGEOGRAPHY

During the early Silurian the study region, which includes the Michigan structural basin and the distal western part of the Appalachian Basin, was largely covered by shallow, subtropical epicontinental seas with variable circulation and stratification patterns (*see* Johnson 1987; Witzke 1987, 1990; Brunton, Turner and Armstrong 2009; Cocks and Torsvik 2011). Sedimentation in the Appalachian Basin was strongly influenced by collisional tectonics in the east that were accompanied by episodic shedding of siliciclastic detritus from highlands into the foredeep; carbonate production was largely restricted to the siliciclastic-starved western part of the foredeep. The amount of siliciclastic sediment delivered to the distal part of the Appalachian Basin varied largely in step with phases of orogenesis (tectophases; *see* Figure 9). Increases in sediment supply appear to have immediately followed phases of broad uplift, and changes in sediment dispersal patterns appear to have been associated with relative changes in sea level, as controlled by the interplay between tectonics, subsidence rates and responses to glacio-eustasy (*see* Brett et al. 1998).

In contrast to the Appalachian foreland basin region, the area of the Laurentia craton referred to as the Michigan structural basin received relatively little siliciclastic sediment during the early Silurian (*see* Figure 10). Shallow marine through more restricted marine environments persisted intermittently during much of the early Silurian in the Michigan structural basin, resulting in largely carbonate sedimentation and associated growth of small microbial mounds and decimetre-scale composite microbial-skeletal mounds, as well as more skeletal-rich shoals and vast, relatively muddy lagoonal environments (Copper and Brunton 1991; Brunton et al. 1998; Brunton et al. 2012). These stacked, shallowing-upward, carbonate-dominated successions possess numerous disconformities, of variable temporal and spatial significance, in response to changes in accommodation and differentiated forebulge movements along the inferred western edge of the Appalachian foreland basin (Brunton et al. 2012).

The prevailing view at present of the Michigan Basin during early Silurian Lockport Group time is that of a slowly subsiding concentric basin that became rimmed by “Pinnacle reef” buildups that led to restriction of water circulation from the open ocean (Appalachian Basin) and the progressive migration of evaporitic conditions toward the basin centre as sediment accretion continued to fill the basin inward from its margins (*see* Figure 10; cf. Sanford 1969a; Huh et al. 1977; Briggs et al. 1980; Gill 1985; Bailey 1986, 2000; Shaver 1996). Significant to the Guelph Formation are the so-called “Pinnacle reefs” that are interpreted to have grown closer to the basin slope and centre where subsidence rates are presumed to have enhanced vertical reef growth relative to more marginal areas where lower subsidence rates favoured lower-relief patch reef and biostromal buildups.

Recent paleogeographic reconstructions by Carter, Trevail and Smith (1994) and Coniglio, Zheng and Carter (2003) have combined the patch reef (reef banks) and barrier reef belts of Sanford (1969a) and the inner and middle platforms of Bailey (1986) to form the “Ontario Platform” (*see* Figure 10). Carter, Trevail and Smith (1994) also renamed the “Pinnacle reef belt” of Sanford (1969a) as the “Basin Slope”, a gently dipping platform to basin zone (*see* Figure 10). The “Pinnacle reef belt” has been studied by many throughout Ontario and Michigan, with key studies by Pounder (1962), Textoris and Carozzi (1966), Hill (1966), Mesolella et al. (1974), Gill (1973, 1977a, 1979, 1985), Huh, Briggs and Gill (1977), Sears and Lucia (1979, 1980), Petta (1980), Pearson (1980), Cercone (1984), Grimes (1987), Smith and Charbonneau (1990), Charbonneau (1990, 1991), Smith (1990a, 1990b), Carter, Trevail and Smith (1994), Bailey (1986, 2000) and Coniglio, Frizzell and Pratt (2004). Most notably, Bailey (2000) outlined lithologies and exposure features in these “Pinnacle reefs” that contradict the traditional Niagaran reef depositional models of Mesolella et al. (1974) and Sears and Lucia (1979). Our regional stratigraphic study does not support this basin-centric view (see discussion below).

Alling and Briggs (1961) showed isopachs of the Michigan Basin where Lockport strata (N.B., there are nomenclatural issues regarding what they include in Lockport; *see* Brunton et al. 2012) increased in thickness towards the inferred eastern and western edges of the "so-called" basin, in contrast to other Silurian units (Cayugan) that dipped towards the "basin centre". Subsequently, Pounder (1962) was the first to suggest that the distribution of the Guelph–Lockport strata did not fit the bowl-shape of the Michigan Basin, an observation that was generally disregarded in subsequent studies. Bailey (2000) proposed that the Silurian seas washed over the low-lying Algonquin Arch from both the Michigan and Appalachian basins and suggested that the water replenishment flowed to the southeast, where the "barrier reef" or "reef bank complex" is located (*see* Figure 10). This would have produced a shallowing and brining water column in the "Pinnacle reef" belt. More recently, Smith (2002) suggested that the

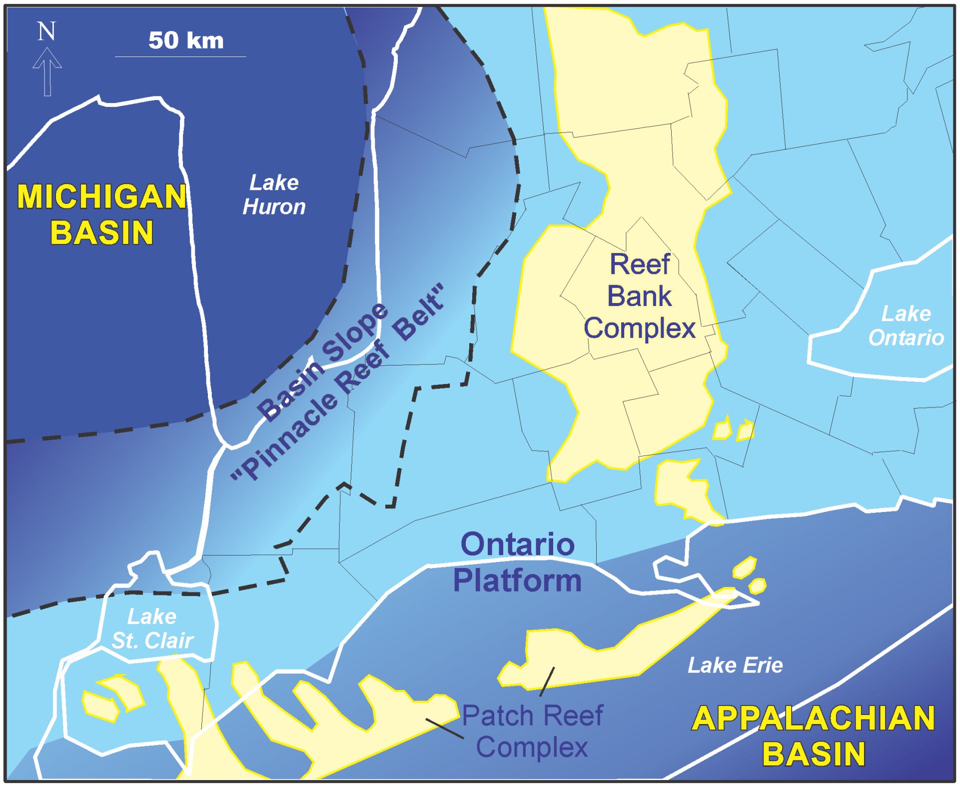

Figure 10. Generally accepted paleoenvironmental interpretation of upper Lockport Group Guelph Formation and basal Salina Group A-0, A-1, A-2 rock units: "Pinnacle reef" belt and slope region in basin-sinking Michigan Basin (blue shading darkening to northwest) and shallower carbonate bank with reef mounds (yellow areas in shallow carbonate shelf (light blue)) and deepening to southeast into Appalachian Basin (data compilation *after* Sanford (1969a) and Bailey (1986); map *modified from* Carter, Trevail and Smith 1994). Variations of this early Silurian paleoenvironmental reef model have been proposed since the 1940s (*see* Roliff 1949; Lowenstam 1949, 1950, 1957; Evans 1950; Shouldice 1955; Alling and Briggs 1961; Ulteig 1964; Burgess and Benson 1969; Mesollela et al. 1974; Budros and Briggs 1977; Huh et al. 1977; Briggs et al. 1978; Briggs et al. 1980; Gill 1973, 1975, 1977a, 1977b, 1979, 1985, 1994a, 1994b; Sears and Lucia 1979; Bailey Geological Services Ltd. and Cochrane 1990; Bailey 2000; Bailey and Smith 2000; Smith 1990a, 1990b, 1992; Smith and Charbonneau 1990; Smith, Grimes and Charbonneau 1988; Smith, Charbonneau and Grimes 1993; Copper and Brunton 1991; Brunton et al. 1998; Brunton et al. 2012). Regional subsurface and outcrop mapping of Lockport Group strata in Ontario over the past decade has demonstrated that both the Lake Erie patch reef complexes and landward reef bank complex have reef mound phases in Gasport, Goat Island and Guelph formations. "Pinnacle-reef" structures occur both in Cambridge and City of Guelph regions (not extensively paleokarsted or in pinnacle belt) and Lambton County to southeastern Michigan regions (extensively paleokarsted, with Gasport and Goat Island lithofacies dominating many of structures). Our revised interpretation of paleoenvironments, which include regional cross-sections from northwest to southeast (Michigan to southwestern Ontario and northern New York State), has been outlined in Brintnell (2012) and Brunton et al. (2012) (*see* revised paleoenvironments and reef mound phases in Figures 11, 12; and well logs in Appendixes 2 to 7). A key problem with historic paleogeographic and paleoenvironmental interpretations of the various reef mound phases concerns the fact that not all reefal facies belong to the Guelph Formation and basal Salina Group.

siliciclastic-free karsted carbonates and evaporites of the Guelph Formation and Salina Group strata record a time when the Michigan Basin was an epeiric sea, not a central basin.

The significance of the juxtaposition of Salina Group evaporites that, in places, encase and infiltrate the 3-D Lockport Group subsurface structures (Guelph "Pinnacle reefs"), combined with the concentric dip of the Paleozoic strata (resulting from downwarping centred on the midcontinent Rift region) support the interpretation of the Michigan Basin being a structurally influenced tectonic region during the creation and subsequent dispersal of supercontinent Pangaea. The present-day regional dip of Silurian strata towards an inferred Michigan structural basin centre is a response of mantle readjustments that most likely happened during supercontinent assembly in late Devonian and Carboniferous time. The Paleozoic bedrock units of the midcontinent region today display an erosional karstic terrain, whereby strata have been eroded off the northern Canadian Shield and form a series of cuesta steppes and scarps.

"PINNACLE REEF" PROBLEM – REVISED LOCKPORT GROUP

The Lockport Group comprises, in ascending order, the following formations: 1) the Gasport Formation, comprising thickened encrinites and reef mounds dominated by tabulate and rugose corals with minor calcified sponges or stromatoporoids; strata display a reefing-upward succession; 2) the Goat Island Formation, comprising basal encrinites and crinoidal reef mound complexes dominated by stromatoporoid sponges; 3) the Eramosa Formation, comprising a basal, darker brown Vinemount Member of thinly bedded, shaly dolostones that form a subregional aquitard, and an upper Reformatory Quarry and Stone Road members that reflect a wide variety of sedimentary environments (and when at surface may display a variety of karst landforms such as caves, sinkholes); and the Guelph Formation, comprising a lower transgressive, more open marine reef mound phase of deposition, followed by the establishment of regional muddy, lagoonal and high-nutrient conditions dominated by gastropods, megalodontid bivalves and minor stromatoporoids.

Brunton et al. (2012) and Brintnell (2012) documented that the Lockport Group is characterized by a series of transgressive–regressive (T–R), carbonate-dominated or stacked cyclic dolostones that generally display progressive shallowing and more pervasive regional karstification from east to west moving toward the inferred central Michigan structural basin (*see* Figure 11; Appendix 7). They proposed that the remnant, stacked carbonate banks (pinnacles) are a complex mosaic of paleokarsted Gasport and Goat Island Formation paleohighs capped by variably karsted Guelph Formation. The elongate 3-D bedrock geometries of the Lockport Group strata within the Michigan structural basin (as 2 curvilinear belts or scarps) are similar to some karst tower landforms in China (Brintnell 2012; Brunton et al. 2012). Therefore, we reinterpret these bedrock features as scarps within an overall karst basin terrain that formed prior to onset of continental-scale Salina deposits that characterize much of the remaining Silurian deposition across large parts of Laurentia (Brunton et al. 2012; Brintnell et al. 2012; Figures 12, 13).

Regionally the Guelph Formation is a karstic breccia–caliche–paleosol unit that reflects an extended period of karst erosion at the end of Lockport deposition (Brunton et al. 2012). This was followed by the establishment of a salt-pan playa that extended across much of Laurentia. Phases of karstification during deposition of the overlying playa deposits resulted in further, deep karstification and infiltration of salts and gypsum/anhydrite into the paleotopographic features, up to 100 m thick, incorrectly named Guelph "Pinnacles" (*see* Figures 12, 13).

In the outcrop–subcrop area of southwestern Ontario, the Gasport Formation is the thickest where it possesses composite crinoidal–microbial–tabulate coral reef mounds (darker red areas in Figure 12). The tops of the reef mound cycles and the upper part of the composite reef mounds display paleokarst fabrics. The Lockport Group "Pinnacle" reef mound structures in this area display the stratigraphic relationships outlined in the cartoon log in Figure 12. The Gasport Formation represents the bulk of the former

"Amabel" Formation lithofacies in the City of Guelph–Cambridge through Luther Lakes region. Detailed logging of rock core and key outcrops has shown that the relative thickness of the Gasport Formation controls the nature of overlying Lockport Group 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 on the inferred far-field site of the ephemeral and migrating forebulge. The thicker the Gasport Formation facies and nature of composite reef mound growth, the younger the stratigraphic unit that rests disconformably on it. In areas where the reefal Gasport Formation exceeds 50 m in thickness (dark maroon areas at bottom of Figure 12; the thickest units of the Gasport Formation are in the Cambridge–Hespeler areas in the southwest region of the map (not labelled)), the Guelph Formation may rest disconformably on the Gasport Formation (*see* stratigraphic cartoon in Figure 12). There is no lithologic or diagenetic evidence to suggest that the Goat Island Formation or basal Eramosa Formation lithofacies were deposited and eroded prior to deposition of Eramosa and Guelph formations on the Gasport disconformity. Some of the cores display paleokarstification 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.

This complex sequence stratigraphic framework led to spurious, historic interpretations of bedrock aquifer resources in Cambridge. Bedrock aquifers, or flow zones, in well fields now known to be in the Gasport Formation (confirmed from recently cored monitoring wells being drilled), were incorrectly assigned to Guelph Formational aquifers (e.g., Lotowater 1997) because gamma ray logs in adjacent monitoring wells off the reef mound complexes suggested the presence of Eramosa Formation below the water zones.

The thickened Gasport Formation composite reef mound complexes (subcircular red to maroon contoured regions in Figure 12) observed in Cambridge–Guelph region were previously unknown in relation to what was reported from quarries situated at the edge of the Niagara Escarpment (Johnson et al. 1992). Deep drill cores and geophysical logs within and away from these regional-scale structures, along with lithofacies relationships observed in the Dolime and Reformatory quarries in the City of Guelph (see sections below), confirm the stratigraphic relationships shown in the cartoon columns depicted in Figures 11 and 12). The three-dimensional structures in the deeper subsurface of southwestern Ontario and southeastern Michigan and in the northern part of Lower Peninsula of Michigan (northern pinnacle reef belt), which can be hundreds of metres to a few kilometres across by kilometres long, are enveloped and encased and capped by variably karsted strata and subsequently remobilized salts and anhydrite that are derived from what was a much more widespread (Laurentia-scale) Salina Group sabkha and hypersaline succession (Brunton et al. 2012; see variety of pinnacle models depicted in Figure 13).

Sedimentologic and stratigraphic evidence to support Brunton and others' (2012) re-interpretation of early Silurian depositional settings includes (i) the most open marine strata of the Lockport Group units that display the thickest preservation and least subaerial exposure occur in the eastern outcrop–subcrop belt of southwestern Ontario (cities of Guelph and Cambridge areas; Figure 12); (ii) cyclic crinoidal–microbial reef mounds with the largest and most abundant crinoid and invertebrate corals and calcified sponges in the Gasport and Goat Island formations occur in the east (Ontario, northwestern New York State); (iii) karstification and other subaerial exposure features are most prevalent in the Goat Island and Guelph formations in the central and western portions of the Michigan structural basin (Gill 1973; 1977a; Cercone 1988; Smith, Grimes and Charbonneau 1988; Kahle 1971, 1974, 1988; Charbonneau 1990, 1991; Carter, Travail and Smith 1994; Bailey 2000; *see* Figure 13 and Appendix 7) and are minimal in the eastern outcrop–subcrop belt.

The regional lithofacies mosaics of the Lockport Group suggest that the Michigan Basin was tilted to the southeast during early Silurian time and that Guelph and basal Salina Group strata were subjected to regional karstification and exposure prior to the development of regionally continuous karstified basal

Salina Group strata that filled in the erosional early Silurian karst basin terrain. The overlying gypsiferous and salt-bearing units of the Salina Group capped the early Silurian karst basin terrain and were subsequently infiltrated by late Silurian and Devonian groundwaters, resulting in large-scale brecciation and "breccia chimneys" and/or removal (Brunton et al. 2012; Brintnell 2012).

The regional changes in these depositional and diagenetic features strongly suggest that the Michigan Basin did not have a bowl-shaped geometry during deposition of the Lockport Group (*see* Figure 11).

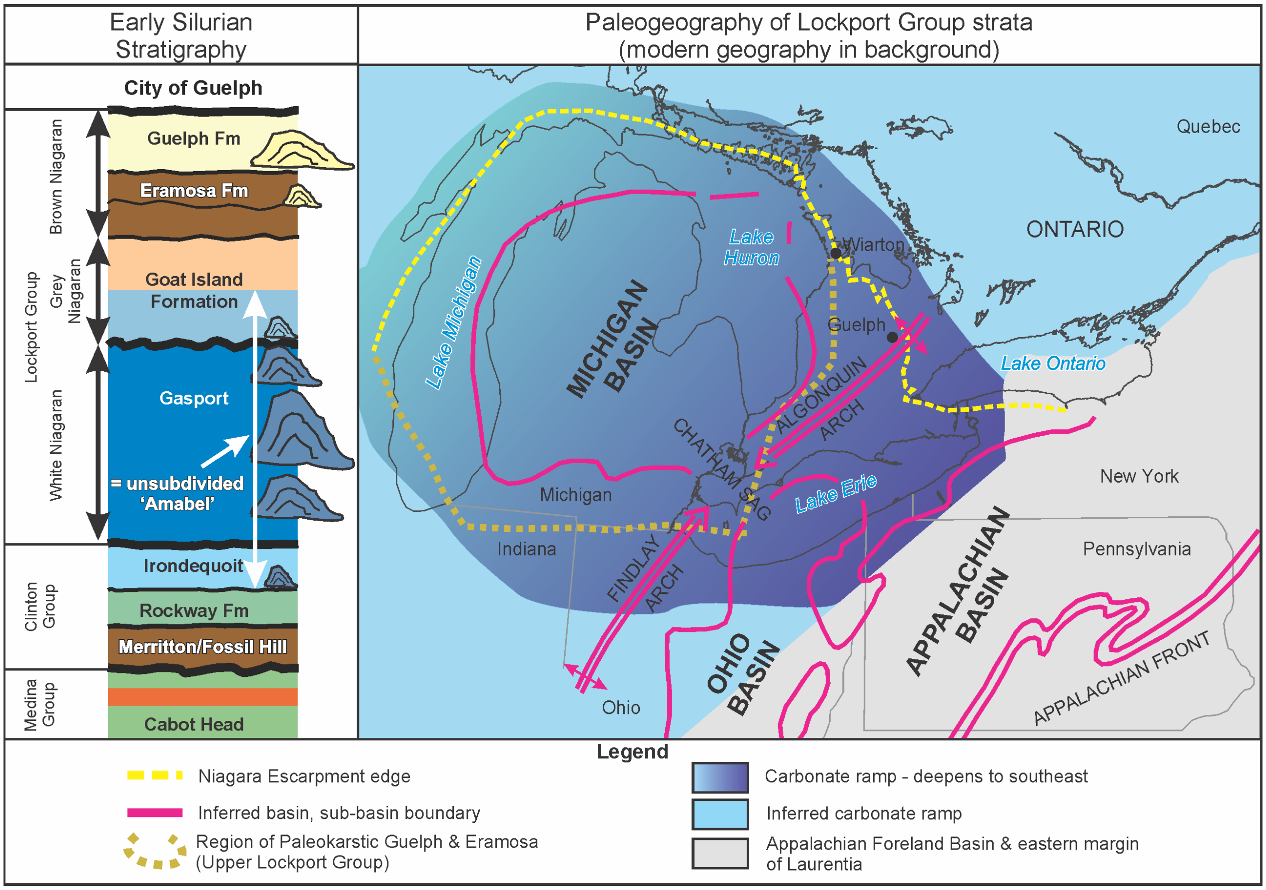

Figure 11. Early Silurian paleogeography relative to present-day erosional boundaries of key foreland (Appalachian) versus intracratonic (Michigan structural) basins (*modified from* Haynes 2000). This revised paleogeographic map is very different from the generally accepted view of early Silurian Michigan Basin outlined in Figure 10. The thick pink lines depict present-day erosional boundaries of the Michigan, Appalachian and Ohio sub-basins in relation to the Algonquin–Findlay arches (areas where forebulge migration and development were influencing marine sedimentation and subsequent erosion between the inferred basin areas). The carbonate ramp region (graded blue area) represents areal extent of this study in subsurface and outcrop; paleoenvironmental cross-sections of Lockport Group for this region are summarized in Appendix 7 (*see* Brintnell 2012; and Brunton et al. 2012). The lighter blue area depicts regions where shallow early Silurian carbonates extended on Laurentia and, in places, have been differentially eroded (south-central Ontario and Grenville shield regions of Ontario). The stratigraphic column on left spans upper Cabot Head (Medina Group) through Guelph formations (comprising part of Clinton Group and entire Lockport Group; *see* Brunton 2009; Brunton et al. 2012). These strata represent mostly dolostones with minor noncalcareous and calcareous shales and siliciclastic intervals. The relative thickness of black lines separating formations represents significance of disconformities associated with sequence boundaries within and away from forebulge regions (Salinic tectophases). The terms White, Grey and Brown Niagaran reflect general subsurface core descriptions referred to as Niagaran (Alguire 1962). Such terms have added to the confusion of regional stratigraphic nomenclature and formational distributions across Ontario and Michigan and surrounding areas on Laurentia cratonic side of the Appalachian foreland basin (*see* Figures 10, 12, 13; Appendix 7).

Preferential preservation of the ephemeral, thick Salina Group salts and gypsiferous beds in the more deeply buried parts of the Paleozoic succession on the Laurentia craton (southwestern Ontario and Michigan) is the result of fresh groundwaters not being able to penetrate and erode the salts and gypsiferous zones and create solution-collapse breccias. The depositional and erosional character of the early Silurian strata support a more complex paleogeographic setting during deposition of the Lockport Group and basal Salina Group strata, whereby marginal marine and karst terrain development occurred in the present-day region of Michigan (up-ramp to nonmarine setting) during Guelph time, and a broad carbonate ramp reflecting more open marine conditions can be found from Lake Erie and New York State into southwestern Ontario, reflecting Silurian marine conditions. Early Silurian marine deposition was interrupted and influenced by glacially-influenced, sea-level fluctuations and intermittent forebulge migration and relaxation during short-lived Salinic tectophases.

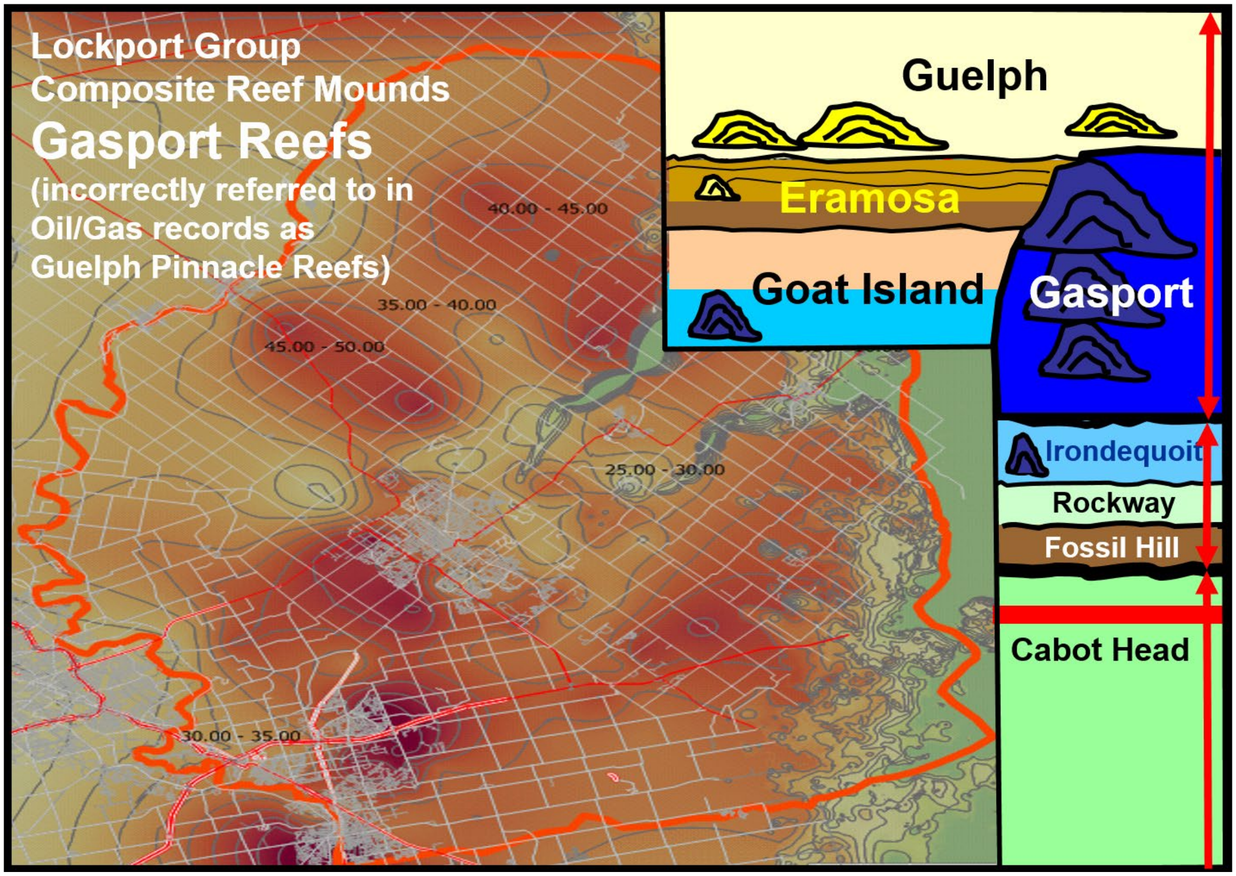

Figure 12. Regional view showing locations of thickened (numbers are in metres), composite reef mounds and crinoidal shoal complexes of the Gasport and lower Goat Island formations in Cambridge through City of Guelph and surrounding regions, southwestern Ontario. These ovoid-shaped, thickened composite crinoid–microbial–coral reef mound complexes appear to trend northeast-southwest, like geometries of deeper buried Guelph "Pinnacle reefs" from Sarnia to southeastern Michigan (*see* Figures 11, 12) and described from Chicago area (Mikulic and Kluessendorf 1999). The stratigraphic section on right illustrates that the Lockport Group strata and its potable groundwater-flow zones sit disconformably on the Irondequoit crinoidal encrinites (entire Rochester Formation is eroded and missing) of much older Clinton Group dolostones, and which sit disconformably on the much older Cabot Head Formation red and green shales of the Medina Group (*see* Figure 13). The stratigraphic relationships of the Lockport Group (Gasport, Goat Island, Eramosa and Guelph formations) illustrated reflect complexity of stratigraphic relationships in the City of Guelph–Cambridge regions: the thicker the Gasport Formation in a given area, the younger the overlying unit is that sits disconformably on it. The thickness of lines between formations is meant to indicate relative temporal importance of sequence stratigraphic, or time, breaks. The regional aquitard is the Cabot Head Formation shales; red and green shales occur in upper unit.

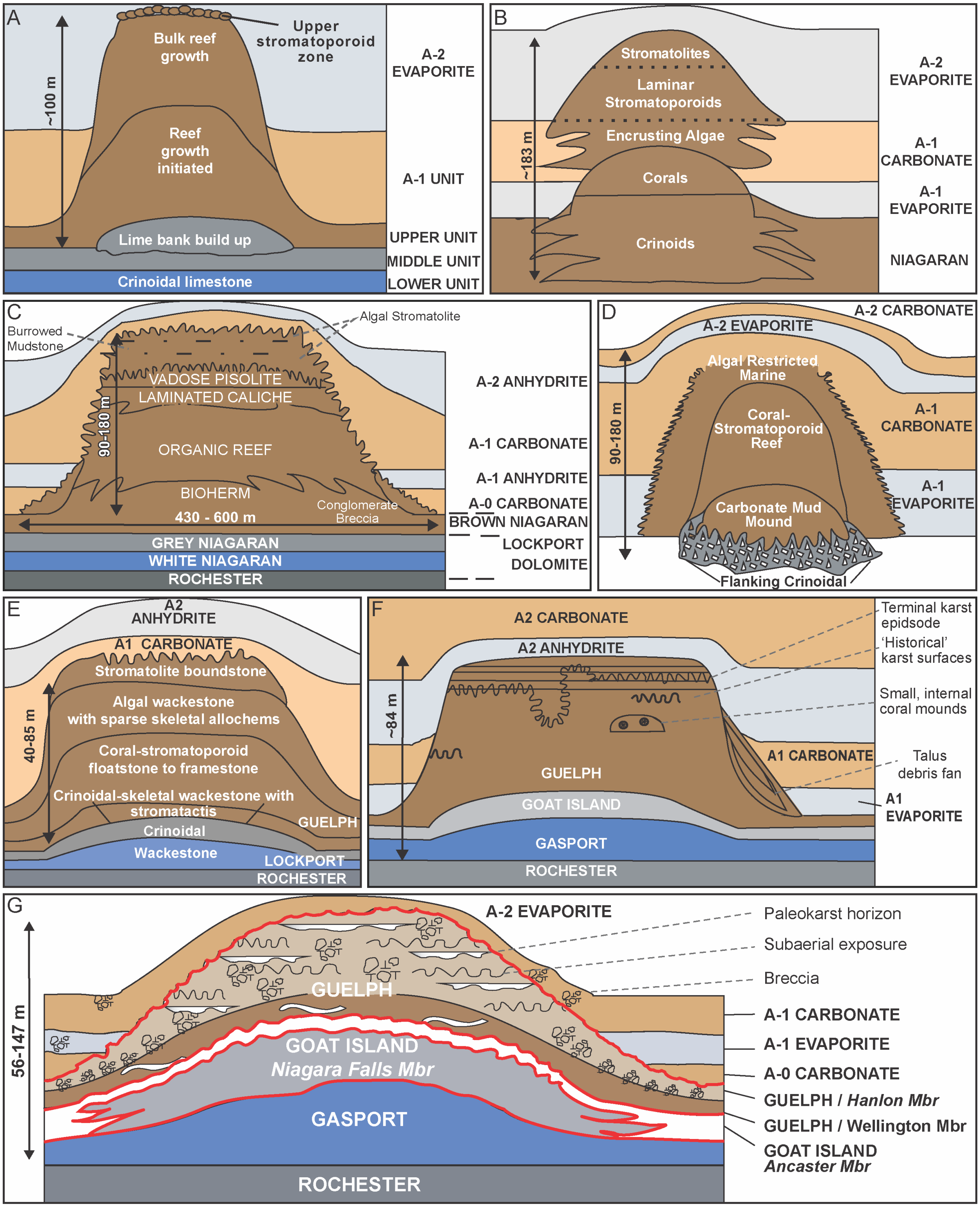

Figure 13. Comparison of historic Niagaran–Guelph–Lockport "Pinnacle Reef" models to the current proposed *karst tower* model (*from* Brintnell 2012; Brunton et al. 2012). These models have evolved over time. Below is a brief description of select models and nomenclature used relative to updated terminology adopted in this study:

A) Pounder (1962; Ontario) recognized (i) the "Guelph–Lockport" is composed of 3 units; (ii) the "pinnacle reef" growth began in the Middle Unit (= Niagara Falls Member, Goat Island Formation); (iii) and the presence of unconformities. He also suggested that the "Guelph–Lockport" paleogeography does not fit the bull's eye shape of the Michigan Basin.

B) Mesolella et al. (1974; Michigan) recognized (i) a subaerial exposure event following deposition of their "coral-reef" phase; (ii) a short hiatus between Niagaran and Cayugan time (Salina Group). They suggested that "reef" development took place in a "quasi-contemporaneous depositional setting", the first being a carbonate setting and the second, evaporitic.
C) Huh et al. (1977; Michigan) recognized evidence for exposure in the entire uppermost portion of the "pinnacle reef", including vadose sediments, caliche crusts, solution leaching, erosional surfaces, iron oxides, flat-pebble conglomerates. They also discussed a Guelph–Salina unconformity.
D) Sears and Lucia (1979; Michigan) recognized that the "pinnacle reef" buildup reflects increasing salinity. They suggested continuous reef growth and only one subaerial exposure event, post-Niagaran deposition.
E) Charbonneau (1990; Ontario; and Leigh Smith and students) recognized (i) several episodes of subaerial exposure; and (ii) the correlation of 2 separate, possibly regional, exposure surfaces: a lower surface, at the top of the Lockport (= Goat Island Formation, Niagara Falls Member), and an upper surface (at top of Guelph Formation).
F) Bailey (2000; Ontario) first acknowledged that these carbonate structures are actually mud mounds and not "reefs".
G) The proposed karst tower model, this study *(modified from* Brintnell 2012 and Brunton et al. 2012). Sequence boundaries and associated paleokarst horizons highlighted by red lines. The karst tower or remnant bank is a carbonate-dominated, three-dimensional structure with variable disconformities separating the Gasport and Goat Island formations and displays the most significant erosional episodes during Lockport Group depositional and erosional time, especially Eramosa (which is absent or poorly delineated in most subsurface cores of southwestern Ontario and southeastern Michigan) and Guelph and post-Guelph depositional phases and stratigraphic relationships (see more detailed discussion of karst tower model in Brintnell (2012) and Brunton et al. (2012)).
Note: Following publication of the Brunton et al. (2012) paper, Bob Trevail shared with the authors an unpublished seminar presentation to students at University of Western Ontario, London, Ontario, where he entertained the hypothesis that the Guelph "Pinnacle Reefs" in southwestern Ontario may represent accentuated karst towers (Trevail 1981). Focused studies that are further investigating this hypothesis are currently underway and beyond the scope of this study.

Revised Silurian Stratigraphy and Sequence Stratigraphy – Southwestern Ontario and Surrounding Areas

This project incorporates and builds upon the major revisions to early Silurian stratigraphic nomenclature and lithologic descriptions outlined in Brett, Goodman and LoDuca (1990), Brett et al. (1998), Brett et al. (1995), Brett and Ray (2005) and McLaughlin, Brett and Wilson (2008) for parts of the Great Lakes region (New York, Ohio, Wisconsin) and Ontario. A detailed historical review of the early Silurian stratigraphic nomenclature is beyond the scope of this study. Recent summaries for southwestern Ontario can be found in (Johnson et al. 1992; Brett et al. 1995; Armstrong and Carter 2010). Some of the nomenclature proposed below for the early Silurian stratigraphy of southern Ontario (*see* Figures 11, 12, 14, 15, 16) 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, 2010; Armstrong and Dodge 2007). Key stratigraphic and chemostratigraphic logs with formation picks that support the revised regional stratigraphic framework and sequence stratigraphic relationships are presented in Appendixes 2 to 7.

The early Silurian strata described below, and which form part of this multiyear study, occur between the basal Cabot Head Formation shales and mixed carbonates (regional aquitard of central to northern portions of Ontario's Niagara Escarpment) and/or Rochester Formation shales and mixed carbonates (southern portion of Ontario's Niagara Escarpment) and overlying Salina Group. The basal units of the Salina Group comprise microbial laminites and gypsiferous sabkha cycles, making the contact between the restricted marine carbonates of the Guelph Formation and microbialites and Salina Group difficult to pick when using gamma-ray logs alone. Clinton and Lockport Group strata sit above the significant disconformity (Salinic Disturbance I tectophase) 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 Medina Group strata of west-central New York (*see* Brett et al. 1995) and extending into Hamilton to Waterdown areas of southern Ontario (*see* Figures 14 to 16). A second significant regional cut-down of Clinton Group strata (i.e., regional removal from the top to base of Rochester and underlying DeCew formations in the Niagara Peninsula region and removal of lower Fossil Hill, St. Edmund, Wingfield and Dyer Bay formations in Manitoulin to southern Bruce Peninsula regions) reflects a Salinic Disturbance II tectophase. A regional cut-down of Gasport Formation strata and the presence of a bentonite horizon at the Gasport–DeCew contact in the city of Hamilton area, and presence of seismite beds in the overlying Eramosa Formation all suggest continued, episodic and subregional continuation of Salinic Disturbances (III) or tectophases.

This intermittent interplay of forebulge migration tectophases and changes in relative sea level are reflected in both the variability of condensed sequences and drastic lateral lithofacies changes and aspects of the sedimentary architecture of early Silurian dolostones and mixed siliciclastics of the upper Medina, Clinton and Lockport groups of western New York extending into southwestern Ontario, from Niagara Falls to the Manitoulin area (Figure 15; *see* revised early Silurian stratigraphic nomenclature in Cramer et al. 2011). Also of importance and not readily recognized prior to the regional drilling programs that form part of this Niagara cuesta study, is the fact that forebulge migration and associated maximum uplift and erosion of early Silurian strata shifted through time in southwestern Ontario from the Dundalk–Fergus Elora corridor to city of Hamilton corridors, from Medina through Clinton and Lockport groups deposition. Such observations bring into question the general influence and position and orientation of structural features referred to as "arches" and "basins" within the eastern region of Laurentia. Changes in the regional stratigraphy record the interplay between sedimentation, erosion and sea level fluctuations relative to Salinic tectophases and associated forebulge migration and relaxation episodes that reflect a more complex response to underlying inherited older basement tectonic structures and boundaries.

The significant differences between the overall Silurian stratigraphic nomenclature outlined by Brett et al. (1995) and OGS Special Volume 7 (Armstrong and Carter 2010) and the findings of this study, which are documented in the subsequent sections of this report, include the recognition of the following:

1) The Cabot Head Formation forms a regional aquitard, or barrier, to vertical flow of potable, karstic groundwater within the overlying Lockport Group dolostones from Shelburne through Guelph areas. The younger Rochester Formation shales play this role on the foreland basin side of forebulge between Hamilton and Niagara Falls. Vertical movement of groundwater through these shale intervals, and laterally within them, is extremely low, and formational waters in stratigraphic units below these regional aquitards are not potable groundwater resources.
2) The basal 3 informal members of the lower Clinton Group Fossil Hill Formation (see Brunton, Turner and Armstrong 2009; Brintnell et al. 2009; Brintnell 2010) and the underlying St. Edmund, Wingfield and Dyer Bay formations, are not present south of the Owen Sound area.
3) The Rockway and Irondequoit formations, which belong to the Clinton Group, are much more regionally extensive dolostone units than previously shown, extending well onto the Laurentia craton's "structural Michigan Basin" (i.e., across the broad region of southwestern Ontario affected by Salinic tectophases and forebulge migration and relaxation);
4) The Irondequoit Formation crinoidal grainstones were mistakenly lumped into the basal "Amabel" Formation encrinites. This formation ("Amabel") can be traced from Niagara Falls and Lake Erie region northwesterly to the Bruce Peninsula and Huron County area. Misidentification of the Irondequoit Formation regionally, due to the subregional erosion of the Rochester and Lions Head formations (as a result of forebulge migration and associated uplift and erosion of these units during the Salinic tectophase), resulted in the resurrection of the Amabel Formation (see below). Within this ephemeral forebulge region, encrinites of the

younger Gasport Formation occur disconformably on older Clinton Group encrinites of the Irondequoit Formation, representing a significant time break, because the Rochester, DeCew and Glenmark formations are absent.

5) The Lions Head Member of the basal former "Amabel" Formation (= Lions Head Formation; Brunton 2009; Brunton et al. 2012) is a carbonate equivalent of part of the Rochester Formation. This thinly bedded dolostone unit separates the underlying Irondequoit Formation crinoidal grainstones from overlying Gasport Formation crinoidal grainstones in the central and northern parts of the Niagara Escarpment cuesta in southwestern Ontario. It appears that the forebulge migration and resultant uplift that resulted in the erosion of the Rochester and DeCew formations, enabled cleaner carbonate sedimentation on the cratonic side of the forebulge region on the far-field side of the Appalachian foreland basin. The most southerly occurrence of the Lions Head Formation is in the subsurface of the Fergus–Elora region. This dolostone unit thickens northward to the Bruce Peninsula. Interestingly, this formation controls the base of karstification and cave development on and along the Bruce Peninsula shoreline. It is not equivalent to the Rockway Formation as outlined in Brett et al. (1995) and as stated in Brunton (2008).

6) The "Amabel" Formation (Bolton 1953) should be retained as an industrial minerals term only and abandoned as a formal stratigraphic term because it comprises the Irondequoit Formation, a carbonate equivalent of the Rochester Formation (Lions Head Formation), the Gasport Formation, and overlying Goat Island and Eramosa formations. As mentioned above this rock unit includes a major sequence stratigraphic break that separates Clinton and Lockport Group strata representing Salinic tectophases that extended from Late Ordovician through early Silurian time (see Brunton 2009; Brunton and Brintnell 2011; Brunton et al. 2012).

7) The Eramosa Formation is a mappable rock unit and therefore warrants a formational rank. The basal Vinemount Member shaly dolostone beds (Barton Member beds; Hewitt 1960; Telford 1978), which were placed in the upper Goat Island Formation by Brett et al. (1995), form the basal member of 3 previously unrecognized units of the Eramosa Formation (Vinemount, Reformatory Quarry, Stone Road members) in Ontario (Brunton 2009; Brunton and Brintnell 2011; Brunton et al. 2012; Cramer et al. 2011). The Stone Road Member is only recognized locally in the City of Guelph–Fergus regions.

8) The Guelph Formation, which forms the uppermost rock unit of the Lockport Group, comprises 2 mappable rock units that have been assigned member names: the basal, biostromal and biohermal-bearing, wackestone to grainstone Wellington Member, and the overlying gastropod- and megalodontid bivalve-bearing mudstone- to wackestone-dominated Hanlon Member (Brunton 2009; Brunton and Brintnell 2011; Brintnell 2012; Figure 14). These 2 members reflect initial transgressive, higher-energy and more skeletal-rich deposition during the regional transgression, resulting in Guelph lithofacies being deposited onto either Eramosa or Goat Island seafloor strata. The upper Hanlon Member lithofacies of the Guelph Formation reflect overall shallowing and restricted marine conditions that eventually resulted in the onset of Laurentia-scale playa conditions and the onset of Salina deposition.

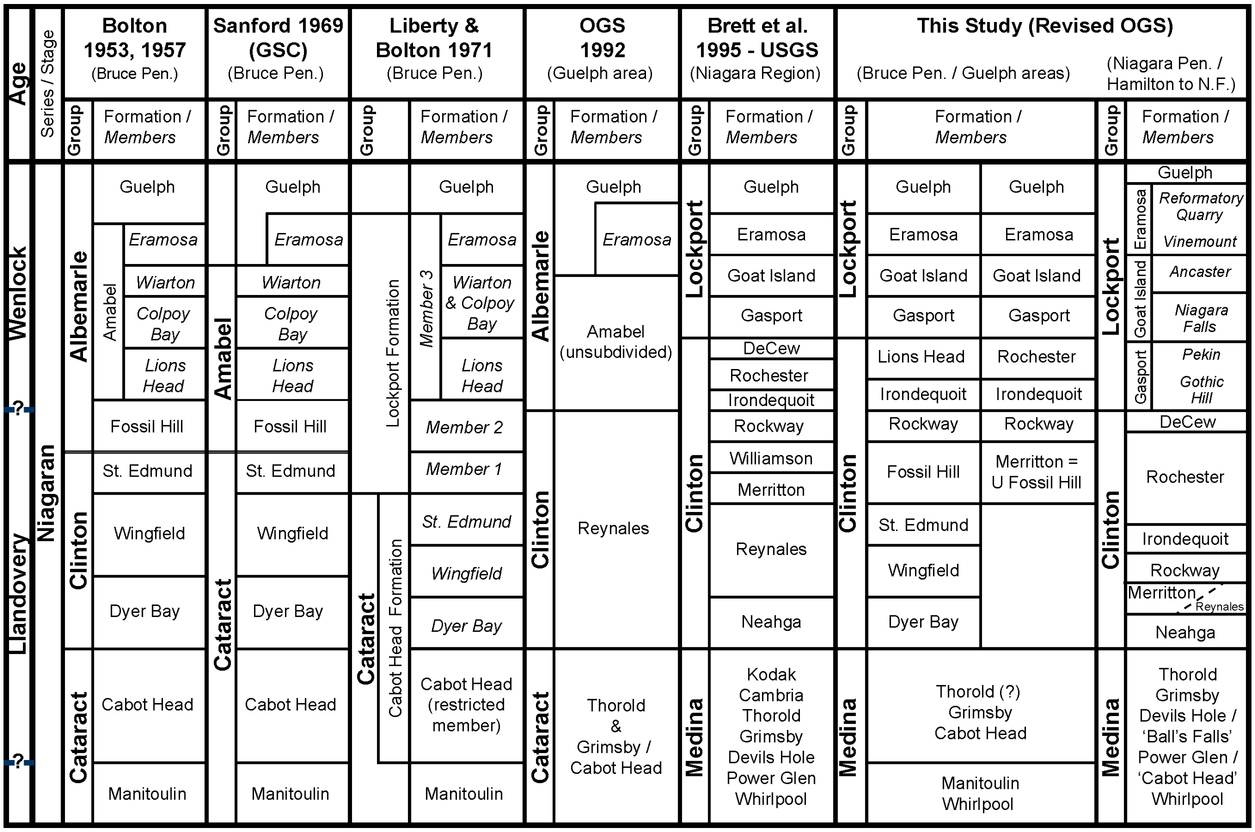

Figure 14. Selected early Silurian stratigraphic nomenclature for the Niagara Escarpment region of southern Ontario (see discussions in Brunton 2008, 2009; Brunton and Brintnell 2011; Brintnell 2012; Brunton et al. 2012). Abbreviations: "OGS 1992" refers to Johnson et al. (1992); U = upper; Sanford 1969a is full reference. Group names are in bold, Formation names in upper and lower case, Member names are italicized. Cramer et al. (2011) designated the entire early Silurian succession in southwestern Ontario as the Niagaran Series. Note, other stratigraphic units are mentioned in the text (*from* Brett 1983; Brett, Goodman and LoDuca 1990; and Brett et al. 1995).

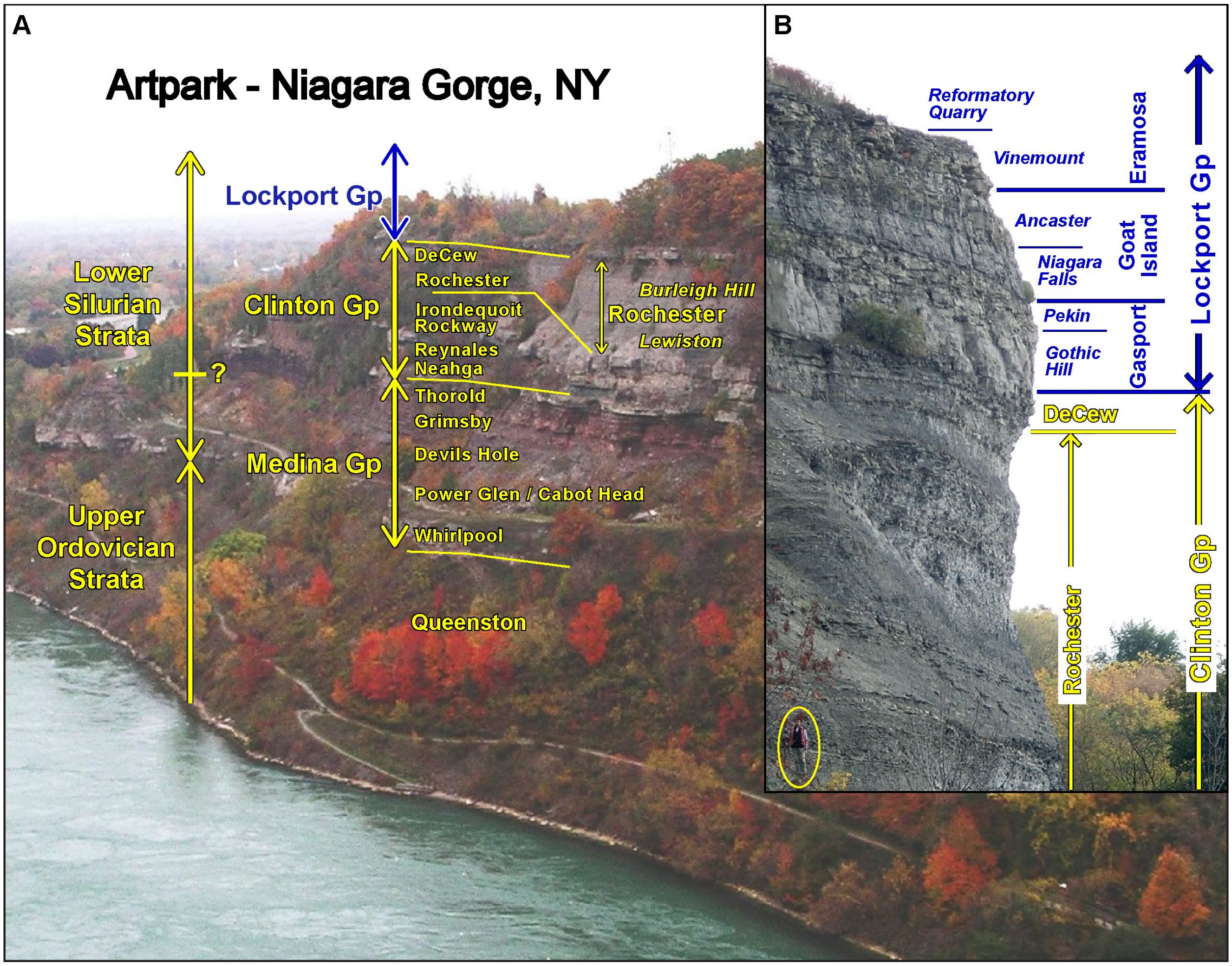

Figure 15. Upper Ordovician and early Silurian stratigraphy along the Niagara Gorge, Artpark, New York. The stratigraphic units follow the updated stratigraphy of Brett et al. (1995) and Brunton et al. (2012). Group (Gp) names in larger text, formation names in smaller text, and member names are italicized. The early Silurian stratigraphic succession, as traditionally interpreted, ranges in thickness from approximately 80 m at Artpark to just over 100 m at Niagara Falls, Ontario. More recent research provides palynological (microfossil) evidence that suggests that the Ordovician and Silurian boundary may be at top of Devils Hole Formation sandstones in the Niagara Gorge region in New York State (*see* Schröer et al. 2016; and discussion and references in Brett, Brunton and Calkin 2018).

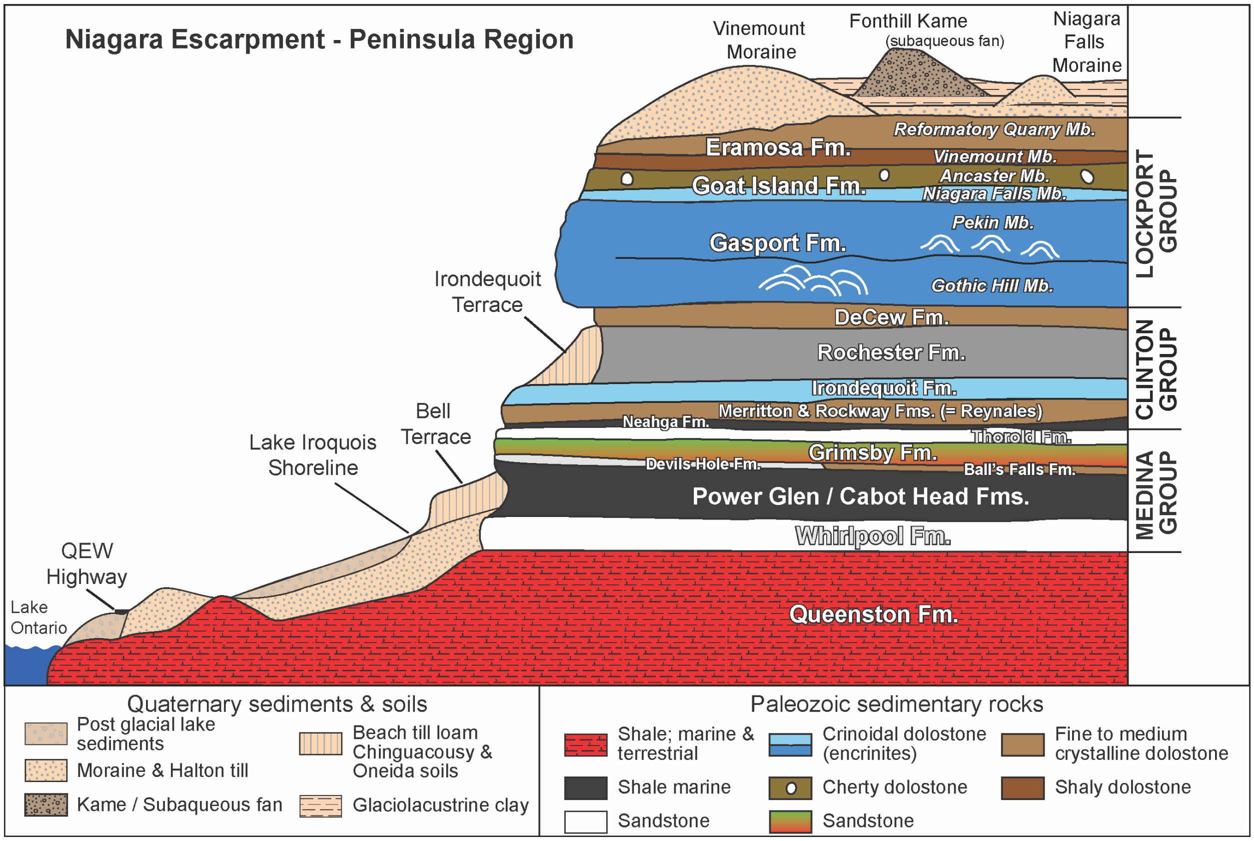

Figure 16. Upper Ordovician and early Silurian Paleozoic stratigraphy and simplified Quaternary geology of the Niagara Peninsula region, southwestern Ontario. Recent changes in the position of the Ordovician–Silurian boundary and significance of the Devils Hole Formation (quartz arenitic sandstones) and Ball's Falls Formation (dolostone) are discussed in text. The figure is *modified from* Haynes (2000). The Cabot Head, Devils Hole, Ball's Falls formations and the younger Merritton and Rockway formations have been added. The latter 2 units were incorrectly correlated with the Reynales Formation in western New York. The Lockport Group and Gasport, Goat Island and Eramosa formational rank rock units are recognized. The Guelph Formation is generally not found at or near the edge of the Niagara Escarpment or cuesta margin in the Niagara region.

FOSSIL HILL AND MERRITTON FORMATIONS

The Fossil Hill Formation, which consists of 4 informal members at the type section on Manitoulin Island (Brunton et al. 2009; Brintnell et al. 2009; Brintnell 2010), consists of thinly bedded, very cherty, sparsely fossiliferous, argillaceous dolostones and relatively pure, fossiliferous, nonchert-bearing dolostones, and is well indurated, which partly accounts for its regional extent. It is present from northern Michigan (where it is also known as the Manistique Formation) to the Thorold area, where it is referred to as the Merritton Formation (Brett et al. 1995; Brunton 2008, 2009; see also discussion below). Other good exposures of the Fossil Hill Formation are located on the Bruce Peninsula (Bolton 1957; Liberty and Bolton 1971; Stott and von Bitter 2000; Armstrong, Goodman and Coniglio 2002; Armstrong and Dodge 2007; Brintnell et al. 2009). 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; Sanford 1978). Williams (1919, 1937) referred to this rock unit as the Lockport.

At its type section on Manitoulin Island, the Fossil Hill Formation can be separated into informal lower, middle and upper rock units based on faunal components and lithofacies. The lower part possesses a brachiopod-rich wackestone succession with large pentamerid (*Pentamerus* sp.) brachiopods in condensed beds, suggesting low sedimentation rates. The rock unit immediately above the basal condensed fossiliferous unit consists of poorly fossiliferous dolomudstone to wackestone and resembles the underlying St. Edmund Formation, or "Mindemoya" Formation (Liberty 1968; herein termed the "false Mindemoya"). This "false Mindemoya" or St. Edmund Formation lithofacies unit is present in the northern cores on the Bruce Peninsula and thickens northward to the type section on Manitoulin Island (Brunton et al. 2009; Brintnell et al. 2009; Brintnell 2010). Hardgrounds are present in this unit. The upper 2 informal members of the Fossil Hill Formation, referred to as "upper Fossil Hill Formation", show a return to richly fossiliferous brachiopod beds of *Pentameroides* and an abundant megafauna of tabulate corals, calcified sponges and related faunas (*see* Copper 1978). No bioherms have been described from this unit. The uppermost beds are wackestones and packstones with pentamerid-rich horizons. The condensed nature and taphonomic character of the fauna indicates palimpsest conditions and/or low sedimentation rates.

There are at least 4 significant disconformities in the Fossil Hill Formation at its type section on Manitoulin Island. The intermittent and systematic regional cut-down of the lower 3 rock units (informal members) within this formation from Manitoulin Island to southern Bruce Peninsula (Brintnell et al. 2009) supports the observed changes in relative ages of the formations exposed in outcrops (based upon conodonts) described along the Bruce Peninsula by Stott and von Bitter (2000). The regional cut-down of the middle and lower Fossil Hill Formation and underlying St. Edmund, Wingfield and Dyer Bay formations from Manitoulin Island to Owen Sound region of Bruce Peninsula, reflects a major Salinic tectophase and associated forebulge migration and relaxation phase in Telychian time. More than 100 m of strata has been cut-down from Manitoulin Island to the southern Bruce Peninsula.

In southern Ontario, the uppermost Fossil Hill Formation is everywhere disconformably overlain by the Rockway Formation from the northern Bruce Peninsula to Thorold region. In general, the *Pentameroides*-dominated facies of the upper Fossil Hill Formation is equivalent to the Merritton Formation (Brett et al. 1995) and seems to be a regionally persistent rock unit. Phosphatic grains have been observed at the Cabot Head–Merritton Formation and Merritton–Rockway contacts, inferring a significant hiatus in sedimentation, representing a disconformity. The Merritton Formation disconformably rests on the Thorold Formation along much of the Niagara Peninsula between Hamilton and Niagara Falls, and older Grimsby or Cabot Head formational units north of Highway 401 along the outcrop and subcrop belt of Niagara Escarpment cuesta.

The type section of the Merritton Formation is in Thorold (Brett et al. 1995; Brunton 2008, 2009). Strata referred to as the Merritton Formation are generally less than a metre thick. Merritton Formation strata possess the same pentamerid brachiopods and tabulate corals as the upper Fossil Hill Formation, although this rock unit is thicker in some cores in the City of Guelph than at the Merritton Formation type section in Thorold (see Brett et al. 1995). Given that the Merritton Formation and upper Fossil Hill Formation strata possess the same pentamerid brachiopods and corals, the Merritton Formation has been correlated with the upper Fossil Hill Formation.

In the Niagara Peninsula area rocks of the upper Fossil Hill Formation were originally identified as a member of the lower Reynales Formation of New York State (Kilgour 1963) because of similar lithologies. The Hickory Corners Member of the Reynales Formation is present at the Niagara Gorge and is older (Brett et al. 1995, p.31-34; Figures 1, 15, 16).

From the Luther Lake–Mount Forest area to Thorold region of southwestern Ontario, the upper Fossil Hill (= Merritton) Formation comprises up to 3 well-indurated beds of unequal thickness that are separated by dark, shaly partings. The basal bed has a distinctive, bioturbated, pinkish brown, finely crystalline matrix, and may possess a black, phosphate pebble-bearing hardground unit. The middle bed possesses *Planolites*-type burrows, which locally contain glauconite, and the lower bed is rich in pyrite. The lower beds are wackestones and 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 City of Guelph region.

The Merritton Formation acts as a vertical barrier that limits the downward movement of potable bedrock groundwater between the overlying Gasport Formation and underlying shales of the Cabot Head Formation, which is the main regional aquitard that separates upper potable bedrock groundwaters from formations with marine porewaters.

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).

The Rockway Formation is an argillaceous dolomicrite to wackestone with no discernible megafaunal elements. It possesses a distinctive, greenish grey, finely crystalline matrix separated by styloseam sets and thin shaly partings. This formation has a consistent thickness of 1 to 2 m throughout the study area and, unlike the underlying upper Fossil Hill Formation (= Merritton Formation), is present in cores across southwestern Ontario. It has a very distinctive and erosional contact with the overlying Irondequoit crinoidal grainstone unit, making it easy to delineate in core and outcrops. 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 a highly erosional contact, between the Rockway and Irondequoit formations.

The predictability or uniformity in character and thicknesses of the upper Fossil Hill (= Merritton) and Rockway formations (incorrectly referred to as the Reynales Formation in historic literature; *see* Bolton 1957) from the City of Guelph to Niagara Falls suggests that the Algonquin Arch, or forebulge region, was relatively stable during this time interval and that erosional phases were subdued prior to the transgressive phases that enabled deposition of the regionally extensive, transgressive crinoidal shoal facies of the overlying Irondequoit Formation.

IRONDEQUOIT FORMATION

The Irondequoit Formation was originally assigned to the Amabel Formation of the Lockport Group in parts of southern Ontario north of the city of Hamilton (Bolton 1957; Figures 1, 14). Brintnell (2012) and Brunton et al. (2012) regional lithofacies mapping of strata has shown that this fine- to medium-crystalline encrinites is a valid stratigraphic unit (Figures 1, 14). The Irondequoit Formation is a crinoidal grainstone to packstone unit that possesses a consistent thickness of approximately 3 m throughout the study area. It is a thick- to medium-bedded, thoroughly bioturbated, medium grey to pinkish grey, buff-weathering, dolomitic, brachiopod-rich encrinite 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). It possesses distinctive stylolites and thin styloseam sets, reflecting short-lived time breaks. These styloseam sets and stylolites possess secondary pyrite, gypsum and pyrolusite in several cores in the City of Guelph area. These secondary mineral phases are a common feature of the Irondequoit Formation (Brett et al. 1995).

Encrinitic units of the Irondequoit Formation 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. In areas where Rochester Formation shales (of the Appalachian Basin) and Lions Head Formation dolostones are absent, the Irondequoit Formation is easy to identify in geophysical (gamma) logs because the more clay-rich nature of this rock contrasts greatly from the profile of the overlying Gasport Formation encrinites. The most consistent features associated with the styloseam cryptic contact between the Irondequoit and overlying Gasport formations are a drastic increase in crinoid pluricolumnal size and associated increase in crystallinity and change in matrix colour and texture. Gypsum is present in many cores and outcrops of the Irondequoit Formation. The presence of this glassy, interparticle gypsum highlights the different early diagenetic and depositional characteristics because these encrinites were deposited in different seaways separated by the time required to deposit and remove the Rochester and Glenmark formations (latter formation was observed in some Lake Erie cores and a core drilled at Mannheim in Kitchener–Waterloo).

The Irondequoit Formation has historically been associated with a low transmissivity zone of the lower Amabel Formation by hydrogeologists studying bedrock aquifers in the City of Guelph and Cambridge areas (*see* Gartner Lee, Braun Consulting and Jagger Hims 1999).

ROCHESTER FORMATION

The Rochester Formation consists of interbedded shales and carbonates and extends from the Rochester region in northern New York State, where it is up to 90 m thick (type section is located at Rochester; Brett 1983), to across much of southwestern Ontario. Details of the members of the Rochester Formation are outlined in Brett (1983), Brett et al. (1995), and Brett et al. (1998). The Rochester Formation pinches out just north of Hamilton and Cambridge, where it is approximately 1 m thick. Pinch-out of the Rochester Formation is partly a function of westward thinning of the mixed siliciclastic and carbonate lithofacies. Near Hamilton, contacts within and at the top of the Rochester Formation clearly are erosive in character and prove that the Rochester was systematically cut-down from the top to bottom at its type section in Rochester, New York, to where it disappears north of Hamilton. Only in the regions of recognized tectonic lows (e.g., Chatham Sag region; *see* Figures 8, 11) does the Rochester Formation persist further onto the Laurentia craton and the inferred Michigan structural basin. The Lions Head Formation, which first shows up in cores north of the City of Guelph through Elora–Fergus–Luther Lakes areas and on the Bruce Peninsula, is a carbonate equivalent to the largely calcareous shales and dolostones of the Rochester Formation observed in outcrops between Hamilton and Niagara Falls (e.g., Sanford 1969a; Liberty and Bolton 1971; Johnson et al. 1992; Brunton et al. 2012).

As mentioned above, one of the most significant stratigraphic relationships discerned during subsurface core logging is the subregional distribution of the Lions Head Formation (formerly a member of the Amabel Formation; Sanford 1969a; Liberty and Bolton 1971; and Johnson et al. 1992). This formation comprises thin- to medium-bedded, horizontally bioturbated, finely crystalline dolostones with characteristic styloseam sets and intermittent chert development and pseudonodular fabrics. The Lions Head Formation was deposited on the far side of an ephemeral forebulge migration tectophase. The Lions Head Formation lithofacies rest disconformably on the Irondequoit Formation crinoidal grainstones in every core on the Bruce Peninsula and extending to the Fergus and Elora areas (*see* Figure 14). This rock unit is also disconformably overlain by crinoidal grainstones of the Gasport Formation (Brunton 2009). An additional and potentially significant finding in the west Cambridge through Mannheim areas of the Region of Waterloo is that the Rochester Formation and overlying Glenmark Formation green shales persist in what may be a previously unrecognized “structural sag” area that is oriented subparallel to the Chatham Sag (inferred orientation is north-northwest–trending, extending from Southampton on Lake Huron shore to Lake Erie). Very few deep wells exist north of Waterloo to confirm the regional extent of this tectonic feature that is subparallel to the Chatham Sag (CS, *see* Figure 8) and may follow some of the Grenville basement tectonic zone boundaries. Episodic uplift of the forebulge apparently resulted in cannibalization of the largely unlithified or poorly lithified mixed calcareous and terrigenous muds and silts of the Rochester Formation.

DECEW FORMATION

Although the DeCew Formation is present in outcrops and cores between the Rochester and Gasport formations from the city of Hamilton to Niagara Falls region of the Niagara Peninsula, it is absent throughout much of the Niagara cuesta and scarp margin that is the focus of this study. The DeCew Formation is important from both a tectonic perspective, because the lower part shows seismogenic disturbance, and from a sequence stratigraphic perspective, because its stratigraphic position and regional distribution highlights a time break between the end of Rochester Formation deposition and the onset of Gasport Formation deposition. Also, the DeCew Formation sits disconformably on older and older Rochester Formation shales in cores from eastern to west-central Lake Erie and towards the Chatham Sag, highlighting the disconformable nature between it and the underlying Rochester Formation. The contact between the DeCew and overlying Gasport Formation is sharp and erosional, with rip-up clasts of the finely crystalline DeCew Formation dolostones rafted in the basal encrinites of the Gasport encrinites.

GASPORT FORMATION

In Ontario, the Gasport Formation has a confusing nomenclatural history (*see* Figure 14). Some examples include the formation being referred to as the Lockport Dolomite (Williams 1914); Gasport Dolomite Member of the Lockport Dolomite Formation (Williams 1919); Amabel Formation (Bolton 1953, 1957; Johnson et al. 1992); Gasport Formation (Sanford 1969a); and Member 3 of the Lockport Formation (Liberty and Bolton 1971). Results of the regional drilling programs along the Niagara Escarpment between 2006 and 2011, in partnership with the City of Guelph, Region of Waterloo, City of Hamilton and Halton Region, Town of Shelburne, and Parks Canada, have shown that none of the above-mentioned stratigraphic terms and associated rocks coincide with the Gasport Formation as described in this report.

The type section for the formation is in Gasport, New York (*see* Kindle and Taylor 1913; Winder 1961; Brett et al. 1995). *Ozarkodina sagitta* conodonts in the Gasport Formation (LoDuca and Brett 1991) indicate an Early Homerian age. Recent conodont data of the overlying Eramosa Formation in the City of Guelph area of Ontario indicate that the Gasport and Goat Island formations in Ontario are older; the overlying Eramosa Formation facies have an Early to Middle Sheinwoodian age (Bancroft, Kleffner and Brunton 2016).

On the Bruce Peninsula the coarsely crystalline encrinites of the Gasport Formation (Wiarton and Colpoy Bay Members of the former Amabel Formation; Johnson et al. 1992) disconformably overlie finely crystalline dolostones of the Lions Head Formation (Rochester Formation equivalent) and are disconformably overlain by finely crystalline encrinites of the Goat Island Formation (Niagara Falls Member).

The Gasport Formation consists of a basal cross-bedded crinoidal grainstone–packstone succession with incipient microbial–crinoidal reef mound facies that change upward to rhynchonellid brachiopod–bryozoan–bivalve coquinas and larger-scale stacked microbial–crinoidal reef mounds dominated by crinoidal holdfasts that are often greater than 1 cm in diameter (e.g., *Periechocrinites* sp. and possibly *Eucalyptocrinites* sp. pluricolumnals). The basal Gasport Formation, which represents a regional transgressive crinoidal succession, is generally a fine- to coarsely crystalline sand- to gravel-grade encrinite (skeletal gravel deposit). In select areas, the crinoidal–microbial reef mounds form multiple stacked cycles ranging from 25 to more than 70 m in thickness (*see* Figure 12). 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 Ontario and Michigan (within Michigan Basin), this succession is known as the "White Niagaran" (*see* Alguire 1962; *see* Figures 11, 12, 13).

These stacked transgressive systems tracts (grainstone- and mound-dominated transgressive systems tract (TST) packages) make up the key hydrogeologic units in the City of Guelph–Cambridge region (*see* Brunton 2009; Brunton and Brintnell 2011; Banks and Brunton 2017). Transmissivity values can range widely in the sequence stratigraphically-controlled architectural packages of stacked dolostones (*see* Priebe, Brunton and Lee 2012; Priebe, Neville and Brunton 2014, 2017; Priebe and Brunton 2016; Priebe 2019; Priebe et al. 2019).

The Gasport Formation in this region thickens from less than 1 m thick at Red Hill Valley and Clappisson's Corners road cut sections in the city of Hamilton area to more than 50 m thick in the City of Guelph area (*see* Figure 12). The formation comprises metre-scale shallowing-upward cycles, composite reef mound cycles, and paleokarst zones at the tops of the microbially cemented and crinoid-rich microbial mounds. Where the Gasport Formation thickens (e.g., the three-dimensional, thickened oval geometries in Figure 12), off-mound cores may display onlapping and interfingering of Niagara Falls Member encrinites and cherty Ancaster Member lithofacies of the overlying Goat Island Formation. This interplay of lithofacies highlights the significance of the time break represented by the boundary between the top of the Gasport Formation (nature of sequence boundary) and overlying Goat Island to Guelph formations of the Lockport Group. The Lockport Group does not show a simple layer cake stratigraphy in the vicinity of Cambridge through City of Guelph regions.

In the southern part of the city of Hamilton area (Red Hill Valley Parkway section), a thin bentonite is preserved at the boundary between the DeCew Formation and lowermost beds of a very thin Gasport Formation (W. Huff, Emeritus Professor, University of Cincinnati, personal communication, June 2013). The Gasport Formation north of Hamilton and extending from the City of 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 facies that envelopes the Gothic Hill Member reef mounds (as observed in quarries in and around Lewiston, New York; *see* Figures 16, 17). The Gothic Hill Member faunas and reef mound characteristics are reflected in the Wiarton and Colpoy Bay Members of what has historically been referred to as the Amabel Formation (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 material in the Pekin Member facies of the Gasport Formation presumably were cut off by the migrating forebulge during deposition of the Gasport Formation. This tectonically-induced phenomenon enabled increased accommodation space and resultant thicker composite reef mound development on the far-field side of the migrating forebulge, in what is now the eastern structural Michigan Basin (Cambridge to City of Guelph regions). The gamma-ray logs for these Gasport composite reef mound structures reveal very little clay material and are therefore distinctive from the Gasport succession in the Niagara Falls region.

Much of the Gasport Formation along the erosional edge of the Niagara Escarpment, near Mount Nemo (Nelson Quarry) – Mountsberg (proposed Flamborough Quarry) – Singhampton (Duntroon Quarry) 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). This succession is thinner than in the City of Guelph–Cambridge areas (see discussion of stratigraphy and hydrogeology in Shelburne area in Banks and Brunton 2017). Gamma-ray logs for the thickened Gasport Formation succession suggest very clean encrinites with very little clay content, indicating that these stacked complexes possess excellent to poor secondary porosity and permeability and karst-conduit development.

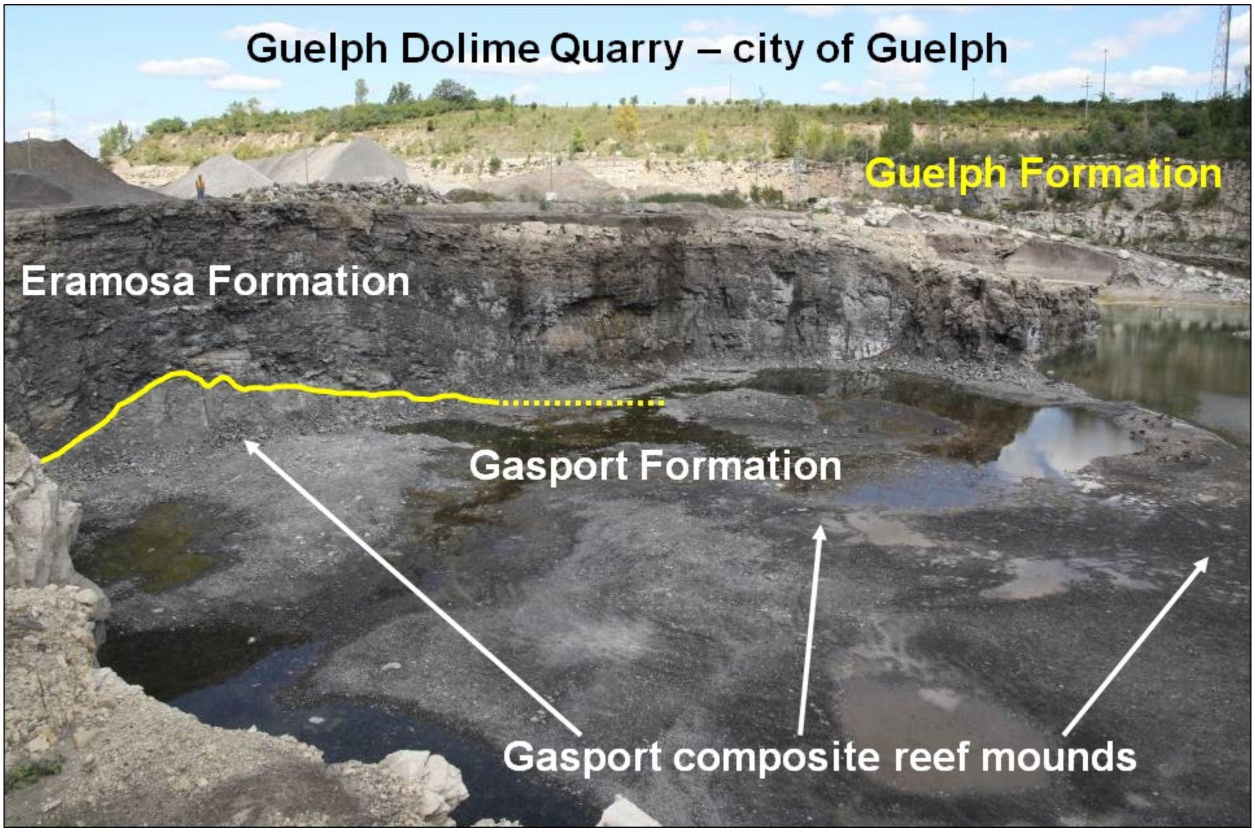

Figure 17. Lockport Group stratigraphy in the Guelph Dolime Quarry, City of Guelph. Rock faces display the stratigraphic relationships described in text and in Figure 12. Although no Goat Island Formation is evident at this outcrop exposure, the Goat Island Formation is present in a core located approximately 700 m to the north of the exposure on the north side of the Speed River. This reflects the irregular topography produced by thickened, stacked composite reef mounds of the Gasport Formation during Silurian deposition and erosion. The Eramosa Formation (Vinemount and Reformatory Quarry members) disconformably overlies and onlaps the composite Gasport Formation reef mound facies at this location. The beds of the Eramosa Formation drape over the irregular topography of the Gasport Formation and show variably steeply dipping beds across the quarry. The circular nature and three-dimensional relief of the Gasport Formation crinoidal reef mound bedrock surface is shown on the floor and in the wall of the proximal quarry face. The Lockport Group surrounding and within the Dolime Quarry clearly shows localized onlapping relationships of the Goat Island, Eramosa and the Guelph formational lithofacies on an irregular Gasport paleotopographic surface. The quarry floor shows bedrock groundwaters entering the quarry and concentric patterns highlighting the composite reef mound geometries of the uppermost Gasport Formation.

GOAT ISLAND FORMATION

The Goat Island Formation is composed of 2 members: the Niagara Falls Member and the Ancaster Member (Brunton 2009; Brunton et al. 2012). The formation is variable in thickness and extends from Manitoulin Island to Niagara Falls and across southwestern Ontario in the deeper subsurface. The basal member of the Goat Island Formation is the crinoidal grainstone facies of the Niagara Falls Member (*see* Brett et al. 1995). This unit commonly has a distinctive pin-striped appearance and is finely crystalline and cross laminated. The Niagara Falls Member encrinites range in thickness from a few metres to up to 10 m thick in the City of Guelph area. It is important to distinguish the coarsely crystalline encrinites and reef mound facies of the underlying Gasport Formation from the finer crystalline encrinites of the overlying Goat Island Formation (Niagara Falls Member) because the contact is often karstic and shows evidence of dissolution and weathering of the Gasport Formation and forms a karstic groundwater-flow zone horizon. The Niagara Falls Member facies represent the basal units of a transgressive systems tract within the Silurian seaways enveloping significant paleotopographic relief created by the differential deposition and erosion of crinoidal–microbial reef mounds that characterize the underlying Gasport Formation. The Niagara Falls encrinite is well indurated and behaves as a vertical barrier to groundwater flow between the Goat Island and underlying Gasport formations. The Niagara Falls Member often possesses clay minerals that provide a distinctive gamma ray signature from the underlying "clean" (clay-poor and diagenetic sulphide-mineral-poor) Gasport encrinites and reef mounds.

The overlying Ancaster Member of the Goat Island Formation is a chert-rich, finely crystalline dolostone that is medium to ash-grey in colour, thin to medium bedded and bioturbated (Figure 18). It is a more regionally extensive lithofacies of the Goat Island Formation. 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 and extending to Manitoulin Island. In the Guelph region, some of the cores display an interfingering of facies of the Niagara Falls Member and the Ancaster Member. This intercalation of units, forming a kind of "hybrid" rock unit, occurs where the Gasport Formation is more than 30 to 50 m thick. The variability in water depths associated with the irregular paleotopography of the underlying Gasport Formation during the marine transgression and onset of Goat Island Formation deposition resulted in the juxtaposition of Niagara Falls Member encrinites and/or cherty Ancaster Member lithofacies. Generally, the Niagara Falls Member is the basal crinoidal grainstone phase of the transgressive systems tract. Where the Gasport Formation is less than 20 to 25 m thick, as is the case in the Niagara Falls through Hamilton corridor, the Niagara Falls Member may be up to 10 m thick and the overlying Ancaster Member up to 6 m thick.

The Goat Island Formation is a regionally extensive rock unit in southern Ontario and forms the fossiliferous cores of many of the three-dimensional stacked carbonate structures referred to as Guelph "Pinnacle reefs". On the far-field side of the ephemeral forebulge region in southern Ontario (City of Guelph northward), stromatoporoid-dominated microbial–crinoidal reef mounds occur in the Niagara Falls Member of Goat Island Formation, resulting in thickened rock units of the Lockport Group (*see* Figure 12). These mounds differ from Gasport Formation microbial–crinoidal reef mounds, which are dominated by tabulate corals and calcified sponges (stromatoporoids). Siliceous sponges (responsible for the predominance of chert nodules in Ancaster Member facies) and calcified sponges (stromatoporoids) are the dominant megafaunal elements in Goat Island Formation facies, including the reef mounds of the basal Niagara Falls Member. Some of the reef mound facies found in Cambridge and City of Guelph cores may possess favositid corals, but they are low in diversity and number. This denotes a temporal change in nutrient and marine conditions throughout deposition of the Lockport Group, a trend that is also observed laterally from Ontario into Michigan (*see* Brintnell 2012; Brunton et al. 2012).

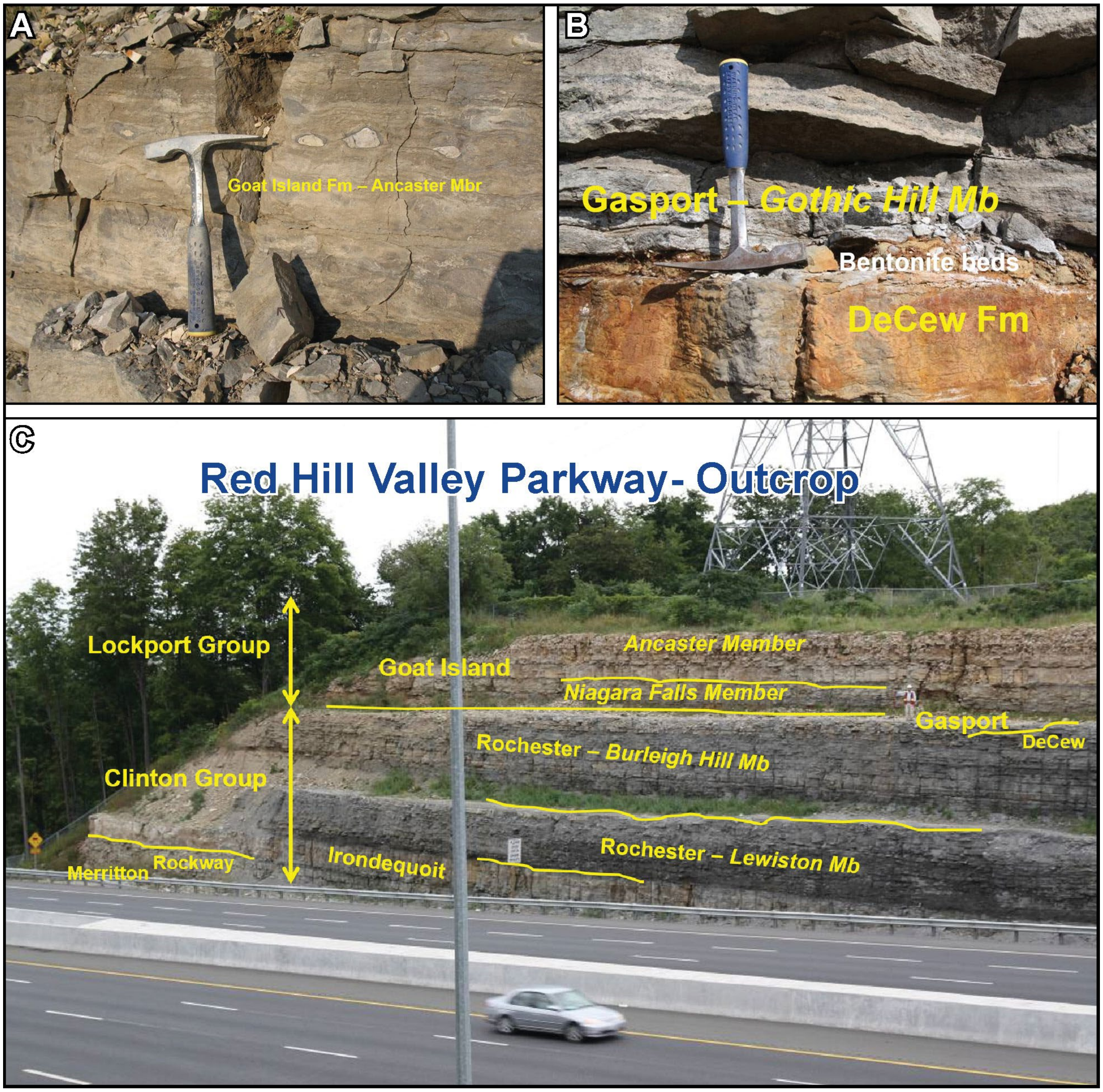

Figure 18. Medina Group (Thorold Formation in ditch to far left of outcrop), Clinton Group and lower Lockport Group strata, Red Hill Valley Parkway, city of Hamilton, Ontario (Derek Armstrong for scale). **A**) Cherty dolostones of the Ancaster Member of Goat Island Formation. **B**) Bentonite beds separating finely crystalline dolostones of the thin DeCew Formation (reduced thickness here due to tectonic cut-down) and basal thin (<1 m) Gasport Formation, highlighting disconformable contact between the formations (a sequence boundary; see delineation of sequences in Brett et al. 1990; 1995). In other outcrops along the Niagara Peninsula, rip-up clasts of the DeCew Formation are evident in the basal Gasport Formation encrinites. **C**) Outcrop of upper Clinton Group and lower Lockport Group strata within Appalachian sub-basin. The Rochester Formation lithofacies preserved here reveal evidence of a progressive erosional cut-down (from top to bottom) of this formation in vicinity of active forebulge migration of poorly lithified sediments. A thin DeCew Formation is still present here, suggesting a complex series of cut-downs of Clinton Group strata prior to deposition of the overlying Lockport Group.

ERAMOSA FORMATION

The Eramosa Formation is more laterally continuous along the Niagara Escarpment than is generally depicted in the literature (*see* Sanford 1969a, 1969b; Brett et al. 1995; Brunton and Dekeyser 2004; Brunton, Dekeyser and Coniglio 2005; Brunton, Armstrong and Dekeyser 2006). The regional scope of this study supports the formational rank for Eramosa lithofacies (*see* Figures 1, 14; see discussions in Brunton 2008, 2009). 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 the Niagara Escarpment cuesta region. This work verifies the regional continuity and lithologic variability, and temporal significance of this rock unit. Therefore, this paper refers to those facies assigned to the Eramosa interval by Williams (1915a, 1915b, 1919), Shaw (1937), Bolton (1953, 1957), Sanford (1969a), Telford (1978), Armstrong and Meadows (1988), Armstrong and Dubord (1992), Smith (1990a, 1990b), Tetreault (2001) and von Bitter et al. (2007) as the Eramosa Formation (Brunton 2009; Brunton and Brintnell 2011; Brunton et al. 2012; *see* Figure 14).

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 facies that make up part of the Reformatory Quarry Member (Brunton 2009) were incorporated into the previous definitions. This paper recognizes 3 formal members for the Eramosa Formation, from bottom to top: Vinemount, Reformatory Quarry, and Stone Road (Figures 19, 20). 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 (Brett et al. 1995), correlate faunally and lithologically with lithofacies assigned to the Eramosa Formation in the City of Guelph through Wiarton areas (cf. original descriptions in Williams 1914, 1919). 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 structural basin (referred to here as Laurentia cratonic carbonate ramp; *see* Appendix 7) and Appalachian foreland basin.

Lower Eramosa Formation facies, previously named Vinemount Shale Beds or Vinemount beds, are herein referred to as the Vinemount Member. This rock unit averages 10 m in thickness when present in the City of Guelph region. It comprises thinly bedded, finely crystalline, cyclic horizontally bioturbated traction current deposits with interbeds rich in partially silicified diminutive *Whitfieldella* brachiopods and distinctive digitate tabulate corals (cladoporids). The cladoporid corals are also evident in upper Goat Island (Ancaster Member) lithofacies. The Vinemount Member is most shaly near the Vinemount Quarry, east of Hamilton, and becomes less shaly to the west and northward away from the influence of the Appalachian Basin and may form sabkha deposits with eurypterids. 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 black chert-bearing, incomplete sabkha-like cycles and low-diversity coral and/or siliceous and calcareous sponge biostromes and wackestone to packstone facies that vary greatly in faunal and sedimentological character.

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 facies of the Reformatory Quarry Member. 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 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* Figures 19, 20). 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 facies of the upper Eramosa Formation (locally preserved Stone Road Member; *see* Figures 12, 17, 19, 20). The type section for the Eramosa Formation is the Reformatory Quarry, City of Guelph (Figure 19). The Reformatory Quarry Member possesses a strongly deformed, tabular, coral-bearing and pseudonodular interval, herein interpreted as a seismite (earthquake-deformed bed) that varies in thickness regionally (<30 cm to 1.6 m thick; *see* Figures 19, 20). It is mappable in well-exposed sections from the Niagara Gorge through the City of Guelph to the Wiarton areas of the Bruce Peninsula. The thickness of the upper, Stone Road Member at the Reformatory Quarry is approximately 5.5 m; this rock unit is not present in all cores and outcrops.

The Eramosa Formation is a very significant rock unit because it is a petroleum source rock and reservoir, a host of sulphide MVT mineralization in the form of sphalerite, galena and pyrite, and a source of aggregate and building stone products (*see* Armstrong and Meadows 1988; Brunton and Dekeyser 2004; Brunton, Dekeyser and Coniglio 2005). The lower Vinemount member of the formation also acts as a local to regional aquitard from the Niagara Peninsula through City of Guelph area (Brunton et al. 2007; Brunton 2009; Brunton et al. 2012). The Reformatory Quarry Member possesses exceptionally preserved soft-bodied biota (fauna and flora) at sites between the City of Guelph and the Bruce Peninsula (*see* Williams 1915b; Copeland and Bolton 1985; Hewitt and Birker 1986; Tetreault 2001; von Bitter and Purnell 2005; von Bitter et al. 2007; Collette and Rudkin 2010; Härling 2012; Waddington, Rudkin and Dunlop 2015); such sites of exceptional fossil preservation are referred to as Lagerstätten.

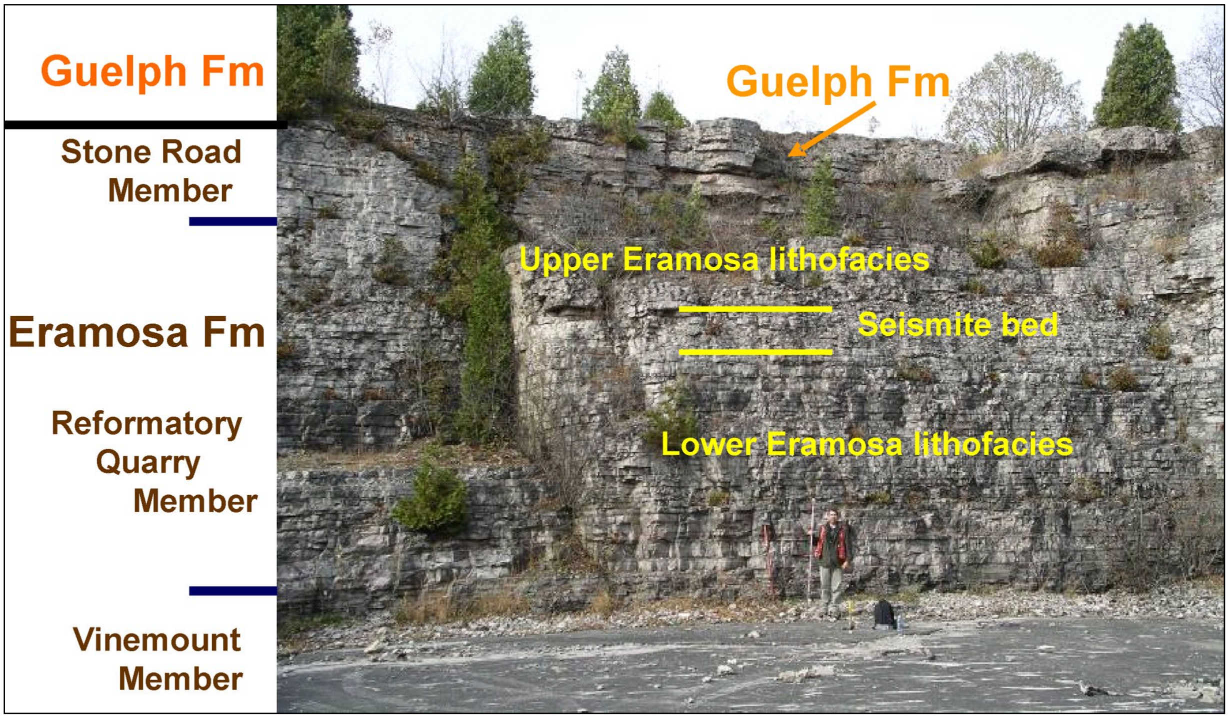

Figure 19. Proposed type section of the Eramosa Formation, at the Reformatory Quarry, City of Guelph, Ontario. This abandoned quarry cuesta face enables the examination of the Eramosa Formation (Reformatory Quarry Member and upper ostracod-dominated facies of Stone Road Member), which occurs immediately below Guelph Formation lithofacies (Brunton 2008, 2009; Brunton et al. 2011; Brunton et al. 2012). This cuesta steppe of the Eramosa and Guelph formations occurs on the east side of the Eramosa River from where Williams (1919) proposed Eramosa and Guelph lithologies as a type section. The disrupted, earthquake bed (seismite) present in this section can be correlated to the Dolime Quarry face situated approximately 10 km to the west (*see* Figure 20), and is found as far north as Wiarton, on the Bruce Peninsula, and to the south in Niagara Falls Gorge.

The Reformatory Quarry Member of the Eramosa Formation also displays a significant response to karstification because of its uniform fine dolomite crystallinity (e.g., Eramosa Karst, in Stoney Creek; Buck, Worthington and Ford 2003).

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; biostromal and small biohermal complexes possessing a low diversity bryozoan–microbial–coral composition; stromatoporoid–tabulate coral–bryozoan–microbial composition; 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 City of Guelph to Rockwood areas display evidence of more open marine storm-influenced deposition, including swaley cross-stratification (SCS) or possibly hummocky cross-stratification (HCS). The presence of seismites in the Reformatory Quarry Member supports the inference that deposition of the Eramosa Formation was during an intermittently tectonically-active period of Lockport Group deposition (*see* Figures 19, 20).

Whole rock geochemistry and microprobe analyses have revealed 3 phases of diagenetic pyrite formation in the Eramosa Formation. Elevated levels of arsenic occur within microbially precipitated, matrix-bearing, framboidal pyrites (*see* Brunton et al. 2007; Banks and Brunton 2017). 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 (δ^{13}C carb) isotope stratigraphy of the Eramosa Formation reveals a middle Sheinwoodian through possibly late Sheinwoodian age (Bancroft et al. 2016; see Silurian stages in Figure 6). The presence of *Ozarkodina sagitta rhenana* and *Kockelella walliseri*, combined with elevated carbonate carbon ($\delta^{13}C_{carb}$) 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; Bancroft et al. 2016). 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 and the overlying Guelph Formation is most likely late Wenlock or Homerian in age.

GUELPH FORMATION

Although the Guelph Formation was first recognized by Logan (1863) in the City of Guelph and Galt, Ontario, no type section was allocated. Arey (1892) was the first to recognize the fauna and strata of the Guelph Formation in New York. The Guelph was separated into the Upper and Lower Shelby Dolomite in New York by Clarke and Schuchert (1899) based upon differing faunal types. Kindle and Taylor (1913), Schuchert (1914), and Ulrich and Bassler (1923) all observed Guelph fauna in the uppermost Lockport Dolomite. Zenger (1965) correlated what he named the Oak Orchard Member, Lockport Formation, of New York with the Guelph Formation of southern Ontario (Williams 1919; Shaw 1937; Caley 1940; Bolton 1953, 1957). Rickard (1975) renamed the Oak Orchard Member, the Guelph Dolomite of the Lockport Group. Rickard's (1975) nomenclature was adopted by Brett et al. (1995). In the subsurface of Michigan, the Guelph Formation has been correlated with the uppermost formation of the Niagara Group and the Engadine Group in northern Michigan (*see* Catacosinos et al. 2001).

In Ontario, the Guelph Formation has been classified as a formation of the Albemarle Group (Bolton 1953, 1957; Johnson et al. 1992); the formation above the Amabel Group or Lockport Formation (Sanford 1969a, 1969b; Liberty and Bolton 1971; Armstrong and Carter 2006, 2010); and the uppermost formation of the Lockport Group (Brunton 2008, 2009; Brunton and Brintnell 2011; Brunton et al. 2012; *see* Figures 1, 14).

Regional mapping of the Guelph Formation supports the view that it represents the uppermost carbonate rock unit of the Lockport Group (Brunton 2009; Brunton and Brintnell 2011; Brintnell 2012; Brunton et al. 2012) because it displays mappable facies and predictable sequence stratigraphic architectural themes on a regional basis. In Ontario, the outcrop belt of the Guelph Formation extends along the southern portion of the Niagara Escarpment (eastern erosional edge of cuesta); the strata dip gently into the subsurface in a southwesterly direction towards the Michigan Basin, the result of mantle movements during the Carboniferous Period when supercontinent Pangaea was forming. There is much confusion in the literature regarding the facies that make up the Guelph Formation and what has been mistakenly correlated as Brown Niagaran, Grey Niagaran and White Niagaran rock units of the Lockport Group throughout the subsurface of the Michigan Basin and northwestern portion of the Appalachian Basin (*see* Alguire 1962; Sanford 1969a, 1969b; *see* Figures 11, 12, 13). Therefore, Guelph Formation rock units are best described in the context of their cyclic and stratigraphic relationships with underlying reef mound and lagoonal carbonate cycles of the Eramosa, Goat Island, and Gasport grainstone-wackestone transgressive–regressive (T–R) cycles.

The Guelph Dolime Quarry, City of Guelph, Ontario, has been chosen as the type section for the Guelph Formation (*see* Figure 20; Brunton 2009). Approximately 16 m of strata are well exposed in the

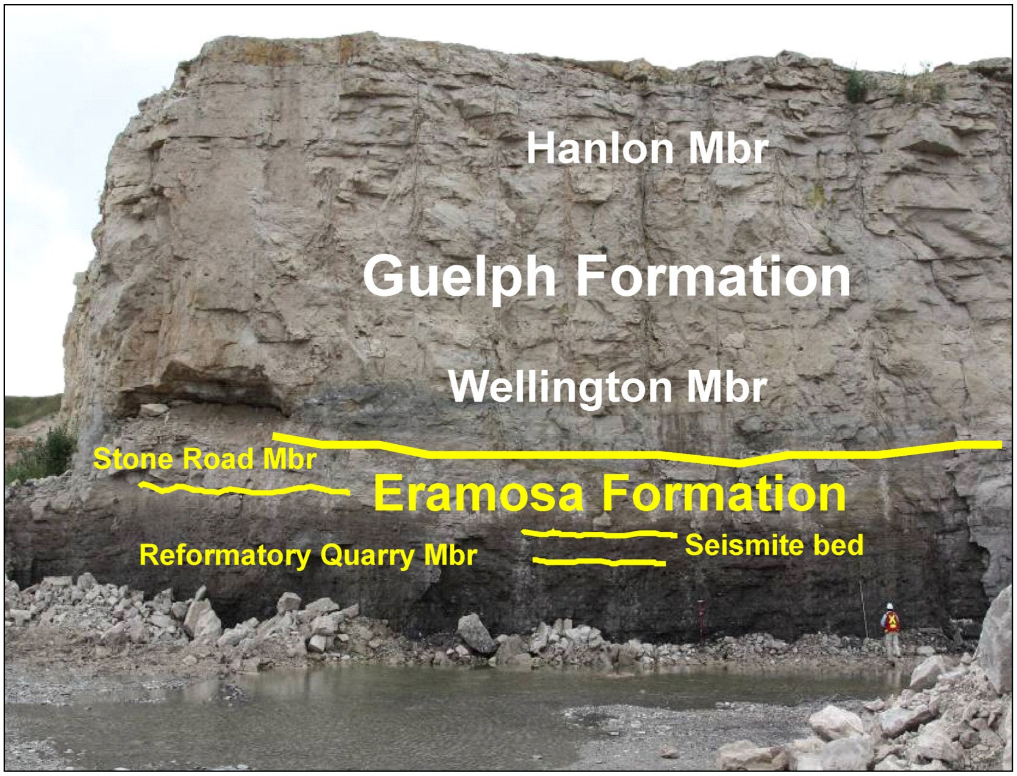

Figure 20. Type section for Guelph Formation, southern quarry face within the Guelph Dolime Quarry, situated in the City of Guelph. It comprises both members of the approximately 16 m of the Guelph Formation (Derek Armstrong for scale). The Guelph Formation is no longer quarried at this quarry. The Eramosa and Guelph formations here both display key regional lithofacies characteristics outlined in the report and observed in the Guelph–Cambridge–Fergus–Elora region.

upper quarry bench and display all key facies 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). Two regional cores, one drilled in the Elora area and the other at Luther Lakes, possess more than 100 m of Guelph Formation strata and are described in Brintnell (2012). This stratigraphic unit possesses a cream to light brown matrix colour and is known regionally in the subsurface as the "Brown Niagaran" (Alguire 1962; Sanford 1969a, 1969b). It is generally 15 to 22 m thick in the Cambridge through City of Guelph region and thickens toward Luther Lakes and northern Bruce Peninsula regions, where thicknesses exceed 60 to more than 100 m.

Regional surface and subsurface mapping of the Guelph Formation during this study has demonstrated that the initial informal members allocated to the Guelph Formation within the type section area in the City of Guelph are present on a regional basis (Brunton 2009). These 2 members include, from base to top 1) the Wellington Member, a lower, carbonate reef mound-bearing and more open-marine grainstone- to wackestone-dominated facies (Brunton 2009); and 2) the Hanlon Member, an upper, mid-shelf, open marine to lagoonal facies that changes through time to more restricted marine microbial-bearing sabkha facies cycles that display varying degrees of exposure and cave textures or karstification (Brunton 2009). However, there is considerable variation in the facies character, thicknesses and presence and/or absence of these 2 members regionally, and this has resulted in much of the confusion over what constitutes the Guelph Formation throughout the subsurface and outcrop belt.

In Ontario, 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 formation displays a sharp, erosional basal contact with the underlying Eramosa and/or Goat Island formations. This contact generally possesses a discontinuous stromatoporoid–favositid biostromal unit with a greyish-tan peloidal mud matrix. 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.

Eight major facies have been delineated in the Guelph Formation, 3 facies in the Lower Guelph Member (Wellington) and 5 facies in the Upper Guelph Member (Hanlon) (Brintnell 2012). Facies of the Wellington Member include stromatoporoid-algal-skeletal packstone to wackestone, coral-stromatoporoid-skeletal floatstone and skeletal-algal wackestone to mudstone. Facies of the Hanlon Member include gastropod-bryozoan-algal wackestone to mudstone, gastropod-megalodont-algal wackestone to mudstone, pisolitic-gastropod wackestone to mudstone, microbial-laminated mudstone, and brecciated microbial laminites and/or mudstones (Brintnell 2012).

SALINA GROUP

In Ontario and Michigan, the Guelph Formation is overlain by the lowermost microbial carbonates and evaporites of the Salina Group (Sonnenfeld and Al-Aasm 1991; Armstrong and Carter 2010), previously called the Salina Formation (Sanford 1969a; Johnson et al. 1992). In Ontario, the Salina Group comprises up to 420 m of carbonates, evaporites, and shales underlying the Bass Island and Bertie formations and overlying the Guelph Formation (Armstrong and Carter 2010). Older papers considered the Salina Group to be the lower unit of the Cayugan Series (Schuchert 1903) or Cayugan Period or Group (Clarke and Schuchert 1900; Caley 1940). Landes (1945) first subdivided the Salina Group into 8 formations, which from base to top are referred to as rock units A to H. Evans (1950) refined this work, subdividing the

A unit into A-1 and A-2. The H Unit was correlated with the upper unit of the Cayugan Series in Michigan (Lane et al. 1909) and renamed the Bass Island Formation in Ontario. An additional subunit, termed the A-0 carbonate subunit, was described from Michigan by Gill (1977a).

The geology of the Salina Group has been determined from wells and mines, as there is no type section in Ontario because these strata are easily eroded and are currently covered by thick Quaternary sediments. In Michigan, 8 formational units A-1 to G are recognized in the Salina Group (Lilienthal 1978; Sonnenfeld and Al-Aasm 1991). Ontario follows a similar nomenclature scheme, where Armstrong and Carter (2010) recognize 9 units in the Salina Group: A-0 through G (*see* Figure 1). In the Appalachian Basin of western New York and adjacent jurisdictions, the Bertie Formation was included in the Salina Group (Rickard 1975). There, the Salina Group is composed of only 4 formations: the Vernon, Syracuse, Camillus and Bertie formations (Rickard 1975). In the Michigan Basin, the Salina Group is dominated by cyclic evaporitic packages that grade upwards from carbonates to anhydrites (locally replaced by gypsum) to halite and capped by shaly units (Armstrong and Carter 2006, 2010). These cycles gradually become more shale dominated in the uppermost Salina Group and towards the Appalachian Basin in the southeast. Brintnell (2012) has provided more detailed descriptions of the cores and outcrops containing Lockport Group strata, and specifically Guelph Formation and basal Salina Group facies and paleokarst features. A comparison of Lockport Group "Pinnacle reef" models relative to overlying Salina Group strata is summarized in Figure 13.

Utility of Gamma-Ray Logs for Interpreting Early Silurian Stratigraphy

The natural gamma-ray, caliper and conductivity logs, in combination with the optical and acoustic televiewer logs, provide the most helpful information to relate geophysical, porosity-permeability and karstic features observed in the bedrock within a borehole to the development of groundwater-flow zones. Appendices 2 and 3 contain borehole logs, including the 12 OGS-regional wells with multilevel ports, which show stratigraphy and natural gamma-ray profiles. The boreholes extend from the northern Bruce Peninsula to the City of Guelph–Hamilton regions. The logs of a few select wells are illustrated below to show how the gamma-ray signatures of the various stratigraphic units that make up the Medina, Clinton, and Lockport groups can be used to help undertake regional correlations when rock core and optical televiewer logs are not available, to facilitate the identification of the positions of formational and member boundaries.

The gamma-ray log for the Valens borehole, situated in the city of Hamilton region, provides a good example of the lithologic character of the various stratigraphic units encountered above the regional Cabot Head Formation aquitard (Figure 21). The high gamma-ray signature at the base of the borehole log coincides with the Cabot Head Formation, which is the regional shale aquitard that extends from the northern part of the City of Hamilton jurisdiction (south of Highway 401) northward to Manitoulin and Cockburn islands in Lake Huron. The sharp drop in the gamma-ray signature at the top of the Cabot Head Formation coincides with the sharp, unconformable lithologic contact with the overlying Merritton Formation dolostone. This contact represents a significant regional disconformity (unconformity) related to forebulge migration and regional cut-down of Clinton Group strata during the early Silurian (Salinic Disturbance tectophase; see sequence stratigraphy discussion later in report; Brunton et al. 2012).

The overlying Merritton, Rockway and Irondequoit dolostones (IRM, depicted in many of the borehole logs in the appendixes), which are relatively clay-free and diagenetic mineral (sulphide)-free, or "clean", compared to the underlying Cabot Head Formation shales, show a step-down decrease in gamma-ray counts upward within the 3 dolostones. This thin stacked dolostone succession (generally less

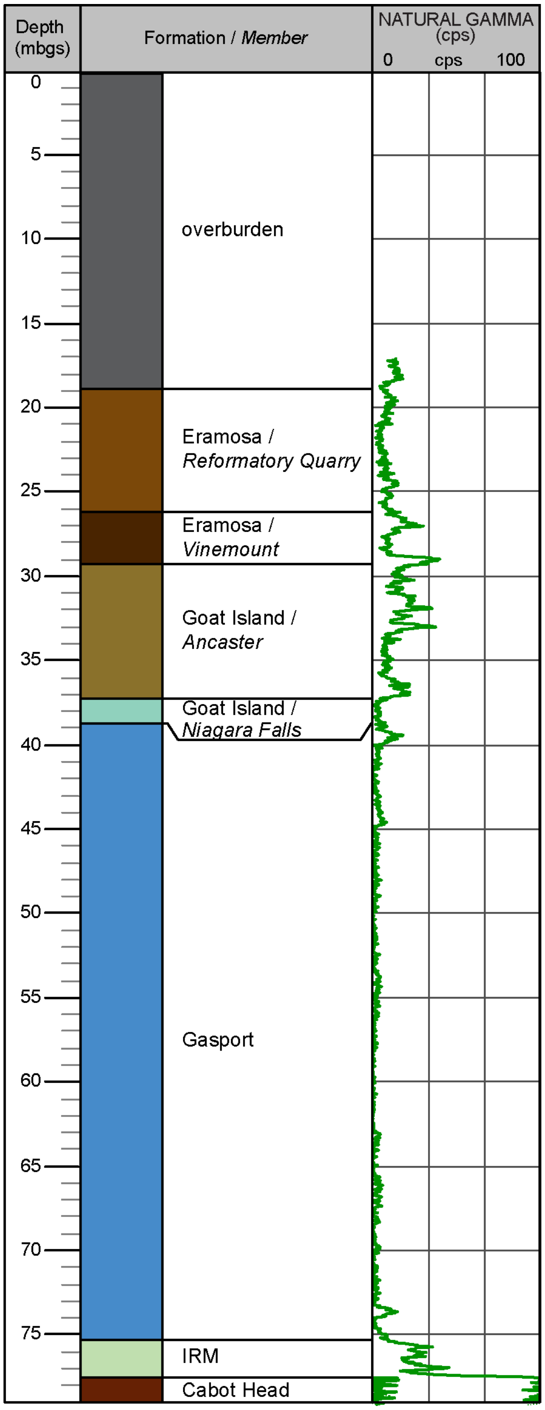

Figure 21. Geologic and natural gamma-ray log for Valens borehole, drilled in collaboration with City of Hamilton Water Works and Source Protection staff (*see* Brunton et al. 2010). Abbreviations: cps = counts per second; IRM = Irondequoit, Rockway and Merritton; mbgs = metres below ground surface. Note the step-down gamma-ray signature from the disconformable contact between the basal Cabot Head and overlying Merritton formations to the contact between the Irondequoit Formation encrinites and "clean" clay-poor Gasport Formation encrinites. The slight gamma-ray kick just above the formational contact reflects a karstic interval that is observed in many of the wells regionally. Older groundwater studies in Cambridge–Hamilton areas that did not collect core or cuttings misinterpreted this gamma-ray kick as a thin Rochester Formation interval. The contact between the Ancaster Member of Goat Island Formation and the Vinemount Member of the overlying Eramosa Formation is difficult to pick where cut-down surfaces are not present. In this core the contact is at the 28.8 m interval, marking the inflection to a peak gamma-ray kick that resembles the McDonalds "golden arches" or "M" signature.

than 10 m thick), which separates the potable groundwater-flow zones of the overlying Lockport Group from the high TDS (total dissolved solids) and marine pore waters of the Cabot Head Formation, are persistent packages of strata that extend to the northern Bruce Peninsula (*see* OGS-DDH15 borehole log in Appendixes 2 and 3). Gamma-ray logs were instrumental in helping to characterize and define the contact between the crinoidal grainstones and packstones of the Irondequoit Formation and the overlying encrinites (carbonate rocks with more than 50% crinoidal skeletal material) of the Gasport Formation.

There is often a phosphatic lag deposit of granule- to sand-grade grains in the uppermost Cabot Head and basal Merritton rock units (resembles black pepper corns mixed in the matrix). The gamma-ray kick associated with the phosphatic lag (representing a hiatus in sedimentation: Brett, Goodman and LoDuca 1990; Brett et al. 1995; McLaughlin et al. 2008) coincides with a sequence boundary of variable temporal significance. The gamma-ray signature of this lag deposit is often masked by the high shale content of the underlying Cabot Head Formation, which itself possesses phosphatic pebble- to silt-grade grains. The finely crystalline and bioturbated Rockway Formation comprises 10 to 30 cm thick dolostone cycles with thin, calcareous shaly seams resulting in a slight kick in gamma-ray signature. The uppermost unit of the Clinton Group throughout the regional boreholes north of Hamilton consist of Irondequoit Formation encrinites. This rock unit superficially looks like overlying Gasport Formation encrinites, but with important distinctive characteristics. The Irondequoit Formation possesses trace clay minerals in its matrix and secondary glassy matrix-void-filling gypsum. The Rochester Formation shales and interbedded carbonates that separate the Irondequoit from the Gasport formations all along the Niagara Peninsula region are absent in most wells north of the city of Hamilton (representing a significant tectonically-induced cut-down and unconformity). Therefore, the top of the Irondequoit Formation is often darkened in colour because it represents a sequence boundary surface that was variably affected by karstification prior to the subsequent transgression and return of marine deposition of Gasport encrinites and reef mound phases; as a result, the Irondequoit Formation has a weak gamma-ray signature that steps down to virtually zero at contact with overlying Gasport Formation.

The overlying Gasport Formation comprises stacked crinoidal-rich and heavily bioturbated grainstones and packstones deposited under normal marine conditions with virtually no clay or silt size terrigenous minerals present. Deposition in this part of the carbonate ramp was further away from the influence of terrigenous material from the Appalachian foreland basin. Therefore, the Gasport Formation generally shows a flat gamma-ray signature in boreholes north of the city of Hamilton to Manitoulin Island. The small deflections, or kicks, in the gamma-ray signature of the Gasport Formation in some boreholes reflect karstic dissolution zones of variable development and preservation (as seen in the basal part of the Valens borehole; *see* Figure 21). Other boreholes record slight gamma ray kicks associated with karstification or exposure and weathering of reef mound-complex tops or crinoidal dune complexes, during either short-lived regressive phases or a combination of sea level change and minor forebulge migration and uplift phases along parts of the early Silurian carbonate ramp (i.e., sequence stratigraphic breaks reflecting a variable amount of time). The variability of lithofacies in the Gasport Formation associated with cyclic sedimentation and crinoidal shoal and periodic exposure of reef mound complexes has resulted in development of regional-scale, karstic, groundwater-flow zones. In general, the “noisier” the gamma-ray signature is and the thicker the Gasport Formation, the greater the chance of the formation having multiple bedrock groundwater-flow zones. Also, the stratigraphic and geophysical characteristics of the Gasport Formation discussed above represent the “production zone”, or key water-bearing zones, of the now abandoned “Amabel Formation” (*see* Figure 1 and stratigraphic column in Figures 11, 12) in older groundwater studies for City of Guelph (Belanger et al. 2006; Brunton et al. 2007).

The slight gamma-ray kick at the contact between the Gasport Formation cyclic encrinites and reef mound phases and the overlying encrinites of the Niagara Falls Member of the Goat Island Formation represents a time of exposure and karstification and associated concentration of secondary, or diagenetic, clay minerals and sulphides. The cross-laminated encrinites of the Niagara Falls Member seldom display karstic features within the unit and are well indurated and possess trace clay materials reflecting the onset of a regional transgression across the carbonate ramp in southern Ontario and highlighting its temporal distinction from the depositional environments of the underlying Gasport Formation. The contrast in diagenetic history between the karstic weathered upper Gasport Formation and the well-indurated transgressive encrinites of the overlying Goat Island Formation, which represents a sequence boundary of variable temporal significance, has enabled the development of productive karstic groundwater-flow zones in the upper Gasport Formation (at and below the sequence boundary). Bedrock groundwaters within the cuesta are forced through and along the upper Gasport Formation (variably karstic zone permitting development of higher porosity and permeability zones) and below the less vertically and horizontally permeable Niagara Falls Member.

The contact between the Niagara Falls and Ancaster members of the Goat Island Formation can be sharp and disconformable (some cores show a sharp, angular erosional contact) and the lithologic contrast results in the development of karstic, planar horizontal fractures that may be productive groundwater-flow zones. The karstic flow zones may coincide with gamma-ray kicks in the middle to upper parts of the Ancaster Member cyclic dolostones because karstic zones possess concentrations of insoluble clays and sulphide and/or oxide minerals.

The contact between the finely crystalline, thinly bedded, variably cherty wackestones of the deeper water, cladoporid-bearing Ancaster Member dolostones of the Goat Island Formation and the overlying dark shaly dolostones of the Vinemount Member of the Eramosa Formation is sharp and, in some places, displays an erosional cut-down. The Valens gamma-ray log shows the characteristic multiple spikes in signature related to cyclic deposition of thinly bedded to laminated finely crystalline, shaly dolostones. There is a distinctive cladoporid coral-bearing unit that, when present, occurs in the uppermost units of the Ancaster Member lithofacies, and results in a stepped "noisy" increase in the gamma-ray signature for the member. The stratigraphic relationships observed suggest that there was not continuous deepening from the Ancaster marine environments and associated sponge-bearing faunas into the Vinemount marine conditions, but that there was a hiatus in sedimentation on parts of the ramp, with a sharp ravinement contact observed in some cores and outcrops followed by a subsequent sea level rise. The Vinemount Member appears to fill in paleotopographic lows on a variably karstic terrain (paleo-seafloor) comprising either Ancaster lithofacies of the Goat Island Formation and/or an upper Gasport composite reef mound complex (representing paleo-islands or highs). The Vinemount Member is a very effective vertical barrier to groundwater movement and behaves as a subregional aquitard from the Niagara Falls Peninsula through to the City of Guelph and Cambridge regions. This stratigraphic unit is missing across a large area of the cuesta from Fergus–Elora region to southern Bruce Peninsula, where it reappears and can be found throughout much of the Bruce Peninsula (Brunton et al. 2012; Banks and Brunton 2017).

The overlying Reformatory Quarry Member of the Eramosa Formation, which possesses the most complex and varied regional pattern of lithofacies and depositional settings (*see* Brunton 2009; Brunton and Brintnell 2011; Brunton et al. 2012), shows evidence of significant karstification when it forms the upper caprock carbonate unit (steppe) of the Niagara Escarpment cuesta (Hamilton to Niagara Falls; parts of City of Guelph; parts of Bruce Peninsula). The gamma-ray profile shows the typical step-down in signature from Vinemount to Reformatory Quarry lithofacies to the overlying Guelph Formation (see Membro well gamma-ray profile below; Figure 22). The Membro well profile from the central region of the City of Guelph, which is tens of kilometres away from Valens well, displays a similar gamma-ray profile and possesses the topmost Guelph Formation of the Lockport Group (*see* Figure 22).

The characterization of fractured bedrock aquifers is one of the most challenging problems in the field of hydrogeology. This is especially true when one tries to relate the various gamma-ray kicks in geophysical profiles to horizontal and vertical fractures versus more significant horizontal karstic fractures that represent time breaks of generally thousands to millions of years and which coincide with

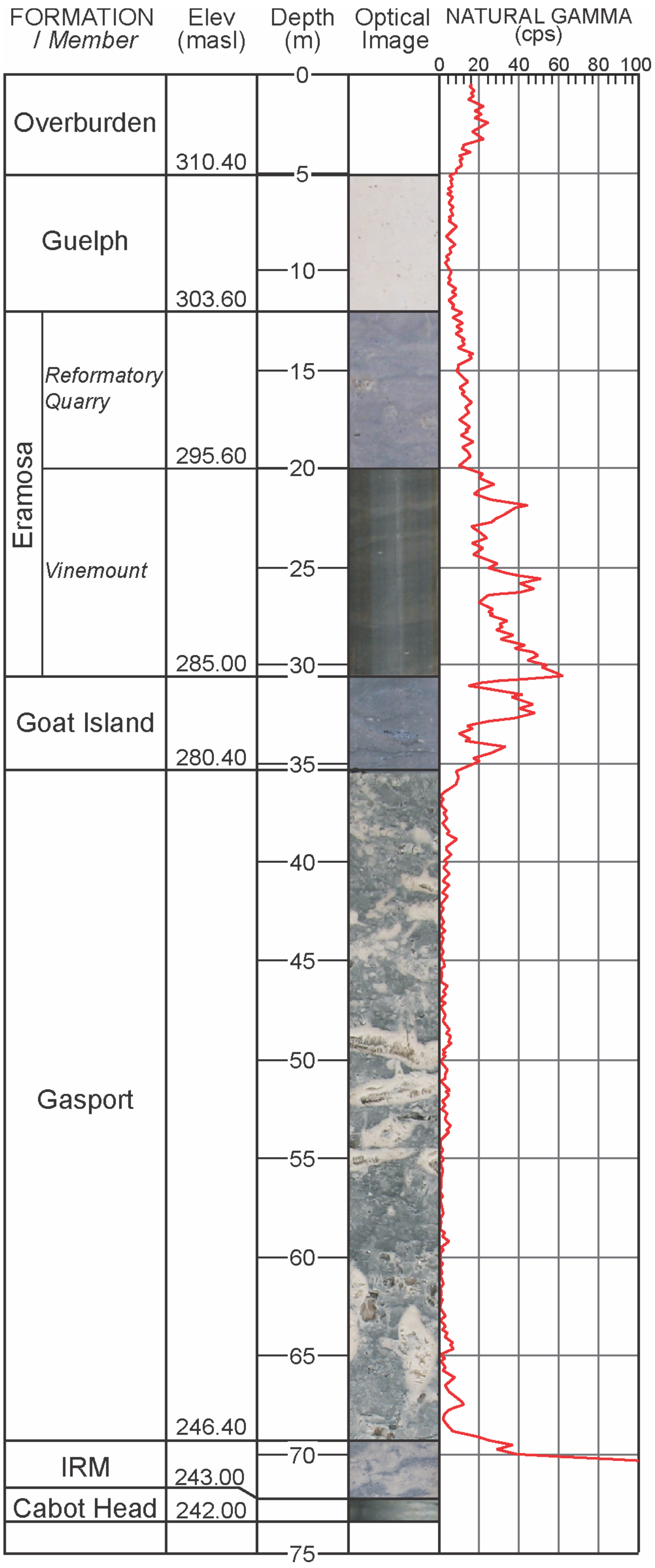

Figure 22. Geologic and natural gamma-ray log for Membro well, City of Guelph. Geological investigations are part of a collaborative 3-D geologic and groundwater characterization study with water works staff at City of Guelph (*see* Belanger et al. 2006; Brunton et al. 2007). From top to bottom, IRM = Irondequoit, Rockway and Merritton formations. Other abbreviations: masl = metres above sea level; cps = counts per second.

erosional or karstic events and associated secondary clay mineral precipitates. Some of these features represent regional-scale cut-downs (sequence stratigraphic breaks, or unconformities). Integration of the gamma-ray logs with the stratigraphy also involves unravelling, with extreme difficulty, the complex geologic history of the Silurian carbonates of the Niagara Escarpment cuesta: 1) from the initial early diagenetic burial history to the formational fluid history that took place during the Silurian through Carboniferous time; 2) to the post-Pangaea tectonic readjustments and differential erosion of a now southwesterly dipping Paleozoic strata that is under a compressive plate tectonic stress field; 3) to the hundreds of millions of years of pre-glacial, karstic carbonate cuesta development; 4) to the past few million years of continental ice sheet glacial sculpting of the bedrock and introduction of large volumes of cold, chemically aggressive (CO_2-laden) glacial waters under variable hydraulic pressure gradients (loading and unloading of variably thick ice sheets and subglacial meltwaters); and 5) to the groundwater infiltration history of the present-day hydrologic regime.

The televiewer logs, combined with core logging, reveal that the gamma-ray kicks coincide with cyclic breaks in sedimentation and more regionally significant cut-downs or erosional and/or exposure events associated with short-lived drops in sea level during deposition of each of the Lockport Group formations across a broad southeasterly dipping carbonate ramp. Some of the secondary minerals may have been introduced during basinal fluid migration up dip into the early Silurian ramp dolostones during late Silurian through Carboniferous tectophases associated with intermittent Appalachian Basin orogenesis. Some boreholes reveal karst dissolution and vugs with residual mineral precipitates that most likely coincide with groundwaters that penetrated the Niagara cuesta for millions of years following supercontinent assembly and breakup, which resulted in the Paleozoic sedimentary strata having the southwesterly regional dip and cuesta geometries. Other karstic intervals that show gamma-ray kicks coincide with the introduction of Quaternary sediment-derived material that would have taken place during one of the many advances and retreats of the Laurentide ice sheet during the past few million years. The discovery of glacial sediments in karstic bedrock cavities tens of metres below the bedrock surface is generally observed near the main escarpment margin or proximal to bedrock valley walls or near sinkholes and generally not observed in the middle of cuesta plains.

Chemostratigraphic Profiles and Regional Stratigraphy

Chemostratigraphy studies were undertaken on key bedrock cores along the Niagara Escarpment to better delineate local to regional changes in stacking patterns of the early Silurian Clinton and Lockport Group successions, correlate the early Silurian stratigraphy, and to facilitate groundwater-flow zone mapping regionally.

Carbon isotopic profiles from the regional cores (Figure 23) reveal that the Llandovery (two Aeronian, one Telychian) and Wenlock (Ireviken) carbon isotopic excursions are present in the northern part of the study area (Manitoulin Island), where a greater thickness of Llandovery-age carbonates are preserved (Dyer Bay, Wingfield, St. Edmund and Fossil Hill formations; *see* Brunton et al. 2009; Rowell and Brunton 2011; Figure 24), and in the southern part of the Niagara Escarpment (*see* Figures 15, 16). In the central parts of the Niagara Escarpment region much of the Aeronian and Telychian succession is removed as a result of intermittent tectophases and resultant forebulge migration onto the Laurentia craton on the far-field side of the Appalachian foreland basin and resultant erosion of marine strata.

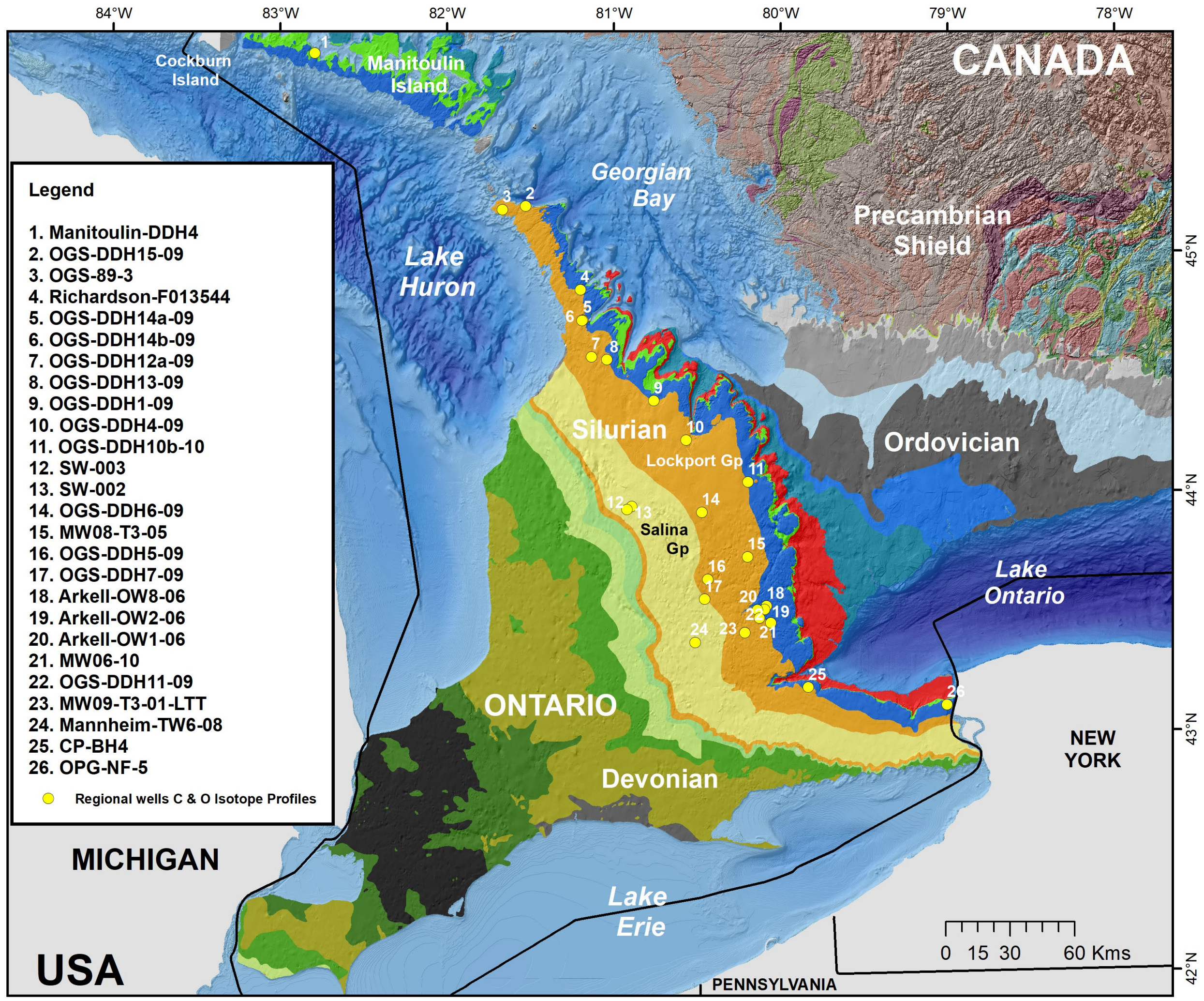

Figure 23. Location map of selected boreholes with carbon, oxygen and strontium chemostratigraphy profiles (*see* Appendix 4). The legend for the OGS bedrock geology layer (*modified after* Armstrong and Carter 2010) that is draped on the OGS bedrock topography surface (Gao et al. 2006, 2007) can be found in Figure 7. The red unit is the Ordovician Queenston Formation.

CARBON, OXYGEN AND STRONTIUM ISOTOPE PROFILES OF THE SILURIAN STRATIGRAPHY

Approximately 5200 carbon and oxygen isotope analyses were processed from 24 cores that occur from Manitoulin Island, in the northern part of the study area, to Niagara Falls, in southern part of study area. The sampling was on a variable scale (10 cm to metre scale), depending upon the complexity and thickness variations of major lithofacies. Sampling also took place below and above major lithologic contacts representing sequence stratigraphic boundary surfaces (*see* Appendix 4; Figure 24).

The carbon isotope curves for every borehole from Manitoulin to Niagara Falls show a similar positive rise in carbonate carbon ($\delta^{13}C_{carb}$) isotope values beginning in the upper Clinton Group strata (Irondequoit to DeCew formations) and through the Gasport, Goat Island and parts of the Eramosa Formation of the Lockport Group strata, which are the focus of the regional bedrock groundwater study. The values begin, in the upper Fossil Hill/Merritton, from slightly positive values of +1 to 2‰ and rise

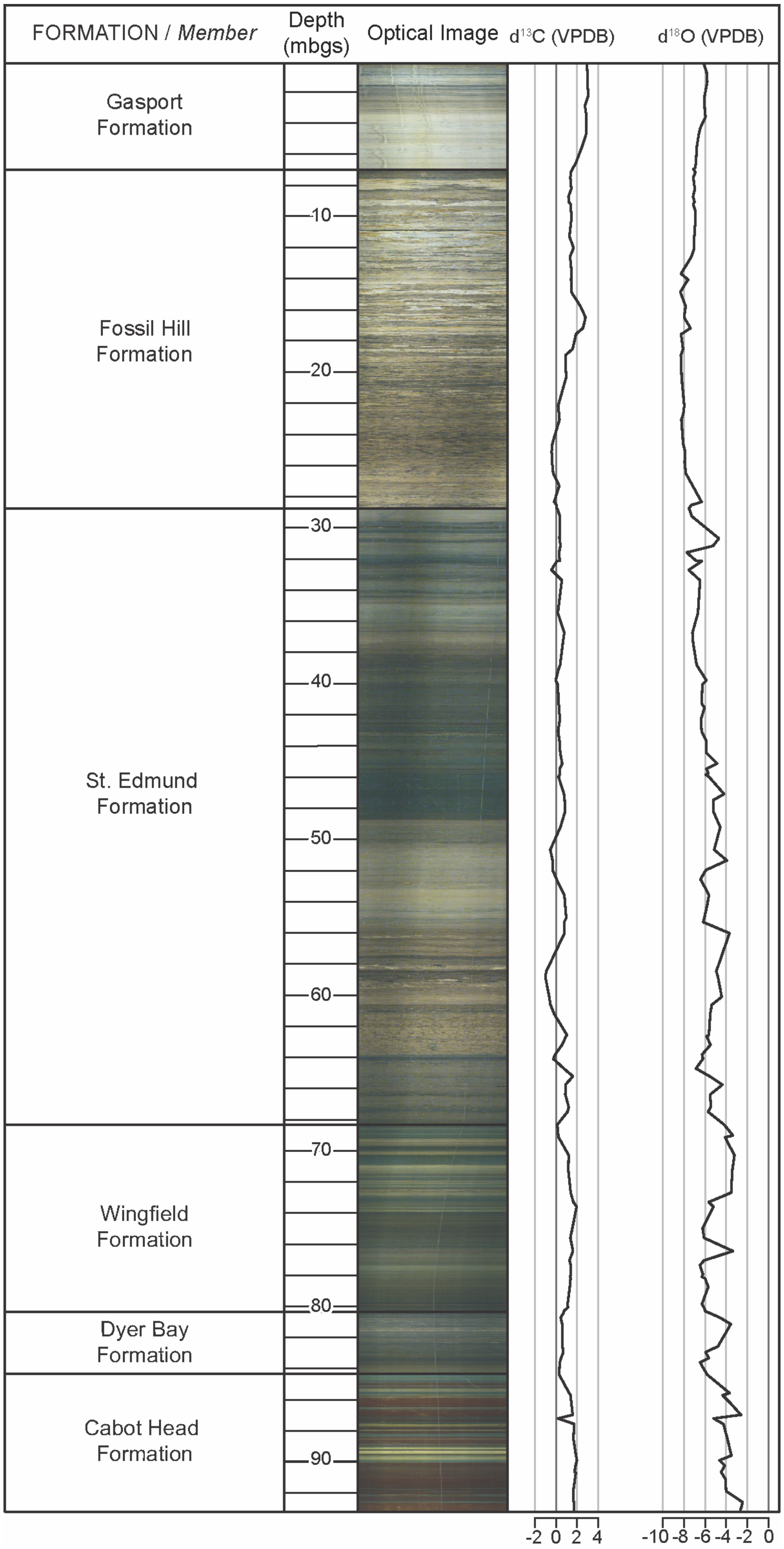

Figure 24. Carbon and oxygen isotope curve for Manitoulin core DDH-4 from a northern quarry in Lockport Group strata, Niagara Escarpment cuesta, Manitoulin Island. The carbon isotope curve shows a few small, up to +2 per mil rises and falls in value within the Wingfield, St. Edmund and Fossil Hill formations (thick succession of Clinton Group strata). The positive rise in the carbon isotope data from the Fossil Hill to Gasport formations reflects a similar trend observed in regional cores. Abbreviations: mbgs = metres below ground surface; VPDB = Vienna Pee Dee Belemnite (carbon-13 isotope standard).

through the Rockway, Irondequoit, Rochester, Gasport and Goat Islands formations, where numbers may reach 5 to 6‰. Such trends represent the rise and fall of the Ireviken isotope excursion (Figure 24; see logs in Appendix 4) that spans the Llandovery–Wenlock boundary globally. The Manitoulin carbon isotope profile also shows some +2 $\delta^{13}C_{carb}$ excursions that may reflect bioevents in the Aeronian and Telychian of the Llandovery Stage (see Silurian Stages in Figure 6).

Conodont biostratigraphy data from Niagara Falls, New York, and in southwestern Ontario place the Llandovery–Wenlock Stage boundary in the upper part of the Rockway Formation (Kleffner 1991, 1994; Bancroft et al. 2016). Detailed carbon isotope sampling was undertaken to test whether the stacked carbonates of the Lockport Group on Manitoulin Island (*see* Figure 24) are of similar age as the stacked encrinites in the Niagara Region, particularly because the lithofacies characteristics vary regionally within each of the Lockport Group formations. A more detailed assessment of the isotope stratigraphy, conodont biostratigraphy and sequence stratigraphic framework is underway with colleagues from the USA to correlate and identify the presence and/or absence of small-scale stratigraphic units both within and away from the Appalachian foreland basin (awaiting results of conodont sample processing from the Lockport Group, southern Ontario).

Niagara Escarpment Geomorphology, Hydrology and Groundwater-Flow Zones

Paleozoic-age strata in southern Ontario are under a regional horizontal compressive stress field (Lo 1978; Lo and Hori 1979; Lee 1981; Zoback 1992) as a result of the westward movement of North America since the Atlantic Ocean began to open and the supercontinent Pangaea broke up. The present-day Niagara Escarpment cuesta landform exposes part of the Paleozoic succession that has been subjected to differential erosion and karstification for the past 300 million years. This arcuate scarp is capped by early Silurian-age carbonate-dominated strata of the Lockport Group and extends from western New York State through southern Ontario and Manitoulin Island to the Upper Peninsula of Michigan and ending in central Wisconsin (approximately 1500 km long; Figure 25).

The sedimentary rocks that comprise the Niagara Escarpment display a complex but predictable stratigraphic architecture that has been revealed through acquisition and detailed logging and sampling of cores and outcrops both within and away from the "Arch", or forebulge region (*see* Figure 8 for location of this structural high traditionally referred to as the "Arch", but now recognised as a forebulge region; *see* also logs in Appendixes 2 to 5). Because of regional stress fields that developed prior to, during, and after breakup of the supercontinent Pangaea, Paleozoic strata of southwestern Ontario presently dip gently in a southwesterly direction away from the topographic high of the Niagara scarp face (*see* discussion in "Geologic Setting"; *see* Figures 25, 26). The present-day geographic location of the Niagara Escarpment (which is the highest topographic feature in southwestern Ontario)—to the east of 3 Great Lakes and in the midcontinent region—relative to the prevailing wind directions in the North American continent, controls the regional hydrology of the cuesta.

The Lockport Group, which comprises stacked carbonates of highly variable thickness, porosity and permeability, and paleokarst and reactivated karstic features, forms the caprock of the Niagara Escarpment and cuesta. Differential erosion over hundreds of millions of years, since the breakup of Pangaea, including the most recent and atypical glacial-induced physical and chemical erosion over the past few million years, has resulted in the present-day bedrock topography and hydrology (*see* Figure 26). Large bedrock valleys and re-entrants occur in the Paleozoic strata across much of southern Ontario (Karrow 1973; Eyles et al. 1997; Gao 2011; *see* Figure 26). The most commonly held view of their formation is polygenetic, with valleys initially having formed pre-glacially, resulting from millions of years of physical and chemical erosion of vertical bedrock lineaments, joints, fractures that resulted in the cuesta geomorphology. Following this, bedrock valleys were modified by physical and hydraulic carving or erosion by ice and subglacial meltwaters and proglacial lakes, and subsequent variable infilling of Quaternary sediments, during the past few million years of Laurentide ice sheet advance and retreat in southern Ontario (Straw 1966, 1968a, 1968b; White and Karrow 1971; Karrow 1973; Eyles et al. 1997; Barlow 2002; Gao et al. 2006; Gao 2011; Bajc et al. 2017; Priebe et al. 2019; see also discussions of glaciotectonic and glaciohydrogeologic processes in Ravier and Buoncristiani 2018).

The Silurian sedimentologic, stratigraphic and tectonic history, specifically concerning how and when sequence breaks formed, provides an important context for understanding present-day carbonate bedrock groundwater systems (*see* Brunton et al. 2012; Banks and Brunton 2017; we follow the concepts concerning cratonic Silurian sequence stratigraphy outlined in Brett, Goodman and LoDuca 1990; Brett 1995, 1998, 1999; Brett, Boucot and Jones 1993; Brett et al. 1995; Brett et al. 2012; Brett et al. 2018).

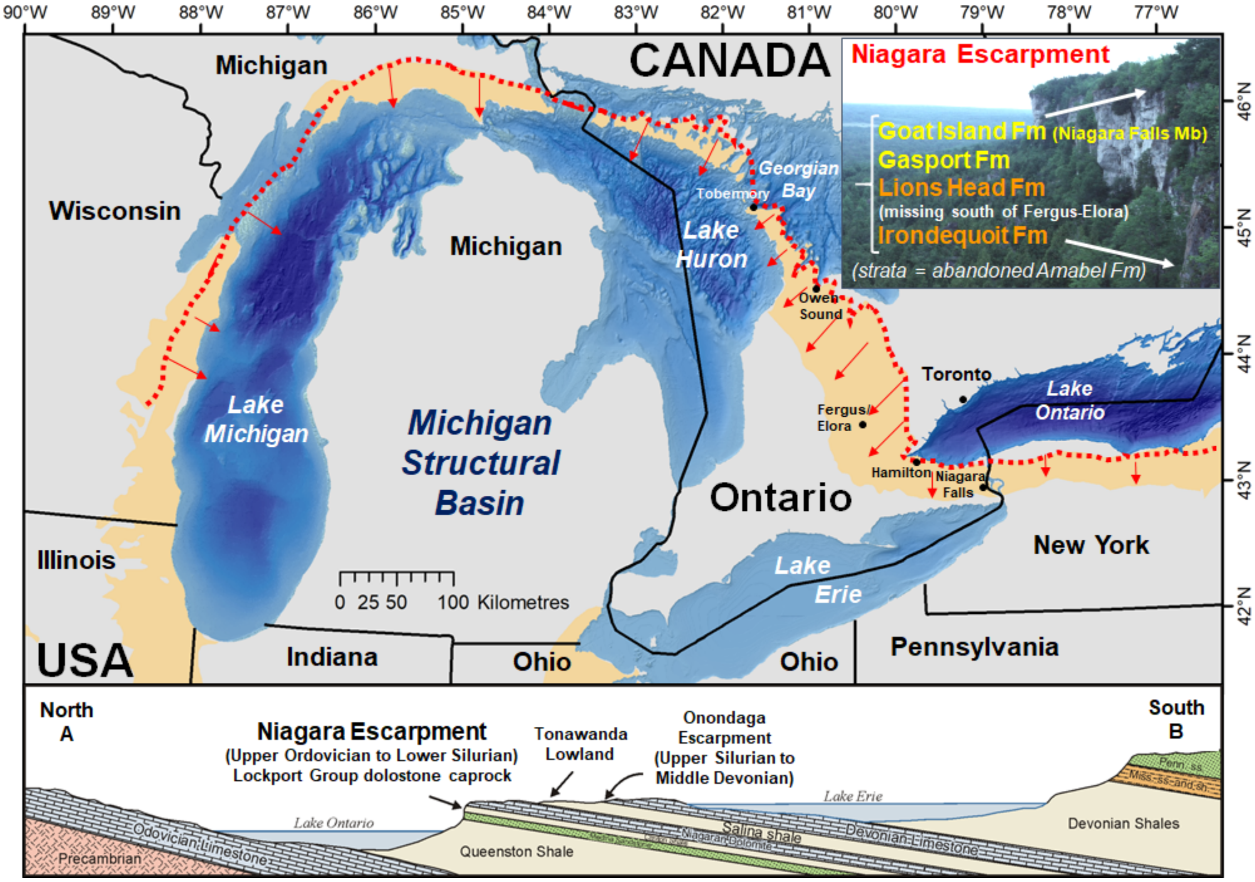

Figure 25. **A**) Great Lakes regional map depicting extent of Niagara Escarpment cuesta scarp (red dash line) extending from Rochester, New York, in east through Ontario and Upper Peninsula of Michigan to central Wisconsin, in the west (approximately 1500 km in length). The escarpment cliff, which is capped by early Silurian-age Lockport Group strata, may exceed 100 m in height. The arrows depict the structural dip of the eroded early Silurian cuesta resulting from adjustments in the mantle during the formation of the supercontinent Pangaea in the Carboniferous. The Paleozoic strata once covered much of the Canadian Shield in Ontario and have eroded back to the present scarp because of erosion that happened during supercontinent assembly and break-up (more than 300 million years). Differential erosion of Paleozoic strata under the current horizontal regional stress regime is the result of the opening of the Atlantic Ocean and the westward movement of what is now North America. **B**) Regional cross-section of the various cuesta landforms that influence regional bedrock groundwater flow systems across south-central Ontario (from left to right: Upper Ordovician Coboconk–Gull River strata comprise the Carden Plain cuesta region north of Lake Ontario, early Silurian Lockport Group forms the caprock of the Niagara Escarpment, and Upper Silurian to Middle Devonian carbonates form the Onondaga Escarpment; *from* Sanford 1969b; *see* Figure 2b).

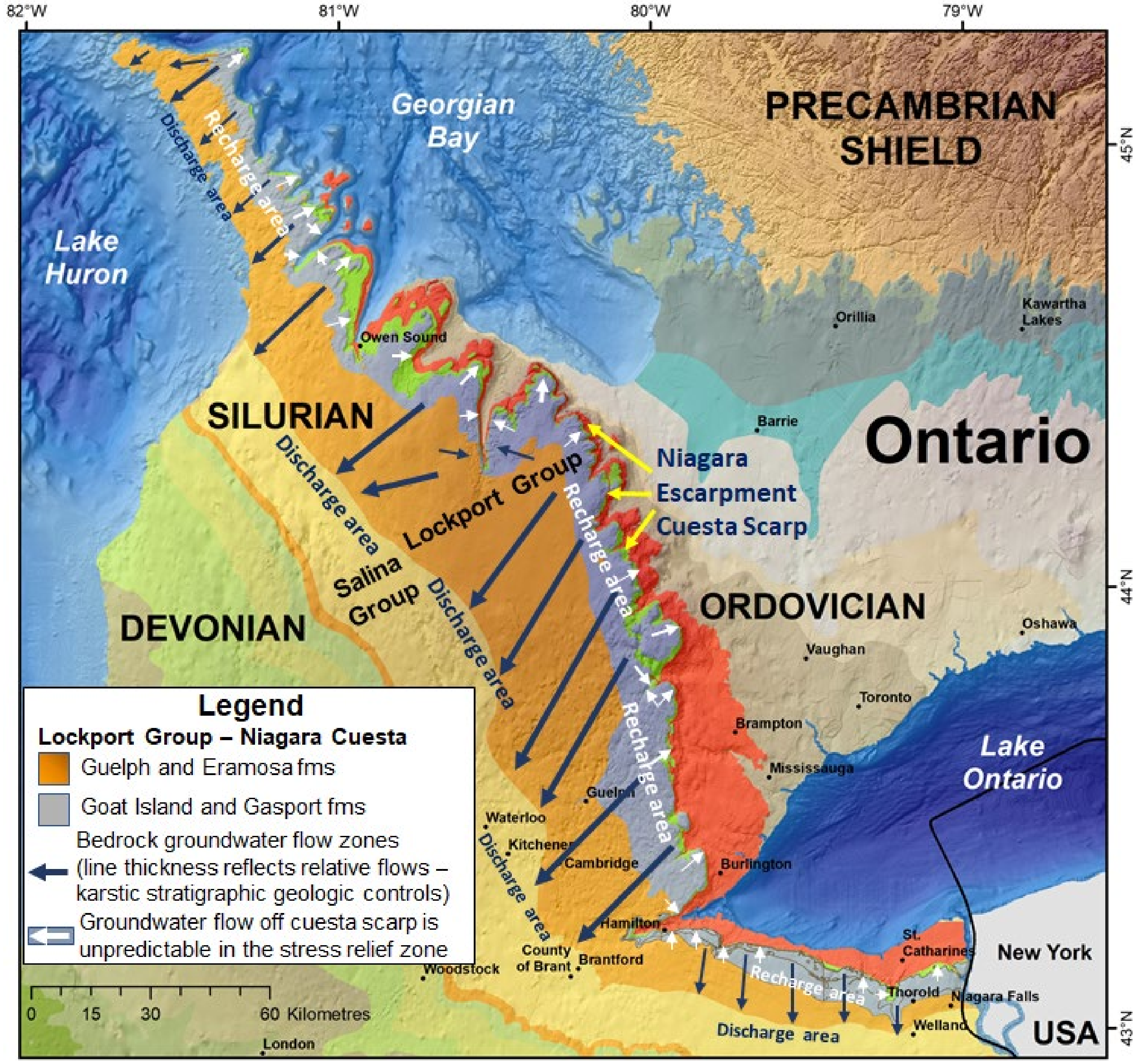

Figure 26. Bedrock topography and geology map for southwestern Ontario summarizing main flow directions of potable groundwater-flow systems within the Lockport Group karstic dolostone strata of the Niagara Escarpment cuesta region (Brunton et al. 2012; Banks and Brunton 2017; *see also* Figures 27, 28, 29). Topographically controlled recharge areas associated with thin-drift areas in eastern and northern parts of the cuesta enable rain and snow melt to enter regional-scale bedrock groundwater-flow zones in up-dip regions of the cuesta where bedrock is exposed or buried under thin Quaternary sediment cover. Once rain and snow melt have entered bedrock through overburden or directly, bedrock groundwaters follow regional, karstic flow zones situated at sequence boundaries within the Lockport succession and flow to discharge regions, which are largely buried under variably thick Quaternary sediments or basal Salina Group strata. A bedrock stress-relief zone that occurs within a few kilometres of the cuesta margin (scarp face – white arrows) and re-entrant, or bedrock valley cliffs (e.g., Beaver Valley, Rockwood Valley, Dundas Valley), results in more unpredictable and off-cuesta scarp bedrock groundwater-flow directions, waterfalls, springs and karst. The blue arrows depict flow directions in intermediate to deeper Lockport Group strata. Flows are generally within preglacial and postglacial karstic horizontal bedrock voids that are controlled by a combination of regional variations in stratigraphic architecture, positions of major lineaments and bedrock valleys, and dip of the Paleozoic strata.

Simplified sequence stratigraphic models and the associated jargon and nomenclature are difficult to establish for stacked carbonate and shale successions deposited on the far-field side of foreland basins, as is the case for this study area (*see* McLaughlin et al. 2008; Brett 1995, 1998; Brunton et al. 2012). Sequences are variably thick packages of sedimentary strata that record between 0.5 to 3 million-year intervals of the relative rises and falls of sea level and associated sediment deposition and erosion, and interplay between tectonic uplift, subsidence, eustasy (global sea-level changes) and sedimentation (Vail et al. 1991; Ettensohn 1994; Brett 1995, 1998; Schlager 2005).

In carbonate-dominated and tectonically influenced ramp depositional environments (see definitions of ramps in Schlager 2005), like that of the study area, sequences may be divided into 3 phases: the lowstand, transgressive, and high-stand systems tracts (Brett 1995, 1998; McLaughlin et al. 2008), each delimited below by a discontinuity, referred to here as the sequence break or boundary. Intermittent tectonic activity can cause the carbonate strata to be uplifted and eroded, resulting in the development of sequence breaks of varying duration. Because sequence breaks can represent long breaks in deposition, the bedrock may display evidence of physical and chemical erosion (paleokarstification and/or diagenesis) prior to subsequent deposition of overlying geological units. These sequence stratigraphic breaks often resemble a bedding plane; however, their formation tends to represent time breaks of generally greater duration than background marine deposition and storm-based (event bed) depositional processes (see karstic groundwater-flow zone positions relative to sequence stratigraphic breaks in Lockport Group strata of Niagara Escarpment in Figure 27; see also discussion of aquifer characterization in carbonate environments in Maliva 2016).

The Lockport Group is an approximately 100 m thick package of marine carbonates that displays sequence stratigraphic breaks of variable hydrostratigraphic significance across the study area. The carbonate depositional cycles are largely the result of vertical (temporal) transitions from transgressive (open-marine) to regressive (more restricted marine) conditions on a formation-scale, with karstic intervals that vary spatially and temporally in relation to the sequence stratigraphic architecture (Brunton et al. 2012; *see* Figures 27, 28). The stratigraphic variability and preservation of the Lockport Group is the result of a complex interplay between tectonic activity (tectophases: Ettensohn 1994), forebulge migration, paleogeography, sea level fluctuations and variable paleokarstification (Ettensohn and Brett 1998, 2002; Brunton et al. 2012). Despite this complex interplay of tectonics and sedimentation, the strata display a predictable stratigraphic architecture that is evident through the acquisition and detailed logging and sampling of cores and outcrops across the study area (*see* Figures 1, 27 to 29).

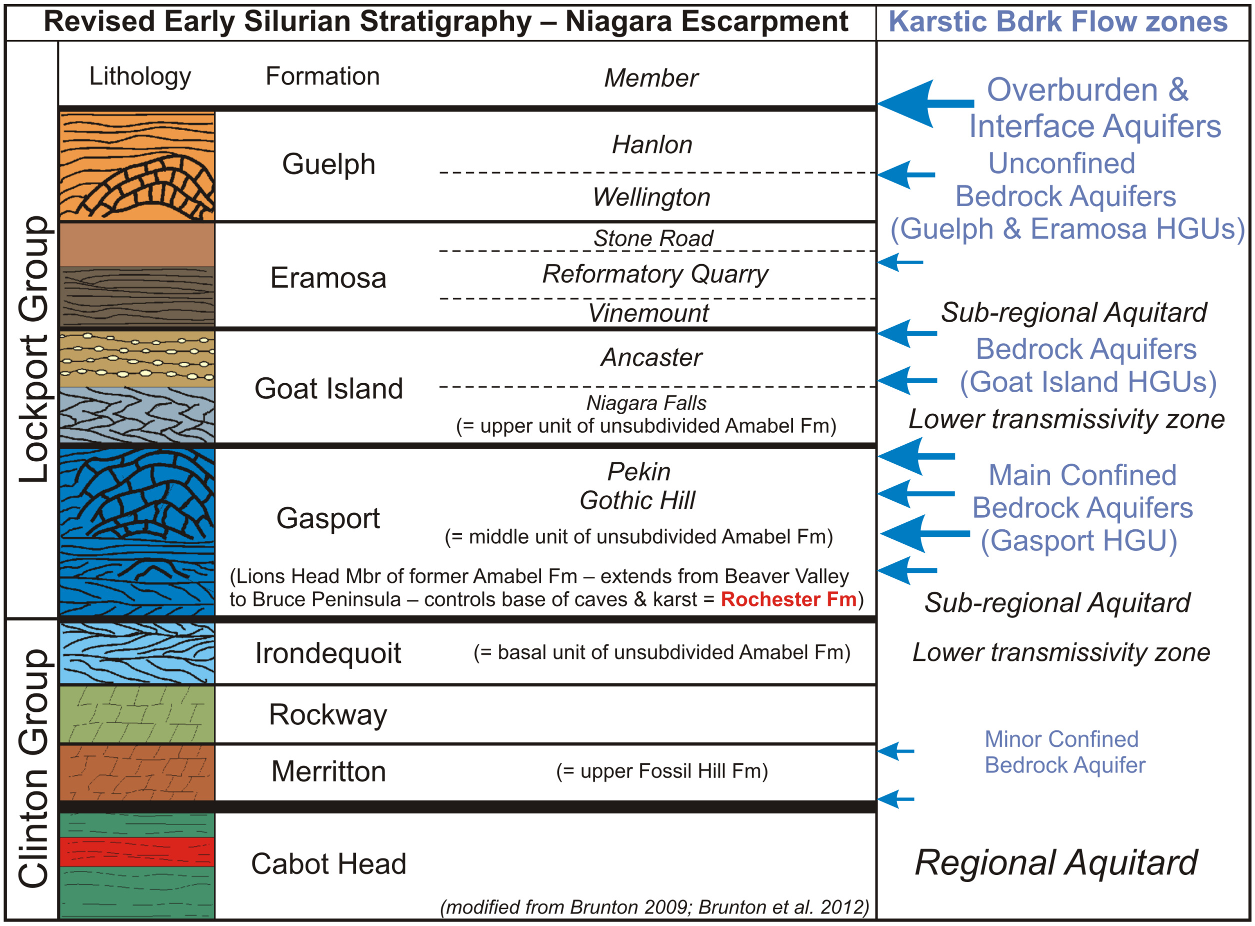

Figure 27. Revised Silurian stratigraphy of Clinton and Lockport groups for City of Guelph to Shelburne regions (updated from Brunton 2009). Relative thickness of lines separating formations in centre column reflects the significance of diastems (thicker lines indicate greater time break). Key aquitards include Cabot Head Formation, overlying Merritton and Rockway formations, Niagara Falls Member of Goat Island Formation, and Vinemount Member of Eramosa Formation. The Fossil Hill Formation correlates with Merritton Formation to the south, and the Lions Head Member of abandoned Amabel Formation correlates with Rochester Formation. Recent mapping in Rockwood area, southeast of Guelph, suggests that Vinemount Member equivalent shales are present between the Gasport Formation and overlying Eramosa Formation lithofacies (Reformatory and Stone Road members; see Brunton et al. 2009; Brunton et al. 2012). Abbreviation: HGU = hydrogeologic unit.

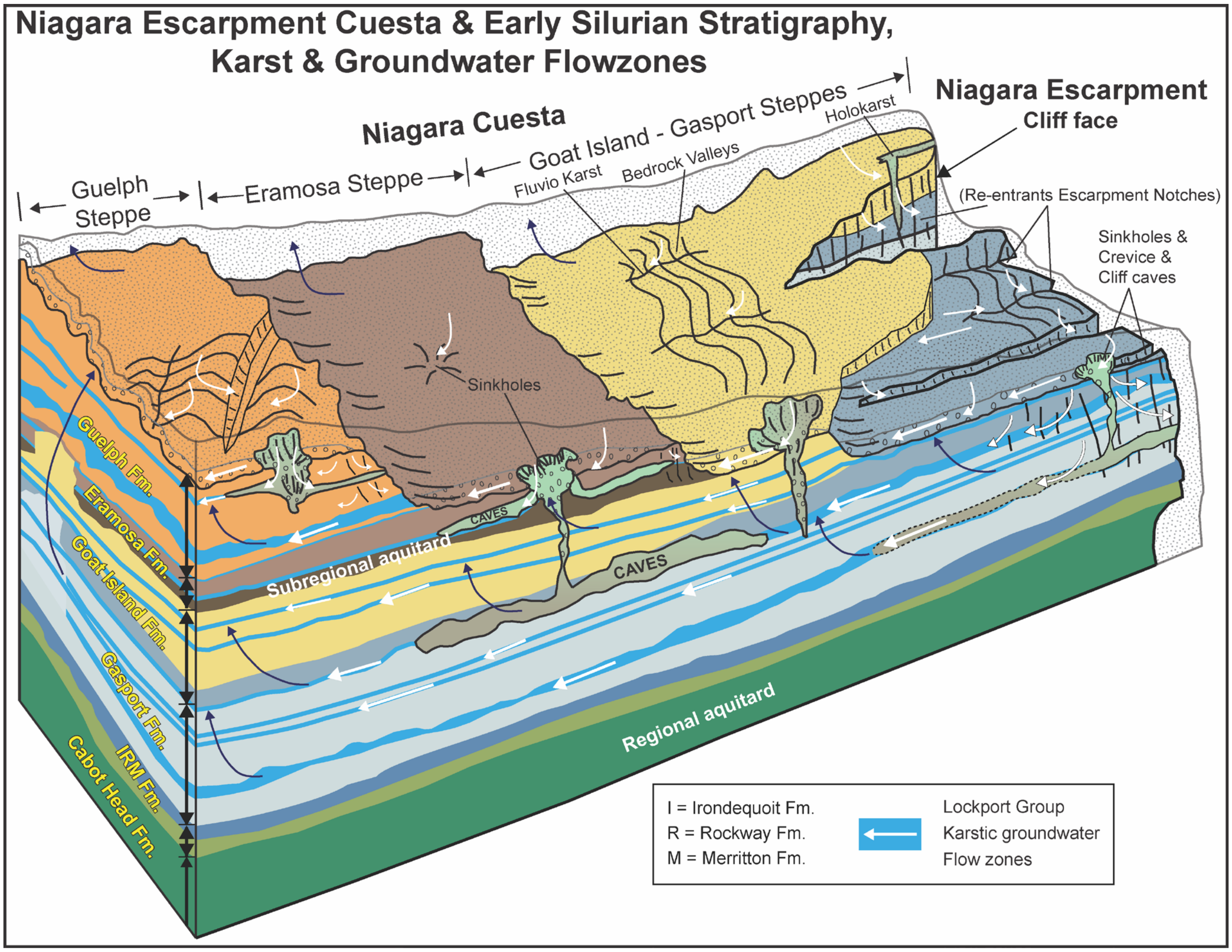

Figure 28. Three-dimensional conceptual model of Niagara Escarpment cuesta (view to the north-northeast) showing regional relationships of early Silurian caprock carbonates (dolostones) and resultant smaller cuestas or steppes of the Lockport Group, southwestern Ontario. The geologic and geomorphologic features are not to scale vertically or areally but meant to capture the variety of bedrock topographic and karst features observed from City of Guelph to Orangeville–Shelburne areas (approximately 40-50 km from southwest to northeast). The translucent dotted pattern draped on the bedrock surface reflects an oversimplified Quaternary sediment succession whereby tills (coarser fill pattern), which tend to occur at the bedrock surface, are overlain by gravels, sands and/or silty clays (dotted pattern) that represent the variety of glacial and/or proglacial depositional environments and landforms that cover much of the Niagara Escarpment cuesta. The Irondequoit Formation (and missing Rochester, DeCew and Lions Head formations) and Gasport Formation and lower Niagara Falls Member of Goat Island Formation (previously lumped together as abandoned “Amabel” Formation) form the caprock and prominent cliffs at the Niagara Escarpment scarp face throughout much of southern Ontario; the Guelph and Eramosa formations generally form smaller cliffs and cuestas, or steppes, down-dip of the main regional scarp face. Mapping the differential weathering of the Niagara cuesta beneath the Quaternary sedimentary cover, in conjunction with understanding the sequence stratigraphic architecture and regional variations in stratigraphy of the stacked dolostones, is very important for understanding the geological controls on regional bedrock groundwater flow in the Lockport Group. The karst features of the Niagara Escarpment are discussed in Brunton and Dodge (2008). The diagram depicts more penetrative vertical joints and lineaments near the escarpment margin—in the stress relief zone—than in more distal areas. The stress-relief region displays unpredictable groundwater flow directions and well yields. Lockport Group strata further down-dip are under the regional, horizontal compressive, plate tectonic stress field and display highly variable vertical and horizontal fractures and secondary rock matrix porosity and permeability. The region is also rebounding from the last advance of the Laurentide ice sheet. Key recharge areas are located up-dip and to the east (*see also* Figure 26), where ground elevations are highest and where precipitation and runoff penetrate through the variably thick Quaternary sediments or exposed bedrock surface and enter the enhanced postglacial karst (Holokarst) drainage bedrock-flow systems within the stacked Goat Island–Gasport dolostones and/or the Eramosa and Guelph steppes further down-dip on the cuesta. Stratigraphic architectural and geological controls have resulted in differentiated bedrock groundwater-flow systems across the cuesta. The Niagara cuesta bedrock groundwater-flow systems generally flow down-dip along sequence stratigraphic breaks (within layers of enhanced porosity and permeability due to lithologic contrasts and diagenetic history) and form a karst-

influenced, shallow-dipping plumbing system (white arrows depict a southwesterly to southerly dominant flow direction conforming to the overall regional geometry of the early Silurian dolostones; both down dip and upward gradients). The larger, cuesta-scale deeper bedrock flow paths extend beyond the southwestern edge of the diagram and display upward flow paths and artesian conditions of variable age groundwaters, extending from the Gasport and Goat Island formations to above the bedrock surface. They are not shown in this conceptual diagram to reduce the complexity of the regional flow systems. The blue arrows show artesian conditions (not meant to show flow paths) that were encountered in some wells further down dip in the cuesta where the deeper flow zones in Gasport, Goat Island and Eramosa formations are confined and separated from the surface groundwaters and surface waters residing on and in the Quaternary cover and shallow karstic bedrock surface zone.

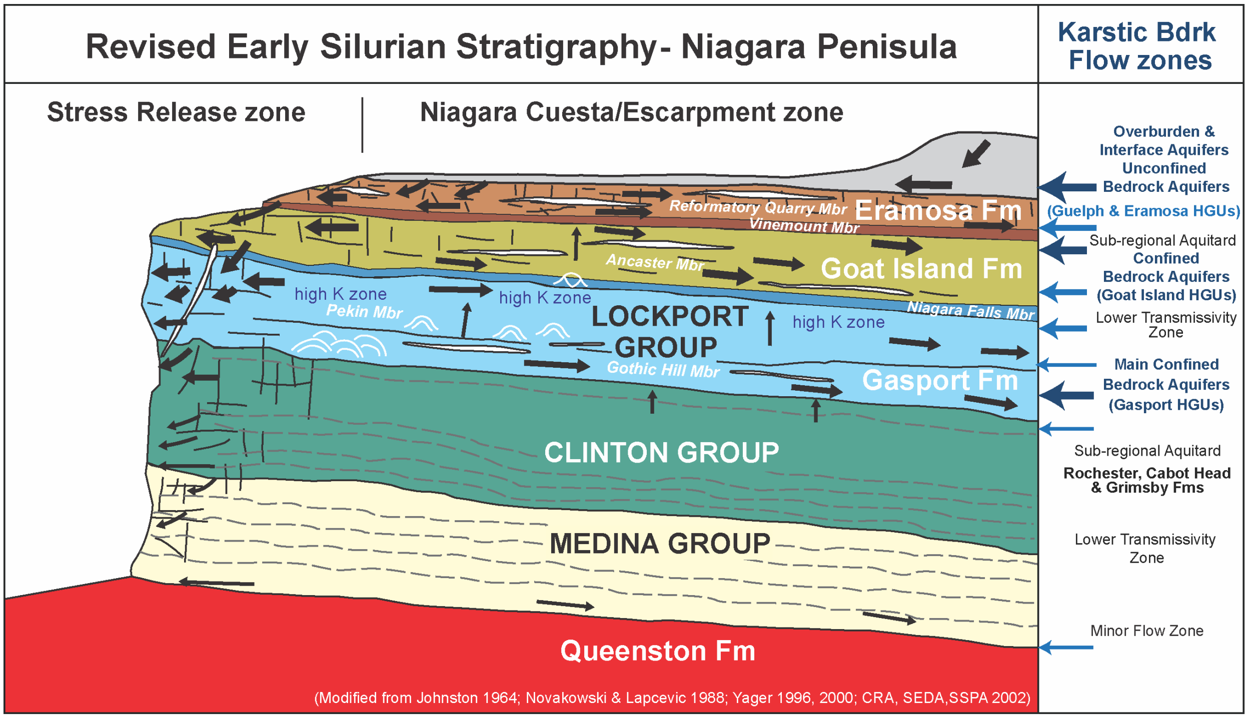

Figure 29. Bedrock groundwater flow within the early Silurian succession in the Niagara Falls to Ball's Falls region of southern Ontario (*modified from* Johnston 1962, 1964; Novakowski and Lapcevic 1988; Worthington 2007; Worthington and Ford 1999, 2009; Yager 1996). Black arrows represent relative bedrock flow directions. Vertical joints and lineaments affecting groundwater-flow directions near the escarpment margin (in the stress relief zone) also shown. Abbreviations: HGU = hydrogeologic unit; K = hydraulic conductivity.

The regional cuesta geomorphology, with strata dipping from northeast to southwest, enables groundwater flow from areas of high potential to low potential energy. This flow system represents one of the most significant regional bedrock aquifer systems in North America. The Cabot Head Formation forms a regional aquitard across the study area, and the Vinemount Member of Eramosa Formation forms a subregional aquitard from Niagara Falls to the City of Guelph region and then re-appears in parts of the Bruce Peninsula. The regionally extensive Cabot Head Formation shales of the underlying Clinton Group form a regional aquitard to the potable waters that flow through the overlying Lockport Group carbonates in an area extending from north of the city of Hamilton to Manitoulin Island (*see* Figure 28). Between Hamilton and Niagara Falls and east-central Lake Erie, the potable waters of the Lockport Group strata are underlain by a younger subregional aquitard – the Rochester Formation shales and mixed carbonate units of the Clinton Group (Figure 29).

Field- and lab-based protocols have been established to both undertake lithostratigraphic and sequence stratigraphic studies and integrate rock and water geochemistry and hydraulic conductivity estimates to demonstrate the geological controls on the groundwater-flow systems (Brunton et al. 2007; Brunton and Brintnell 2017; Priebe and Brunton 2016; Priebe, Neville and Brunton 2014, 2017).

Bedrock flow zones take advantage of sequence stratigraphic and cyclic breaks represented by lithologic contrasts at formational, member and rock unit contacts; these diastems, or disconformities, can be mapped from the Niagara Falls region of southern Ontario to the Bruce Peninsula region (Brunton 2009; Brunton et al. 2012; Banks and Brunton 2017; *see* Figures 26, 27, 28, 29). Some of the key bedrock flow zones are situated in crinoidal (encrinitic) grainstones and packstones of the Gasport and Goat Island formations, and others have been defined in the more finely crystalline Eramosa and Guelph formation dolostones (Brunton 2009; Brunton and Brintnell 2011; Brunton et al. 2012; Banks and Brunton 2017; *see* Figure 27).

The glacial sediments that overlie the bedrock in the study area comprise parts of the Guelph drumlin field, Paris Moraine, and Fonthill Kame and subaqueous fan deposits (Chapman and Putnam 1984; *see* Figures 28, 29). Overburden cover is thin or absent near the edge of the Niagara Escarpment cliff margin and in some bedrock valleys well away from the scarp face, or where bedrock topography is highest. In other areas, overburden cover may exceed 100 m in thickness and may infill bedrock valleys (*see* Figure 28; *see* Greenhouse and Karrow 1994; Gao et al. 2006; Gao 2011; Bajc et al. 2017).

Although a fraction of the precipitation (rain and snow melt) infiltrates into the shallow to deeper, variably karstic bedrock strata of the Lockport Group across the Niagara Escarpment region, the number and importance of various flow zones in the bedrock are not of equal significance across the region. Various studies of contaminated sites in the Niagara Falls and Smithville regions of southwestern Ontario and tunnel projects in the city of Hamilton region reveal groundwater-flow zones in the Gasport and Goat Island formations and in the upper Reformatory Quarry Member of the Eramosa Formation (Novakowski and Lapcevic 1988, Novakowski and Bickerton 1997; Oxtobee and Novakowski 2002, 2003; Zanini et al. 2000; *see* Figure 29). The Guelph Formation does not outcrop or subcrop in this part of the Niagara Peninsula region (*see* Figure 29). None of these flow systems provides the higher flow rates observed in flow zones from the Highway 401 corridor northward to Shelburne and southern Bruce Peninsula regions.

These more northerly regions have a much thicker preserved Gasport, Goat Island and Guelph formational stacked carbonate succession and a much higher, present-day bedrock elevation above mean sea level (Brunton and Brintnell 2011; Brunton et al. 2012; Banks and Brunton 2017). The prevailing westerly winds, which bring moisture from different regions across North America, depending upon the seasons, and from Lake Michigan and Huron, enable the highest levels of precipitation via snow and rain onto the Niagara Escarpment topographic highs (Ministry of Natural Resources 1984). The regional geology controls the infiltration of surface waters (rain, snow melt, rivers) into the overburden and karstic stacked dolostone units of the Niagara Escarpment (see recharge versus discharge areas depicted in Figures 2, 26). These regional geomorphologic and geologic features control the regional distributions of bedrock groundwater resources along the Niagara cuesta and escarpment region.

Summary of Findings

This report summarizes the regional lithostratigraphic and sequence stratigraphic character of subsurface and outcrop strata and provides new paleogeographic, paleoenvironmental and paleobiostratigraphic interpretations of the early Silurian succession in southern Ontario. It also summarizes the main geologic controls on the hydrologic setting and positions of groundwater-flow zones for the Niagara cuesta and escarpment margin area in southern Ontario.

Key sequence stratigraphic findings include the following, in ascending stratigraphic order:

1. There is significant differential erosion on the Cabot Head Formation surface regionally, especially in the region of the inferred Algonquin Arch, or forebulge zone, across southwestern Ontario.
2. The Reynales Formation does not extend very far into southern Ontario from New York State (occurs as far as the Thorold to Niagara Falls region and arguably within the Chatham Sag area in southwestern Ontario). Strata previously assigned to the Reynales Formation belong to the younger upper Fossil Hill (Merritton Formation of Brett et al. 1995) and Rockway formations, and form part of the underlying Clinton Group.
3. The upper Fossil Hill Formation (= Merritton Formation), which disconformably overlies the Cabot Head Formation, Grimsby Formation and Thorold Formation surfaces between Milton–Acton and Hamilton through Niagara Falls areas, extends across the "Algonquin Arch" without significant change in thickness and character and only thickens in the Meaford through Bruce Peninsula to the type section area on Manitoulin Island.
4. The Rockway Formation disconformably overlies the upper Fossil Hill (= Merritton) Formation and forms a persistent rock unit across the "Algonquin Arch" into the southern Bruce Peninsula region – it has been recognized in cores from Kincardine area through Bruce Peninsula. This formation has not been recognized on FitzWilliam, Manitoulin or Cockburn islands.
5. The Irondequoit Formation, previously assigned to the now abandoned Amabel Formation (*see* Cramer et al. 2011; Brunton and Brintnell 2011; Brunton et al. 2012), rests disconformably on the Rockway Formation and exhibits a distinctive welded contact. It has a consistent thickness across the "Algonquin Arch" and extends northward to Tobermory on the Bruce Peninsula.
6. The Rochester Formation shales, which pinch out north of Hamilton and Cambridge areas, are represented as a finely crystalline dolostone (= Lions Head Member of former Amabel Formation) referred to here as the Lions Head Formation (Figures 14, 27) from the centre Wellington (towns of Fergus–Elora) region northward to the Beaver Valley area and on the Bruce Peninsula to Manitoulin Island regions.
7. The Gasport Formation, which consists of variably thick composite reef mounds and interreef crinoidal shoal facies 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 the type section on the Bruce Peninsula). These terms are no longer formal stratigraphic units of formational and member rank in Ontario (*see* Cramer et al. 2011; Brunton et al. 2012). The term Amabel may be retained for industrial minerals purposes. A sharp, disconformable contact separates the Gasport Formation from the overlying basal crinoidal grainstones (Niagara Falls Member) of the Goat Island Formation. The Niagara Falls Member has been referred to locally in some hydrogeological reports as a low permeability unit of the unsubdivided Amabel Formation. It has a highly variable hydraulic conductivity (*see* Priebe, Neville and Brunton 2014, 2017). The significant paleotopography on the Gasport Formation is the main control on the character and presence and/or absence of overlying Goat Island and Eramosa formation strata in the Niagara Escarpment cuesta subcrop–outcrop belt of City of Guelph and Cambridge regions;
8. The Goat Island Formation comprises 2 members which, in ascending order, include the Niagara Falls and Ancaster. The basal Niagara Falls Member is evident in the type section of the Amabel Formation in Wiarton and along the northern coast of the Bruce Peninsula.

This lower unit also forms the bedrock cap away from the Niagara Escarpment cuesta margin between Shelburne and Orangeville to Erin, Acton, Guelph and Waterdown areas (*see* Figure 28). This rock unit and the underlying composite reef mound cycles of the Gasport Formation may be reefal and display facies characteristics that resemble both discrete members of the Goat Island Formation. Niagara Falls reef mounds can be distinguished from underlying Gasport reef mounds by their dominance in stromatoporoid versus tabulate coral megainvertebrates and variably crinoid-rich fabrics. The Ancaster Member of the Goat Island Formation is generally found above the Niagara Falls Member south and east of Hamilton, but interfingers with Niagara Falls Member facies in selected cores in the City of Guelph–Cambridge region and in more westerly cores of Michigan Basin in southwestern Ontario (*see* Brintnell 2012).

9. The Eramosa Formation lithofacies constitute a regionally persistent and faunally and lithologically distinctive rock unit in the eastern region of southern Ontario (along the Niagara Escarpment area) 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 (Brunton and Brintnell 2011; Cramer et al. 2011; Brunton et al. 2012). The middle Reformatory Quarry Member possesses a distinctive seismite bed that is recognizable from Niagara Falls to the central Bruce Peninsula and has been described from Ohio. This formation is not present in outcrop or quarries on FitzWilliam, Manitoulin and the Upper Peninsula of Michigan and was not readily distinguishable in drill cores examined from northern, west-central and southern Michigan State. This formation was either never deposited in Michigan or was removed prior to deposition of karstic Guelph Formation and Salina Group lithofacies;
10. The contact between the Eramosa and overlying Guelph formation rock units may be difficult to identify, but in some outcrops and cores the contact is marked by an erosional disconformity. Regional studies confirm the two-fold division of the Guelph Formation into a lower reef-mound-bearing unit (Wellington Member) overlain by largely gastropod (high- and low-spired snails) and megalodontid bivalve (Hanlon Member) lagoonal muddy facies.
11. Significant erosion and karstification of the Guelph Formation is evident in cores from across southern Ontario and Michigan. The most penetrative and intensive brecciations of restricted marine Guelph Formation facies, which extend downward into the Goat Island Formation and upward into overlying basal Salina Group mixed evaporite, shale and microbial carbonate cycles (A1 and A2 carbonate packages), are observed in Michigan cores. Eramosa Formation facies are largely not present in cores from southwestern Ontario and southern Michigan. These subaerial karstic features exist in an environment that is supposed to be the deepest water facies of the slowly subsiding Lockport Group basin (compare Figures 10, 11 to revised paleogeographic and sequence stratigraphic model in Appendix 7). The thickest preserved and least karstic Guelph, Eramosa, Goat Island and Gasport successions are found on the far eastern side of the Niagara Escarpment cuesta of southern Ontario (Brunton and Brintnell 2011; Brintnell 2012; Brunton et al. 2012).

These findings have led to the reinterpretation of the depositional history and paleogeographic setting of the Lockport Group succession in the Michigan structural basin in the following scenario (*see also* Appendix 7). The deposition of Eramosa and Guelph carbonates took place on an easterly dipping carbonate ramp of Gasport and Goat Island Formation grainstones, packstones and localized reef mound complexes and paleotopographic highs that record more restricted marine to open marine environs from west to east during Wenlock time. The Guelph Formation was subjected to regional erosion and karstification towards the end and after deposition, which is reflected in extensive brecciation of the upper member facies of the Guelph Formation and the overlying basal Salina Group strata (A0, A1 and A2 units). The proximal juxtaposition of younger Salina Group strata enveloping Lockport Group strata (Guelph through Gasport facies) in the subsurface of Michigan Basin is due to the regional development of karst towers within the terrigenous-poor and well-cemented Lockport carbonates. The paleotopographic relief of the Michigan Basin bullseye shelf (incorrectly referred to as Guelph Formation), which is rimmed by the upper Lockport Group, reflects the remnants of a regionally extensive and structurally influenced paleokarst basin. As such, the paleotopographic low of the upper Lockport Group in central Michigan, which gives the false impression of a depositional basin, is an erosional karstic terrain depression and not a deeper water marine basinal feature.

Perhaps the three-dimensional oil and gas plays in what is referred to as the Guelph “Pinnacle Reef” belt (e.g., Carter, Trevail and Smith 1994) should be considered an expansion of the Gasport hydrocarbon plays described from New York State (e.g., Crowley 1973), and that this *Lockport Group play* should be extended through Lake Erie and into southwestern Ontario and Michigan. The Guelph “Pinnacle Reef” play may in fact be remnant Gasport and Goat Island targets with paleokarsted Guelph caprocks and spatially associated Salina Group carbonate source rocks and traps (A1 and A2 carbonates). The Guelph Formation in the pinnacles does not display reefal textures or fabrics. The variably karstic and brecciated Guelph Formation caprock facies possess mostly restricted marine and muddy facies with abundant gastropods, megalodontid bivalves and low diversity stromatoporoids. Microbially-bound stromatactoid fabrics occur in some basal Gasport Formation and more abundant megafaunas occur in the overlying Goat Island Formation.

This reinterpretation helps to explain some of the significant observations made by Bailey (2000) regarding the challenges in characterizing the variable facies of Guelph “Pinnacle Reef” structures and highly variable production character. These three-dimensional subsurface structures comprise the entire Lockport Group succession and display recognizable disconformities (sequence boundaries) and multiple phases of karstification and infiltration of remobilized salts and secondary gypsum (indicating a complex post-depositional history; *see* Smith 1990a, 1990b, 1992, 1997, 2002; Smith and Charbonneau 1990; Smith, Charbonneau and Grimes 1993). Collection of multiple cores and use of optical televiewer logging of boreholes across the three-dimensional bank or cuesta structures has been helpful to characterize the regional variability of the Lockport Group. Regional ramp facies mosaics, three-dimensional block diagrams depicting the karst tower hypothesis, and detailed logs of the Lockport Group from across the Michigan Basin are the focus of future Ontario Petroleum Institute articles and journal articles.

Following examination of the regional, up-dip, shallower potable water wells, in combination with the more than 16 000 deeper oil and gas wells, it became apparent that the sequence stratigraphic character of the early Silurian strata was more complex than previously reported. It was also discovered that similarities exist between the up-dip and more deeply buried three-dimensional structures referred to as Guelph “Pinnacle Reefs” (up to 100 m thick by kilometres in width and length). The more deeply buried Guelph “Pinnacles” are not biogenic reefs and comprise older and variably paleokarsted Lockport Group strata dominated by the basal Gasport and Goat Island formations. These structures are like the transmissive three-dimensional structures described from the Cambridge and Guelph areas in the Niagara Escarpment region (Brunton 2009; Brunton and Brintnell 2011; Brunton et al. 2012). The up to 100 m of paleorelief of the Lockport Group strata represent an ancient (early Silurian), discontinuous, northwesterly-facing and northeasterly-trending set of scarps (cf. mesa and butte topography in karstic landforms) enveloped by much younger Salina Group shallow marine microbialites and interbedded evaporites (salt and gypsum beds that are variably paleokarsted and brecciated).

The Guelph Formation is a karst breccia unit regionally (referred to in oil and gas subsurface literature as interreef Guelph) in what is supposed to be slope and deeper shelf facies near the Lake Huron shoreline in southwestern Ontario. The Guelph Formation comprises two distinctive members in the City of Guelph and Cambridge through Elora–Fergus and Luther Lakes areas of the Niagara cuesta that are more open marine shelf or carbonate ramp lithofacies that change vertically to more restricted marine, muddy, nutrient-rich lagoonal facies with only selective paleokarstification (Brintnell 2012; Brunton et al. 2012). If the generally accepted depositional model was correct, we would expect to see much more karstified Lockport Group strata on the carbonate bank area (reef bank complex in Figure 10) in Guelph–Cambridge areas while the supposedly deeper water "pinnacle reefs" were undergoing karstification.

The Gasport Formation becomes less reef-mound bearing and thins northward in the outcrop–subcrop belt of Niagara Escarpment region and the younger Goat Island and Guelph formations thicken and possess reef mound phases and distinctive, karstic groundwater-flow zones. The Eramosa Formation displays a complex lithofacies mosaic in southwestern Ontario. Basal Vinemount Member lithofacies depict transgressive, deeper marine and cyclic deposition associated with a short-lived adjustment of the Appalachian foreland basin that resulted in mixed terrigenous-carbonate sedimentation and cladoporid-bearing coral beds onto the structurally complex Laurentia cratonic ramp that formed on the far-field side of the basin. The overlying Reformatory Quarry Member comprises open marine and higher energy lithofacies from the Niagara region through City of Guelph areas. This paleoenvironmental setting changes northward to more varied open to restricted marine, evaporitic lagoonal to possibly estuarine conditions, based upon faunas and stratal packages. Seismite-bearing units are evident within this member, from the central Bruce Peninsula region through City of Guelph to Niagara Region, supporting the interpretation of episodic disturbances of marine deposits during multiple, short-lived, Salinic tectophases following the major Salinic I disturbance cut-down evidenced in Clinton Group stratal architectural packages.

The regional changes in the stacking patterns of carbonate-dominated rock units of the Lockport Group, in combination with the hundreds of millions of years of differential erosion since the onset and demise of the supercontinent Pangaea (Carboniferous through Jurassic Periods), has resulted in the development of preferred karstic, bedrock groundwater-flow paths. Between the Guelph–Cambridge through Hamilton and Niagara regions, variably confined, bedrock groundwater-flow paths are preferentially developed in the Gasport Formation reef mound and interreef encrinites and overlying Goat Island Formation wackestones and packstones. The unconfined, karstic shallow bedrock groundwater-flow system is present in the Eramosa Formation's Reformatory Quarry Member lithofacies and overlying Guelph Formation lithofacies. Northward of the Lockport-time forebulge area (north of City of Guelph), the deeper-bedrock, confined groundwater-flow zones change from Gasport Formation-dominated flow zones to Goat Island, upper Eramosa and Guelph formational bedrock flow zones.

The preglacial hydrologic and hydrogeologic conditions of southwestern Ontario are largely controlled by a combination of the structural reconfiguration of Phanerozoic strata during the creation and break up of the supercontinent Pangaea (Carboniferous to Jurassic: 290 Ma to 170 Ma), and subsequent tens of millions of years of erosion that resulted in the cuesta geometries evidenced from Manitoulin and North Channel Islands in Lake Huron through to the south-central Ordovician cuestas. The apparent circular shape and general concentric dip of Phanerozoic strata of the structural Michigan Basin is not a depositional feature but a plate tectonic and structural (mantle-derived) response followed by differential erosion of once more regionally extensive marine Paleozoic strata that have been eroded off the Precambrian shield to its present-day configuration. Manitoulin Island possesses regionally distinctive cuesta steppes of Upper Ordovician- and early Silurian-age stacked carbonates and mixed siliciclastics and carbonates represented by an Upper Ordovician Coboconk–Gull River steppe, and a lower Silurian Manitoulin Formation, Fossil Hill Formation and Lockport Group (Niagara Escarpment) steppe consisting of a succession of dolostone alvars and variably karstic carbonate plains. These steppes are not as pronounced or evident across the thin-drift-covered, karstic, alvar dolostone plains of the Bruce Peninsula region, and the largely sediment-covered stacked dolostones from the southern Bruce Peninsula to Niagara Falls area and southwestward to Upper Silurian Bass Islands and Middle Devonian stacked carbonate steppes. Prior to the glacial advances and retreats over past few million years, this St. Lawrence

Lowland physiography was subjected to millions of years of physical and chemical bedrock weathering that resulted in development of a regional-scale karstic drainage characterized by sequence boundary-controlled, karstic bedrock groundwater-flow systems and surficial maze-cave karst development. The multiple advances and retreats of continental-scale ice sheets over this bedrock topography introduced enormous volumes of cold and chemically aggressive waters that accentuated and enhanced existing karst drainage networks.

The current Great Lakes drainage basins and surficial watershed boundaries in the postglacial sediment regime has resulted in a more complex, and in part, disconnected surface water–groundwater drainage network on the various cuestas of south-central and southwestern Ontario. The regional hydrologic system involves rain and snow melt being concentrated on the topographic highs of the Niagara Escarpment (*see* Ministry of Natural Resources 1984; Singer, Cheng and Scafe 2003). The deeper bedrock, karstic groundwater-flow systems recharge in the thin drift and exposed bedrock regions well up-dip (on topographic highs of the Niagara Escarpment) from where municipal wells may be drawing waters and do not correspond to the shallower, overburden-controlled watershed drainage divides. These geological controls, which influence the separation of shallower and deeper groundwater-flow systems across the Niagara Escarpment cuesta region, were not generally recognized prior to this regional study of deeper potable bedrock-flow systems. Another key observation has been that the cuesta margins (within a few kilometres of the cuesta edge), which represent areas of regional stress field relaxation, display much more complex recharge conditions, whereby precipitation infiltrates through overburden and exposed bedrock areas and either flows off the escarpment or is directed by vertically connected and solution-enhanced, joint-controlled openings, in unpredictable directions. Surface and shallow groundwaters entering the bedrock further away from the cuesta scarp margin penetrate the variably karsted joints and preglacially and glacially-enhanced karstic bedding planes and sequence boundaries, and generally follow the regional dip and stratigraphic architecture within the cuesta.

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Appendixes

Appendixes 1 to 7 are folders located in the root of Groundwater Resources Study 13.

Appendix 7 is also included here in the report as it presents conceptual depositional models for the Lockport Group stacked dolostone units.

Appendix 1.	Table of Stratigraphic Formation Picks for Key Niagara Escarpment Boreholes
Appendix 2.	Regional Boreholes FLUTeTM-Hydraulics Wells - GAL
Appendix 3.	Select Regional Boreholes Multilevel Ports and Gamma Logs
Appendix 4.	Select Chemostratigraphy and Isotope Regional Boreholes
Appendix 5.	Additional Geological Stratigraphic Logs – Regional Boreholes
Appendix 6.	Select Outcrop Stratigraphic Sections – Niagara Peninsula
Appendix 7.	Sequence Stratigraphic and Conceptual Depositional Models, Early Silurian Lockport Group, Southwestern Ontario to Michigan

Appendix 7

Sequence Stratigraphic and Conceptual Depositional Models, Early Silurian Lockport Group, Southwestern Ontario to Michigan

The following figures provide a conceptual model of the regional variability in lithofacies character and stratigraphic architecture for the Lockport Group stacked dolostone units (Brunton 2009; Brunton and Brintnell 2011; Brunton et al. 2012; Brintnell 2012) and overlying basal Salina Group A-Units (Cain Formation = A-0 Carbonate + A-1 Evaporite: Gill, Briggs and Briggs 1977, 1978; Gill 1979; Briggs et al. 1978; Briggs et al. 1980; and Ruff Formation: Budros and Briggs 1977). The first 2 figures (Figures A7a and b) show: 1) the regional extent of study area and locations of select wells and outcrops used to create the cross-sections, and 2) legend for the 7 paleoenvironmental and depositional cross-sections.

The cross-sections are shown from oldest to youngest formational-rank unit. The simplified geometry of the basal Clinton Group strata (DeCew and Rochester formations) depicts the inferred gently dipping to flat ramp-like paleo-seafloor topography along the eastern margin of Laurentia craton (far-field side of Appalachian foreland basin) during the early Silurian (late Llandovery–Wenlock). The thicknesses of these 2 basal units are not to scale because the Rochester Formation has been systematically cut down from southeast to northwest throughout southwestern Ontario prior to DeCew Formation deposition and erosion, supporting the contention that significant time is represented by the varied contact relationships between the Gasport, DeCew and Rochester formations. Our regional assessment of the Lockport Group enables a new regional paleogeographic and paleoenvironment interpretation for this succession. There are no sedimentologic or stratigraphic relationships that support the contention of a depositional basin centre or subsidence and deep-water conditions in Michigan during Lockport and Salina time.

Paleozoic strata in Ontario dip gently to the southwest and south due to mantle adjustments during Pangaean supercontinent assembly (late Devonian and Carboniferous) that led to downwarping of the Michigan structural basin. Prior to the mantle readjustments associated with the creation of Pangaea, the Upper Ordovician to Middle Devonian strata on the eastern margin of Laurentia craton were flat lying or dipped gently toward the Appalachian foreland basin. Localized juxtapositions of lithofacies thickness variations are spatially associated with the interplay between basement structures and intermittent forebulge migration and relaxation activity in areas referred to as “arches” and which run subparallel to the Appalachian Orogen. The “sags” which separate the “arches” generally occur where major ancient rifts or inherited transform fault systems have been inferred or mapped largely through regional geophysical surveys.

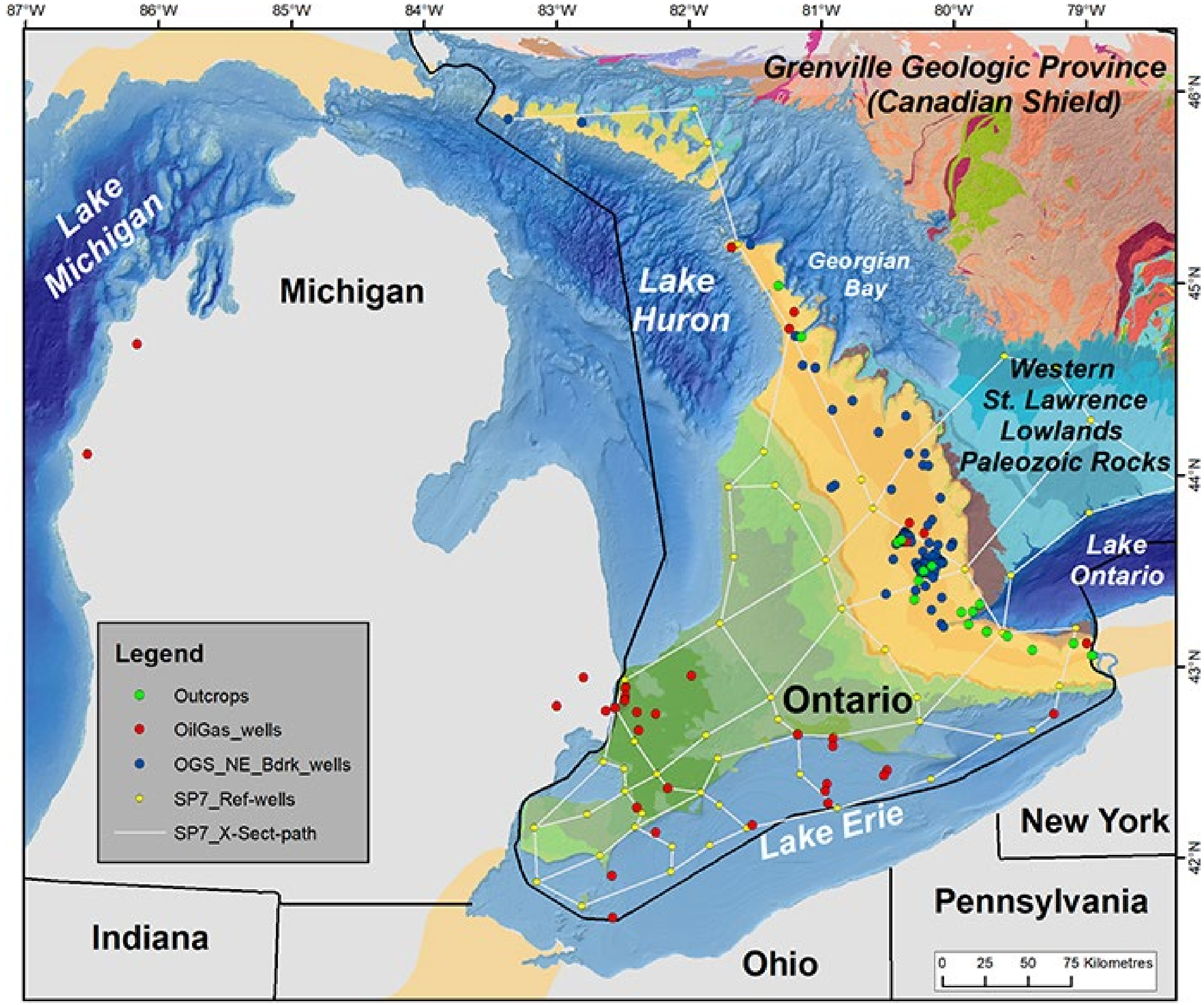


Figure A7a. Location map of Lockport Group study area and select wells used to construct the depositional model cross-sections (time slices) of the Lockport Group and basal Salina Group A-Units. Depositional models are drawn from northwest (2 red dots near Lake Michigan) to southeast (deep oil-gas wells in southwestern Ontario and shallow OGS wells and outcrops on Niagara Escarpment cuesta and scarp). Tectonically, the cross-sections extend from the central region of the "Michigan structural basin" to the far-field side of the Appalachian foreland basin (Alleghany basin or sub-basin; *see* Figure 8 in report). Paleozoic sedimentary rocks in southwestern Ontario are part of the Western St. Lawrence Lowland region and are underlain by Proterozoic-age Grenville geologic province terrains that have boundaries and fabrics oriented in north-northeast and north directions. The more significant lithofacies and thickness variations of the Lockport Group strata across the study area were most likely influenced by the response of the basement terrains and boundary zones to episodic tectophases and forebulge migration and relaxation phases taking place along the Appalachian Orogen. The orientations of major lineaments, bedrock valleys or re-entrants, and vertical offsets (faults) in the Paleozoic strata generally reflect the varied basement tectonic fabrics (e.g., positions of Grenville terrain boundaries, Grenville Front Tectonic Zone, the divergent orientation of the Mid-Continent Rift; and the east-oriented lineaments that cut all Paleozoic strata associated with the breakup of Pangaea and opening of a failed rift reflected by the orientation of St. Lawrence River and Lake Ontario; *see* Figure 8 text).

Green dots = key outcrops and quarry sections on the regional Niagara Escarpment and cuesta scarp; red dots = oil and/or gas cored wells; blue dots = OGS regional groundwater exploration cored wells; and yellow dots and grey lines = OGS Special Volume 7 (SV7) oil and/or gas reference wells used for regional cross-sections (*see* details for logs in Brintnell 2012; Brunton et al. 2012; this report; updated Lockport Group formation picks of key SV7 logs (OGS Special Volume 7, Armstrong and Carter 2010).

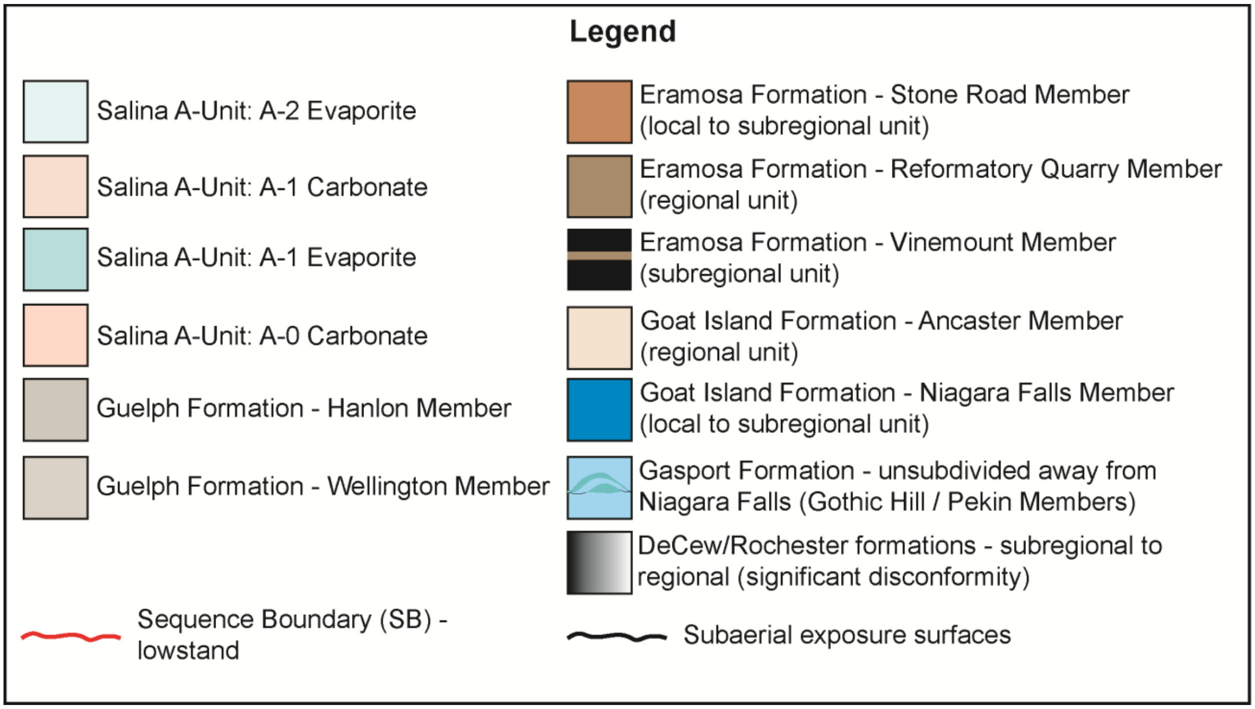


Figure A7b. Legend for the depositional model cross-sections (time slices) of the Lockport Group and basal Salina Group A-Units (*see* Figures A7.1 to A7.7).

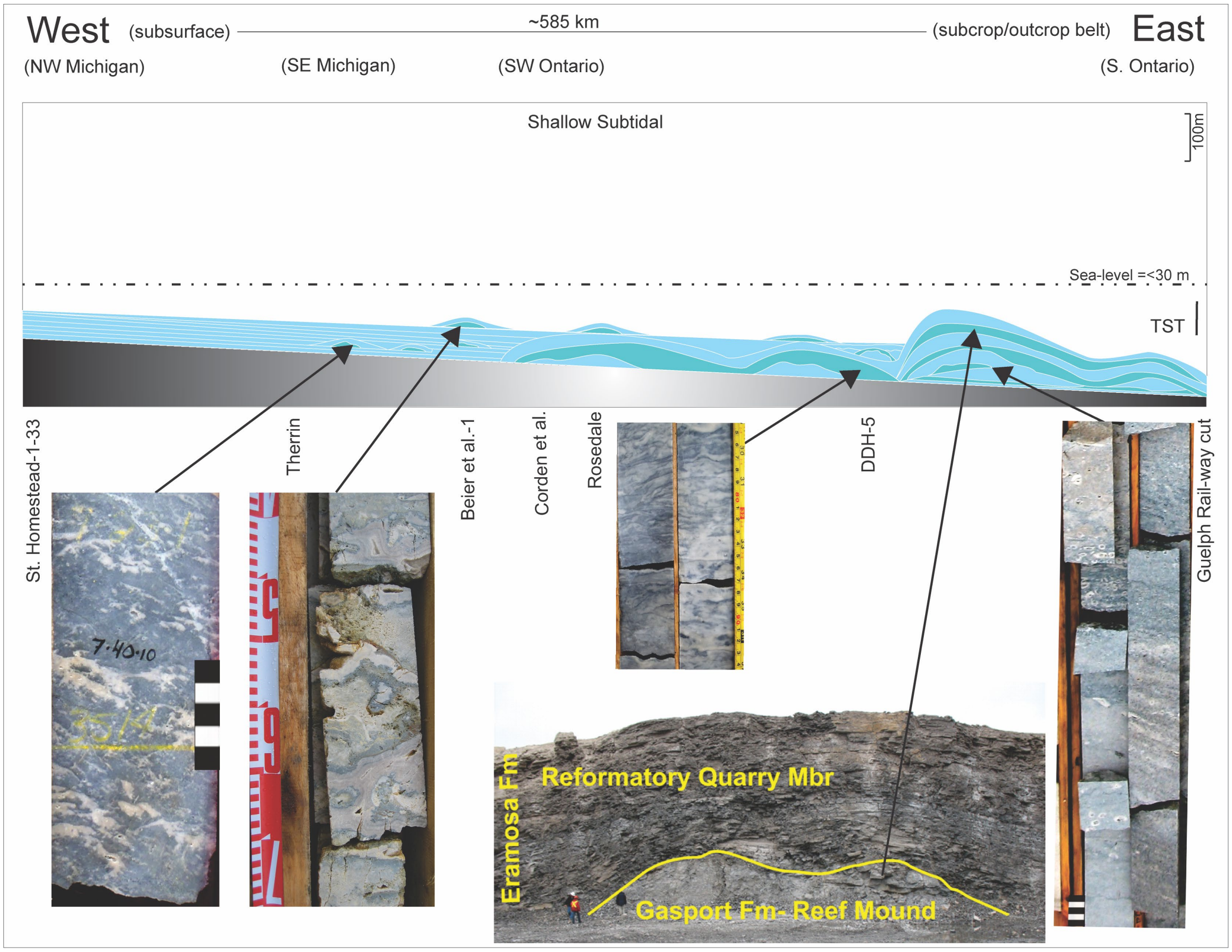
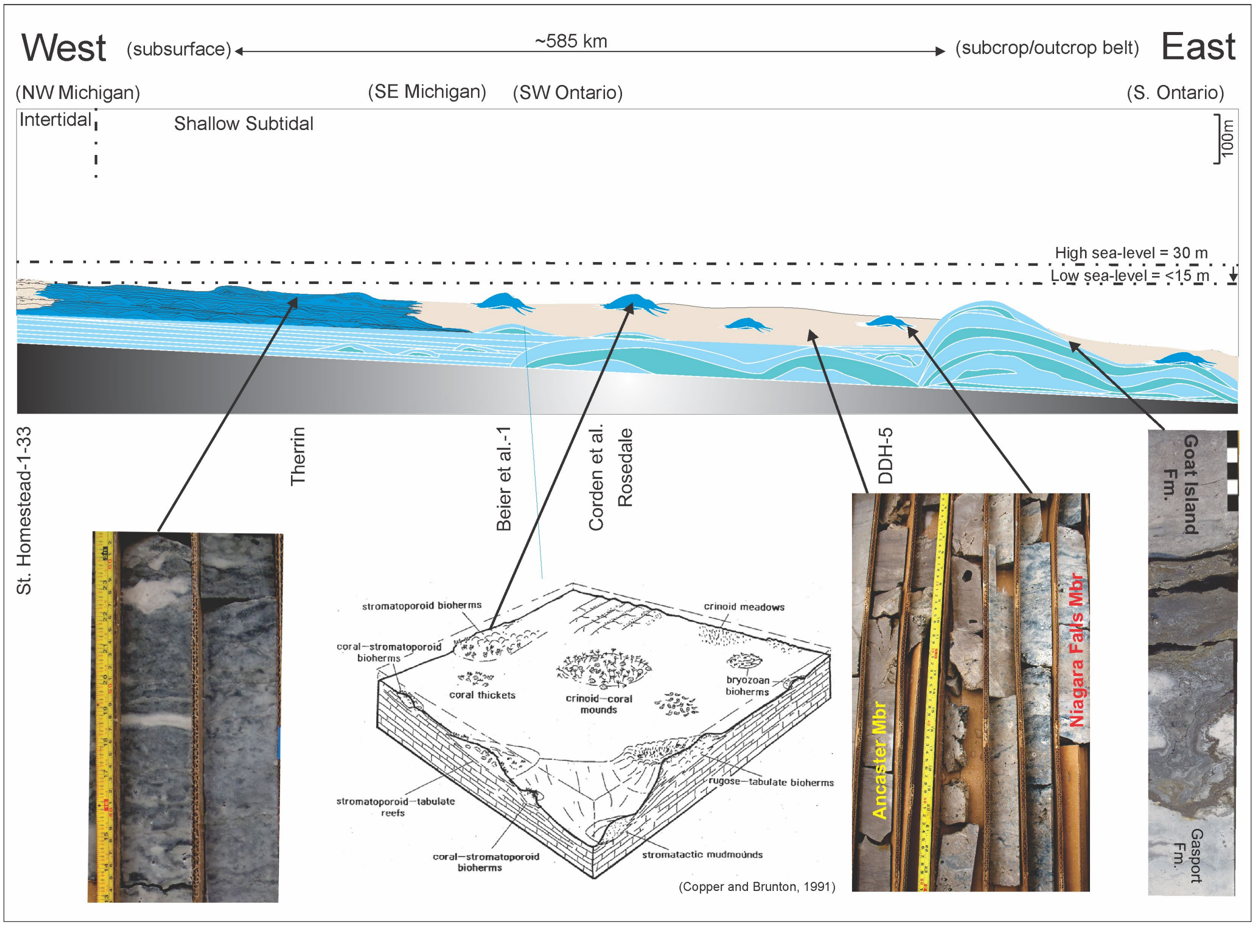


Figure A7.1. Depositional model for the Gasport Formation, basal Lockport Group. The Gasport Formation disconformably lies on formations of different age regionally (ranging from disconformable contacts on the DeCew Formation in the Niagara Peninsula region, to the much older Rochester, Irondequoit and Rockway formations from north of City of Hamilton to Bruce Peninsula and Manitoulin Island areas of southern Ontario). The onset of deposition of the Gasport Formation crinoidal encrinites onto this irregular topographic and varied sea floor represents an initial transgressive system tract: open-marine, clear and clean waters facilitated the development of a crinoid-dominated seaway across the eastern Laurentia ramp on far-field side of the Appalachian foreland basin. The basal Gasport Formation is generally characterized by cross-laminated to cross-bedded, finely crystalline crinoid-pluricolumnal-dominated sands and gravels (*see* core photo far right bottom of figure). Tabulate coral-crinoid-bryozoan microbial reef mounds are never found in the basal lower transgressive phases of this higher energy depositional regime. In the central to western areas, in the up-dip parts of ramp, small, stacked stromatactis-crinoidal-microbial mounds may occur almost immediately above a thin DeCew finely crystalline dolostone and much older, cut-down Rochester mixed shale and dolostone succession. The middle to upper Gasport Formation comprises cyclic, stacked crinoidal-microbial-tabulate coral-bryzoan-dominated reef mounds and extensive cross-bedded stacked crinoidal gravels and sands in the down-ramp regions to the east and on the far-field side of the Algonquin Arch (*see* photo of stacked Gasport reef mounds in quarry outcrop and photos to left and above the quarry photo showing paleokarstic caprock and microbial-crinoidal reef mound fabrics). The interplay between sea level fluctuations and tectonics (short-lived forebulge migration phases) influenced the depositional and erosional architecture of crinoidal-dominated skeletal carbonate gravels on an irregular paleotopographic seafloor. The Gasport Formation is the only one of the stacked dolostone units of the Lockport Group that displays reefing-upward cycles in the mid-ramp to down-ramp settings. The regional degree of cut-down and paleokarstic erosion following Gasport deposition may in part be due to differential uplift due to forebulge migration tectophases. The tops of these metre- to decametre-scale reef mound cycles are capped by paleokarstic cement-filled vugs and brachiopod-bivalve-gastropod coquina deposits that are often bleached white (due to potable bedrock groundwaters preferentially flowing through these carbonate skeletal gravel and sand units that separate the stacked reef mound phases and possess higher secondary porosity and permeability). In areas where the Gasport Formation reef mound cycles attained more than 40 to 50 m in thickness, paleokarstic caprock facies are well developed and younger Lockport Group strata disconformably onlap the paleotopographic highs (*see* quarry photo from Guelph Dolime Quarry, City of Guelph). In the quarry face shown above, the Eramosa Formation disconformably onlaps the Gasport Formation composite reef mounds (*see* Figure 17 in report). Approximately 700 m to northwest of this outcrop photo, and on other side of the Speed River, an OGS-cored well records both the Niagara Falls and Ancaster members of the older Goat Island Formation sitting disconformably on Gasport Formation encrinites. Prior to this regional subsurface study, there was no indication of the irregular, stacked “pinnacle-like” structures of the Gasport Formation (and Lockport Group) in the subcrop–outcrop belt of Niagara Escarpment and cuesta. These transgressive–regressive (T-R) cycles of the Gasport Formation are readily visible in select cores in the Cambridge–City of Guelph regions and in select quarries near the Niagara Escarpment cuesta edge, or scarp, face (e.g., Acton–Milton to Duntroon areas). Abbreviation: TST = transgressive system tract.



(Copper and Brunton, 1991)

Figure A7.2. Depositional model for Goat Island Formation of Lockport Group. A sea-level fall and then subsequent transgression onto Laurentia resulted in changing oceanographic conditions across parts of Laurentia from the precursor Gasport seaway. Both the blue-grey encrinites of the basal Niagara Falls Member (superficially similar lithofacies to Gasport Formation) and the overlying brown to tan cherty wackestones and packstones of the finely to medium crystalline Ancaster Member of the Goat Island Formation have a higher gamma-ray signature than the underlying Gasport Formation encrinites. The oceanographic conditions became muddier and more nutrient rich in the Goat Island seas, with terrigenous clay influxes and the establishment of small reef mound complexes in the Niagara Falls Member succession. The main differences between the Gasport and Goat Island reef mound complexes are that the former were crinoidal-microbial-tabulate coral-dominated composite structures and the latter are more isolated and singular crinoidal-microbial-bryozoan-stromatoporoid-dominated structures. The Goat Island Formation has reef mounds in the basal part of succession and generally deepens upward, culminating in medium to dark grey, thinly bedded, cyclic medium crystalline dolostones with pulses of cladoporid coral-dominated beds. The core photos above show, from right to left: the sharp, disconformable and paleokarstic contact between the underlying Gasport reef mound complex “paleo-seafloor” and the onset of encrinites of the overlying basal Niagara Falls Member of Goat Island Formation. Smaller-scale transgressive–regressive cycles in the eastern shallow subtidal zone resulted in the growth of crinoidal-bryozoan-sponge reef mounds in the basal Niagara Falls Member. Some of these mounds sit disconformably on and adjacent to composite Gasport Formation reef mounds. Smaller, stunted forms of these crinoidal-microbial-bryozoan fauna, with a dominance of laminar stromatoporoids, are scattered in the western portion of the cratonic seaway. The upper Ancaster Member of the Goat Island Formation consists of tan to medium brown, finely to medium crystalline dolostones and siliceous sponge faunas (resulting in characteristic chert-bearing nature of the rock unit from Hamilton to Niagara Falls). Where deposition took place on irregular paleotopography of the Gasport encrinites and mound complexes (Cambridge and City of Guelph areas), deeper water Ancaster Member lithofacies disconformably rest on the Gasport Formation seafloor highs, and the Niagara Falls Member encrinites may form cyclic interbedded deposits that onlap the Gasport composite reef mounds (*see* Figure 12 in report). In the western part of study area (in central region of Michigan structural basin), shallow intertidal conditions persisted, forming mud cracks and caliche horizons. A final sea-level fall resulted in a lowstand tract and subaerial exposure that shows variable contact relationships, from sharp erosional cut-down contacts and/or sharp changes in lithofacies above and below contacts: (i) after deposition of the Goat Island Formation, (ii) during deposition of the overlying Eramosa Formation, or (iii) after Eramosa deposition and erosion or ravinement.

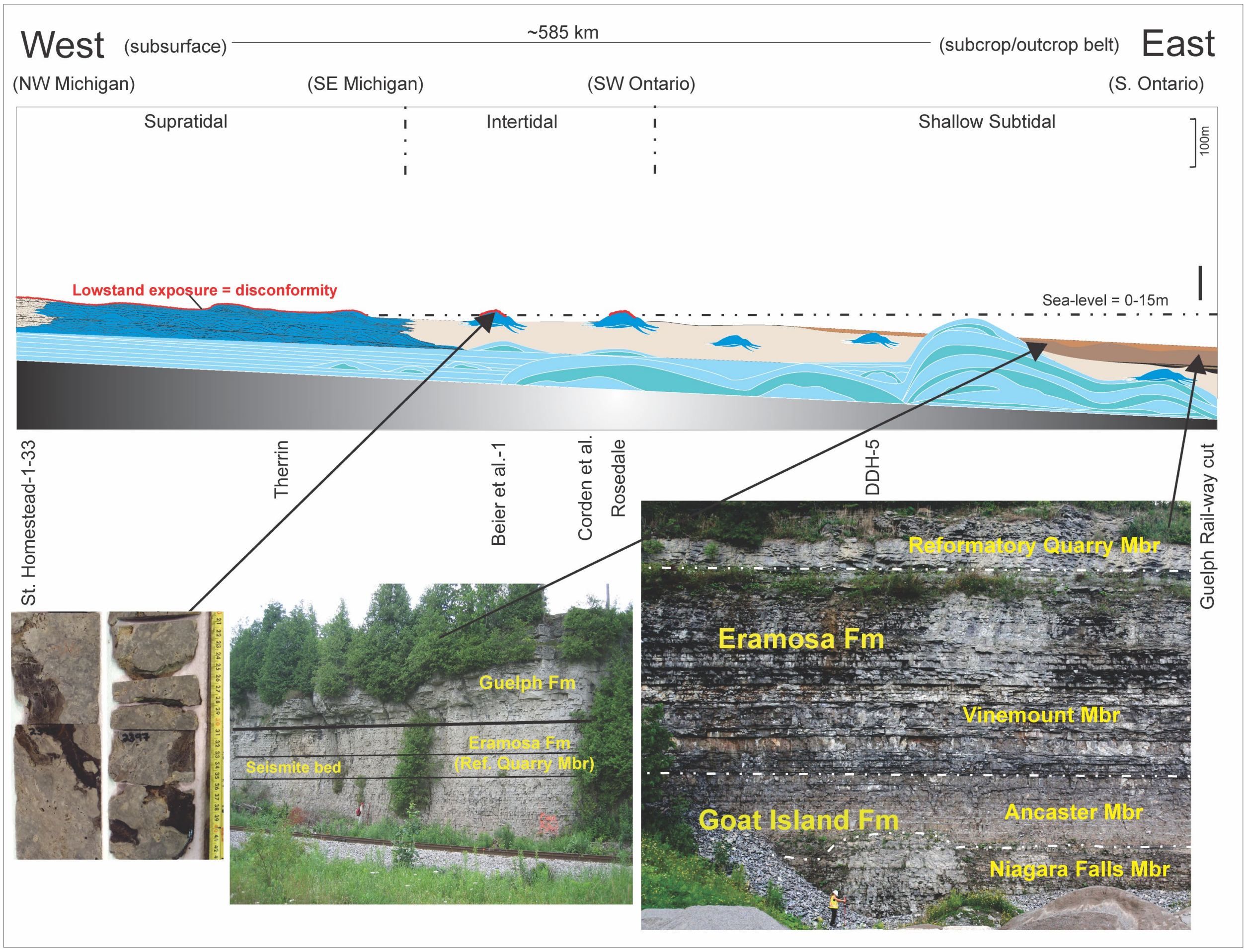


Figure A7.3. Depositional model for the Eramosa Formation. In the south and eastern part of the study area in southwestern Ontario, a cladoporid-bearing deeper water Ancaster Member dolostone unit was deposited just prior to what may have been a forced regression due to a forebulge migration pulse. The forced regression created shallower subtidal conditions in the east and south and exposure in the northwest region. This was followed by a relative sea level rise (relaxation of the forebulge uplift phase) and an influx of terrigenous-clay-bearing dolostones of the Vinemount Member of the Eramosa Formation. The contact between the Ancaster Member lithofacies of the Goat Island Formation and overlying Vinemount Member of the Eramosa Formation is generally sharp and in places erosional (photo on far right is of the type section for Vinemount Member and comprises a good section of the overlying Reformatory Quarry Member of the Eramosa Formation, Vinemount Quarry). It is one of few places where both the Goat Island and Eramosa and Vinemount and Reformatory Quarry Member contacts are exposed and can be walked out. The Vinemount Member lithofacies were deposited during a transgression and are restricted to the eastern and southeastern part of the study area. In the Cambridge and City of Guelph areas, Vinemount lithofacies appear to fill in paleotopographic lows, where Goat Island Formation lithofacies onlap thickened, “pinnacle-like” stacked reef mound complexes of the older Gasport Formation. Renewal of tectonic activity resulted in the deposition of these terrigenous clay- and silt-bearing carbonates of the Vinemount Member, and to a lesser degree, the overlying Reformatory Quarry Member. Subsequent shallowing and cut-off of the terrigenous supply resulted in the onset of middle and upper Reformatory Quarry Member lithofacies. The Reformatory Quarry Member possesses the most varied juxtaposition of depositional environments of all the Lockport Group strata (middle photo is of the Williams (1919) type section of the Eramosa rock unit along Guelph Railway Line, City of Guelph). The Eramosa Formation shows flat-lying to highly undulatory bedding (where the Eramosa onlaps composite Gasport and Goat

Island reef mound complexes; *see* Figure 17 in report) and records the widest variety of depositional environments of any Lockport Group rock unit. The Reformatory Quarry Member possesses small microbial-bryozoan-sponge mounds and favositid-stromatoporoid-bryozoan biostromes to hummocky and swaley cross-stratified beds and traction current beds, to classic metre-scale sabkha cycles, and seismite beds that can be traced from the Bruce Peninsula in Ontario to Ohio and Kentucky, confirming that deposition occurred during an intermittently tectonically active period. The upper Reformatory Quarry Member lithofacies record overall shallowing and the onset of restricted marine conditions resulting in deposition of low diversity ostracod-dominated finely crystalline dolostones (Stone Road Member). The contact with the overlying Guelph Formation is sharp and erosional in some places and difficult to pick in other areas. The middle photo shows typical outcrop of Guelph Formation caprock in an Upper Lockport Group (Guelph–Eramosa) cuesta scarp. Note the typical increase in thickness of Guelph Formation beds. Gamma-ray logs generally display a flatter “cleaner” profile for the Guelph Formation compared to underlying Eramosa Formation lithofacies (reduced terrigenous content).

The Eramosa Formation is arguably the most challenging Lockport Group rock unit to map regionally and one of the most important from a hydrogeological and oil and gas exploration perspective. The Reformatory Quarry Member is a self-sourcing hydrocarbon dolostone (black bitumen and oil leak out of freshly blasted quarry walls in the upper sabkha cycles; see far left core photo). The thick black bitumen-laden units occur in dissolved cauliflower-size gypsum vugs immediately below laminites (inferred leathery microbial mats), marking tops of metre-scale cycles at Guelph Dolime Quarry (*see* Figure 20 in report). This unit also possesses Mississippi Valley Type (MVT) mineralization in the form of sphalerite (ZnS of variable red, black and yellow or brown varieties that occurs in corals and vugs, suggesting varied fluid temperatures), galena (PbS predominantly occurs on vertical joint surfaces and is largely restricted to the southern part of the study area, south of the City of Guelph and Highway 401), and calcite crystals, up to 20 cm long, that grow on walls of caves in the upper Reformatory Quarry Member (City of Hamilton to Lincoln areas of Niagara Peninsula).

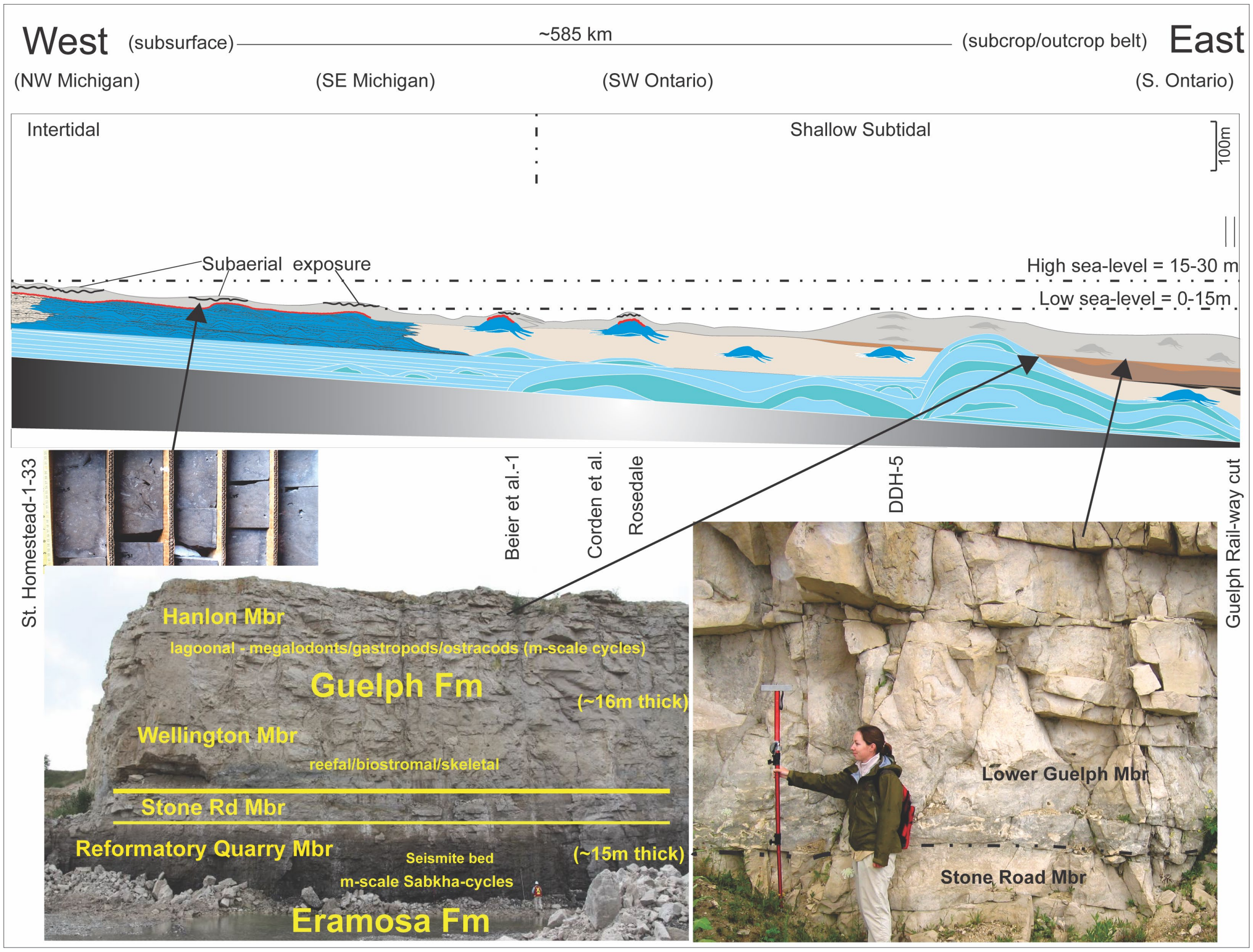


Figure A7.4. Lower Guelph Formation (Wellington Member). The contact between the Guelph Formation and underlying Stone Road Member of the Eramosa Formation is sharp and erosional (see right photo showing type section quarry face in Guelph Dolime Quarry, City of Guelph; Lona-Kate Dekeyser for scale). The basal Wellington Member of the Guelph Formation is a transgressive unit possessing a low-diversity stromatoporoid and coral megafauna with a varied benthic skeletal faunal assemblage (e.g., crinoids, brachiopods, bivalves, trilobites; large white fossils next to Lona-Kate are stromatoporoids; Brunton 2009; Brunton et al. 2012). Composite reef mounds of variable thickness (generally less than 5 m thick and 20 to 25 m across) occur approximately 2 to 3 m above the base of the Guelph–Eramosa formational contact across the south wall of the Guelph Dolime Quarry (difficult to see these mounds in left photo). The eastern Laurentia cratonic sea was a clean, calcareous algal muddy shallow ocean with scattered skeletal benthic communities. The Wellington Member lithofacies and fauna are largely missing in the central and northwestern parts of the study area. In this mid-ramp to upper-ramp region, muddy lagoonal, low diversity faunas are dominated by gastropods, ostracods and megalodontid bivalves, all aragonitic shelly benthos largely preserved as moulds. The lithofacies character, dominated by variably high-spired snails as detritus feeders, reflect regionally extensive, shallow, subtropical, nutrient-rich seas with hypersaline and warm water temperatures. It is difficult to correlate the lower Guelph lithofacies regionally. Periodic subaerial exposure in the west resulted in crack-fills and paleokarstic breccias of microbial laminites (possible teepees and other shallow marine to coastal environs; it is difficult to infer regional character from cores). The irregular topography and differential erosion of the underlying Gasport, Goat Island and Eramosa sea-floor also influenced deposition of variable facies across this complex cratonic ramp.

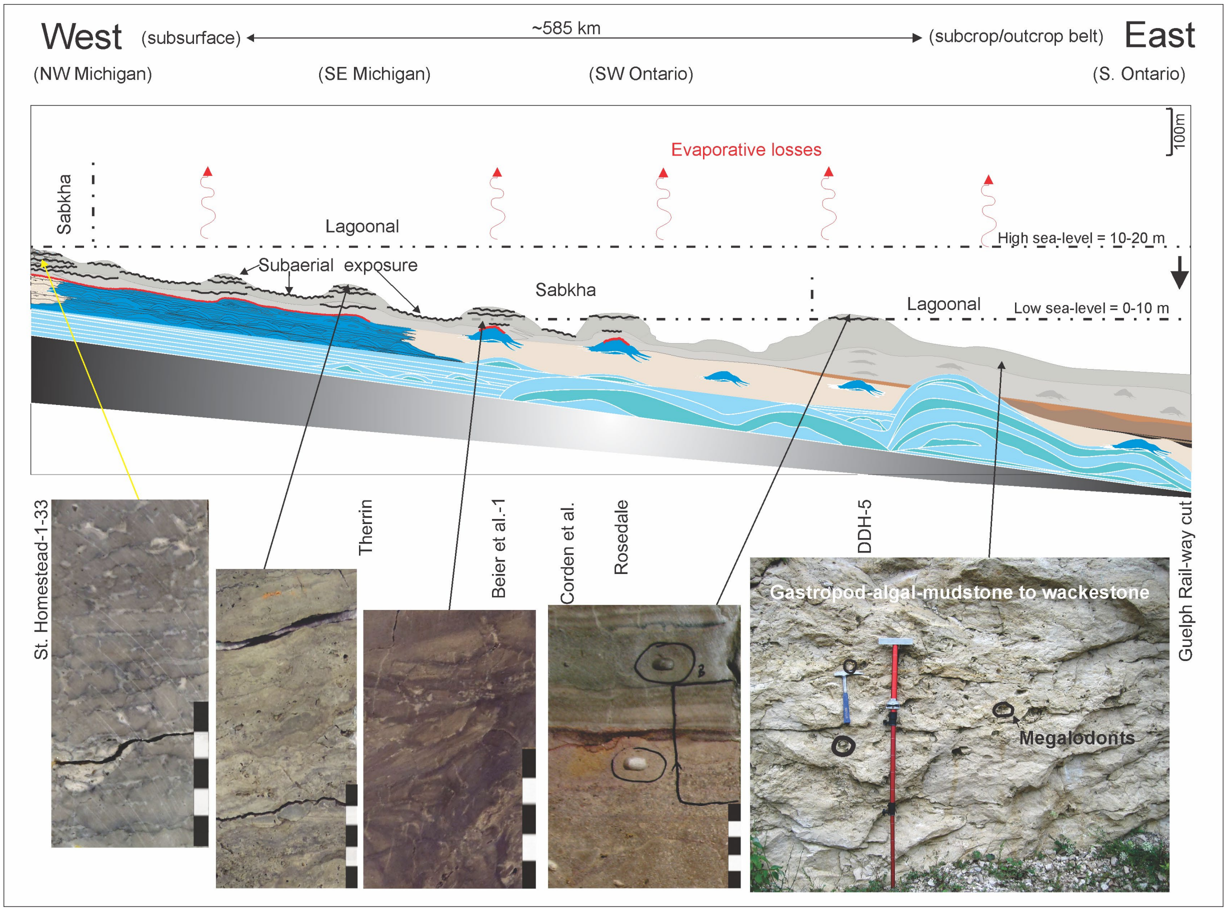


Figure A7.5. Depositional model for upper Hanlon Member of the Guelph Formation. The upper Guelph Formation possesses lithofacies that reflect overall regressive and regional hypersaline, oxygen-poor, muddy lagoonal conditions across a regionally extensive cratonic ramp. The circled areas in Guelph Formation outcrop are megalodontid bivalves in muddy, metre-scale cyclic deposits. The Jacob's Staff (monopod) in the right photo is 1.5 m long and divided into 10 cm increments; hammer (30 cm long) also for scale. The circled areas in second photo from right (core photo) are pisolites within a pisolitic-gastropod-ostracod–bearing dolomudstone to wackestone and laminites of upper Hanlon Member of Guelph Formation. At least 7 varieties of high-spired gastropods, algae and soft-bodied organisms dominated the muddy, saline waters. As sea-levels continued to fall, sabkha environs developed adjacent to lagoonal conditions in paleotopographic lows. At this time, the ramp was blanketed by microbialites in highly saline waters (up to 70 g/L). Subaerial exposure events towards the west formed the following: (i) karst and brecciation of lithified sediments; (ii) vadose pisolites; iii) teepees; and (iv) beachrock. The most restricted marine conditions persisted in the western region of study area (on Laurentia craton), where the interplay of freshened and marine groundwaters on the sabkhas precipitated gypsum-bearing muds. In the eastern part of the study area, upper Hanlon Member lithofacies were periodically bleached and oxidized, resulting in thin green and reddish units interbedded with restricted marine lagoonal muds. Scale bar in left 4 core photos has 1 cm divisions.

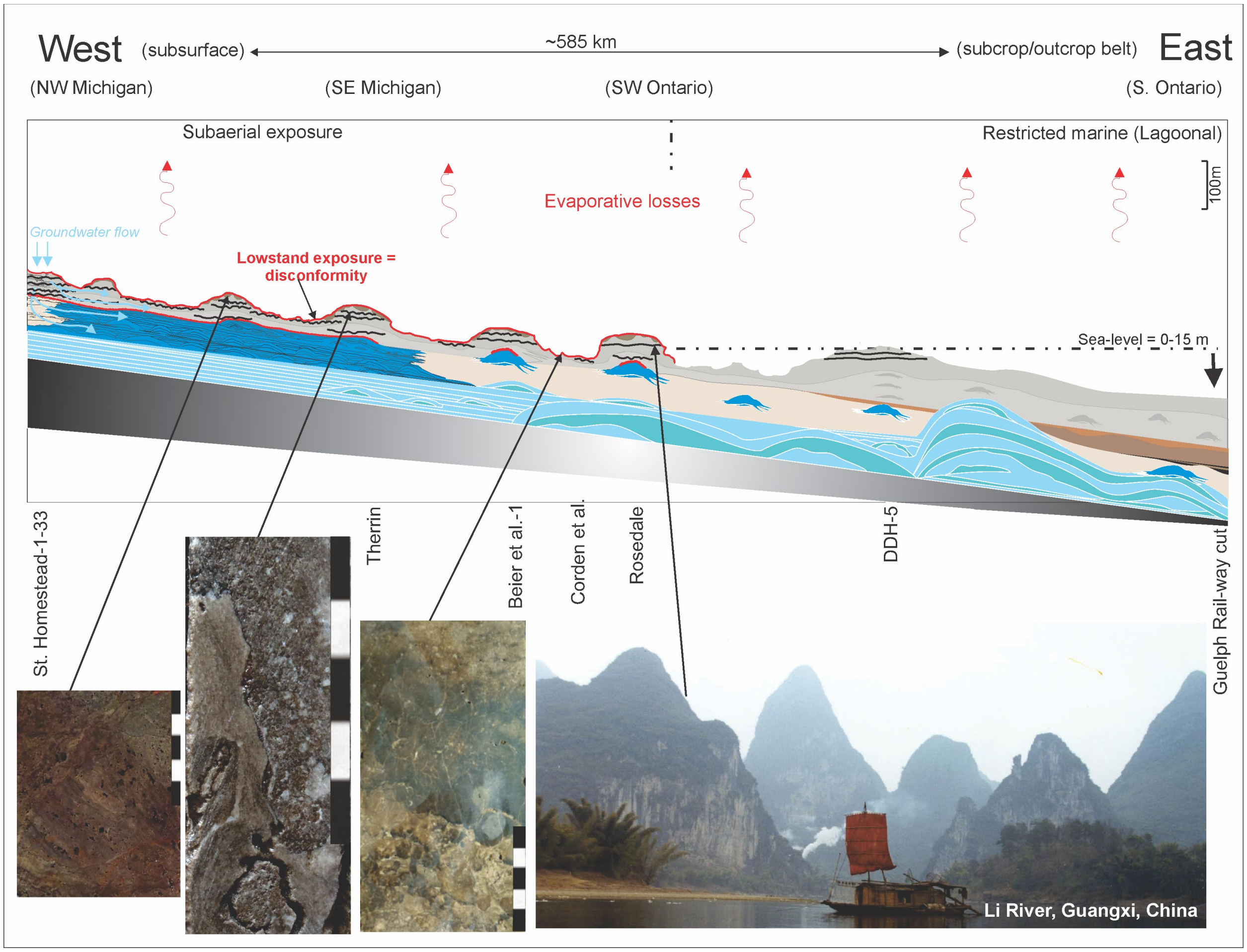


Figure A7.6. Salina Group A-unit deposition after deposition of the Guelph Formation. Salina Group A-Units (Cain Formation = A-0 Carbonate + A-1 Evaporite: Gill, Briggs and Briggs 1977, 1978; Gill 1979; Briggs et al. 1978; Briggs et al. 1980; and Ruff Formation: Budros and Briggs 1977) are finely to medium crystalline dolomudstones and laminites with interbedded anhydrite and halite. The A-1 Carbonate is an important hydrocarbon source rock (comparable but more regionally extensive than the Reformatory Quarry Member of Eramosa Formation). The western part of the study area represents extensive restricted marine lagoons, salt pans and sabkha environs. Lithofacies of the basal Salina Group A-units show more extensive karstification phases and breccias in the western and central parts of study area and comprise microbial to massive restricted marine dolostones in eastern and southeastern parts of study area. The most pervasive and deepest paleokarstification of basal Salina Group and Lockport Group strata occurs in the western and central parts of the study area. The deep KCl occurrences (sylvite) recorded in the A-1 Salt in Michigan (Mesolella et al. 1974) may be preserved in paleokarst lows of the Goat Island Formation and not in the younger Guelph Formation (brown Niagaran). In general, the more brecciated and karsted the Salina and upper Lockport Group carbonates on the “3-D pinnacle structures”, the greater the number of karst zones in underlying Goat Island and Gasport formations. The previously termed “interreef” or “Guelph pinnacle” three-dimensional structures “interreef Guelph pinnacle” lithofacies represent a regional caliche and brecciated paleosol that is laterally extensive. No deep water or slope lithofacies were observed in the basal Salina Group or upper Lockport Group (Guelph) strata in the west-central Michigan and southwestern Ontario regions. Therefore the regional variations in stratigraphic patterns of the Lockport Group and basal Salina Group suggest that the previously termed “Guelph pinnacle reefs”, which are predominantly made up of older Gasport and Goat Island lithofacies, are arguably more correctly interpreted as paleokarst towers and/or isolated mesa or butte landforms that developed within a regionally extensive and structurally-influenced *paleokarst basin terrain*, resulting in the development of residual columns of weathered *karst towers* (ranging in thickness from 56 to 148 m and kilometres in areal extent). The linear orientation of a number of these three-dimensional bedrock landforms most likely are early Silurian escarpments that may have been influenced by a combination of differential accumulation and erosion along basement structures or lineaments, but there is little evidence for subvertical to vertical offsets of Lockport or basal Salina Group strata. The Guelph *paleokarst basin terrain* has similarities to the modern karst terrain of Li River, Guangxi Zhuang Autonomous Region, China (*see* right photo). Scale bar in left 3 core photos has 1 cm divisions.

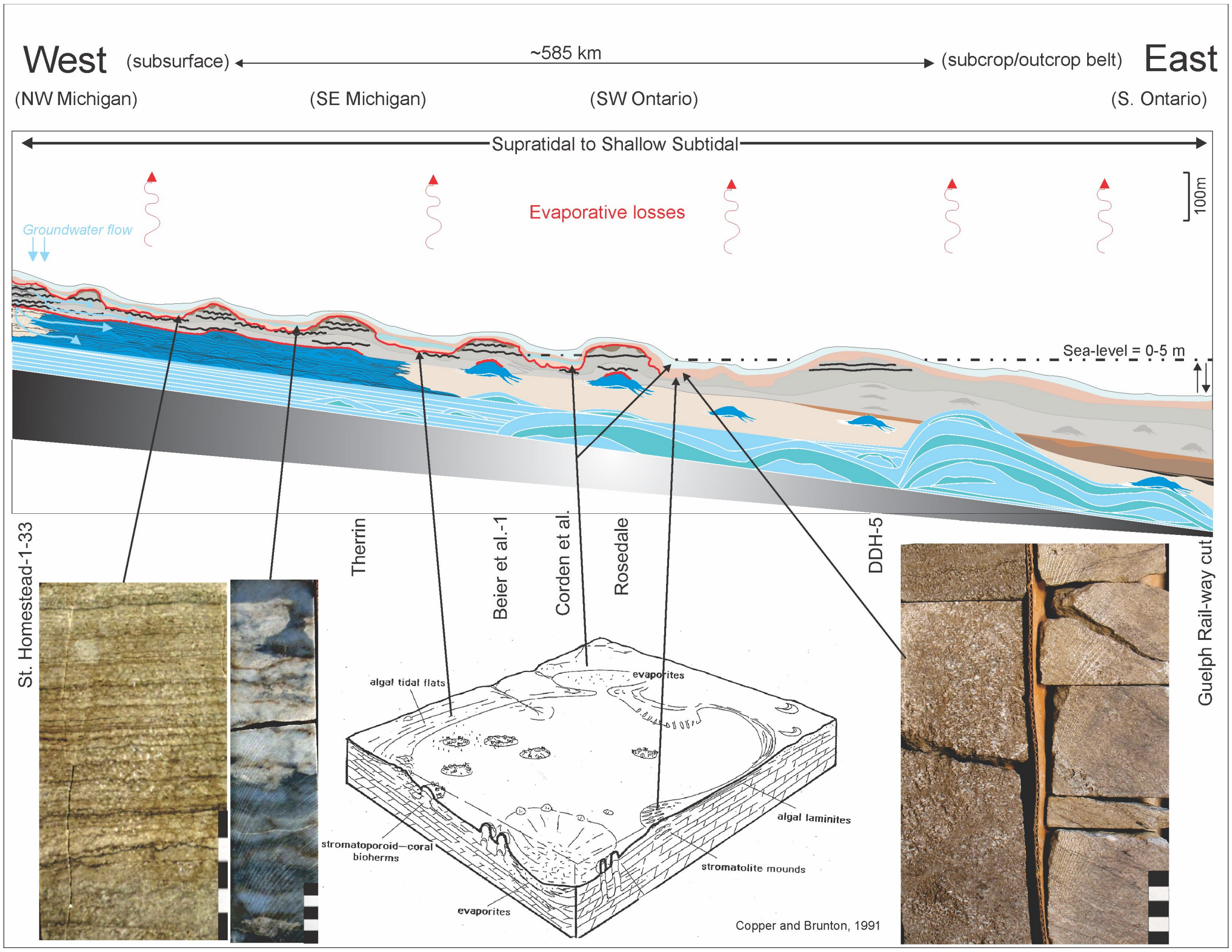


Figure A7.7. Depositional model for Salina Group A-Units (*see* legend, Figure A7b). The *Lockport Group paleokarst basin terrain* formed largely after deposition of the Guelph Formation, and is filled by laminites and evaporites via flooding events in an evaporative-dominated setting, in what was a vast Laurentia craton-wide salina or playa environ; today we only see vestiges of this once expansive playa (unconformities and variably thick breccias, in some regions reaching thicknesses of 100 m and separating Lower Silurian and Middle Devonian strata). The initial stage of marine flooding is recorded by the microbialites of the A-0 Carbonate and A-1 Evaporite (Cain Formation; Gill 1979). Evaporation lead to development of a desiccated brine-pan and the precipitation of the A-1 Evaporite. The A-1 Carbonate, the second phase of shallow marine playa development, surrounds (entombs) the *Lockport karst towers*. Some authors show the A-1 Carbonate covering some of the "pinnacles" and other papers show it juxtaposed but not enveloping the karst breccia units that form the caprock of many "pinnacle" structures. Completing the second series of transgressive–regressive (T-R) cycles resulted in the accumulation of the A-2 Evaporite and A-2 Carbonate. Scale bar in core photos has 1 cm divisions.

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Metric Conversion Table

Conversion from SI to Imperial			Conversion from Imperial to SI		
SI Unit	*Multiplied by*	*Gives*	*Imperial Unit*	*Multiplied by*	*Gives*
LENGTH					
1 mm	0.039 37	inches	1 inch	**25.4**	mm
1 cm	0.393 70	inches	1 inch	**2.54**	cm
1 m	3.280 84	feet	1 foot	**0.304 8**	m
1 m	0.049 709	chains	1 chain	20.116 8	m
1 km	0.621 371	miles (statute)	1 mile (statute)	**1.609 344**	km
AREA					
1 cm^2	0.155 0	square inches	1 square inch	**6.451 6**	cm^2
1 m^2	10.763 9	square feet	1 square foot	**0.092 903 04**	m^2
1 km^2	0.386 10	square miles	1 square mile	2.589 988	km^2
1 ha	2.471 054	acres	1 acre	0.404 685 6	ha
VOLUME					
1 cm^3	0.061 023	cubic inches	1 cubic inch	**16.387 064**	cm^3
1 m^3	35.314 7	cubic feet	1 cubic foot	0.028 316 85	m^3
1 m^3	1.307 951	cubic yards	1 cubic yard	0.764 554 86	m^3
CAPACITY					
1 L	1.759 755	pints	1 pint	0.568 261	L
1 L	0.879 877	quarts	1 quart	1.136 522	L
1 L	0.219 969	gallons	1 gallon	**4.546 090**	L
MASS					
1 g	0.035 273 962	ounces (avdp)	1 ounce (avdp)	28.349 523	g
1 g	0.032 150 747	ounces (troy)	1 ounce (troy)	**31.103 476 8**	g
1 kg	2.204 622 6	pounds (avdp)	1 pound (avdp)	**0.453 592 37**	kg
1 kg	0.001 102 3	tons (short)	1 ton(short)	**907.184 74**	kg
1 t	1.102 311 3	tons (short)	1 ton (short)	**0.907 184 74**	t
1 kg	0.000 984 21	tons (long)	1 ton (long)	**1016.046 908 8**	kg
1 t	0.984 206 5	tons (long)	1 ton (long)	**1.016 046 9**	t
CONCENTRATION					
1 g/t	0.029 166 6	ounce (troy) / ton (short)	1 ounce (troy) / ton (short)	34.285 714 2	g/t
1 g/t	0.583 333 33	pennyweights / ton (short)	1 pennyweight / ton (short)	1.714 285 7	g/t

OTHER USEFUL CONVERSION FACTORS

	Multiplied by	
1 ounce (troy) per ton (short)	31.103 477	grams per ton (short)
1 gram per ton (short)	0.032 151	ounces (troy) per ton (short)
1 ounce (troy) per ton (short)	20.0	pennyweights per ton (short)
1 pennyweight per ton (short)	0.05	ounces (troy) per ton (short)

Note: Conversion factors in ***bold*** *type are exact. The conversion factors have been taken from or have been derived from factors given in the* Metric Practice Guide for the Canadian Mining and Metallurgical Industries*, published by the Mining Association of Canada in co-operation with the Coal Association of Canada.*