Geology of the Grand River Watershed

An Overview of Bedrock and Quaternary Geological Interpretations in the Grand River watershed

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1.0 Introduction

The geology of the Grand River watershed, both bedrock and surficial sediment, forms the foundation of the Grand River watershed. The Grand River watershed is bounded on the northeast and southwest by two bedrock escarpments and to the northwest by an ancient bedrock arch. Bedrock, and the glacial deposits blanketing much of the bedrock in this region of Ontario, host significant aggregate and groundwater resources.

Work by the Ontario Geological Survey (OGS) over the past 15 years has updated our understanding of both bedrock and surficial geology within the boundaries of the Grand River watershed. The objective of this report is to provide an overview of the bedrock stratigraphy, karst locations and influences, and a characterization of the overburden sediments.

In a general sense, the geology of the watershed is separated into two events that shaped the landforms as we know them today: the formation of the Paleozoic sedimentary bedrock sequences followed by the North American Quaternary glacial events. The Paleozoic sedimentary bedrock is primarily composed of shales, sandstones, dolostones, and limestones. The North American Quaternary glaciations then altered the expression of the top of bedrock and draped the underlying bedrock with unconsolidated sediments composed of primarily gravel, sand, silt, clay, and diamicton.

This report is structured to review the major bedrock features and formations within the watershed, followed by a review of the Quaternary geology.

2.0 Bedrock Geology

The sediments that formed the bedrock within the Grand River watershed were deposited as a result of the rise and fall of global sea levels. Sea water inundated all of southern Ontario depositing different types of sediments relative to the depth of the sea along with marine Animalia that lived and died within the sea (Westgate *et al*., 1999). This has allowed researchers to piece together a history of the biotic life and the settings in which they were deposited during this time period.

The bedrock underlying the Grand River watershed consists largely of marine sediments deposited in shallow seas that periodically covered eastern North America during the Paleozoic Era. These seas were occasionally centered on depressions of the lithosphere, also referred to as sedimentary basins, which were separated by structural highs, or arches. The Grand River watershed is located in the northern Appalachian Basin, on the southern flank of the Algonquin Arch as shown on **Figure 2-1**.

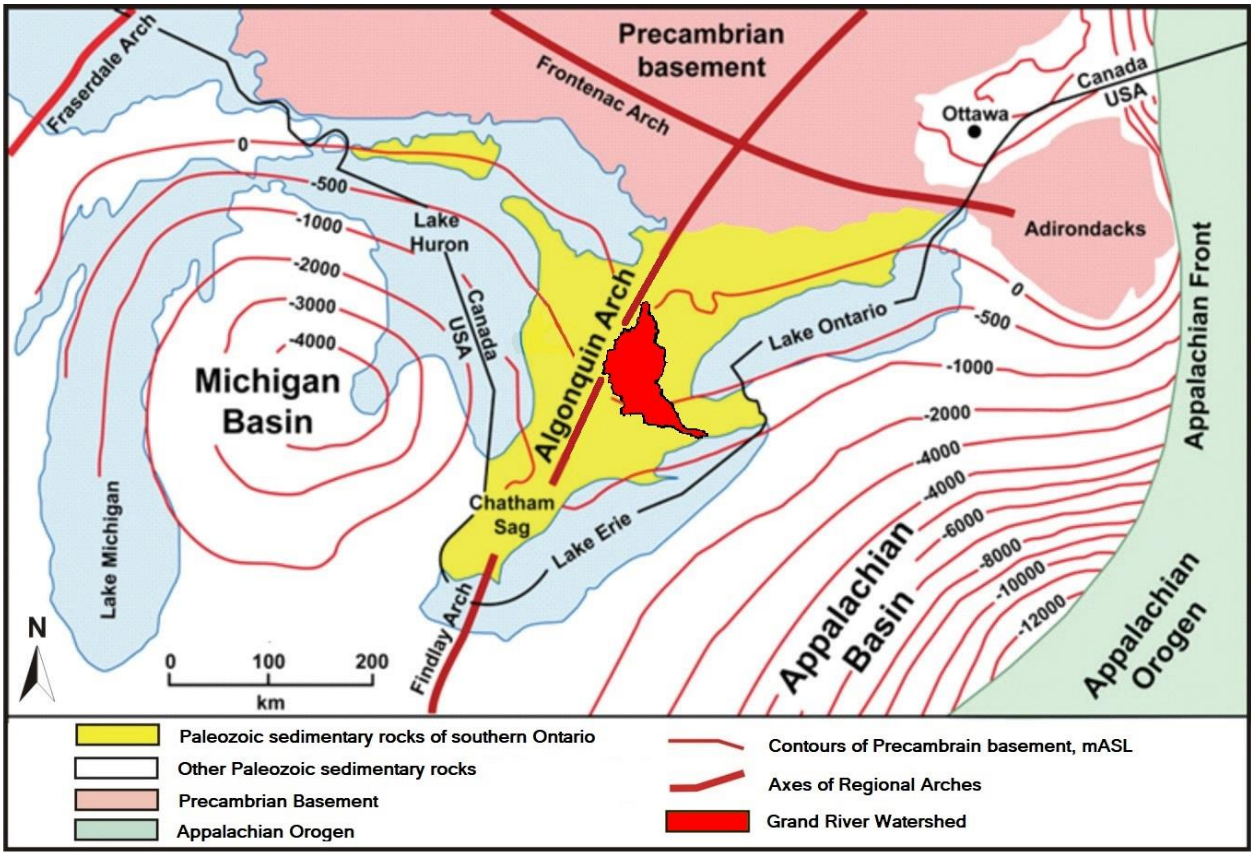


Figure 2-1: Structural basins and arches of southern Ontario. Modified from Frizell et al. (2011) after Johnson et al. (1992).

Three bedrock features, shown in **Figure 2-1,** underlie the Grand River watershed and help define the shape of the watershed:

- the Algonquin Arch forebulge
- the Niagara Escarpment cuesta
- the Onondaga Escarpment cuesta

Algonquin Arch

The Alleghanian orogeny, a mountain building event caused by tectonic plate movement, occurred approximately 325 million to 260 million years ago to the east of Southern Ontario. This orogenic event was responsible for the development of the arch and basin bedrock expression found in Southern Ontario (Root and Onasch, 1999). Mountains are created through the collision of tectonic plates. The area behind the newly formed mountain range is folded and faulted creating a network of bedrock highs (arches) and basinal foreland lows, such as the Algonquin arch to the west of the Grand River watershed and the associated bedrock lows of the Michigan basin to the west of the Algonquin arch and the Appalachian foreland basin to the east.

The Algonquin Arch is a northeast to southwest trending forebulge zone separating the Michigan and Appalachian Basins. A forebulge is a flexural bulge in the lithosphere (earth's crust) caused by a load (e.g. mountains created by an orogeny) depressing a tectonic plate. Forebulges are developed on the inland side of a foreland basin. The Algonquin Arch trends from the Chatham area, through Dundalk and continues to the northeast. The western edge of the Grand River watershed divide appears to follow this trend from the Woodstock area, where the Onondaga Escarpment meets the Algonquin Arch, and follows it to the northeast where it meets Dundalk. The interpreted bedrock structures are shown in **Figure 2-1** and display the importance of bedrock structures in shaping the Grand River watershed.

The Grand River watershed is situated adjacent to the southeastern edge of the Algonquin Arch, within the westernmost part of the Appalachian foreland basin. Bedrock formations within the Grand River watershed consists of upper Ordovician, Silurian, and lower Devonian aged mainly marine sediments that straddle the broad northeastern oriented basement high of the Algonquin Arch.

Paleozoic sedimentary rocks were deposited in the Grand River watershed area between 458 to 393 Ma (Thurston *et al.*, 1992; Armstrong and Carter, 2010; Sun, 2018). The sedimentary bedrock contains shales, sandstones, limestones, dolostones, and evaporites with varying degrees of disconformable (erosion has removed a part of the sedimentary record due to low sea levels) and conformable (continuous deposition of sediments) surfaces. The type of sedimentary rock is highly dependent on the geologic setting that existed during deposition. The rise and fall of sea levels determined the type and characteristics of the rock deposited. The bedrock formations generally subcrop (beneath Quaternary drift) in long parallel bands of varying width generally aligned in a north-west to south-east direction that is parallel to the outline of the Appalachian basin in this area.

Bedrock Cuestas

A cuesta is defined as a ridge that contains a gentle slope on one side and a scarp on the other. Cuestas typically form in response to erosional undercutting of resistant bedrock units and trend parallel to the basin margin with the bedrock units dipping towards the basin center.

The Niagara Escarpment cuesta is located to the east and is nearly parallel, at a distance of approximately 10 to 20 km, to the eastern boundary of the Grand River watershed from Dundalk, south to Hamilton. There are multiple re-entrant bedrock valleys that cut perpendicular through the rock face and many areas above the Niagara Escarpment that have been subjected to karstification (Cowell and Ford, 1983; Ford and Williams, 2007; Brunton *et al*., 2012; Burt, 2017).

The Onondaga Escarpment cuesta trends east-west near the Lake Erie shoreline from the Niagara Region to South Cayuga before turning northwest to the Woodstock area, then trending approximately south-north to the County of Bruce. The Grand River cuts through the Onondaga escarpment at its terminus at Port Maitland on Lake Erie but the southern and southwestern boundary of the watershed trend along this escarpment from South Cayuga, northwest, to the area east of Listowel.

Bedrock Surface

The bedrock surface displayed on **Map 2-1** is based on information from Gao *et al*. (2006). The highest elevation in the Grand River watershed is the northern extent coincident with the 'Dundalk Dome' at approximately 525 masl, which is also one of the highest elevations in southern Ontario. The bedrock slopes uniformly to the south where it dips beneath Lake Erie at approximately 173 masl. The lowest bedrock elevation within the Grand River watershed is found within the Dundas Buried Valley near Copetown. A 198 m deep borehole was drilled here by the City of Hamilton during an investigation of the sediments filling the Dundas Buried Valley. Bedrock was not intersected, but drilling reached 30 masl which is 44 m below the surface of nearby Lake Ontario (Bajc *et al*, 2017). Additionally, a borehole was drilled on the Burlington Bar, to the east, that reached a depth of 195 m without intercepting bedrock suggesting this valley reaches depths of at least 120 m below sea level, which is 193 m below the surface of Lake Ontario (Burt, 2017).

The interpreted locations of buried bedrock valleys, which are also referred to as thalwegs, are displayed on **Map 2-2** (Gao, 2011). The origin of these buried bedrock valleys has been interpreted as being formed through either glacial and subglacial meltwater erosion, non-glacial/interglacial fluvial erosion, or a polygenetic origin resulting from preglacial incision and subsequent modification by glacial/deglacial processes (Karrow, 1973; Gao, 2011; Marich *et al*., 2011).

Bedrock valleys are an important hydrogeological feature within the Grand River watershed as they provide targets for municipal groundwater exploration and also serve as conduits or transport paths for groundwater between sub-watersheds and surrounding watersheds. These deeper aquifers are advantageous as municipal water supplies since their depth tends to provide protection from surficial contamination, separating them from surface water, and limit interference from other pumping wells. Overall, these aquifers are often more reliable and less prone to degraded water quality so long as recharge is sufficient enough to sustain prolonged pumping.

Bedrock valleys within the Grand River watershed include the Dundas, Rockwood, and Elora Buried Valleys, along with several other buried and re-entrant valleys surrounding the watershed. The origin of the buried valleys in the Grand River watershed have been interpreted by Gao (2011) as being formed through glacial and subglacial drainage carving out the underlying bedrock prior to the deposition of sediments, while Marich *et al*. (2011) argues for a polygenetic origin where deglacial meltwaters reoccupied previously carved nonglacial fluvial channels prior to the deposition of sediments.

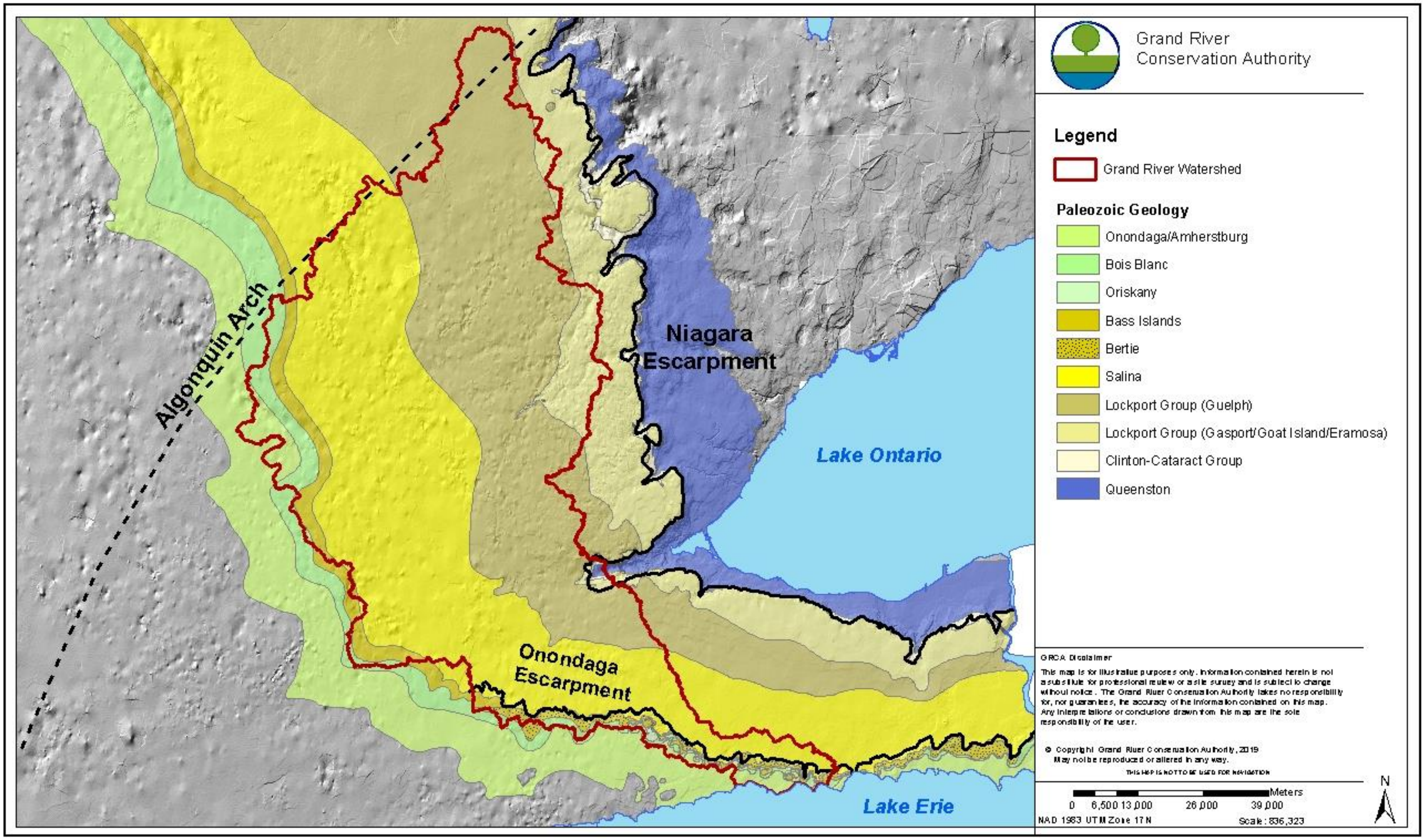
The Dundas Valley, aside from having the lowest bedrock surface elevation in the watershed, is a buried bedrock valley with little to no surface expression as it has been infilled with glacially-derived sediments. The valley is the deepest at Copetown because it is thought to be a knickpoint (a sudden drop in the slope of a river) for the drainage system, creating a deeply incised, narrow channel below a large waterfall, very much like Niagara Falls today (Marich *et al*., 2011). From Copetown, the channel trends west and northwest within the Guelph and Salina Formations, displaying a dendritic drainage network with limited valley incision that is controlled by the elevation of the knickpoint (Marich *et al*., 2011). The channel then continues northwest through Wellesley and the Onondaga Escarpment as it once again returns to a linear, deeply incised, bedrock depression known as the Milverton Buried Valley (Marich *et al*., 2011).

The Rockwood Valley is also a buried bedrock valley system with no surface expression which trends southwest to northeast from the Rockwood area past the town of Erin bisecting the Niagara Escarpment at the Credit River Valley (Burt *et al*., 2011).

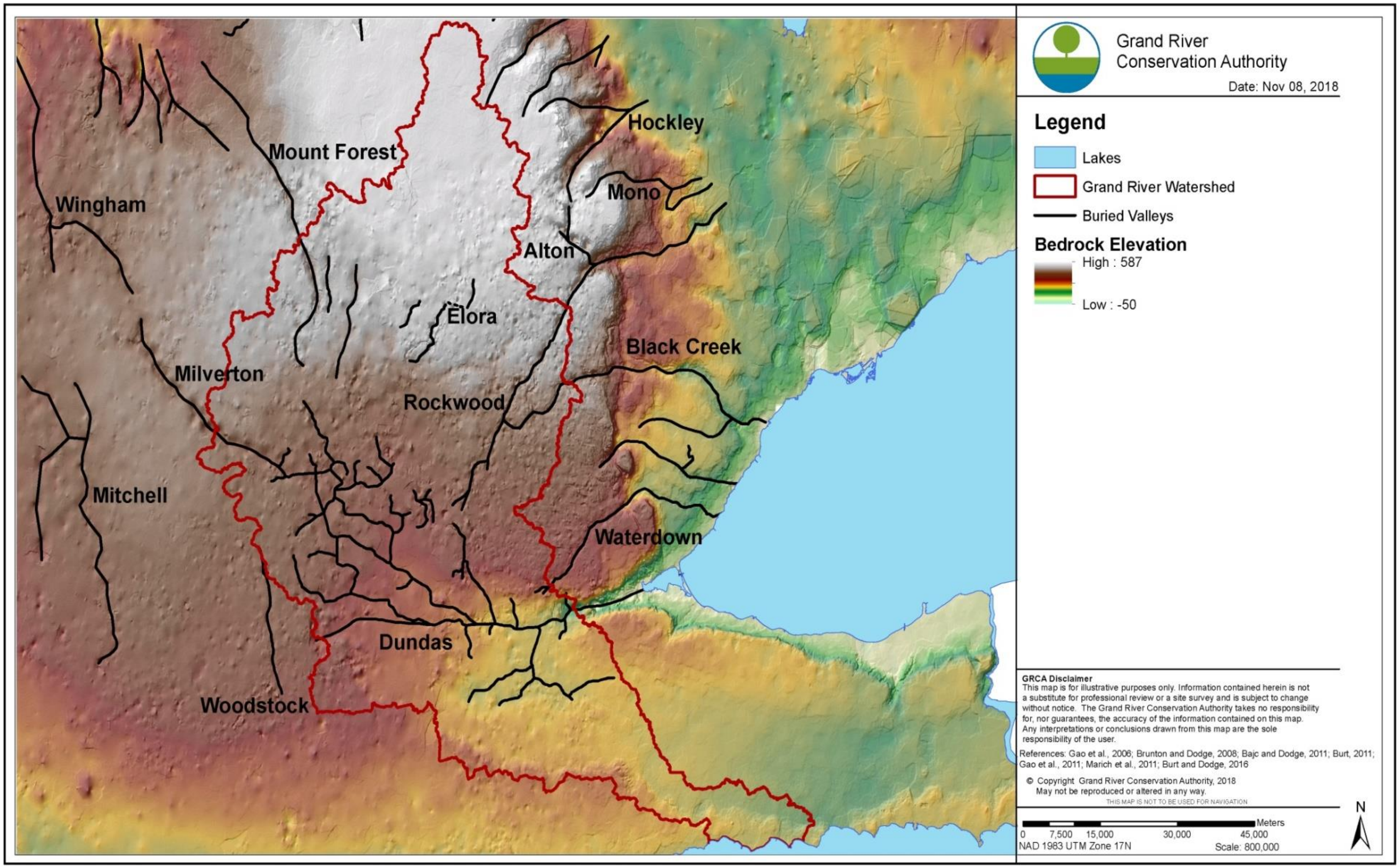
The Elora Buried Valley is a discontinuous feature. The valley originates to the north of Fergus, trends toward the south, and east of Belwood Lake, then disappears for several kilometers before re-appearing on the west side of Belwood Lake suggesting that water flowed in an underground conduit, as is a common occurrence in karst landscapes (Burt *et al*., 2011; Burt and Dodge, 2016). It should be noted that these interpretations have been inferred through water well and geophysical records and have not been confirmed through drilling.

Additional buried valleys within the Grand River watershed include the Woodstock, Mitchell, Wingham, and Mount Forest Buried Valleys, as well as the Waterdown, Black Creek, Alton, Mono, and Hockley re-entrant valleys (partially filled valleys along the Niagara Escarpment).

Map 2-1: Paleozoic bedrock geology and structural features within the Grand River watershed. Niagara and Onondaga escarpment locations interpreted from the bedrock surface elevation (Gao, 2011).



Map 2-2: Bedrock topography and interpreted buried bedrock valleys.



Bedrock Formations of the Grand River watershed

This section provides a description of the bedrock formations located within the Grand River watershed. **Map 2-1** shows the bedrock formations and interpreted arch and escarpment locations discussed in Section 2.1 relative to the watershed. **Table 2-1** provides generalized descriptions of the bedrock formations with subsequent sections providing additional detail.

Within the Grand River watershed, bedrock outcrops are most commonly found in two areas; along the eastern boundary of the watershed from Erin to Hamilton near the Niagara Escarpment, and along the southern boundary of the watershed from Port Maitland / Dunnville west to Hagersville, near the Onondaga Escarpment.

The eastern area outcrops are commonly found along river valleys, road cuts, and quarries. They consist of the Gasport, Goat Island, Eramosa, and Guelph Formations (Brunton, 2009; Brunton *et al*., 2009). The southern watershed outcrops are commonly found along the Onondaga Escarpment, associated river valleys, and quarries. The stratigraphy of the southern outcrops commonly consist of the Bertie, Bass Islands, Oriskany, Bois Blanc, and Onondaga/Amherstburg Formations (Armstrong and Carter, 2010; Sun, 2018).

The outcropping or subcropping bedrock formations within the Grand River watershed were originally deposited horizontally. The bedrock strata in southwestern Ontario now dip shallowly as a result of subsequent structural deformation. Regional dip generally increases with depth and distance away from the crest of the Algonquin Arch. Along the arch crest, the dip is 3 to 6 m/km to the southwest, increasing to 3.5 to 12 m/km down the flank of the arch into the Appalachian basin (Armstrong and Carter, 2010).

Table 2-1: General descriptions of the bedrock geology of the Grand River watershed. Formations are organized stratigraphically from the most recently deposited, uppermost, rock formation (Onondaga/Amherstburg) to the oldest deposited and lowermost rock formation (Queenston) within the watershed. All units are formations unless otherwise indicated. Descriptions are from various sources including Brett *et al*., 1995; Brunton, 2009; Armstrong and Carter, 2010; Sun, 2018; and all others cited in the full body of text.

Group	Formation	Member	Lithology Description*
Onondaga/ Amherstburg			Tan to grey-brown to dark brown, fine- to coarse-grained, bituminous, bioclastic, fossiliferous limestones and dolostones. Includes stromatoporoids, rugose and tabulate corals, brachiopods, crinoids, cephalopods and trilobites. Towards the Appalachian Basin, the Formation gives way to crinoidal, coral-rich limestones and grey-brown argillaceous, cherty limestones. The basal member of the Formation consists of cherty, fossiliferous (up to 50%), locally biohermal, locally argillaceous limestone, grading upward to a very abundant black chert, sparsely fossiliferous limestone, which in turn, is overlain by variably cherty, very fossiliferous, locally biostromal limestone.
Bois Blanc			Greenish grey to grey-brown, thin- to medium-bedded, fine- to medium-grained, fossiliferous and bioturbated, cherty limestone and dolostone. Fossils are brachiopods, bryozoans, small rugose corals and rare tabulate corals. Chert is white to grey to black in colour and may constitute up to 90% of the rock volume. It may also contain glauconitic and phosphatic, white to green-brown, quartzitic sandstones and minor sandy carbonates, either at the base or as interbeds in the lower part of the Formation.

Group	Formation	Member	Lithology Description*
Oriskany			Grey to yellowish white, medium to coarse grained, loosely cemented, thick- to massive-bedded, calcareous quartzose sandstone (arenite). Quartz grains are well-rounded to subangular and well sorted. The formation contains fossiliferous horizons with abundant brachiopods, bryozoans and fragments of other fossils. The bottom 30 cm of the unit may be conglomeratic with fragments of reworked Bass Islands Formation. Lenses of subangular sandstone conglomerates may occur locally.
Bass Islands			Dark brown to light grey, variably laminated, mottled, argillaceous or bituminous, very fine- to fine-crystalline and sucrosic dolostone, commonly with intraclastic breccias, evaporate interbeds, and blue-grey mottling.
Bertie			Cyclic successions of dark brown to light grey-tan, very fine- to fine-crystalline, variably laminated and massive, argillaceous or bituminous dolostones and minor shales
Salina		F Unit - Carbonate, Shale, and Evaporite	Dark green shales with pink and light blue anhydrite nodules in the upper half; mixed dolostones, shales and anhydrite in the lower half. Dolostones are commonly tan, massive to laminated, and fine grained with evaporite mineral molds.
		E Unit - Carbonate and Shale	Interbedded tan laminated to massive dolostone, with light grey-green argillaceous dolostone, and dark to light green laminated to massive shale and anhydrite. The top is marked by a distinctive bed of shaly dolomite or dolomitic shale.
		D Unit -	Thin package of strata containing the insoluble

Group	Formation	Member	Lithology Description*
		Carbonate and Evaporite	or nonsalt constituents of previously deposited beds of halite and dolostone to shaly dolostone.
		C Unit - Carbonate, Shale, and Evaporite	Lower bed of shaly anhydrite or dolostone grading upwards to green shale with anhydrite nodules. Contains minor, thin dolostone beds and local red shale.
		B Unit - Carbonate	Dolostone, anhydritic to argillaceous dolostone, anhydrite, and anhydritic shale.
		B Unit - Evaporite	Coarse crystalline halite that varies from clear white to dark translucent brown. Contains thin interbeds and partings of yellowish to light green-grey shale and dolostone. The base of the unit is marked by an anhydrite-rich zone with minor dolostone and shale.
		A2 Unit - Carbonate	Dark to light grey-brown laminated to thin-bedded, very fine- to fine-grained dolostone and limestone, with patches of microsucrosic dolostone, minor argillaceous dolostone, and anhydrite nodules. A thin, dark grey-green shale marker occurs near the base of the unit.
		A2 Unit - Evaporite	Contains 2 subunits; salt and anhydrite. Anhydrite is common at the top and bottom of the unit. Minor amounts of anhydritic, very fine-grained dolostone. Thick beds of coarse white halite occur. Typically light blue-grey, nodular, very fine-grained and dense.
		A1 Unit - Carbonate	Very fine- to medium-grained, tan-grey to black, variably bituminous, laminated to massive dolostone and limestone. The lowermost few metres are thinly laminated.
		A1 Unit - Evaporite	Anhydrite with minor dolostone and salt.

Group	Formation	Member	Lithology Description*
Lockport	Guelph	Hanlon	Thinly-bedded dolostone containing megalodont–gastropod-dominated wackestone and packstone facies.
		Wellington	Carbonate reef mound-bearing, medium to thickly bedded, cross-stratified, crinoidal grainstone to wackestone-dominated facies.
	Eramosa	Stone Road	Cream-coloured pseudonodular dolomite facies.
		Reformatory Quarry	Light brown to cream coloured thick bedded, coarsely crystalline and coral-stromatoporoid biostromal lithofacies. There is a strongly deformed pseudonodular interval interpreted as a seismite (earthquake-deformed bed).
		Vinemount	Thinly bedded, fine-crystalline, and cyclic horizontally bioturbated dolostone with interbedded partially silicified brachiopods and digitate tabulate corals. Fresh outcrops are black, whereas weathered outcrops are light grey. It contains a petroliferous odour when broken.
	Goat Island	Ancaster	Chert-rich, finely crystalline dolostone that is medium to ash grey in colour, thin to medium bedded and bioturbated. Contains abundant chert nodules and lenses within the basal beds. A shaly interval is present near the top of the member.
		Niagara Falls	Crinoidal grainstone (brachiopod bearing) that contains a distinctive pin-striped appearance, finely crystalline, tight, and cross laminated with incipient small reef mounds.

Group	Formation	Member	Lithology Description*
	Gasport	Pekin	Dark olive-gray, argillaceous, fine- to medium-grained, thin- to medium-bedded dolomicrite with coral-stromatoporoid framestone bioherms up to 6 m high and dark grey, coarse, rubbly dolorudite signifying biohermal flank debris.
		Gothic Hill	Light pinkish-grey, regionally transgressive, cross-bedded grainstone to packstone containing microbial–crinoidal reef mound lithofacies transitioning upward to rhynchonellid brachiopod–bryozoan–bivalve coquinas.
Clinton-Cataract	Rochester		Dark grey to black, calcareous shale with thin interbeds of fine- to medium-grained calcareous to dolomitic calcisiltite to bioclastic calcarenite.
	Irondequoit		Fine to medium crystalline package; thickly- to medium-bedded, medium grey to pinkish-grey, buff-weathering, dolomitic, brachiopod-rich encrinite with distinctive stylolites and thin styloseam sets. The styloseam sets and stylolites contain secondary pyrite, gypsum and pyrolusite. Small, bryozoan-dominated bioherms occur toward the top of this unit.
	Rockway		Argillaceous dolomicrite to wackestone with no distinct macrofaunal components. It contains a distinct greenish-grey fine crystalline matrix and styloseam sets with thin shaly partings.

Group	Formation	Member	Lithology Description*
	Merritton		Thin- to medium-bedded, very fine- to coarse-crystalline, very fossiliferous dolostone separated by dark, shaly partings. The basal bed has a distinctive, bioturbated, pinkish-brown fine crystalline matrix and possesses a black, phosphate pebble bearing hardground unit. The middle bed grades from wackestone to highly fossiliferous dolostone containing *Planolites*-type burrows, halysitid and favositid corals, pentamerids, and is rich in pyrite. The uppermost beds are brachiopod-rich dolostones.
	Cabot Head		Grey to green to red-maroon, noncalcareous siliciclastic shales, with subordinate sandstone and carbonate interbeds. A few thin, bryozoan-rich, shale and argillaceous limestone beds are known.
	Manitoulin		Thin to medium bedded, moderately fossiliferous, fine to medium crystalline, light grey-brown to blue-grey, buff-brown weathered calcareous dolostone with minor limestone and grey-green shale, that commonly contains chert nodules or lenses and silicified fossils.
	Whirlpool		Medium to thickly bedded, light-grey to white, fine to coarse grained, well-sorted, trough cross-bedded, unfossiliferous quartzose sandstone with thin, dark-grey to greenish-grey shale clasts and interbeds.
Queenston			Noncalcareous to calcareous red (maroon) shale with subordinate amounts of green shale, siltstone, sandstone, and limestone.

*Descriptions found in text; references therein

2.1.1 Queenston Formation

The Queenston Formation, shown in **Figure 2-2,** is commonly referred to as the Queenston shale. The formation was deposited during the Upper Ordovician period and is the oldest Paleozoic bedrock formation within the watershed. It underlies all of southwestern Ontario and outcrops within the Grand River watershed along the Niagara Escarpment in a small area of the Dundas Valley in the vicinity of Copetown. It is a noncalcareous to calcareous red (maroon) shale with subordinate amounts of green shale, siltstone, sandstone, and limestone (Armstrong and Carter, 2010).

Figure 2-2: Queenston Formation in Queenston, ON along the Niagara River. Left: Red (Maroon) and Green Shale. The slumped talus section is typical of the Queenston shale in section because it is easily eroded. Scale is 1 m. Right: Hand samples of both the red and green shales of the Queenston Formation. Scale is 7.5 cm.

Clinton–Cataract Group

The Clinton-Cataract Group is represented by a narrow band on **Map 2-1** that overlies the Queenston Formation, and subcrops in the Dundas Valley area of the Grand River watershed. The Clinton-Cataract Group is comprised of several different bedrock formations, including Whirlpool, Manitoulin, Cabot Head, Merritton, Rockway, and Irondequoit; however, these formations are not differentiated on **Map 2-1**. This group, which is exposed along the face of the Niagara Escarpment, was deposited during the Llandovery to Wenlock of the Silurian period (Telford, 1979; Armstrong and Dodge, 2007; Brunton, 2009).

2.1.1.1 Whirlpool Formation

The base of the Silurian Whirlpool Formation is a disconformable contact of an unknown duration with the underlying Ordovician Queenston Formation (Brett *et al*., 1995). A type section of the Whirlpool Formation is shown in **Figure 2-3**.

The Whirlpool Formation is a medium to thickly bedded, light-grey to white, fine to coarse grained, well-sorted, trough cross-bedded, unfosilliferous quartzose sandstone with thin, dark-grey to greenish-grey shale clasts and interbeds (Martini and Salas, 1983; Brett *et al.*, 1995). In Hamilton, the Whirlpool Formation grades laterally into the carbonates of the Manitoulin Formation (Brett *et al*., 1995).

Figure 2-3: Whirlpool sandstone at the whirlpool in the Niagara River Gorge, Niagara Falls, ON. Left: Medium to thick bedded, light-grey to white, fine to coarse grained, well-sorted, trough cross-bedded, unfossiliferous quartzose sandstone in section. Scale is 1 m. Right: Trough cross beds. Scale is 7.5 cm.

Manitoulin Formation

The Whirlpool Formation, where present, gradually grades into the overlying Manitoulin Formation, or, where the Whirlpool is absent, the Manitoulin sharply and unconformably overlies the Upper Ordovician Queenston Formation (Armstrong and Carter, 2010).

The Manitoulin Formation is a thin to medium bedded, moderately fossiliferous, fine to medium crystalline, light grey-brown to blue-grey, buff-brown weathered calcareous dolostone with minor limestone and grey-green shale, that commonly contains chert nodules or lenses and silicified fossils (Armstrong, 1993; Armstrong and Carter, 2010).

Cabot Head Formation

The lower contact of the Cabot Head Formation is very gradational from the dolostone of the Manitoulin Formation to the shales of the Cabot Head (Armstrong, 1993).

The Cabot Head Formation is generally poorly exposed due to its shaley nature. It consists of mainly grey to green to red-maroon, noncalcareous siliciclastic shales, with subordinate sandstone and carbonate interbeds. A few thin, bryozoan-rich, shale and argillaceous limestone beds are known but it is generally unfossiliferous (Armstrong, 1993; Armstrong and Carter, 2010).

Merritton Formation

The Merritton Formation rests disconformably on the Cabot Head Formation in the Grand River watershed.

Within the watershed, the Merritton Formation is a distinctive formation comprising 3 well-cemented beds of unequal thickness (Brunton, 2009). The thin- to medium-bedded, very fine- to coarse-crystalline, very fossiliferous dolostone is separated by dark, shaly partings. The basal bed has a distinctive, bioturbated, pinkish-brown finely crystalline matrix and possesses a black, phosphate pebble bearing hardground unit. The middle bed grades from wackestone to highly fossiliferous dolostone containing *Planolites*-type burrows, halysitid and favositid corals, pentamerids, and is rich in pyrite. The uppermost bed is a brachiopod-rich dolostone (Brunton, 2009; Armstrong and Carter, 2010).

The Merritton Formation is regionally extensive due to its very cherty and well cemented nature. It is present from northern Michigan to Niagara Falls (Brett *et al*. 1995; Brunton, 2009), and is approximately 1 m thick in cores from the Guelph area (Brunton, 2009).

Rockway Formation

The Rockway Formation disconformably overlies the Merritton Formation in southern Ontario from Niagara Falls to Manitoulin Island (Brunton, 2009). It is an argillaceous dolomicrite to wackestone containing a distinct greenish-grey fine crystalline matrix and styloseam sets with thin shaly partings (Brunton, 2009).

The Rockway Formation has a consistent thickness of 1 to 2 m throughout southern Ontario. The upper Merritton and Rockway Formations do not significantly change in overall thickness in southern Ontario suggesting that the Algonquin Arch did not influence regional sedimentation patterns and that erosional phases did not affect this area prior to the deposition of the Irondequoit Formation (Brunton, 2009).

Irondequoit Formation

A distinctive and slightly erosional “welded” contact with the underlying Rockway Formation contains intraclasts from the Rockway Formation that can be identified in the basal beds of the Irondequoit Formation above the contact (Brunton, 2009). The Irondequoit Formation is a medium- to coarse grained, thick- to massive-bedded, medium grey to pinkish-grey, buff-weathered, dolomitic, brachiopod-rich encrinite (Brett *et al.*, 1995; Brunton, 2009; Armstrong and Carter, 2010). There are distinctive stylolites and thin styloseam sets, reflecting short-lived time breaks, containing secondary pyrite, gypsum and pyrolusite (Brunton, 2009). Small, bryozoan-dominated bioherms occur towards the top of this unit (Brunton, 2009; Armstrong and Carter, 2010). This unit contains a consistent thickness of approximately 3 m within the Grand River watershed (Brunton, 2009).

Rochester Formation

The basal contact of the Rochester Formation is sharp and disconformable in Ontario (Brett *et al*., 1995). The Rochester Formation contains dark grey to black, calcareous shale with thin, fine- to medium-grained calcareous to dolomitic calcisiltite to bioclastic calcarenite interbeds (Brett *et al*., 1995; Armstrong and Carter, 2010). It was deposited in accommodation space created by the migration of the Algonquin Arch which resulted in horizontally bioturbated, finely crystalline dolostones with characteristic styloseam sets and intermittent chert development and pseudonodular fabrics (Brunton, 2009). The Rochester Formation thins and pinches out just north of Hamilton and Cambridge, where it is approximately 1 m thick (Brunton 2009).

Lockport Group

The Lockport Group is shown on **Map 2-1** as a band of rock along the eastern margin of the Grand River watershed from Hamilton to Dundalk that overlies the Clinton-Cataract Group. The Lockport Group forms the cuesta edge of the Niagara Escarpment and subcrops at several places within the Grand River watershed.

Some of the best outcrops are located within the Rockwood Conservation Area along the Eramosa River near Guelph, and within the Irvine Gorge near Elora. The Lockport Group is comprised of several different bedrock formations, including the Gasport, Goat Island, Eramosa, and Guelph; all of these formations have been subdivided into several member classes.

The Lockport group was deposited during the Middle to Upper Silurian period and primarily consists of limestones and dolostones.

Karstification of Bedrock

Karst is an important bedrock feature as approximately 20 to 25% of the total global population that depend on groundwater as a water resource, obtain their water from karst landscapes (Ford and Williams, 2007).

Karst systems are developed in terrain that is composed of soluble rocks such as limestone, dolostone, and gypsum. Karstic landscapes develop features such as caves, sinking streams, enclosed depressions, fluted rock outcrops, large springs, and extensive underground water systems (Ford and Williams, 2007). The distinctive terrain and hydrology of karst systems are formed through a combination of high rock solubility and well developed secondary porosity. The structure and lithology of the rock are more likely to produce a karst landscape if they are dense, massive, homogenous, and coarsely fractured rocks (Ford and Williams, 2007).

Hydrological processes are the driving force behind the development of karst through the dissolution of rock along flow paths. Aggressive groundwater has the ability to dissolve and/or erode bedrock due to elevated acidity, high carbon dioxide content, the presence of sulfates, high concentrations magnesium and ammonium ions, and/or a low content of calcium hydrogen carbonate and magnesium hydrogen carbonate (Fendekova *et al.*, 2011). These variables react with carbonate rock resulting in the loss of material from the bedrock into the groundwater and the development of an interconnected karstic porosity in the bedrock (Cole *et al*., 2009; Fendekova *et al.*, 2011). Karst landscapes progressively evolve through the development of groundwater networks by increasingly turbulent flow conditions.

Karstic features such as dolines (sinkholes; enclosed depressions) and stream sinks (streams that disappear underground through a point source) can develop over time through the dissolution of material and act as point recharge sites to the groundwater system. The results in both the surface landscape and subsurface conduit system evolving together (Ford and Williams, 2007).

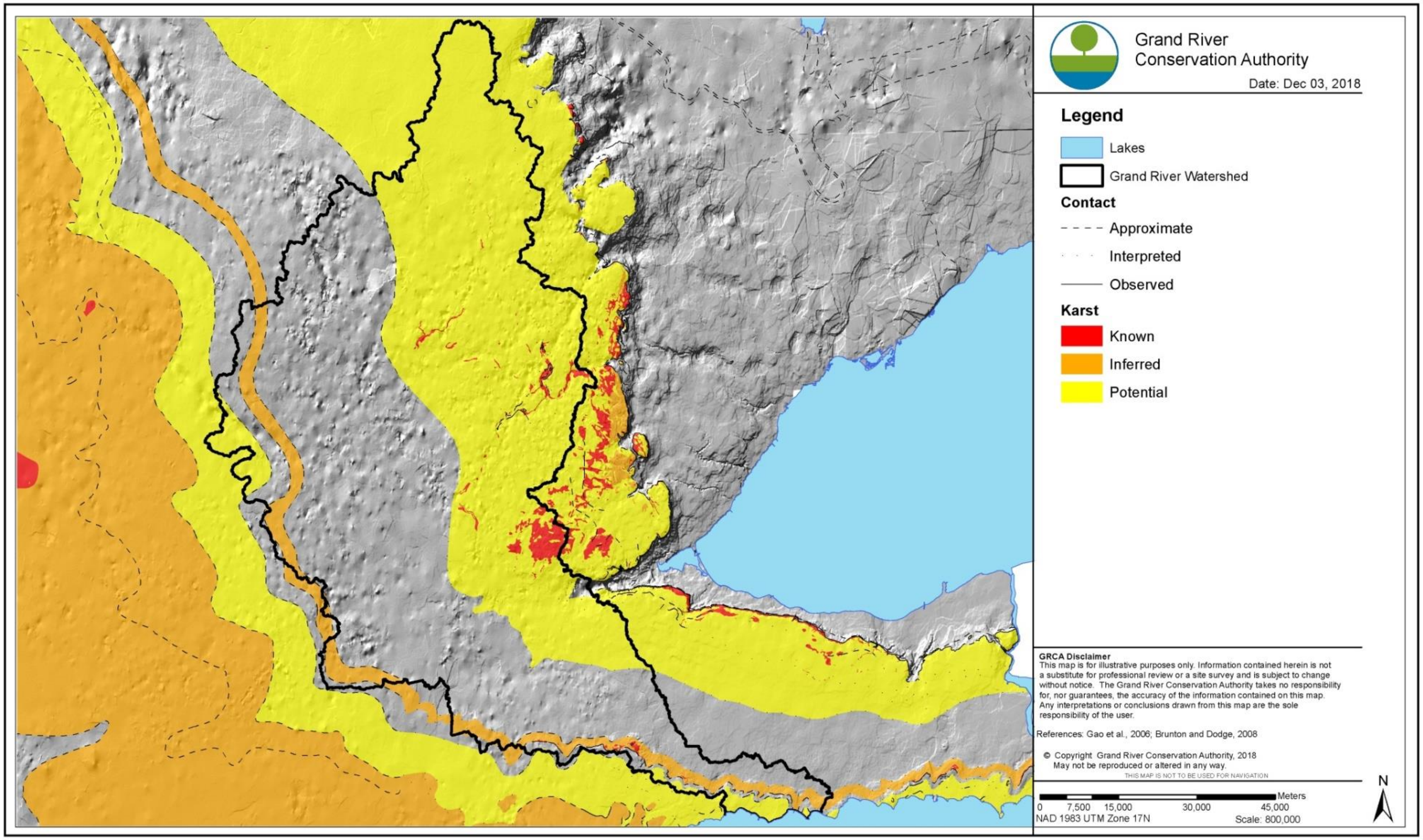
Karst areas located approximately 1 to 3 km behind (above) the Niagara Escarpment are characterized by dolomite solution pavement terrain and lack surficial channel flow (Cowell and Ford, 1983). In these areas, water can flow into fractures in the rock, also referred to as grikes, or diffusively through the overburden, and exit either through springs in the escarpment face or directly into streams and rivers (Cowell and Ford, 1983; Cole *et al*., 2009). **Figure 2-4** provides an example of karstified bedrock in the Rockwood Conservation Area.

The City of Guelph is a prime example of a municipality that derives its potable groundwater almost exclusively from production wells completed within interconnected, cavernous karst of the Guelph, Gasport, and Eramosa Formations (Cole *et al*., 2009).

Map 2-3 identifies areas of known, inferred, and potential locations of karst across the Grand River watershed (Brunton and Dodge, 2008).

Figure 2-4: Karst in the Gasport Formation, Rockwood Conservation Area, Rockwood, Ontario. Student is standing in the entrance to a cave system. There is also a large vertical fracture directly above the student.

Map 2-3: Known, inferred, and potential locations of karst across the Grand River watershed.



Gasport Formation

The Gasport Formation disconformably overlies the Rochester Formation north of Hamilton and Cambridge (Brunton, 2009). South of Highway 401 the Gasport Formation overlies the Irondequoit Formation with an unconformable contact that can be difficult to discern (Brunton, 2009).

The Gasport Formation consists of thick- to massive-bedded, fine- to coarse-grained, blue-grey to white to pinkish grey dolostone and dolomitic limestone (Armstrong and Carter, 2010). The formation outcrops in the Grand River watershed at three points along the eastern boundary: i) in Amaranth Township near Laurel; ii) in a relatively large area surrounding the town of Rockwood; and, iii) in a band surrounding the Dundas Valley.

There are two members to the Gasport Formation; the basal Gothic Hill member and the upper Pekin member. The Gothic hill member is a light pinkish-grey, cross-bedded grainstone to packstone containing microbial–crinoidal reef mound lithofacies changing upward to rhynchonellid brachiopod–bryozoan–bivalve coquinas (Brett *et al.*, 1995; Brunton, 2009). The upper Pekin member is a dark olive-gray, argillaceous, fine- to medium-grained, thin- to medium-bedded dolomicrite with coral-stromatoporoid framestone bioherms up to 6 m high and dark grey, coarse, rubbly dolorudite representing biohermal flank debris (Brett *et al*., 1995; Brunton, 2009). Bioherms extend from the top of the Gothic Hill member grainstones into the Pekin member and occasionally into the overlying Goat Island Formation.

The thickness of the Gasport Formation changes due to an increase in accommodation space during deposition. This resulted in thicker development of the microbial–crinoidal–bryozoan–coral reef mound complexes of the lower Gothic Hill member (Brunton, 2009). In some areas, the reef mounds form multiple stacked cycles that range in thickness from 25 m to more than 70 m (Brunton, 2009). The relative thickness of the Gothic Hill member controls the relationship with the overlying strata. This resulted in the absence of the upper Pekin member north of Hamilton, from Guelph to the southern Bruce Peninsula.

Furthermore, where the Gasport Formation lithofacies is thicker, then the stratigraphic unit that rests disconformably on the sequence boundary will be younger. For example, where the younger Guelph Formation rests disconformably on a sufficiently thick Gasport Formation, the Goat Island and Eramosa Formations (which stratigraphically overlie the Gasport Formation but underlie the Guelph Formation) are absent. Additionally, there is no evidence to suggest that the Goat Island and Eramosa Formations were ever deposited at these locations prior to the deposition of the Guelph Formation (Brunton, 2009).

The Gasport Formation is susceptible to karstification where the Gothic Hill member reef mounds are overlain by the Guelph Formation lithofacies (Brunton, 2009). There are large cavernous pores created by karstification of the subterranean Gasport Formation beneath the City of Guelph (Cole *et al*., 2009). The Gothic Hill member reef mounds form some of the key hydrogeologic units in the Guelph–Cambridge region (Brunton, 2009).

Goat Island Formation

The basal contact of the Goat Island Formation with the underlying Gasport Formation is typically characterized by a sharp disconformable contact (Brett *et al*., 1995). The Goat Island Formation is not always present due to the variably thick lower Gasport Formation. Where present, the Goat Island Formation consists of the lower Niagara Falls member and the upper Ancaster member.

The Niagara Falls member is a crinoidal grainstone (brachiopod bearing) that contains a distinctive pin-striped appearance, is finely crystalline, tight, and cross laminated with incipient small reef mounds (Brunton, 2009). This member is distinguished from the underlying encrinitic Gasport Formation by the finer grained and thinner bedded nature of the Niagara Falls member (Brett *et al*., 1995; Armstrong and Carter, 2010).

The upper Ancaster member is a chert-rich, finely crystalline dolostone that is medium to ash grey in colour, thin to medium bedded and bioturbated (Brunton, 2009). Near Hamilton and among various other locales, it contains abundant chert nodules and lenses within the basal beds. These are informally referred to as the Ancaster chert beds (Armstrong and Carter, 2010).

North of Hamilton, hybridized members of the Goat Island Formation occur where the Gasport Formation is 30 to 50 m thick. The Goat Island Formation may even be absent if the Gasport is sufficiently thick (*i.e*. where significant relief is caused by Gasport Formation reef mounds) (Brunton, 2009). Where the Gasport Formation is less than 20 to 25 m thick, the Niagara Falls member may be up to 10 m thick and the Ancaster member up to 6 m thick (Brunton, 2009). Karst within the Goat Island Formation has been inferred to be absent due to the tight nature and low transmissivity of the unit (Worthington, 2011).

Eramosa Formation

The basal contact of the Eramosa Formation with the underlying Goat Island Formation is conformable but abrupt and characterized by a thin layer of black shale (Brett *et al*., 1995). The Eramosa Formation may disconformably overly a sufficiently thick Gasport Formation where the Goat Island Formation is absent. However, where the underlying Goat Island Formation is present, a thickened Eramosa Formation will typically also be present (Brunton, 2009).

The Eramosa Formation is comprised of three members; the basal Vinemount member, the middle Reformatory Quarry member, and the upper Stone Road member.

The basal Vinemount member is a black (fresh) to light grey (weathered), thinly bedded, fine-crystalline, and cyclic horizontally bioturbated dolostone with interbedded partially silicified brachiopods and digitate tabulate corals, and has a distinctive petroliferous odour when broken (Brunton, 2009). It is most shaly west of Hamilton becoming less shaly to the north.

The middle and upper Reformatory Quarry and Stone Road members are lithologically similar. The Reformatory Quarry member is a light brown to cream coloured thick bedded, coarsely crystalline and coral-stromatoporoid biostromal lithofacies dolomite (Brunton, 2009). It also contains a strongly deformed pseudonodular interval, interpreted as a seismite (earthquake-deformed bed), that varies in thickness from <30 cm to 1.6 m regionally (Brunton, 2009). The Stone Road member is the upper cream-coloured pseudonodular facies dolomite of the Eramosa Formation (Brunton *et al*., 2012).

The Eramosa Formation in general hosts important sulphide minerals such as sphalerite, galena, and pyrite, while also containing petroleum as both a source rock and reservoir (Brunton, 2009). The Eramosa Formation varies in thickness due to the nature of the underlying Gasport Formation reef mounds.

The Eramosa Formation is evident in two sections within the City of Guelph near the Eramosa River; the Guelph Railway cut section on the west side of the Eramosa River; and the Reformatory Quarry section (refer to **Figure 2-5**) approximately 0.5 km away on the east side of the Eramosa River (Brunton, 2009). The Eramosa Formation contains uniformly fine dolomite crystallinity that, when exposed, significantly responds to karstification including sinking streams, dolines, springs, and caves (Buck *et al*., 2003; Brunton, 2009). The Eramosa Formation displays vuggy and cavernous porosity adjacent to a buried valley, near the town of Rockwood, that includes caves and solution-enlarged joints exposed on the surface. This has been correlated with cavernous features located within boreholes drilled in the area (Cole *et al*., 2009). The karst development has been estimated to be between 60 to 75 ka based on the correlation of an undated till at the base of the Rockwood buried valley with the Canning till (Cole *et al*., 2009).

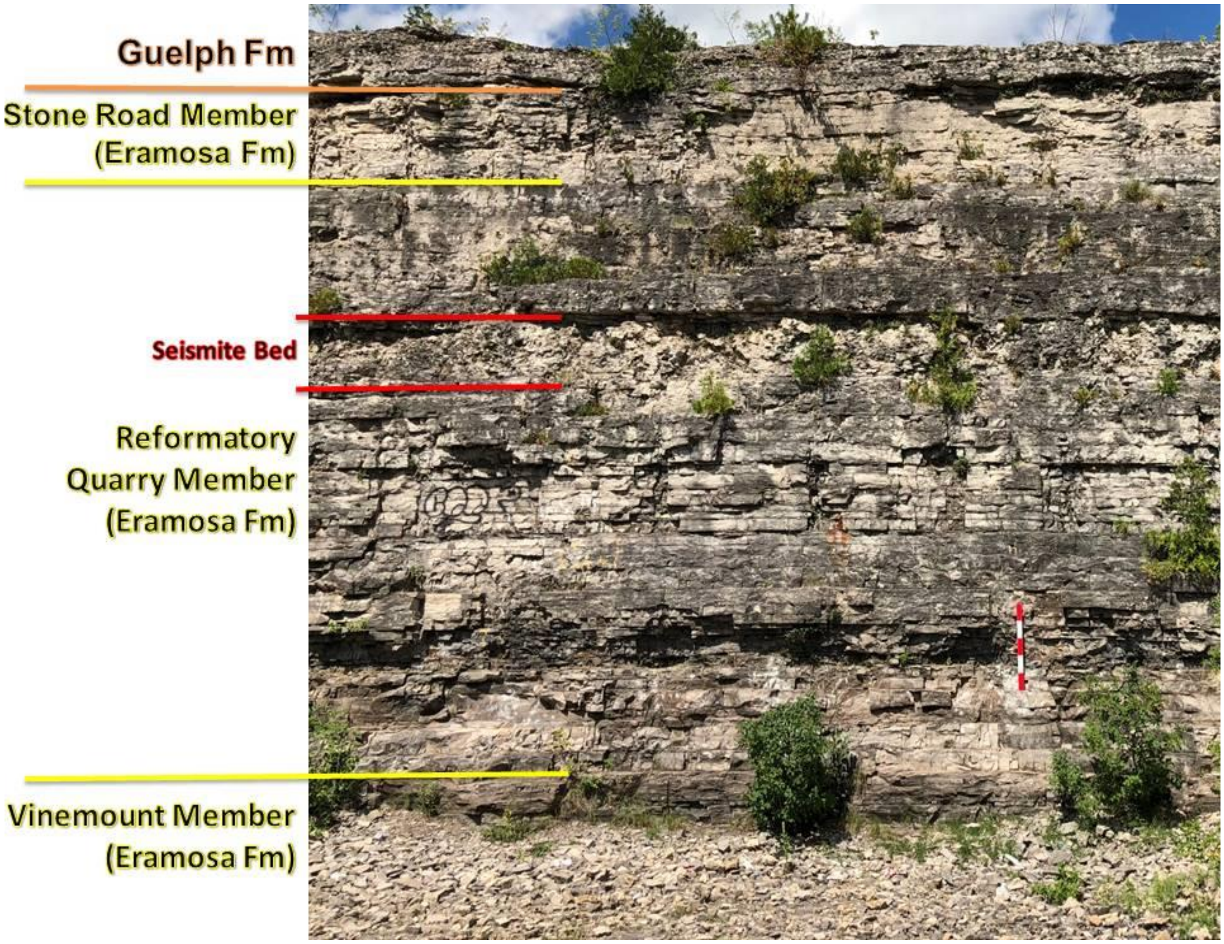


Figure 2-5: Eramosa Formation, Reformatory Quarry, Guelph, Ontario. Each member of the Eramosa Formation is annotated including the seismite bed within the Reformatory Quarry member, and the Guelph Formation overlying the Eramosa Formation. Scale is 1 m.

Guelph Formation

The Guelph Formation is the uppermost bedrock stratum for a large portion of the watershed, stretching in a 30 km wide swath from Dundalk to the Hamilton International Airport (see **Map 2-1**).

The basal contact of the Guelph Formation is marked by a sharp disconformity just below a grey marker bed of stromatolites (Brett *et al*., 1995; Brintnell, 2012). The Guelph Formation is a platformal and reefal dolostone with biostromal and biohermal reef complexes (Armstrong and Carter, 2010; Brintnell, 2012).

There are two members of the Guelph Formation; the basal Wellington member and the upper Hanlon member.

The Wellington member is a carbonate reef mound-bearing and open-marine medium to thickly bedded, cross-stratified, crinoidal grainstone to wackestone-dominated facies (Brunton, 2009; Brunton *et al.*, 2012).

The Hanlon member is a mid-shelf, open marine to lagoonal dolostone that is a thinly-bedded megalodont–gastropod-dominated wackestone and packstone facies (Brunton, 2009; Brunton *et al.*, 2012).

The Guelph Formation is typically 15 to 22 m thick in the Cambridge through Guelph area and thickens to more than 100 m in the Luther Lake region (Brunton, 2009; Brintnell, 2012; Brunton *et al*., 2012). Areas with exposed sections of the Guelph Formation include the Guelph Dolime Quarry (approximately 16 m of strata) and the Irvine Gorge in Elora (**Figure 2-6**) (Brunton *et al*., 2012).

Large, interconnected, cavernous, karstic pores are associated with the Guelph Formation and located at an average depth of approximately 60 m (Cole *et al*., 2009). The karstic features within the Guelph Formation are highly important to the hydraulic function of the watershed.

Salina Group

The Salina Group is aligned in long parallel bands and underlies a large portion of the Grand River Watershed, stretching from Drayton to Dunnville. It is also an important source of gypsum, which is produced in quarries in the Caledonia area.

The Salina Group is subdivided into 7 units in the Grand River watershed; A1, A2, B, C, D, E, and F. Three of these units have been further subdivided into evaporite and carbonate subunits; A1, A2, and B. The geology of each sub-member differs slightly, but in general is composed of algal laminites and gypsiferous sabkha cycles (Brunton, 2009).

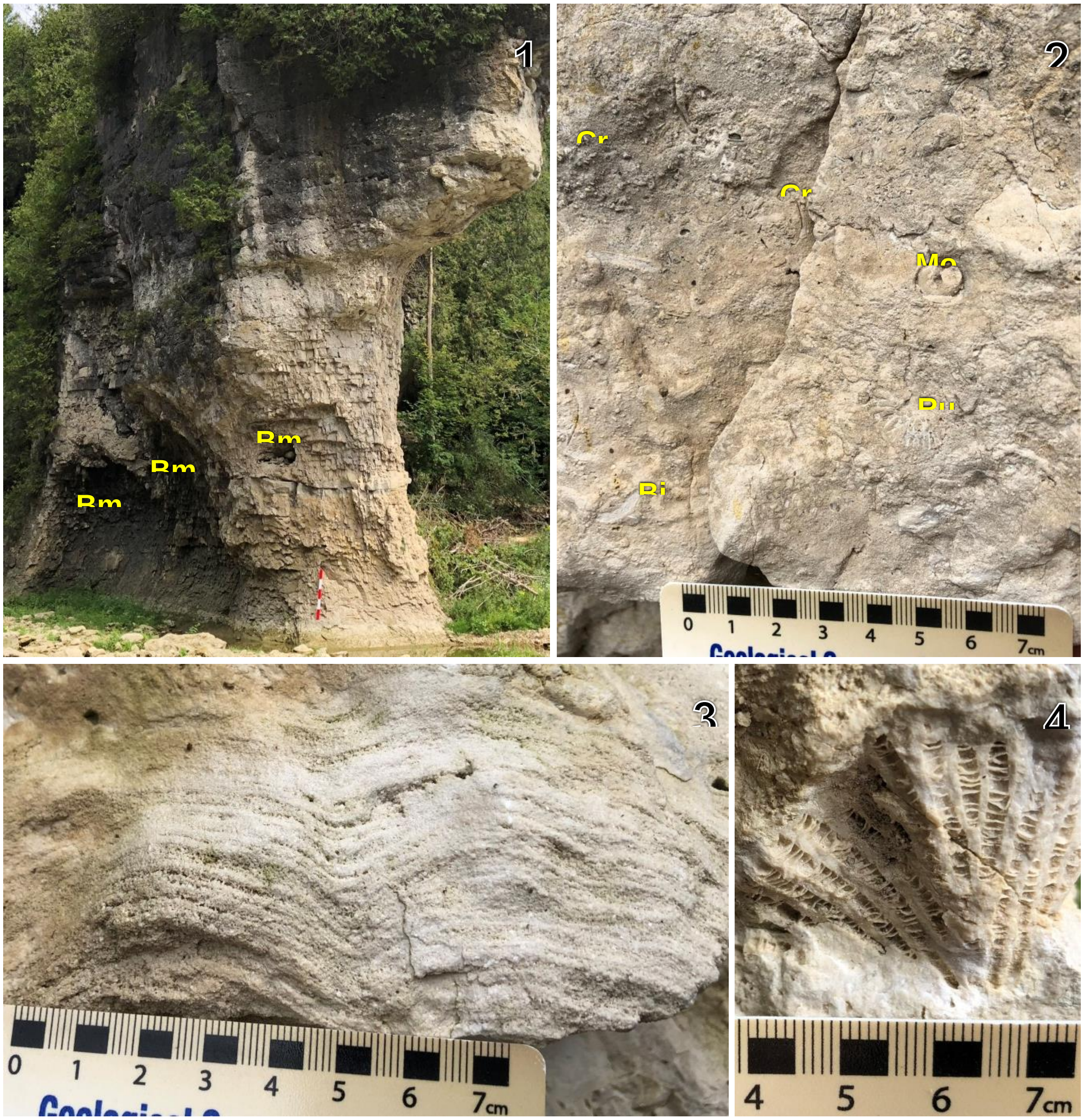


Figure 2-6: Lower Wellington Member, Guelph Formation, Irvine Gorge, Elora, Ontario.

1 (top left): Medium to thickly bedded, crinoidal grainstone to wackestone facies with weathered-out stromatoporoid-microbial-bryozoan mounds (Bm). Note: Scale is 1 m. 2 (top right): Crinoidal (Cr) grainstone to skeletal wackestone facies, including undifferentiated molluscs (Mo), bivalves (Bi), and rugose coral (Ru). Note: only representative samples are labelled. 3 (bottom left): Cross-section of laminar stromatoporoid displaying the distinct parallel laminations. 4 (bottom right): Cross-section of tabulate coral (*Favosite*) with distinctive corallites (“tubes”) and platformal tabula.

The lower contact of the Salina Group carbonates and evaporites with the Guelph Formation is a significant erosional surface (Brunton *et al*., 2012), which is easily discerned when evaporites are present because of the change in lithology. However, when carbonates (dolostone) are present, the contact it is only distinguishable due to the Guelph Formation being slightly more crystalline and coarser grained (Armstrong and Carter, 2010).The flat lying cyclic evaporitic packages of the Salina Group subunits A1 and A2 were deposited around, and on top of, the Guelph reefs to form a disconformable contact between the two formations as illustrated in **Figure 2-7** (Armstrong and Carter. 2010; Brintnell, 2012).

The Salina Group in Southern Ontario consists of up to 420 m of carbonates, shales, anhydrite and halite (Carter, 1987). The units within the Salina Group were deposited consecutively and conformably, however, there are some small-scale internal disconformities due to post depositional dissolution of evaporite beds. Karst has not been identified within the Salina Group.

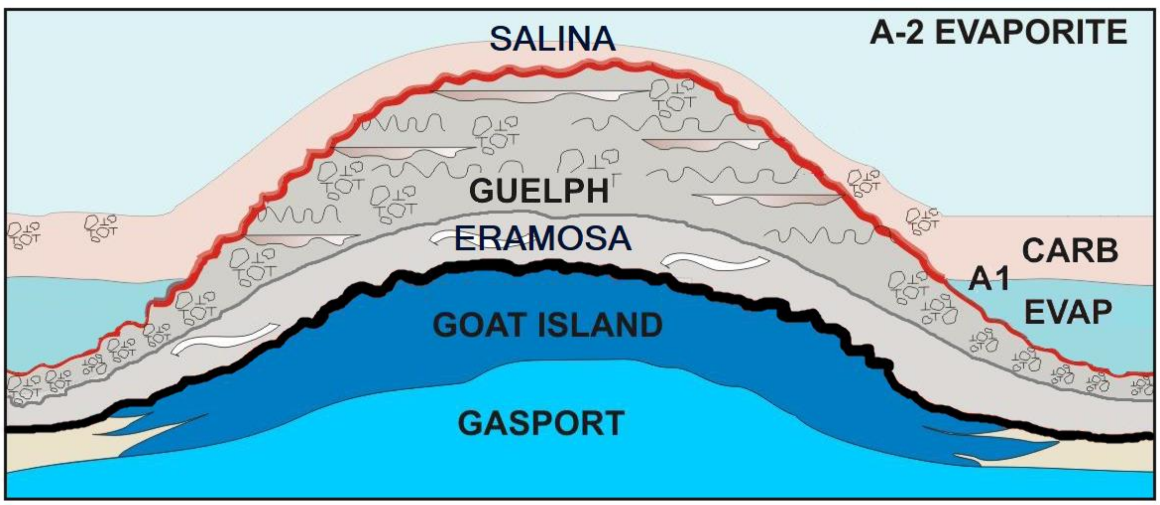


Figure 2-7: Simplified stratigraphy of the Lockport Group and lower Salina Group. Evap = Evaporite; Carb = Carbonate. Modified from Brintnell (2012).

Bertie Formation

The Bass Islands and Bertie Formations are considered to be laterally equivalent. The Bertie Formation is considered an Appalachian basin Formation in the Niagara Peninsula and the Bass Islands Formation is considered a Michigan basin Formation (Johnson *et al*., 1992; Armstrong and Carter, 2010). However, Haynes and Parkins (1992) found that the Bass Islands formation overlies the Bertie Formation in the Dunnville to Hagersville area. Considering this area is within the Grand River watershed, these two formations are discussed as separate formations.

The Bertie Formation extends from Millbank south through Port Maitland. As the basal contact does not have any known exposures, the highest occurrence of evaporite nodules in the Salina Group is used to delineated the base of the Bertie Formation (Sun, 2018). The Bertie Formation consists of cyclic successions of dark brown to light grey-tan, very fine- to fine-crystalline, variably laminated and massive, argillaceous or bituminous dolostones and minor shales (Armstrong and Carter, 2010; Sun, 2018).

Bass Islands Formation

The Bass Islands Formation, similar to the Bertie Formation, extends from Millbank south through Port Maitland and conformably overlies the Bertie Formation. There is a 2-cm thick shale layer at the base of the Bass Islands Formation and is also marked by the preservation of Ostracods and moulds of brachiopods and corals at the top of the Bertie formation (Armstrong and Carter, 2010; Sun, 2018).

The Bass Islands Formation is a dark brown to light grey, variably laminated, mottled, argillaceous or bituminous, very fine- to fine-crystalline and sucrosic dolostone. Intraclastic breccias, evaporite interbeds, and blue-grey mottling are common (Armstrong and Carter, 2010; Sun, 2018).

Within the Grand River watershed, the Bass Islands Formation is 5 m thick and overlies the 16 to 18 m thick Bertie Formation (Sanford, 1969; Armstrong and Carter, 2010; Sun, 2018).

Oriskany Formation

The Oriskany Formation is an Appalachian Basin unit (Sun, 2018). In the Grand River watershed, the Oriskany Formation overlies the Bass Islands Formation by a sharp and irregular erosional surface (Sun, 2018). It is identified by a distinct lithologic break at the erosional surface where the fine-crystalline dolomudstone of the Bass Islands Formation changes to a sandstone of the Oriskany Formation (Armstrong and Carter, 2010; Sun, 2018).The Oriskany Formation is the oldest Devonian deposit in southwestern Ontario and has been assigned a Pragian age based on the presence of *Costispirifer*, *Rosemarie*, *Acrospirifer,* and *Hipparionyx* brachiopods (Sun, 2018).

The Oriskany Formation consists of grey to yellowish white, well-rounded to sub-angular, well-sorted, medium to coarse grained, loosely cemented, thick- to massive-bedded, calcareous quartzose sandstone with fossiliferous horizons (Armstrong and Carter, 2010; Sun, 2018). The bottom 30 cm contains lenses of subangular sandstone conglomerate with fragments of reworked Bass Islands Formation in the Cayuga and Hagersville Quarries (Armstrong and Carter, 2010; Sun, 2018). In Southern Ontario, the Oriskany Formation is discontinuous, thinning from east to west, and eventually pinching out west of the Hagersville area (Sun, 2018). In the Grand River watershed, the Oriskany Formation underlies an area of roughly 6 km^2. Although the Oriskany sandstone does fill in some paleokarst features in the underlying Bass Islands formation; karstic features within the Oriskany sandstone are not readily recognizable.

Bois Blanc Formation

The Bois Blanc Formation subcrops in a band roughly parallel to the western boundary of the watershed from approximately Conestogo Lake to South Cayuga. The basal contact is unconformable with the Oriskany Formation. The Bois Blanc is a similar lithology to, but can be differentiated from, the underlying Oriskany Formation by the presence of abundant phosphate and glauconite minerals, chert nodules, and greater calcite cements (Sun, 2018). The Oriskany Formation tends to contain cleaner, coarser, and poorly cemented sandstones compared to the Bois Blanc sandstones (Armstrong and Carter, 2010).

The Bois Blanc Formation consists of greenish grey to grey-brown, thin- to medium-bedded, fine- to medium-grained, fossiliferous and bioturbated, cherty limestone and dolostone (Armstrong and Carter, 2010; Sun, 2018). Fossils consist of brachiopods, bryozoans, small rugose corals and rare tabulate corals. Chert is white to grey to black in colour and may constitute up to 90% of the rock volume. It may also contain glauconitic and phosphatic, white to green-brown, quartzitic sandstones and minor sandy carbonates, either at the base or as interbeds in the lower part of the Formation (Armstrong and Carter, 2010; Sun, 2018).

The Bois Blanc Formation in the Grand River watershed is up to 8 m thick becoming increasingly thick (up to 75 m) to the northwest in Bruce and Huron counties (Armstrong and Carter, 2010; Sun, 2018). Hydraulic testing conducted by Worthington (2011) suggests the Bois Blanc contains well developed karst, but a lack of surficial outcrop makes this difficult to confirm.

Onondaga/Amherstburg Formation

The Onondaga/Amherstburg Formation is the youngest bedrock formation in the watershed. Within the Grand River Watershed, it is present in the County of Perth and along the western boundary of the watershed, west of Dunnville. The Amherstburg Formation (Michigan basin) correlates with the lower part of the Onondaga Formation (Appalachian basin) and within the Grand River Watershed, these units are mapped as a transition zone (Armstrong and Carter, 2010). Therefore, these two formations are considered as a single unit for the purposes of describing the bedrock geology within the Grand River Watershed.

The Onondaga/Amherstburg Formation overlies the Bois Blanc Formation. The basal contact of the Amherstburg/Onondaga Formation with the Bois Blanc Formation appears to be gradational (Armstrong and Carter, 2010). The identification of this contact is very unreliable as chert is commonly found in both the Amherstburg/Onondaga Formation and the underlying Bois Blanc Formation.

The Onondaga/Amherstburg Formation consists of tan to grey-brown to dark brown, fine- to coarse-grained, bituminous, and bioclastic limestone and dolostone. The fossils in this formation include stromatoporoids, rugose and tabulate corals, brachiopods, crinoids, cephalopods and trilobites. Towards the Appalachian Basin, the Formation gives way to crinoidal, coral-rich limestones and grey-brown argillaceous, cherty limestones. The basal Onondaga/Amherstburg Formation consists of cherty, fossiliferous (up 50% of the rocks), locally biohermal, locally argillaceous limestone, grading upward to a very abundant black chert, sparsely fossiliferous limestone, which in turn, is overlain by variably cherty, very fossiliferous, locally biostromal limestone (Armstrong and Carter, 2010; Sun, 2018). The thickness of the Onondaga/Amherstburg Formation in southern Ontario is 12-18 m (Sun, 2018). The upper contact of the Onondaga/Amherstburg Formation in the Grand River watershed contains dark brown to black bituminous shaly limestone beds near a regional and irregular disconformable contact with the overlying Dundee Formation.

3.0 Quaternary Geology

Multiple cycles of glacial advance and retreat helped shape the Grand River watershed through sediment deposition and glacially derived landforms, although most topographic variations are defined by the most recent glacial cycle. The late Pleistocene glaciations have been subdivided into multiple glacial and non-glacial episodes recorded in a complex record of glacial and non-glacial sediments.

Each glacial episode incorporates and/or buries the sediments from previous episodes to create a new record of deposition. This has resulted in the most recent episode (Wisconsin Episode) containing the predominant expression of overburden sediments across Southern Ontario. The Wisconsinan glaciation is subdivided into several sub-episodes, which in turn have been subdivided into several phases, as shown in (top). Each sub-episode represents a large scale advance or retreat of the ice sheet, whereas each phase is a localized advance or retreat of one or more lobes within the overall ice sheet. The primary sediments present within the Grand River watershed include pre-Michigan sub-episode tills and non-glacial sediments and a series of Michigan sub-episode tills and stratified sediments deposited by regional thick ice, as well as oscillating lobate ice during the advance and retreat of the Wisconsinan Ice Sheet.

There are two primary lobes of the Wisconsin Ice Sheet that affected the Grand River watershed area; the western lobe and the eastern lobe. The western lobe was sourced from the Huron/Georgian Bay basin, whereas the eastern lobe was sourced from the Erie/Ontario basin. These two ice lobes were responsible for the deposition of multiple till sheets throughout the Grand River watershed (, bottom).

Each till sheet has a slightly different composition based on the source material and the energy of the system (higher energy deposits coarser sediments such as sand and gravel, whereas lower energy deposits finer sediments such as silt and clay).

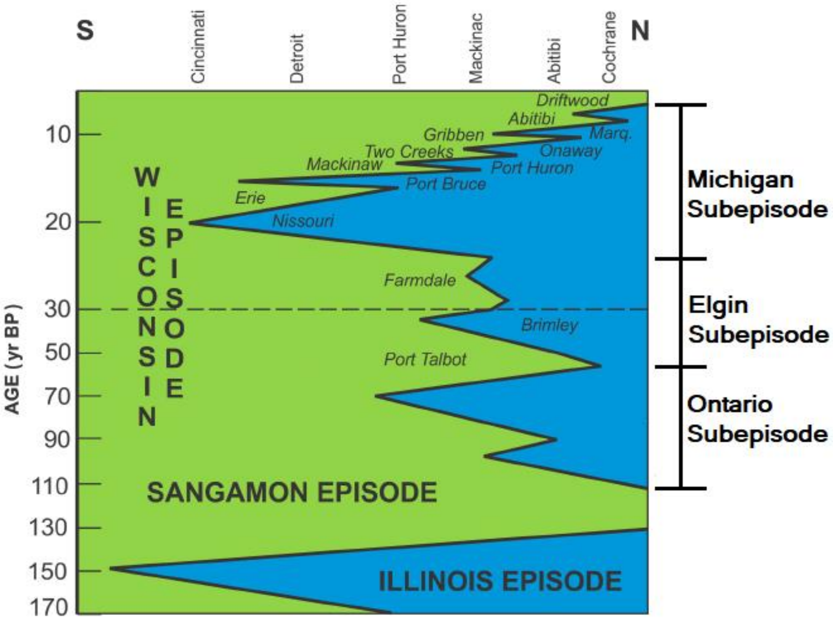
A new till sheet was deposited each time one or both of the lobes advanced and retreated. Interlobate moraines formed between the ice lobes in large ice-walled lakes causing the material from each lobe to mix, leaving a hilly terrain topographically higher than the surrounding area (*e.g.* Waterloo and Orangeville moraines). It also produced end moraines where the ice lobe would “pause” (neither advance nor retreat) leaving a terrain superficially similar to the interlobate moraine except oriented in a band along the edge of the stalled ice lobe. The morphology and structure of the moraines is variable based on the depositional materials and energy in the system.

There are also areas of sand and gravel that represent outwash deposits where the ice melted, and areas of silt and clay where glacial lakes once occupied lower elevations.

Map 4-1 displays the surficial sediments deposited by glacial processes within the Grand River watershed. In general, the surficial geology can be classified into three types of unconsolidated sedimentary material; the northern portion of the watershed is comprised of mostly of till and related diamicton materials, the central portion of the watershed is dominated by coarse-grained moraine sediments, and the southern portion of the watershed is comprised of fine-grained glaciolacustrine sediments. Each of these categories of unconsolidated sediments may be underlain by older pre-Michigan Subepisode sediments but all are unconformably underlain by sedimentary bedrock.

The conceptualization of the Grand River watershed’s Quaternary geology is largely restricted to the Late Wisconsin time period (25,000 to 11,000 yBP). Prior to this, the geological record within the watershed is poorly understood due to the limited amount of data.

The glacial history of the Grand River watershed can be summarized in five oscillating phases of glaciation. First, the Nissouri to Erie Phases, then the Port Bruce to Mackinaw Phases, and finally the Port Huron Phase followed by the current interstadial event. This is illustrated in , but it should be noted that any of the phases in this figure following the Port Huron did not affect the Grand River watershed as the ice sheet had retreated beyond the watershed boundaries by the time any subsequent events took place.



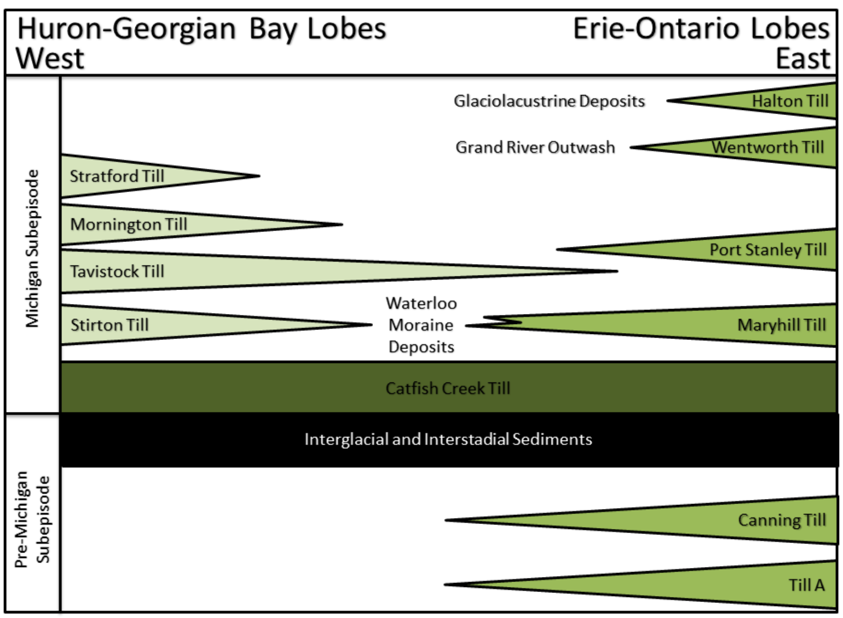


Figure 3-1: Sedimentary timescales Top: Time-distance diagram conceptualizing the Late Pleistocene glacial and non-glacial episodes in the eastern and northern Great Lakes region. Glacial events are blue, while non-glacial events are green. Phase names are in italics. Note: The scale changes at 30,000 radiocarbon yr BP (dashed line). *Modified from* Karrow *et al*., 2000; *via* Burt and Dodge, 2016.

Bottom: Time-distance diagram displaying the timing and extent of till deposition in the Grand River watershed from the Huron-Georgian Bay and Erie-Ontario Lakes basin ice lobes (*modified from* Bajc and Shirota, 2007; and Bajc *et al*, 2017).

Table 3-1: General descriptions of the Quaternary glacial geology of the Grand River watershed. Units are organized stratigraphically from the most recent (Halton Till) to the oldest (Till A) within the Grand River watershed. Descriptions are from various sources including [1]Burt (2014); [2]Burt (2017); [3]Bajc and Shirota (2007); [4]Singer *et al*. (2003); and [5]Bajc *et al.* (2014).

Unit Name	Description
Halton Till	1) Stone-poor clayey diamicton, glaciolacustrine clay[1] 2) Lightly stony, silty clay diamicton[1] 3) Debris flows interbedded with glaciolacustrine sediments[1] 4) Rare glaciofluvial sand and gravel in diamicton[1]
Wentworth Till	1) Somewhat stony to stony silty sand to sand diamicton[2] 2) Slightly silty sand and gravel 3) Occasional beds of gravel and sand 4) Occasional beds of sand, silty sand, and rhythmically bedded silt and clay, slightly to highly deformed[2]
Stratford Till	1) Silty to clayey till, locally sandy[3] 2) Sandy silt to silt diamicton[4]
Mornington Till	1) Silty to clayey till[3, 4] 2) Pebbly, sandy silt to stone-poor silty clay and clayey silt diamicton, massive to laminated[5]
Port Stanley Till	1) Fissile, stony silty sand to sand diamicton[2] 2) Silty to clayey till[3] 3) Pebbly, sandy silt to stone-poor silty clay and clayey silt diamicton, massive to laminated[5]
Tavistock Till	1) Stone-poor to slightly stony, clayey silt to silt diamicton[2] 2) Sandy silt diamicton[2] 3) Silty to clayey till[3] 4) Pebbly, sandy silt to stone-poor silty clay and clayey silt diamicton, massive to laminated[4]
Stirton Till	1) Sandy silt diamicton[2] 2) Silty clay to clayey silt diamicton[4]
Maryhill Till	1) Silt, rhythmically bedded silt and clay, rare beds of silty sand; in places deformed[2] 2) Stone-poor, silty to clayey diamicton[2] 3) Silt and sandy silt diamicton[2] 4) Rhythmically bedded silt and clay with thin and thick beds of

Unit Name	Description
	silty to clayey diamicton, typically deformed[2]
Catfish Creek Till	1) Stone-poor sandy silt to silt diamicton[2] 2) Overconsolidated somewhat stony to stony sandy silt diamicton[2] 3) Overconsolidated somewhat stony to stony sandy silt diamicton with highly deformed laminations of silt and clay and/or beds of silt and clay and occasionally sand and gravel[2] 4) Interbedded diamicton, slightly silty sand and gravel, gravel, sand[1] 5) Rhythmically bedded silt and clay[2]
Interglacial and Interstadial Sediments	1) Sand, silt[2] 2) Rhythmically bedded laminated and rippled sand fining upwards to silty sand and silt, rare organic-rich sandy silt beds[2] 3) Slightly silty sand and gravel, pebbly sand, organic[2]
Canning Till	1) Reddish stone-poor to slightly stony reddish silty to clayey silt diamicton with occasional silty lenses[2] 2) Greyish brown stone-poor silty diamicton[2] 3) Strong red diamicton with abundant red shale clasts[2] 4) Silt, rhythmically bedded silt, and clay, minor diamicton, in places variably slightly to highly deformed[2]
Till A	1) Yellowish brown stony sandy silt diamicton, rare beds of slightly silty sand and/or gravel[2] 2) Coarse- and fine-textured diamicton with gravel and rarely rhythmically bedded silt and clay interbeds[2] 3) Oxidized (stained) stony sandy silt diamicton[2]

Pre-Michigan Sub-episode and Non-Glacial Sediments

Little information is available about the pre-Michigan Subepisode tills and non-glacial sediments in the Grand River watershed as they are associated with sediments that predate the last main glacial advance over the region (Bajc and Dodge, 2011). Where present, these sediments are typically found deep within boreholes or in river cuts, pits, and/or quarries (Burt and Dodge, 2016). The pre-Michigan Subepisode and non-glacial sediments are subdivided into three main units: Till A, the Canning Till, and an alluvial deposit.

The first unit is a buff brown, stony, silty to sandy diamicton and associated stratified granular deposits that rest directly on bedrock (Bajc and Dodge, 2011). It contains a distinct heavy mineral signature that indicates a northern provenance. The age of this till unit is unknown but inferred to be of Illinoian Episode age based on radiocarbon dating of an overlying organic deposit (Bajc and Dodge, 2011; Burt and Dodge, 2016). This unit is based on the 1 m thick, Erie lobe silt loam till A located in a quarry within Zorra Township, northeast of London, Ontario (Westgate and Dreimanis (1967), Bajc *et al*., 2015). It has also been intersected in boreholes drilled for the three-dimensional modeling studies by the OGS in Waterloo Region, Brantford – Woodstock, and Orangeville – Fergus areas (Bajc and Shirota, 2007; Bajc and Dodge, 2011; Burt and Dodge, 2016).

Overlying Illinoian Till A is the second unit; a reddish to mauve-grey, stone-poor, variably textured (typically silty to clayey) diamicton, with fine-textured and interbedded glaciolacustrine sediments (Bajc and Dodge, 2011). Karrow (1963) formally named this unit the Canning Till. Its type-section is located along a cutbank of the Nith River, west of the community of Paris in Brant County. The Canning Till has been interpreted as either Ontario Subepisode or Illinoian age based on a major unconformity that occurs at the top of this unit with an organic layer above it dating to the Elgin Subepisode (Middle Wisconsin) (Bajc and Dodge, 2011). In addition to the cutbank sections along the Nith River, the Canning Till was described by Westgate and Dreimanis (1967) at the Zorra township quarry, and identified within the Grand River watershed at the Preston sand and gravel pit along the Grand River, south of Breslau (Bajc and Dodge, 2011). This unit was also intersected in boreholes drilled for the OGS studies in Waterloo Region, Brantford – Woodstock, and Orangeville – Fergus areas (Bajc and Shirota, 2007; Bajc and Dodge, 2011; Burt and Dodge, 2016).

The third sediment unit, which overlies both Till A and the Canning Till, is an organic-bearing, alluvial and pond deposit (Bajc and Dodge, 2011). The age of this organic-bearing deposit has been assigned to an interstadial period that has been radiocarbon dated with wood samples in the organic material bearing an age range of >50,500 to 23,500 C^{14} yBP (Bajc *et al*., 2009). This time interval spans the Middle Wisconsin but may also extend into the Sangamon interglacial Episode. This unit is the reference for assigning ages to the underlying Till A and Canning Till. The stratigraphic position suggests that the older tills were deposited during the Illinoian Episode or Ontario Subepisode as these organics were deposited during a nonglacial interval (Bajc and Dodge, 2011). These water lain sediments are typically less than 2 to 3 m thick, and contain detrital plant and animal fossils, along with well-preserved pollen (Bajc and Dodge, 2011).

Nissouri to Erie Phases

The Nissouri phase of the Wisconsin Episode occurred during the last glacial maximum (LGM). The LGM is a period when the Laurentide Ice Sheet (LIS) reached its maximum spatial extent. During the LGM, the LIS reached as far as southern Ohio from 25,000 to 17,000 radiocarbon yBP (Karrow, 1988; Bajc *et al*., 2017). This ice advance was characterized by thick and regional ice flow that was unimpeded and not affected by the local topographic variation in southern Ontario.

Approximately 18,000 radiocarbon yBP, the ice began to retreat from Ohio, and at 16,000 radiocarbon yBP the glacier covering southern Ontario began to split along a line following Highway 401 from Ingersoll northeastward to Kitchener-Waterloo then Orangeville (Sibul *et al*., 1980). The ice lobes broke apart, creating low areas which became the focus for sediment-laden meltwaters. During the Erie Phase, these sediment-laden meltwaters formed large deposits of sand and gravel that built up and subsequently formed interlobate moraines, including the Waterloo and Orangeville moraines.

Catfish Creek Till, which is associated with the Nissouri Phase, was deposited regionally as a continuous sheet and underlies most of the Grand River Watershed (Bajc and Shirota, 2007; Bajc and Dodge, 2011; Burt and Dodge, 2016). The till unit becomes thicker in areas characterized by large stratified moraine deposits (*e.g*. Waterloo moraine), and is often used as a stratigraphic marker bed due to its overall consistency in composition (Barnett, 1992; Bajc and Dodge, 2011). There are at least 2 phases of Catfish Creek Till that have been recognized; an early lobate flow from the Huron-Georgian Bay basins and a late lobate flow from the Erie-Ontario basins (Bajc and Dodge, 2011; Burt and Dodge, 2016).

Catfish Creek till is overconsolidated (deposited by thick ice; known as “hardpan” in water well drilling logs), stony, silty to sandy till. Precambrian cobbles and boulders originating from the north shore of Lake Huron, including jasper conglomerate, Gowganda Formation tillite, and quartz-pebble conglomerates/quartzite, have been observed in the till associated with the early deposited Catfish Creek till of a northern provenance (Bajc and Shirota, 2007; Bajc and Dodge, 2011). As the Nissouri Phase ice retreated, meltwaters flowed across the area, resulting in extensive glaciofluvial deposits and numerous small lakes and ponds being formed on the surface of the Catfish Creek till.

The Erie Phase is the first non-glacial phase of the Michigan Subepisode. It is estimated that the ice from the main advance at the LGM thinned and began to disintegrate approximately 15,000 to 16,000 radiocarbon yBP (Karrow *et al*., 2000; Bajc and Dodge, 2011; Burt and Dodge, 2016). The topographically highest areas in the northern part of the watershed became ice-free first. The lobate ice flowed out from the Great Lake basins, effectively blocking drainage during this period. During this time, proglacial lakes occupied topographic lows in the interlobate zone that deposited sediments of mainly sand with localized sand and gravel in conduits that make up the Dorchester, Waterloo, and Orangeville moraines. Subaquatic fan sediments, consisting of glaciolacustrine silt, clay, and interbedded diamicton are also characteristic deposits of this phase (Bajc and Shirota, 2007; Burt, 2011a; Bajc *et al*., 2015; Burt and Dodge, 2016).

Port Bruce to Mackinaw Phases

The Port Bruce phase began approximately 15,000 radiocarbon yBP at a position partially covering the Waterloo and Orangeville moraines (Bajc *et al*., 2017). The ice front then experienced several re-adjustments, slightly oscillating during overall retreat, resulting in the deposition of progressively younger tills away from the interlobate zone near the north-central part of the Grand River watershed. The fine-textured Maryhill Till and the stony, sandy silty Port Stanley Till in the Guelph drumlin field was deposited from the south and east by the Erie-Ontario lobe. Contemporaneously, the northern and western sourced Huron-Georgian Bay lobe deposited the fine-textured Stirton Till, the stone-poor, fine textured Tavistock Till, the fine-textured Mornington, the silty to sandy Stratford till, and the variably textured Elma till (Karrow, 1993; Bajc and Shirota, 2007; Banks *et al*., 2007; Bajc *et al*., 2014; Burt and Dodge, 2016; Bajc *et al*., 2017).

Retreat of the ice during the Mackinaw phase occurred at approximately 13,500 radiocarbon yBP. This resulted in extensive kame and outwash deposits throughout the central parts of the watershed. The Erie-Ontario lobe retreated eastward depositing the stony, coarse-textured Wentworth Till that defines the Paris and Galt moraines (Banks *et al*., 2007; Burt and Dodge, 2016). The meltwaters from the retreating ice sheet deposited extensive coarse-grained braided stream deposits in the Grand River valley near Cambridge both before and after the formation of these moraines (Burt and Dodge, 2011). These deposits created sand and gravel deltas at a series of high-level Erie basin lakes (*e.g*. Whittlesey and Warren) south of Cambridge toward Paris and Brantford (Barnett, 1985; Bajc *et al*., 2017). These lakes also affected the deposition of Port Stanley and Wentworth till in this area, resulting in a facies change that becomes finer to the south (A. Bajc, personal communication, 2018). By approximately 13,300 radiocarbon yBP, the entire Grand River Watershed was ice free.

Port Huron Phase to Present Day

The Port Huron Phase began approximately 13,000 radiocarbon yBP, with the advance of ice to a position just west of the brow of the Niagara Escarpment, or slightly east of the Grand River watershed (Bajc *et al*., 2017). This deposited the stone-poor, silty Halton till in the Waterdown moraine, to the east of the Grand River watershed (Bajc *et al*., 2017). Glacial Lakes Whittlesey and Warren were still present during this time, occupying the low lying area of the southern Grand River watershed, north of present day Lake Erie. In the Paris/Brantford areas, shallow water deltaic sediments were deposited close to the shoreline of Lake Whittlesey creating the Norfolk sand plain. In contrast, the deep water clays and silts south and east of Brantford, were deposited in the deeper Lake Warren basin creating the Haldimand clay plain. A succession of large glacial lakes continued to occupy the Lake Erie basin and southern Grand River watershed until about 12,000 radiocarbon yBP, when the present day drainage system was established (Barnett, 1992; Bajc *et al*, 2017). Since the final glacial retreat from southwestern Ontario, the present day stream system has eroded through the pre-existing surficial geology to create the current landscape.

Map 4-1 presents the Quaternary geology of the watershed. Although the Quaternary geology of the watershed is complex, it can be generally divided into three broad areas:

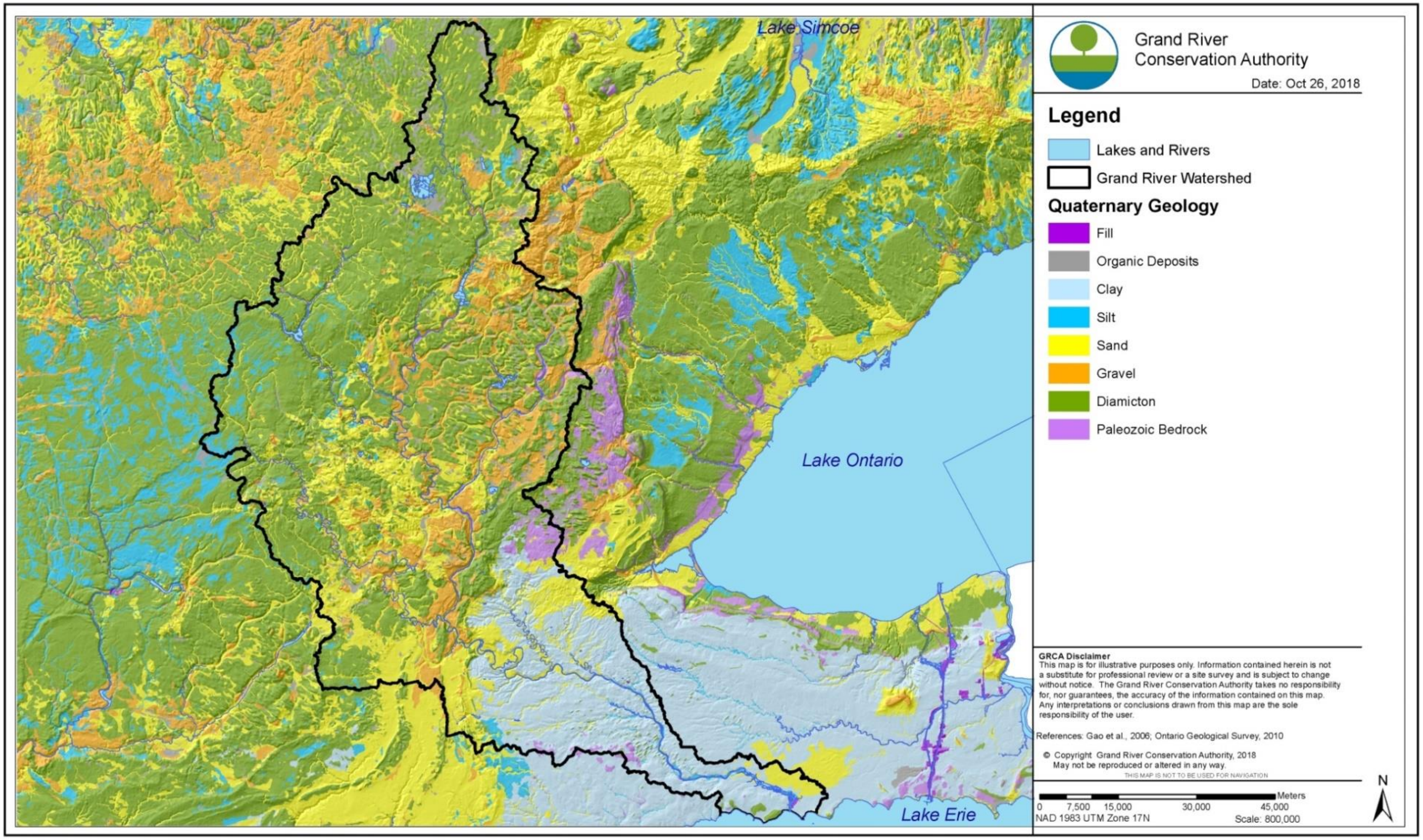
- The northern till plains, with varying relief and lower permeability;
- The central sand and gravel kame moraines and recessional moraines, with moderately high relief and higher permeability;
- The southern lacustrine clay plains, with lower permeability and low relief.

Map 4-2: **Quaternary (surficial) till deposits in the Grand River watershed** illustrates the different till sheets deposited by the lobate ice from the Great Lakes basins, whereasMap 4-3 presents the overburden thickness of the watershed.Map 4-4 illustrates the location of significant moraine complexes within the watershed.

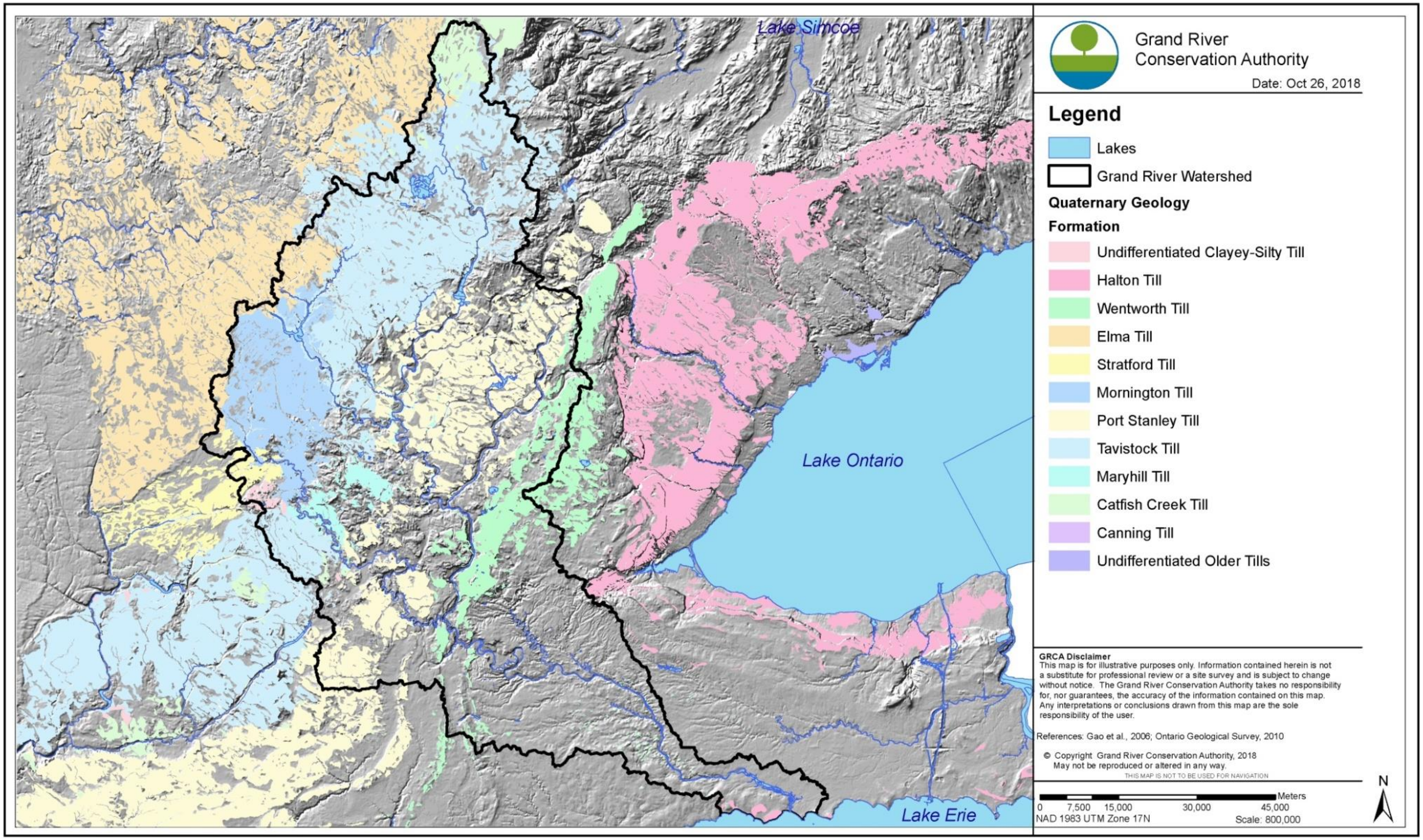
4.0 Conclusions

The Ontario Geological Survey continues their work to define the bedrock and overburden geology in southern Ontario. This work is valuable research which provides the characterization needed for hydrogeological studies in planning applications, such as municipal well development, and in support of technical studies related to the Clean Water Act, 2006.

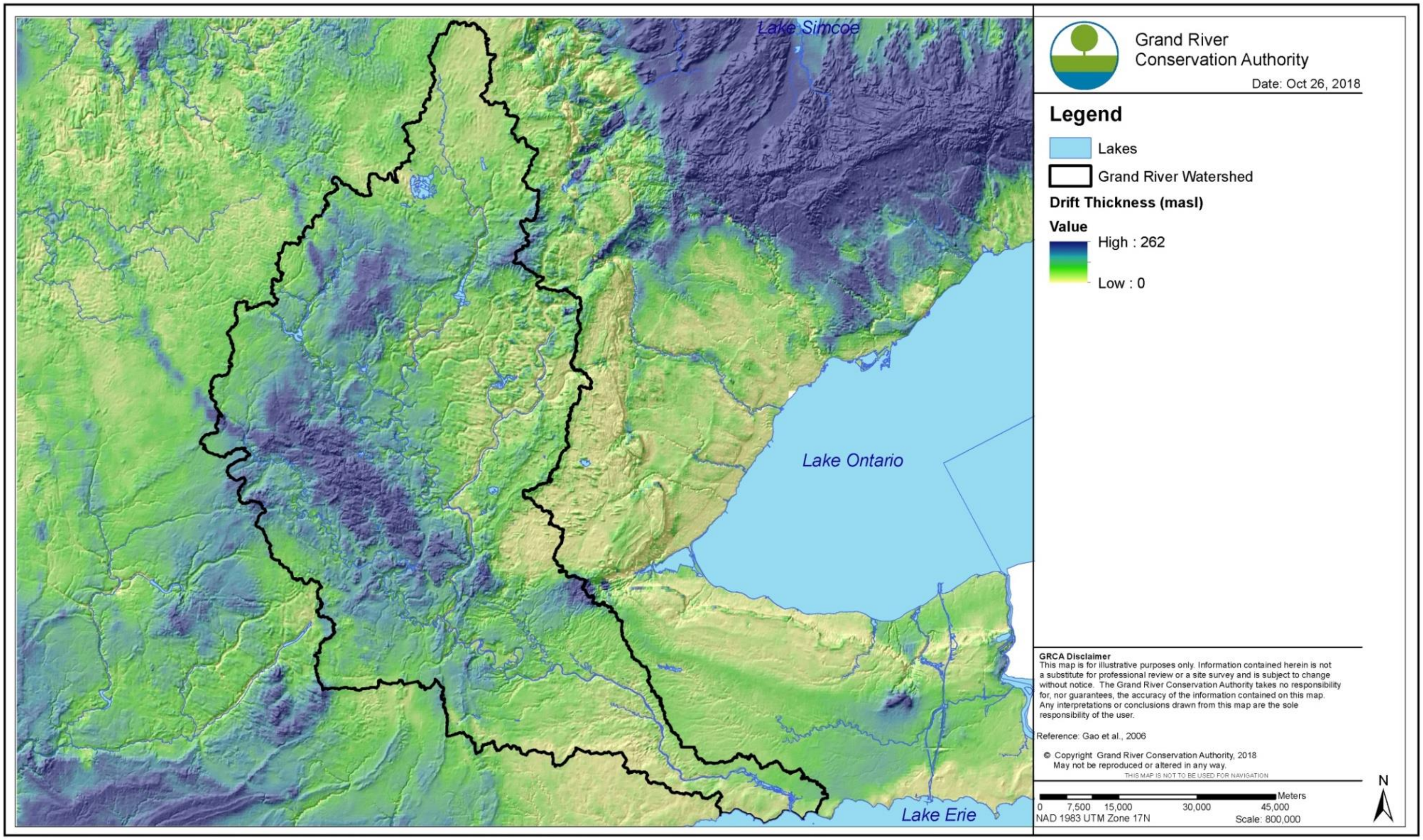
Map 4-1: Quaternary (surficial) geologic materials in the Grand River watershed.



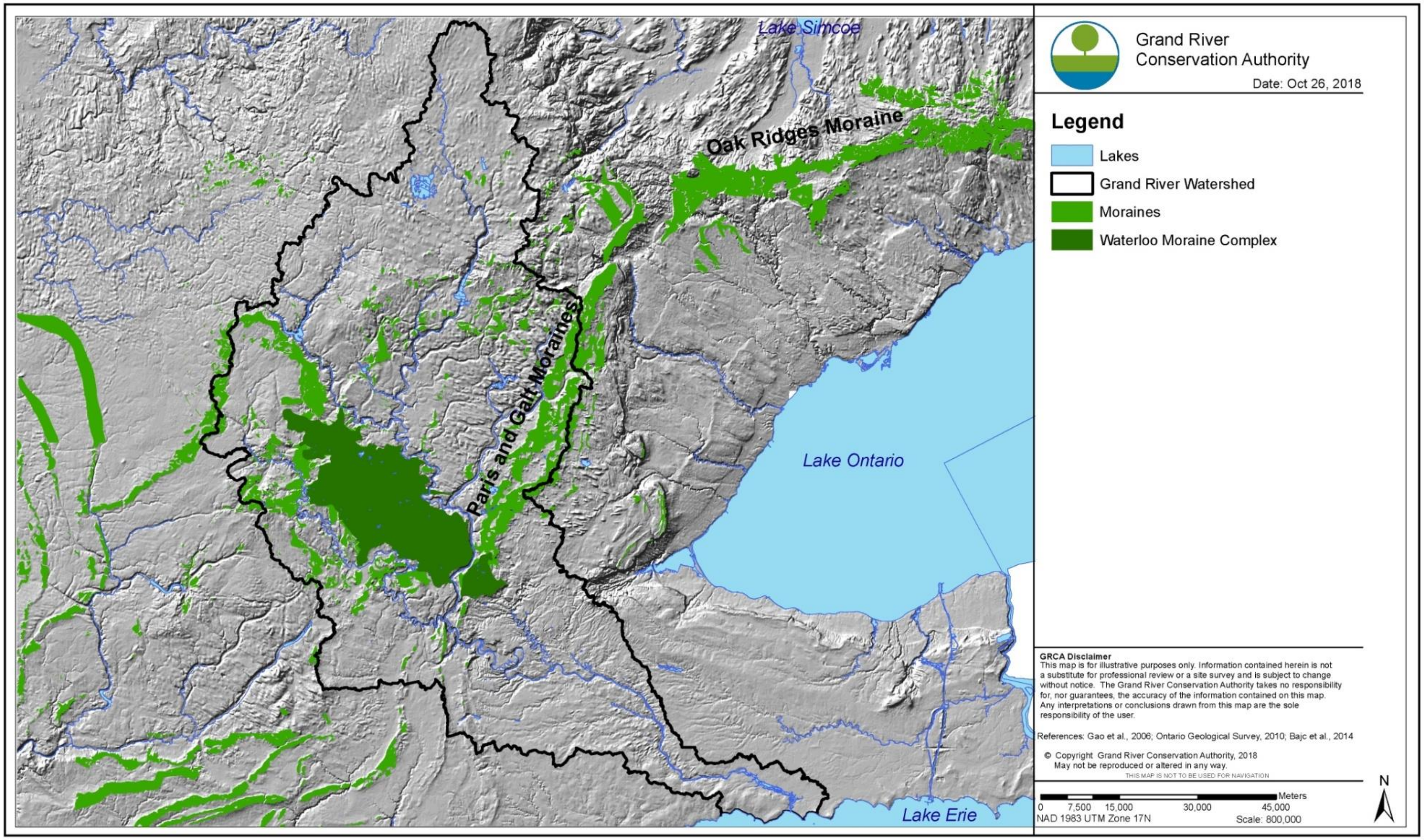
Map 4-2: Quaternary (surficial) till deposits in the Grand River watershed



Map 4-3: Overburden sediment thickness in the Grand River watershed



Map 4-4: Significant moraines within the Grand River watershed



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