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Paleozoic Geology of Manitoulin Island and Adjacent North Channel Islands, Northeastern Ontario: A Geological Guidebook

2023

Ontario

ONTARIO GEOLOGICAL SURVEY

Open File Report 6388

Paleozoic Geology of Manitoulin Island and Adjacent North Channel Islands, Northeastern Ontario: A Geological Guidebook

by

F.R. Brunton, K.E. Hahn, C. Béland Otis and P.J. Julig

2023

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PREFACE

This geological field trip guidebook was prepared initially for use with a field trip (trip number FT04) for the joint annual meeting of the Geological Association of Canada, the Mineralogical Association of Canada and the Society for Geology Applied to Mineral Deposits (GAC–MAC–SGA) in Sudbury, Ontario, May 25–27, 2023.

Sudbury is one of the world's premier nickel-copper mining districts, a significant platinum group element (PGE) producer, and one of the oldest, largest, and best-exposed meteorite impact sites on Earth. As the world's largest integrated mining technology cluster, Sudbury has a vibrant mineral exploration and mining community that includes several major producers, numerous junior exploration companies, dozens of mining supply and service companies, 3 post-secondary educational institutions and associated exploration and mining centres, and several Ontario government mining and mineral ministry offices, making Sudbury one of the best places in the world to host a multidisciplinary meeting of this type. The City of Greater Sudbury, the largest city by landmass in Ontario, lies amidst glacially shaped ridges, green boreal forests, and contains 330 lakes over 10 hectares in size and 112 lakes over 100 hectares in size. The success of more than 40 continuous years of environmental reclamation efforts has led to numerous national and international awards, including a Government of Canada *Environmental Achievement Award*, a United States *Chevron Conservation Award*, and a United Nations *Local Government Honours Award*. And, as part of Sudbury's continuing regreening efforts, the milestone 10 millionth tree was planted in July 2022.

The theme of the GAC–MAC–SGA meeting—"Discovering Ancient to Modern Earth"—reflects the location of the meeting at the intersection of the Archean Superior Province and Proterozoic Southern and Grenville provinces, and Paleozoic–Quaternary cover sequences. The hybrid conference included a technical program of oral and poster presentations in Symposia, Special Sessions and Regular Sessions covering the complete spectrum of geoscience disciplines, which were complemented by 10 field trips, 6 workshops and 1 short course.

The meeting was hosted by the Harquail School of Earth Sciences and the Mineral Exploration Research Centre (MERC) at Laurentian University.

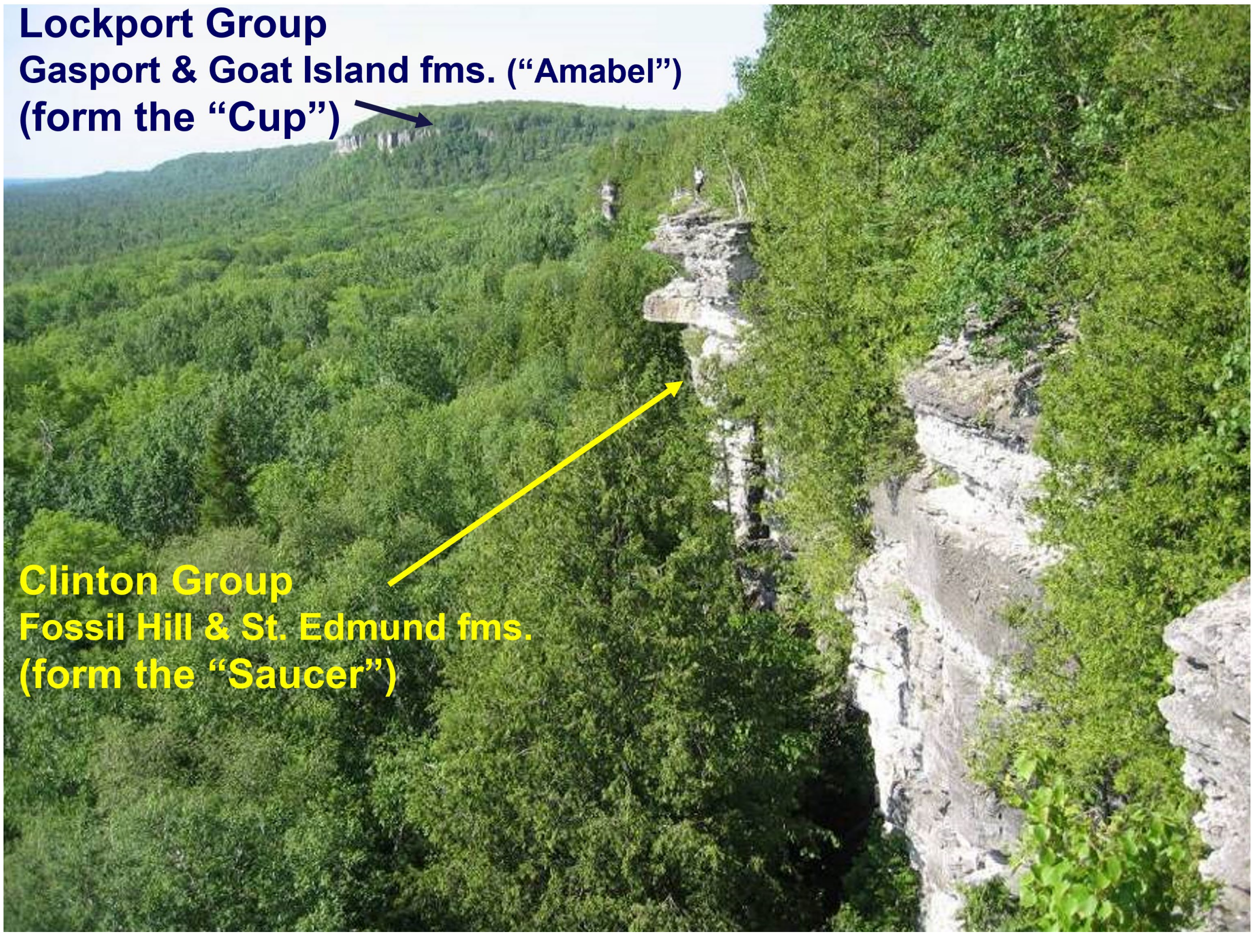
GAC
MAC
SGA
2023 SUDBURY

Abstract

Manitoulin Island is the largest freshwater island in the world. The geography of Manitoulin Island is rugged and spectacular, and marked by a series of north-facing limestone and dolostone scarps and southerly dipping cuestas, each rising above the present-day level of Lake Huron. The topography of Manitoulin Island varies from 185 m to approximately 360 m above sea level and the landscape is broken by many interior lakes within bedrock, some of which are nearly 30 m above the elevation of Lake Huron. Glacially sculpted and weathered sedimentary carbonate rocks and mixed siliciclastic rocks (sandstones and shales) of Late Ordovician through early Silurian age form this majestic and somewhat unique thin-drift and alvar-dominated landscape. The land is largely only suitable for cattle, sheep or Alpaca farming. The Paleozoic bedrock is covered by a thin veneer of Quaternary and Holocene sediments.

This two-day field trip explores the geology of Manitoulin Island. The field trip includes stops examining Late Ordovician and early Silurian sedimentary strata from more freshly excavated quarry and roadside outcrops on Birch, Great La Cloche and Goat islands in the North Channel region of Lake Huron, and at classic roadside outcrops along Highway 6 from Little Current to Tehkummah on the eastern side of Manitoulin Island. Day 1 focusses on Upper Ordovician strata and ends at Sheguiandah where a very interesting rocky shoreline exposure can be examined, and participants may join a guided tour of one of the oldest Indigenous quarry sites in Canada. Day 2 visits Upper Ordovician strata and include select outcrops of classic lower Silurian strata on the eastern side of Manitoulin Island.

Manitoulin Island – Niagara Escarpment – Cup & Saucer Trail



Frontispiece. Southerly facing view of early Silurian carbonates that form the Cup and Saucer Trail, Manitoulin Island, Ontario. This geologic feature is the northern extension of the Niagara Escarpment in southern Ontario. Although of scientific and natural interest providing stunning scenery and views, this trail is not included as a stop in this guidebook. Person, for scale, standing on high point of trail (upper centre of photo). Abbreviation: fms, formations. Photo provided by F.R. Brunton.

Paleozoic Geology of Manitoulin Island and Adjacent North Channel Islands, Northeastern Ontario: A Geological Guidebook

F.R. Brunton[1], K.E. Hahn[1], C. Béland Otis[1] and P.J. Julig[2]

Ontario Geological Survey
Open File Report 6388
2023

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Introduction

Manitoulin Island is the largest freshwater island in the world. The geography of Manitoulin Island is rugged and spectacular, and marked by a series of north-facing limestone and dolostone scarps and southerly dipping cuestas, each rising above the present-day level of Lake Huron (Figures 1 and 2). The topography of Manitoulin Island varies from 185 m to approximately 360 m above sea level and the landscape is broken by many interior lakes within bedrock, some of which are nearly 30 m above the elevation of Lake Huron (*see* Figure 2). Glacially sculpted and weathered sedimentary carbonate rocks and mixed siliciclastic rocks (sandstones and shales) of Late Ordovician through Early Silurian age form this majestic and somewhat unusual combination of thin-drift and alvar-dominated landscape. The land is largely only suitable for cattle, sheep or Alpaca farming. The Paleozoic bedrock is covered by a thin veneer of Quaternary and Holocene sediments.

This two-day field trip includes stops examining Late Ordovician and Early Silurian sedimentary strata from more freshly excavated quarry and roadside outcrops on Birch, Great La Cloche and Goat islands in the North Channel region of Lake Huron, and at classic roadside outcrops along Highway 6 from Little Current to Tehkummah on the eastern side of Manitoulin Island. Day 1 focusses on Upper Ordovician strata and ends at Sheguiandah where a very interesting rocky shoreline exposure can be examined, and participants may join a guided tour of one of the oldest Indigenous quarry sites in Canada. Day 2 visits Upper Ordovician strata and include select outcrops of classic lower Silurian strata on the eastern side of Manitoulin Island. Although brief descriptions of each formation are outlined in the field guide, it is not possible to visit more than a few of the better exposed dolostone and limestone rock units because of both limited road access and the nature of bedrock exposures across this large island. Manitoulin Island is also famous for its fossils (e.g., Fossil Hill Formation and, more recently, the important eurypterid finds in late Ordovician Georgian Bay Formation; *see* discussions by Foerste (1912, 1916, 1924); Caley (1934, 1936); Williams (1913a, 1913b, 1919, 1937); Bolton (1953, 1957, 1968); and Stott et al. (2005)).

The Ontario Geological Survey (OGS) has been compiling Paleozoic bedrock information across southern Ontario over the past 7 years to produce an updated lithostratigraphic chart (Brunton et al. 2017; Carter et al. 2019; Brunton et al. 2021), lexicon of Paleozoic formations, and a seamless ArcGIS® web-based map. The acquisition of more than 40 diamond-drill cores through Silurian strata and examination of numerous other deep diamond-drill cores between 2004 to present, from west-central Manitoulin Island to Tobermory and extending southeastward to Niagara Falls, has enabled a more detailed assessment of the stratigraphic architecture of some of the key lower Silurian and Upper Ordovician strata (Brunton and Brintnell 2020).

Many field guidebooks, theses, geological reports and maps have been published over the past 110 years and summarize the various aspects of the Paleozoic geology of Manitoulin and adjacent islands (e.g., Foerste 1912, 1913a, 1913b, 1913c, 1916, 1924; Williams 1919, 1937; Caley 1934, 1936; Bolton 1953, 1954, 1957, 1968; Liberty 1966, 1968, 1972a-f; Liberty and Bolton 1971; Copper 1978; Barnes, Telford and Tarrant 1978; Barnes and Bolton 1988; Telford, Johnson and Verma 1981; Fay 1983; Copper and Fay 1989; Copper and Long 1993; Copper, Jin and Armstrong 1995; Coniglio, Karrow and Russell 2006; Brunton, Turner and Armstrong 2009). This field trip guidebook builds upon those studies and the pioneering work of geologists A. Murray, R. Bell, A.F. Foerste, D.A. Williams, J.F. Caley, T.E. Bolton, B.A. Liberty, B.V. Sanford and P. Copper and highlights some of their long-lasting contributions to our understanding of the Paleozoic geology of southern Ontario and Manitoulin Island.

Paleontological and geological research in the Manitoulin District has a long and distinguished history. In fact, arguably some of the first fossils to be formally described in Canada were from Manitoulin and surrounding islands (Bigsby 1821, 1824; Bronn 1824; Stokes 1824). A brief overview of the pioneering work of Foerste (1912, 1913a, 1913b, 1913c, 1924), who first attempted to provide a stratigraphic framework for the Ordovician succession on eastern Manitoulin Island, and Williams (1913a, 1913b, 1919, 1937) who did the same for the Silurian succession (*see* Copper, Jin and Armstrong 1995). The first geologic map of eastern Manitoulin was by Bell (1898), and arguably one of the best geologic maps of the entire island was produced by Williams and Caley (*see* Williams 1937). More recent maps have been produced by Liberty (1972a-f) and Johnson and Telford (1985a-f).

The paleogeographic position of Laurentia during the Late Ordovician through the Early Silurian reveals a subtropical environment, with rocks of the study area being deposited south of the paleoequator (Witzke 1987; Johnson 1987; Copper and Brunton 1991). The Late Ordovician to Early Silurian sedimentary succession in the vicinity of Manitoulin Island and the northern Bruce Peninsula reveals a few interesting patterns, including the existence of less completely developed cycles and arguably more erosional phases, yet more richly fossiliferous successions than the equivalent stratal packages to the south (e.g., Bobcaygeon and Fossil Hill successions). Both Ordovician and Silurian stratal packages display a nearshore to offshore facies mosaic from north to south, with the La Cloche Mountains representing a paleoshoreline and landmass within the Laurentia epicontinental seas during deposition of the Paleozoic strata that form Manitoulin Island.

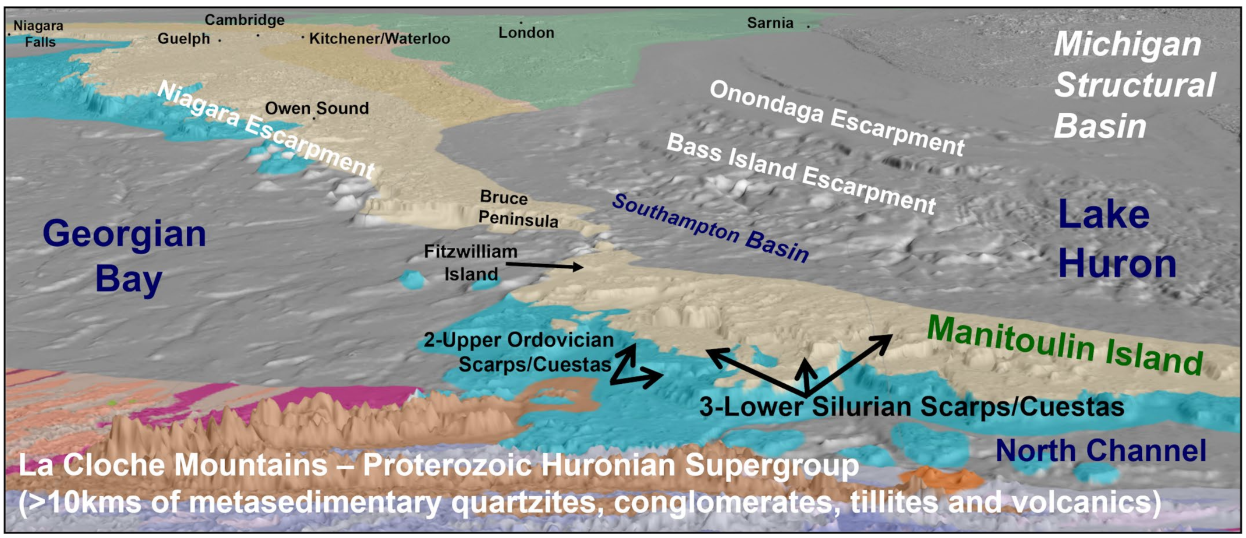

Figure 1. Oblique aerial view, looking south, from north of Manitoulin and adjacent islands and parts of southwestern Ontario and Georgian Bay and Lake Huron, depicting significant bedrock landforms (scarp faces and cuestas). It was generated by integrating a provincial digital elevation model (DEM) and Great Lakes bathymetry (NOAA 2023). Bedrock geology is *modified from* Johnson et al. (1992). Pinks and browns represent Proterozoic Huronian Supergroup metasedimentary strata; blue, Upper Ordovician strata; tan, Silurian strata; green, Devonian strata; grey, area not formally mapped by OGS.

SAFETY

The field trip is 2 days. Day 1 includes stops along Highway 6 on Birch, Great La Cloche, Goat and Manitoulin islands with a visit to the Fisher Wavy Inc. Quarry on Great La Cloche Island. This visit requires hard hats, high-visibility vests, safety glasses (provided), proper footwear and safe collecting practices. Field hazards include steep rock faces, slopes, loose rock, standing water, insects, poison ivy, and proximity to some heavy equipment. Sunscreen, hats and appropriate clothing for spring weather conditions are recommended. Day 2 visits Manitoulin Island and includes select stops at roadside outcrops of Ordovician and Silurian rocks along Highway 6. The shoulder of the highway is relatively narrow and consists of gravel, so care is needed when approaching the outcrops and crossing ditches.

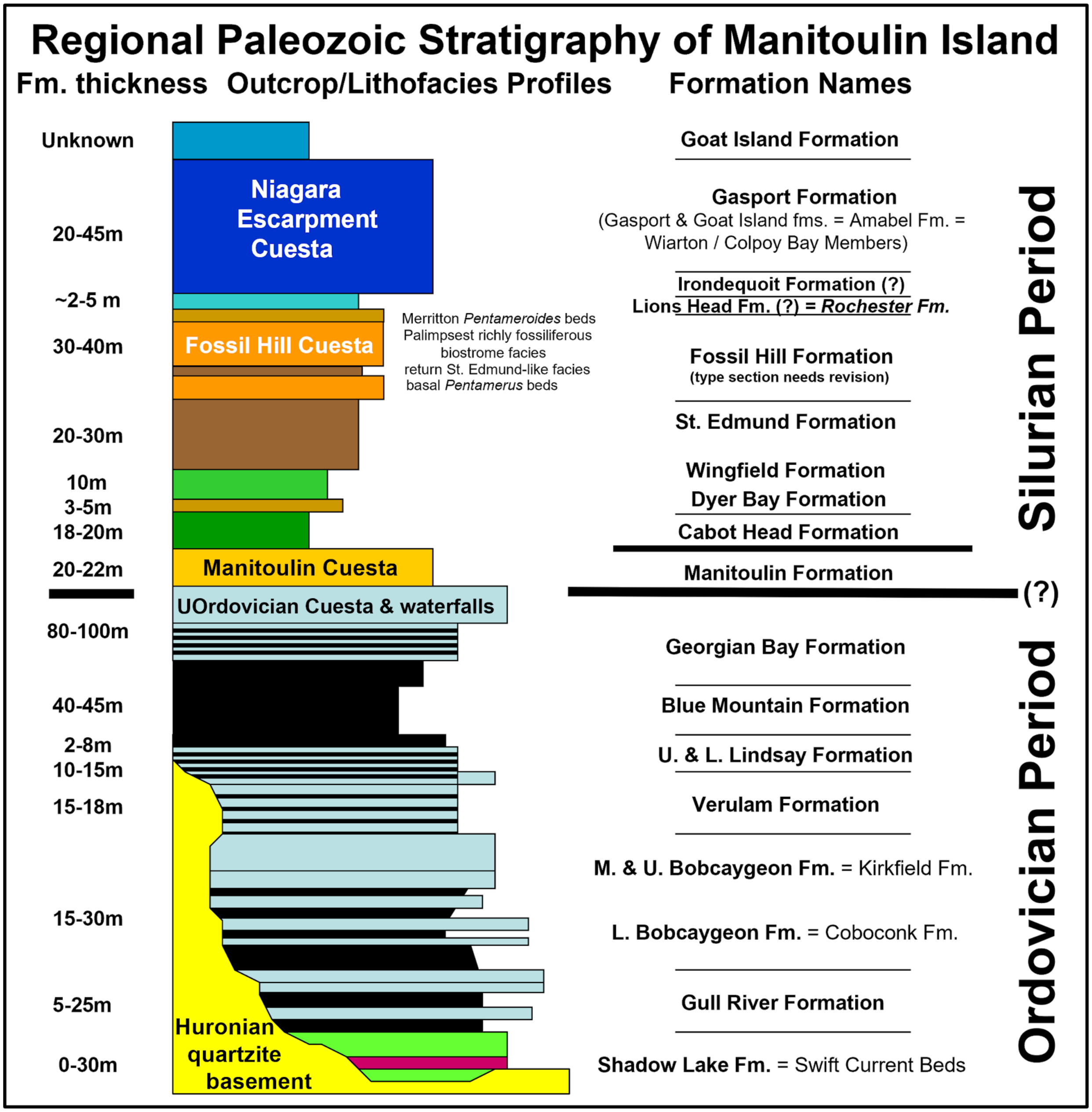

Figure 2. Upper Ordovician and lower Silurian stratigraphy of Manitoulin Island (*modified from* Brunton, Turner and Armstrong 2009). The basement rocks comprise Paleoproterozoic Lorrain Formation quartzites beneath the Shadow Lake Formation on Birch and Great La Cloche islands and younger Paleoproterozoic Bar River Formation quartzites at Sheguiandah, where the Lindsay (Cobourg) Formation rests unconformably on the Paleoproterozoic metasedimentary rocks. The position of the Ordovician–Silurian boundary is in question. The greenish-blue units representing Ordovician strata are predominantly limestones with some dolostone interbeds. The yellow to brown and green units representing Silurian strata are predominantly dolostones and mixed calcareous and terrigenous shales and shaly dolostones. Some of the units listed are not in bold because their presence on Manitoulin Island requires confirmation (lack of decent exposures and drill core preclude proof at present). No Guelph Formation or Eramosa Formation lithofacies have been observed on Manitoulin Island. Chert-bearing, thinly bedded light tan dolostones that sit above Gasport Formation reef mound lithofacies and encrinites belong to the overlying Goat Island Formation of the Lockport Group. Formation thicknesses on Manitoulin Island are approximate and vary across Manitoulin Island and islands within the North Channel of Lake Huron. Abbreviations: Fm., Formation; L., lower; M., middle; U., upper.

Geological Setting

During deposition of the Upper Ordovician and lower Silurian strata on Manitoulin Island, the underlying Proterozoic metasedimentary rocks (erosional landforms comprising the La Cloche Mountains) represented an irregular or undulatory landmass and bedrock surface with substantial paleorelief (*see* Figures 1 and 2). The various Paleozoic formational rank units generally display more restricted marine and shoreline facies mosaics in the north (proximal to the La Cloche Mountains and North Channel bedrock ridges) changing to more open marine facies mosaics to the south, forming a series of ramps that now dip gently to the south and southwest (*see* references in Copper 1978; Fay and Copper 1982, Copper and Fay 1989; Copper and Brunton 1991; Copper, Jin and Armstrong 1995; Coniglio, Karrow and Russell 2006; Brunton, Turner and Armstrong 2009).

The Late Ordovician through Early Silurian sedimentary succession exposed on Manitoulin and adjacent islands of the North Channel and in Lake Huron were deposited within subtropical inland seas on an ancient precursor continent to North America, called Laurentia. The paleoequator is estimated to have been located approximately 15 to 25° to the north during Late Ordovician deposition and slightly farther south during Early Silurian deposition (*see* Witzke 1987; Scotese and McKerrow 1990; Cocks and Torsvik 2002, 2011; Wicander and Monroe 2004). The largely carbonate-dominated succession and faunal diversity within the various Ordovician and Silurian stratigraphic units suggest subtropical depositional conditions with an arid to semiarid climate.

Differential physical and chemical erosion of the Devonian and Upper Silurian strata that may have been deposited above the current Paleozoic bedrock units in the region, following the creation and breakup of supercontinent Pangaea, and the most recent extensive sculpting by continental-scale glacial advances and retreats over the past few million years, has resulted in the majestic landscape of Manitoulin Island and the North Channel Islands (Figure 3). Many of the physically and karstic erosional bedrock and glacial sediment and sculpted landforms across Manitoulin Island are bedrock controlled. Manitoulin Island also represents one of the most significant alvar environments in the Great Lakes region and North America. The retreat of the continental-scale ice sheets, and subsequent episodic rises and falls (phases) of the precursor Great Lakes water levels, enabled ancestral peoples to quarry Bar River Formation quartzite stone tools at Mystic Ridge at Sheguiandah (*see* references and papers in Julig 2002; *see also* Stop 5C).

ORDOVICIAN STRATIGRAPHIC UNITS

The Ordovician strata in Ontario have traditionally been subdivided into Lower, Middle and Upper series (Barnes, Norford and Skevington 1981; Johnson et al. 1992; Sanford 1993a). In general, carbonate-dominated strata exposed in south-central Ontario were assigned to the Middle Ordovician; the calcareous and terrigenous shale-dominated younger rock units exposed from Georgian Bay to Toronto and west to the Niagara Escarpment were assigned to the Upper Ordovician; and the Lower Ordovician strata occur in southeastern Ontario (Johnson et al. 1992; Armstrong and Carter 2006, 2010; Armstrong and Dodge 2007). Recent changes to the Ordovician time scale (e.g., Webby et al. 2004; Gradstein et al. 2012; Bergström, Finney et al.2006) has resulted in the repositioning of the Middle–Upper Ordovician boundary to a lower stratigraphic position such that much of the strata traditionally referred to as Middle Ordovician in Ontario are now considered to be Upper Ordovician (Bergström, Kleffner et al.2006). Much of the descriptive information provided below is derived from the following sources: Armstrong and Carter (2006, 2010), Armstrong and Dodge (2007), Johnson et al. (1992), Copper, Jin and Armstrong (1995) and references cited therein.

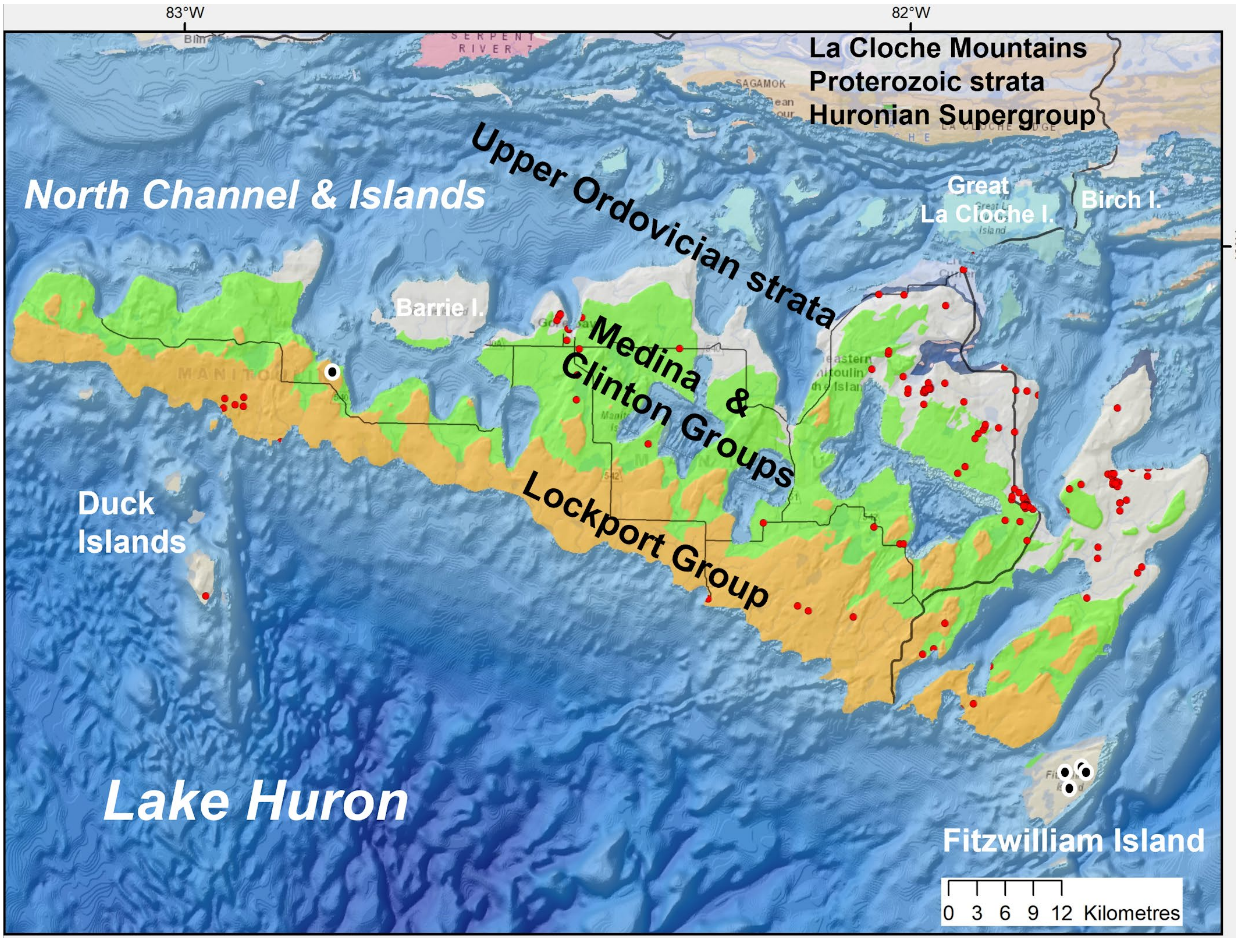

Figure 1. Paleozoic bedrock geology and topography for Manitoulin and adjacent islands and the Precambrian mainland area to the north (Manitoulin Island Paleozoic geology *from* Brunton and Dodge 2008). Locations of petroleum wells are shown as red dots (used to infer regional variations in formational thicknesses shown in Figure 1). Well locations for geological exploration for industrial minerals on Manitoulin and Fitzwilliam islands are shown as black dots (the well in northwestern Manitoulin Island penetrates the Lockport Group (yellow) to the top of Cabot Head Formation; wells on Fitzwilliam Island penetrate the Lockport Group to the top of the Fossil Hill Formation). The north shore of the North Channel is Proterozoic Huronian Supergroup strata (shown in shades of pink). Many of the North Channel Islands are covered by Upper Ordovician Black River Group and Trenton Group strata (light blue and grey). Manitoulin Island is covered primarily by Silurian Medina and Clinton groups strata (green) and Lockport Group strata (yellow). Note how the combination of basement structures, Phanerozoic bedrock geology and Quaternary glacial history have strongly influenced the bedrock topography and geography of Manitoulin Island and the lake bottom. The Duck Islands and Fitzwilliam Island have not been formally mapped by the OGS (grey). The Duck Islands comprise the upper Lockport Group Guelph Formation and Fitzwilliam Island bedrock units range from Clinton Group strata in the northeast to Lockport Group strata (Eramosa and Goat Island formations) in the southwest.

The Ordovician stratigraphic units mentioned below are exposed to varying degrees on the islands of the North Channel and northern Manitoulin Island, and from base to top, include Black River Group (Shadow Lake, Gull River and Coboconk formations), Trenton Group (Kirkfield, Sherman Fall and Cobourg formations) and Georgian Bay and Blue Mountain formations.

Black River and Trenton Groups

The Black River and Trenton groups comprise much of the Upper Ordovician carbonates in southern Ontario. These rocks were deposited during a regional marine transgression and represent an overall deepening upward sequence, from basal siliciclastic rocks to supratidal and tidal flat carbonates to lagoonal and/or shoal, and finally to deep shelf carbonates (Kobluk and Brookfield 1982). They were deposited on a ramp northwest of the Taconic foreland basin. In Ontario, except in the Ottawa basin, the Black River Group unconformably overlies Upper Cambrian siliciclastic and carbonate rocks or lie directly on Precambrian basement rocks of the Canadian Shield. Black River and Trenton group rocks are widely distributed in eastern North America. Although subdivided differently, equivalent rocks referred to as Trenton and Black River occur southward into West Virginia northward into Michigan (Shaver 1985; Patchen, Avary and Erwin 1985). In the south-central Ontario Ordovician outcrop belt, these strata have been collectively referred to as the Simcoe Group (Liberty 1969; Johnson et al. 1992; Armstrong and Carter 2006; Armstrong and Dodge 2007) and, in eastern Ontario they have been referred to as the Ottawa Group (e.g., Wilson 1946; Williams 1991). Terminology for the Upper Ordovician rock units throughout southern Ontario is confusing because of the multitude of stratigraphic assignments; many academic studies use terminology from New York State, whereas OGS mappers have primarily used the terminology of Liberty (1969). Additionally, rock units with the same stratigraphic name may have different lithologic and/or faunal characteristics and subdivisions depending on their geographic location in Ontario. The OGS is currently updating the Paleozoic legend at formational rank for southern Ontario (Brunton et al. 2021). The following formation terminology is based on what is currently in use by the OGS.

The Black River Group comprises the Shadow Lake, Gull River and Coboconk formations, in ascending order (Sanford 1993a). This nomenclature is currently used by the OGS for the subsurface (Brunton et al. 2017). Furthermore, in eastern Ontario, the Gull River Formation is further subdivided into the lower dolomitic beds of the Pamelia Formation and the upper limestone and shale of the Lowville Formation (Salad Hersi and Dix 1999; Béland Otis 2017, 2018, 2019, 2022). The Black River Group ranges from only 10 m to almost 150 m thick, which seems to be related to the presence of basement highs (Bailey Geological Services Ltd. and Cochrane 1984; Trevail, Carter and McFarland 2004). The Trenton Group ranges to more than 170 m in thickness and comprises the Kirkfield, Sherman Fall and Cobourg formations, in ascending order. Again, this OGS terminology is used for the subsurface. In contrast, OGS outcrop studies of these rocks use a different nomenclature (e.g., Simcoe Group, Bobcaygeon Formation for the Black River Group) and different criteria for definition of formations and identification of formational contacts (Melchin et al. 1994; Sanford 1993a; Copper, Jin and Armstrong 1995). In the case of the Trenton Group, the current OGS outcrop nomenclature includes the terms Bobcaygeon, Verulam and Lindsay formations (Brunton et al. 2017, 2021).

Black River Group

SHADOW LAKE FORMATION

The Shadow Lake Formation is the basal unit of the Black River Group (referred to as basal beds; Foerste 1912; Sanford 1978, 1993a). In central and southwestern Ontario, this formation is the oldest Ordovician unit (Caley and Liberty 1950; Coniglio, Melchin and Brookfield 1990; Johnson et al. 1992; Hamblin 1998). It lies unconformably either on the Precambrian basement or on Cambrian strata. This unit is typically devoid of biostratigraphic constraints and in this context could range from Cambrian to upper Ordovician, but, in the Ottawa region, it has yielded a Black River Group conodont fauna (Williams and Telford 1986). However, the Shadow Lake Formation is generally interpreted to represent the onset of Upper Ordovician sedimentation after a prolonged period of exposure and erosion of the underlying Cambrian and older Ordovician strata (Hamblin 1998). The type section for the Shadow Lake Formation is a roadside outcrop on Highway 35, north of the village of Coboconk (Okulitch 1939; Liberty 1969). The Shadow Lake Formation is generally only a few metres thick (Stop 1), but may be up to 15 m thick (Sanford 1978; Johnson et al. 1992). Through much of southern Ontario, the Shadow Lake Formation represents eroded siliciclastic material that onlaps the Precambrian bedrock surface, resulting in a variable age regionally across southern Ontario and the Manitoulin and North Channel Islands (*see* Stop 2). In eastern Ontario, where Ordovician sedimentary strata underlie the Black River Group, the Shadow Lake Formation has been included as part of the Pamelia Formation (e.g., McFarlane 1992; Brown 1997; Salad Hersi and Dix 1999).

The Shadow Lake Formation is characterized by poorly sorted, red and green sandy shales, argillaceous and arkose sandstones, minor sandy argillaceous dolostones and rare basal arkosic conglomerates (Okulitch 1939; Winder et al. 1975; Williams et al. 1992; Hamblin 1998). Sand grains, found in all these rock types, are commonly frosted, suggesting, but not proving, an eolian input to the depositional environment. Subsurface work has revealed 3 recognizable facies (Trevail 1990). These lithofacies are green glauconitic sandstone with abundant frosted sand grains (informally called the "golf ball sands"); interbedded laminated to bioturbated siltstone and sandstone; and fossiliferous (skeletal debris) sandstone.

The upper contact of the Shadow Lake Formation is generally gradational with the overlying Gull River Formation and in the outcrop belt has been placed at different levels depending on which criterion is used (*see* discussions in Melchin et al. 1994; Copper, Jin and Armstrong 1995). Generally, there is a rapid upward lithologic transition through the Shadow Lake Formation into the Gull River Formation from basal, coarse sand grade, arkosic sandstone, to poorly sorted, very argillaceous sandstone, to sandy shale, to argillaceous and sandy dolostone to finely crystalline limestone. These rock types are also commonly interbedded and green or red colouration can extend upward into the carbonate-dominated strata of the lower Gull River Formation. The contact can appear to be sharp where most lithologic characteristics (i.e., colour, argillaceous content and carbonate content) change together. Near Manitoulin Island and Great La Cloche Island in the North Channel of Lake Huron, strata may possess a restricted marine bivalve-lingulid brachiopod assemblage and very rare bryozoans, strophomenids and small rhynchonellids (Copper 1978; Copper, Jin and Armstrong 1995). A sparse Blackriveran conodont fauna was reported in the Shadow Lake Formation of south-central Ontario (Winder et al. 1975).

GULL RIVER FORMATION

The Gull River Formation forms part of the Black River Group and has a varied contact character with the overlying Coboconk Formation (equivalent to (≍) lower Bobcaygeon Formation; Brunton et al. 2021). The contact with the underlying Shadow Lake Formation is also difficult to discern because of its varied character across southern Ontario, Manitoulin Island and eastern Ontario (Armstrong and Carter 2006, 2010; Armstrong and Dodge 2007; Salad Hersi and Dix 1999). Foerste (1912) originally called these strata the "Swift Current Beds" in the vicinity of Manitoulin Island (e.g., Birch Island area; Copper 1978; Copper, Jin and Armstrong 1995). Okulitch (1939) subsequently renamed this rock unit the Gull River Formation. It has been subdivided into either 2 (lower and upper), or 3 (lower, middle, upper) informal members depending on location; and tracing the member designations across Ontario is problematic (*see* Brunton et al. 2021 for discussion). The type locality for the Gull River Formation is a series of outcrops in the vicinity of the village of Coboconk (Liberty 1969). The Uhthoff Quarry in Orillia has a well-exposed section of the Gull River Formation and its upper contact with the lower Bobcaygeon Formation. The Gull River Formation is up to 25 m thick in the Lake Simcoe area (Liberty 1969), 135 m in the subsurface of southwestern Ontario (Johnson et al. 1992), and less than 40 m thick on Manitoulin Island (Armstrong and Carter 2006; Armstrong and Dodge 2007). The outcrop exposures along Highway 6 on Great La Cloche Island expose only a few metres of this formation.

The Gull River Formation comprises limestone with lesser amounts of dolostone, shale and argillaceous sandstone. The formation is characterized by very finely crystalline (lithographic), light grey to dark brown limestones. The abundance of lime mud is a key distinguishing characteristic of the Gull River Formation when compared with the coarser crystalline and skeletal limestones of the overlying Coboconk Formation. Thin shale beds and partings are also more common in the Gull River Formation, and more so in the subsurface. In the North Channel area of Lake Huron, the Gull River Formation can be fossiliferous on a local scale. Tetradiid corals, *Foerstephyllum*, small, calcified sponges of *Stromatocerium* and *Lophiostroma*, all largely recrystallized and poorly preserved, occur with more abundant smooth ostracods and rare small strophomenids. A more diverse neurodontid conodont fauna than the underlying Shadow Lake Formation (basal beds) suggests correlation with the type sections of the Lowville and lower Chaumont formations of New York State (*see* discussions in Barnes, Telford and Tarrant 1978; Winder et al. 1975; Williams et al. 1992).

In general, descriptions of the lower member of the Gull River Formation are relatively consistent through Ontario. It is the most lithologically varied rock unit, containing light to dark grey to brown, finely crystalline dolostones (dolosiltite); light grey to dark brown, very finely crystalline, nonfossiliferous to moderately fossiliferous limestones (mudstone to packstone); green argillaceous sandy dolostones; and minor green-grey argillaceous dolomitic sandstones and green to dark brown shale. Vugs filled with pink calcite, thin quartz sandstone interbeds, evaporite casts and intraclastic beds are all common in the lower member. Bedding style ranges from tabular to planar to slightly irregular and pseudonodular. In the Kingston area, the green dolomudstones and shales form the middle member, whereas, in the Lake Simcoe area, the middle member is described as sparsely fossiliferous lime mudstones that are commonly laminated and intraclastic.

Descriptions of the upper Gull River Formation are more varied geographically. The upper member of the Gull River Formation consists of light grey to dark brown, thin- to very thick-bedded, bioturbated, fossiliferous wackestone. Grey lime mudstone interbeds are locally common toward the base of this unit. Toward the top of this member, coarser crystalline and fossiliferous, peloidal and skeletal packstone to grainstone beds are locally common.

COBOCONK FORMATION (≍ LOWER BOBCAYGEON FORMATION ≍ CLOCHE ISLAND BEDS)

The Coboconk Formation is the uppermost unit of the Black River Group. There has been considerable confusion in the stratigraphic nomenclature about this unit (Foerste 1912; Winder 1961; Liberty 1969; Winder and Sanford 1972; Sanford 1993a). The Coboconk Formation is a term currently used by the OGS for the surface bedrock exposures in south-central and southeastern Ontario (Brunton and Dodge 2008) and for subsurface of south-central and southwestern Ontario (Brunton et al. 2017). Melchin et al. (1994) determined that the equivalent of the Coboconk Formation in the Lake Simcoe area outcrop belt is the lower member of the Bobcaygeon Formation (Liberty 1969). Liberty (1969) created the Bobcaygeon Formation in part to avoid biostratigraphically based units such as the Coboconk Formation (Sanford 1993a). It is less than 5 m thick in the vicinity of Manitoulin Island and attains a maximum thickness of approximately 28 m in southern Ontario (Copper, Jin and Armstrong 1995; Armstrong and Carter 2006).

The Coboconk Formation comprises light grey-tan to brown-grey, medium- to very thick-bedded, fine- to medium-crystalline, horizontally bioturbated to current-laminated, skeletal and intraclastic limestones, mostly pelloidal wackestones, packstones and grainstones. Horizontal bioturbation results in a pseudonodular texture through most of the unit. Skeletal and intraclastic grainstone beds with low- to high-angle cross-stratification are locally abundant. Grains are commonly algal coated and well-sorted grainstones are locally abundant. Fossils are mainly echinoderm debris, as well as large tabulate corals and stromatoporoids, rugose corals, brachiopods, bryozoans, gastropods, bivalves, nautiloids and trilobites. The fauna and sedimentary features indicate deposition in shallow offshore shoals (Copper 1978; Melchin et al. 1994; Copper, Jin and Armstrong 1995). For the North Channel Islands (Stop 2), north of Manitoulin, Foerste (1912) determined that the unit had a typical Blackriveran fauna comprising, calcified sponges *Stromatocerium* and *Cystostroma*, the tabulate coral *Foerstephyllum*, *Receptaculites*, *Maclurites* and a series of nautiloids including *Gonioceras*, and a variety of trilobites of varying size and articulation. This fauna appears approximately 7 m above the base of the formation.

Elsewhere in Ontario, the rocks that occupy the same stratigraphic position of the Coboconk Formation (i.e., between the Gull River and Bobcaygeon formations) have been termed “Chaumont Formation” (Ottawa and Kingston areas), “unit D” of the Gull River Formation (Kingston area), “Moore Hill Beds” of the Bobcaygeon Formation (Lake Simcoe area) (*see* discussions in Williams et al. 1992; Salad Hersi and Dix 1999; McFarlane 1992; Brown 1997; Armstrong and Carter 2010). These units all share some lithologic and faunal descriptions with one another and re-evaluating the utility of these terms is ongoing (Brunton et al. 2021).

Trenton Group

KIRKFIELD FORMATION (≍ UPPER AND MIDDLE BOBCAYGEON FORMATION)

The Kirkfield Formation is the lowest unit of the Trenton Group and corresponds to the upper and middle members of the Bobcaygeon Formation (Liberty 1969) in the outcrop belt in the Lake Simcoe through Bobcaygeon areas of Carden plain (Melchin et al. 1994). The formation has a complex nomenclatural history and is poorly defined (Winder 1961; Liberty 1969; Johnson et al. 1992; Armstrong and Carter 2006, 2010; Armstrong and Dodge 2007).

The Kirkfield Formation comprises thinly to thickly bedded, fossiliferous limestones with shaly partings and locally significant thin shale interbeds. In the outcrop belt east of Lake Simcoe, the Kirkfield Formation can be subdivided into 2 informal units, lower and upper, that correspond to the middle and upper members of the Bobcaygeon Formation, respectively (Liberty 1969; Melchin et al. 1994).

The lower Kirkfield Formation is characterized by thin- to medium-tabular-bedded, pelloidal to skeletal, very fine to finely crystalline limestones with green shale interbeds and partings. These limestone beds typically have flat bases with skeletal and pelloidal lags, horizontal to low-angle cross-lamination, and rippled to undulatory tops, and have been interpreted as storm beds (Melchin et al. 1994).

The upper Kirkfield Formation in the outcrop belt (≍ upper Bobcaygeon Formation) includes similar storm beds that are mixed with a variety of other types of limestone. Shale content is limited to thin shaly partings. Limestones in the upper Kirkfield Formation include fine- to medium-crystalline, dark grey to light brown, thinly bedded to medium-bedded, irregular to tabular bedded, horizontally bioturbated to horizontally or low-angle cross-laminated, fossiliferous limestones, ranging from skeletal wackestones to packstones and grainstones. Fossils in the Kirkfield Formation include echinoderms (e.g., crinoids), trilobites, bryozoans and brachiopods.

Throughout southern Ontario, the Kirkfield Formation attains maximum thickness of 55.4 m in the subsurface and thins to less than 15 m on Manitoulin Island (Armstrong and Carter 2006, 2010). The contact between the lower and upper Kirkfield Formation is gradational. Melchin et al. (1994) report that the lower Kirkfield Formation (≍ middle Bobcaygeon Formation) may be restricted to the Lake Simcoe area outcrop belt. East of Lake Simcoe, toward Kingston, the Bobcaygeon Formation is subdivided into a lower and upper member, but the published descriptions are vague and somewhat inconsistent with the members from Lake Simcoe and Ottawa regions. It is currently unknown how the Kirkfield Formation from Manitoulin is correlative with the members of the Bobcaygeon Formation in eastern and south-central Ontario. In the subsurface, the lower Kirkfield Formation is more argillaceous than the upper part of the formation (Beards 1967). The upper Kirkfield Formation (≍ upper Bobcaygeon Formation) and the contact with the overlying Verulam Formation is poorly exposed in the Manitoulin Island–North Channel area, arguably because of the presence of recessive shale lithofacies of the lower Verulam Formation.

SHERMAN FALL FORMATION (≍ VERULAM FORMATION)

Kay (1929) introduced the Sherman Fall Formation in Ontario for strata equivalent to the type section in Trenton Falls, New York (Winder 1961). Liberty (1955) proposed a new name, Verulam, for these strata and this remains in current usage in the outcrop belt (Liberty 1969; Johnson et al. 1992; *see* alternative views in Sanford 1993a). The term Sherman Fall continues to be used by the petroleum industry and the OGS in the subsurface (Beards 1967; Sanford 1994a; Brunton et al. 2017). In the vicinity of the North Channel and Manitoulin Island areas, several outcrops originally mapped as Bobcaygeon Formation are actually Verulam Formation (Liberty 1972a-f). Foerste (1912) referred to these rock strata as the Curdsville and other Trenton exposures.

The Sherman Fall Formation comprises 2 subunits, a lower shaly or "argillaceous" unit and an upper, thinner, and a coarsely crystalline or skeletal "fragmental" unit (Beards 1967). These subdivisions correspond well with the 2 informal members of the Verulam Formation described by Liberty (1969). The lower member of the Verulam Formation, or the Sherman Fall "argillaceous" Formation, comprises interbedded limestones and calcareous shale. Limestone beds include very fine- to coarse-crystalline, thinly to thickly bedded, nodular to tabular-bedded, light to dark grey-brown, fossiliferous limestone, ranging from lime mudstones and skeletal wackestones to grainstones (Armstrong and Carter 2010). This rock unit is up to 60 to 65 m thick in the outcrop area of south-central Ontario (Melchin et al. 1994). The Sherman Fall Formation ranges in thickness from 16.4 m in the subsurface of Manitoulin Island to 43.8 m under Lake Erie (south of Essex County) to 52.3 m east of Toronto. It has a maximum reported thickness of 66.5 m in the subsurface of Perth County.

The upper member of the Sherman Fall Formation, or the Verulam Formation “fragmental” unit, comprises thinly to thickly bedded, medium- to coarse-grained, cross-stratified, tan to light grey, fossiliferous limestones; dominated by skeletal and intraclastic grainstones. This unit ranges up to 10 m thick in the outcrop belt near Lake Simcoe (Armstrong 2000; Armstrong and Carter 2006, 2010). It is apparently absent or much thinner (perhaps a single bed?) to the east in the Belleville area (Melchin et al. 1994). The upper member, interpreted to represent deposition in a shallow shoal environment, is thought by some to be laterally discontinuous and to not represent a single stratigraphic unit (Brookfield and Brett 1988). Gamma-ray logs indicate that it is widespread in the subsurface. The term Sherman Fall “fragmental” is still in common usage in the petroleum industry (Armstrong and Carter 2006, 2010).

The Verulam (Sherman Fall) Formation is not well exposed in natural outcrops because of its shaly character. Two quarries located in the outcrop belt between Lake Simcoe and Peterborough, the Gamebridge and Lakefield quarries, afford good exposures of the lower and middle parts of the lower member of the Verulam, respectively (Winder and Sanford 1972; Melchin et al. 1994). The upper member is well exposed in roadcut outcrops approximately 7 km south of the village of Kirkfield, east of Lake Simcoe (Melchin et al. 1994).

At the Picton Quarry, south of Belleville, up to approximately 50 m of the uppermost Verulam (Sherman Fall) Formation is exposed, beneath approximately 10 m of the Lindsay Formation (Cobourg Formation) (Armstrong and Carter 2010). The upper member of the Verulam Formation is approximately 5 m thick, although not as well developed as in the Lake Simcoe area. Trough cross-bedding that characterizes the upper member of the Verulam Formation east of Lake Simcoe does not appear to be present here. The formational contact at this locality is picked at the base of nodular to irregularly bedded argillaceous limestones that overlie medium- to thick-tabular-bedded skeletal grainstones (Armstrong and Carter 2010).

In the Manitoulin Island area, this rock unit is richly fossiliferous and displays storm event-style sedimentation, cross-laminated crinoidal grainstones; and winnowing and rapid pulses of muddy sedimentation (cf. Brookfield and Brett 1988). The exposures on Goat Island (Stop 4) display lower units rich in *Rafinesquina* brachiopods, encrinite storm beds, branching bryozoans, rhodolites of *Solenopora*, *Paratetradium* colonies, solitary rugosans, clusters of the calcified stromatoporoid *Stromatocerium*, and giant ripple marks. *Isotelus* trilobites may be found in some micritic beds.

COBOURG FORMATION (≍ LINDSAY FORMATION)

The Cobourg Formation was originally defined in the Ordovician outcrop belt of south-central Ontario based primarily on biostratigraphic grounds (Kay 1937; Melchin et al. 1994). Liberty (1969) redefined these strata based on lithologic characteristics and assigned the name Lindsay Formation, a term still used by the OGS in the outcrop belt. The term Cobourg Formation continues to be used in the subsurface of southern Ontario by the petroleum industry and is used herein for the uppermost unit of the carbonate-dominated Trenton Group (Sanford 1961; Beards 1967; Brunton et al. 2017).

The Cobourg Formation comprises very fine- to coarse-crystalline, fossiliferous, bluish-grey to grey-brown limestones and argillaceous limestones. Shaly partings are common and thin shale interbeds are locally common. Limestones range from nodular bedded to irregular tabular bedded to planar tabular bedded. The planar tabular bedded limestones are typically fine- to coarse-crystalline, horizontally to low-angle cross-laminated, skeletal packstones and grainstones, probably deposited by storms (Armstrong and Carter 2010). There have been numerous attempts to subdivide the Cobourg (or Lindsay) Formation into subunits (other than the Collingwood Member and lower member) or facies; however, these subdivisions have proven difficult to apply regionally. In general, coarsely crystalline skeletal packstone and grainstone interbeds tend to be more abundant toward the base of the formation and fine upward to wackestones and lime mudstones (Melchin et al. 1994). Fossils include crinoids and crinoidal fragments, gastropods, brachiopods, bryozoans and trilobites. Bioturbation is especially evident in the nodular beds, and some grainstone beds show grading, cross-lamination and may contain intraclasts (Melchin et al. 1994).

In the outcrop belt, the Cobourg Formation (Lindsay Formation) ranges up to approximately 60 m thick, whereas, in the subsurface, it ranges from 17 m to approximately 60 m (Sanford 1961; Liberty 1969; Armstrong and Carter 2006, 2010).

Collingwood Member (Lindsay Formation ≍ Cobourg Formation)

Russell and Telford (1983) formally defined the Collingwood Member as the uppermost member of the Lindsay Formation (outcrop belt equivalent of the Cobourg Formation), based mainly on lithologic characteristics identified in the shallow subsurface near its outcrop belt. It has had a long and complicated nomenclatural history (*see* reviews by Russell and Telford 1983; Hamblin 1999). It is defined as consisting of dark grey to black, organic-rich, calcareous shales with very thin, fossiliferous skeletal interbeds containing mainly trilobites or brachiopods with lesser amounts of bivalves, conulariids, and nautiloids (Rudkin et al. 1998). These units gradationally overlie nodular, finely crystalline limestones of the lower member of the Lindsay Formation. Previously, the dark upper organic-rich strata were assigned to the lower member (the Craigleith Member) of the Whitby Formation (Liberty 1969). The Collingwood Member is an impure limestone or lime marlstone (Macauley et al. 1990; Béland Otis 2015) with a high organic content that imparts a dark colour to the strata in fresh outcrops.

Traditionally in the subsurface of southwestern Ontario, the term “Collingwood Formation” has been applied to widespread dark-coloured, noncalcareous shales that overlie the Trenton Group (i.e., Cobourg Formation) carbonate rocks (e.g., Sanford 1961; Beards 1967). The shales identified by the industry as “Collingwood” in the subsurface likely represent part (i.e., Rouge River Member) or all of the Blue Mountain Formation as defined in the outcrop belt by Russell and Telford (1983). The Collingwood Member appears to be equivalent to at least part of the widespread Utica Shale of eastern North America.

The Collingwood Member ranges up to approximately 10 m thick (Johnson et al. 1992). The Collingwood Member gradationally overlies the lower member of the Lindsay Formation (≍ Cobourg Formation). Its upper contact with the somewhat less organic-rich to organic-poor, noncalcareous, black to blue-grey shales of the Blue Mountain Formation is reported to vary from sharp with a possibly phosphatic or pyritized lag to gradational (Russell and Telford 1983; Churcher et al. 1991; Béland Otis 2015).

The Collingwood Member is a potential oil and gas source rock in the subsurface and was assessed as a potential oil shale resource by the OGS (Churcher et al. 1991). Some samples of the Collingwood Member have been found to contain between 10 to 50% bitumen and may represent the main source of oil seeps found on Manitoulin and St. Joseph islands (Barker et al. 1983; Churcher et al. 1991; Béland Otis 2015). Surface mining of the shale and distillation of oil from the shale in open-cast iron retorts was carried out from 1859 to 1863 at Craigleith, on the south shore of Georgian Bay.

Georgian Bay and Blue Mountain Formations

The Upper Ordovician Georgian Bay Formation is characterized by greenish- to bluish-grey shale, interbedded with limestone, siltstone and sandstone (Byerley and Coniglio 1989; Kerr and Eyles 1991; Johnson et al. 1992). Liberty (1964) introduced the term Georgian Bay Formation. It is disconformably overlain by the Queenston Formation and it disconformably overlies the Blue Mountain Formation. This contradicts the original stratigraphic relationships provided by Liberty (1964) and summarized in subsequent summary papers by Johnson et al. (1992) and Armstrong and Carter (2010) (*see* revised stratigraphic chart in Brunton et al. 2017). The Blue Mountain Formation comprises blue-grey to grey-brown shales with thin, minor interbeds of limestone and siltstone. Because of the gradational nature of the contact between the Georgian Bay and Blue Mountain formations and lack of a reliable formation-top pick criteria (for the Blue Mountain Formation) these units are commonly combined in subsurface mapping.

In the lower part of the Blue Mountain Formation, there is a downward gradation from grey to greenish-grey shales to a very dark grey to black shale, also known as the Rouge River Member, a term initially introduced by Liberty (1969) for the middle member of the Whitby Formation. The petroleum industry and Beards (1967) identify these black organic-rich shales as the Collingwood Formation, but the Collingwood Member of the Lindsay Formation, as defined by Russell and Telford (1983), is calcareous and these shales are not. In the Toronto area, the lowermost 10 to 15 m of the Blue Mountain Formation consists of black noncalcareous organic-rich shale, increasing to 45 m beneath eastern Lake Erie, and is readily identified in gamma-ray geophysical logs. Russell and Telford (1983) now refer to these strata as the Rouge River Member of the Blue Mountain Formation.

Strata presently assigned to the Georgian Bay Formation were previously assigned to the Dundas and Meaford formations (Liberty and Bolton 1971). The Blue Mountain Formation strata were previously assigned to the middle and upper members of the Whitby Formation, informally called the Thornbury and Rouge River members (Liberty 1969; Russell and Telford 1983). Russell and Telford (1983) note that the dark brown to black shales of the Rouge River Member were limited to the Toronto area, whereas the overlying shales of the Thornbury Member constituted the remainder of the Blue Mountain Formation. Gamma-ray logs and drill core and cuttings samples from petroleum wells indicate that the black shales of the Rouge River Member have a much wider distribution than mapped by Russell and Telford (1983). In historical Ministry of Natural Resources (MNR) petroleum well records and in Beards (1967), the Georgian Bay and Blue Mountain formations are referred to as the Meaford–Dundas unit (*see* details in Armstrong and Carter 2006, 2010).

The Georgian Bay and Blue Mountain formations are approximately equivalent to (in descending order) the Oswego, Pulaski, Whetstone Gulf and Deer River formations of New York State (Lehmann, Brett and Cole 1994) and with the Utica Shale (or subQueenston part) of the Richmond Group in Michigan (Catacosinos et al. 2001). The Deer River Formation (and equivalent Gulf Stream Formation) of New York are considered lithofacies equivalents to the older Utica Formation of the Appalachian Basin (Armstrong and Carter 2006, 2010; Lehmann et al. 1995).

The Georgian Bay Formation ranges from 125 to 200 m thick and the Blue Mountain Formation ranges up to 60 m thick (Johnson et al. 1992). Both the Georgian Bay and Blue Mountain formations consist of shales with varying amounts of limestone, siltstone and sandstone interbeds. Generally, the abundance and thickness of beds containing no shale (also called “hard beds”) increase stratigraphically upward. In the outcrop belt, limestone beds in the Georgian Bay Formation are reported to decrease in thickness and abundance from north to south (Johnson et al. 1992). This trend is not apparent in the subsurface (Armstrong and Carter 2006, 2010). The shales are generally noncalcareous and range in colour from greenish-grey to bluish-grey to dark grey-brown. Minor amounts of reddish-brown to red shale occur locally near the top of the Georgian Bay Formation. Sandstones and siltstones are commonly calcareous and contain both calcite cement and calcareous skeletal material. Hard beds are typically fossiliferous, with bryozoans, crinoids, pelecypods and brachiopods being the most common fossils. Trace fossils, graded beds, gutter casts and ripple marks are common in the Georgian Bay Formation (Johnson et al. 1992).

Liberty (1972a-f) defined 3 informal stratigraphic units within the Georgian Bay Formation of Manitoulin Island, which compare well with the Wekwemikongsing, Meaford and Kagawong formations defined previously (*see* descriptions and discussions in Foerste (1912, 1916); Caley (1936); Barnes et al. (1981, 1978); Copper (1978)).

SILURIAN STRATIGRAPHIC UNITS

Medina Group

MANITOULIN FORMATION

The Manitoulin Formation was named by Williams (1913a) for thinly bedded to medium-bedded, blue-grey to tan weathered dolostones with intermittent shaly partings on Manitoulin Island (approximately 16 m thick). The uppermost Ordovician(?) (Stott and Jin 2007a, 2007b; Kleffner, Bergström and Schmitz 2005; Bergström, Kleffner et al. 2006; Bergström et al. 2011) or more traditionally allocated basal Silurian Manitoulin Formation is characterized by basal microbial-laminated green calcareous shales that grade upward into both thinly bedded muddy to skeletal dolostone beds and massive barrier reef and bryozoan-microbial and microbially bound coralliferous-calcified and siliceous sponge patch reef mounds (*see* Figure 2; Anastas and Coniglio 1992; Fay and Copper 1982; Fay 1983; Copper and Fay 1989; Copper and Brunton 1991). From the Bruce Peninsula to Manitoulin Island, the Manitoulin Formation disconformably overlies either the Queenston Formation (Cabot Head area of northern Bruce Peninsula) or upper lithofacies of the Georgian Bay Formation (Manitoulin Island area). South of Bruce Peninsula in southern Ontario, Duntroon area to Niagara Falls, the Manitoulin Formation disconformably overlies the Whirlpool Formation. The Whirlpool Formation is not described in this guidebook because it is not observed within the area covered by this guidebook. The Manitoulin Formation extends from the Stoney Creek area of Hamilton (approximately 1.3 m thick) to the northern peninsula of Michigan. It thickens (or perhaps was preferentially preserved) northward and toward Michigan and pinches out to the southeast along a line from eastern Niagara Peninsula to western Lake Erie (Sanford 1969). Therefore, the Manitoulin Formation comprises up to 26 m of dolostone, argillaceous dolostone and minor grey-green shale (*see* discussion below).

On Manitoulin Island, the formation displays at least 2 major changes in lithology vertically and has been divided into 2 informal members (Way 1936; Cumings 1939). A third, basal greenish-grey microbial unit (<1 m thick) observed in a few cores from the Bruce Peninsula, Cockburn Island and northwestern Manitoulin Island may be equivalent to the Centerville Formation in Ohio (Foerste 1901; Brunton and Brintnell 2020). Typically, the lower unit comprises grey, thin- to medium-bedded, moderately fossiliferous, fine- to medium-crystalline dolostone and commonly contains chert nodules or variably fossiliferous argillaceous lenses and silicified fossils (Bolton 1957; Johnson et al. 1992). The upper unit, called the Bidwell member (Way 1936; Cumings 1939), possesses reef mounds and barrier reef complexes (Fay and Copper 1982; Fay 1983; Copper and Fay 1989). Mounds can occur at different levels in the preserved strata of the Bruce Peninsula (Anastas and Coniglio 1992). Analysis of sedimentological features, such as those related to storms and fair-weather processes, indicates that the Manitoulin Formation was deposited on a shallow carbonate ramp that dipped to the south (Anastas and Coniglio 1993) and may not have been affected by short-lived tectophases or forebulge migrations in the Algonquin Arch region.

When the barrier complex south of Manitowaning (Stop 7) was freshly blasted in the early 1970s, thick, black bitumen oozed from vugs on warm summer days (Cameron 1975; Fay 1983). Bitumen is still present in corals and vugs within the Manitoulin barrier reef structure and at other localities across the island. Internal subtle paleokarst surfaces are evident in the roadside barrier reef outcrop.

CABOT HEAD FORMATION

The type locality for the Cabot Head, Wingfield and St. Edmund formations is the cliff exposure at Rocky Bay (also called Clay Cliffs), just east of Cabot Head at the north end of the Bruce Peninsula (*see* Figure 3) (Grabau 1913; Bolton 1953, 1957; Liberty and Bolton 1971). The Cabot Head Formation comprises grey to green to red-maroon, noncalcareous shales, with subordinate sandstone and carbonate interbeds (Bolton 1957; Johnson et al. 1992). Although generally poorly fossiliferous, a few thin, bryozoan-rich, shale and argillaceous limestone beds are known. Throughout much of southwestern Ontario, the Cabot Head Formation shales range from greenish-grey in the upper part of the formation, grading downward into medium grey shales (Sanford 1969). North of the Grimsby Formation, the uppermost Cabot Head Formation red shales pinch out. Also, in the Bruce Peninsula area, a significant part of the Cabot Head Formation is red to maroon in colour (shallow water environments).

The Cabot Head Formation varies in thickness, ranging from a maximum thickness of approximately 40 m under west-central Lake Erie, to approximately 12 m thick over the Algonquin Arch and to over 36 m thick in the Owen Sound area (Sanford 1969). Some variability in thickness can be attributed to the uncertainty of picking its upper contact with the somewhat laterally equivalent Grimsby Formation and its lower contact with the Manitoulin Formation. Also, toward the Algonquin Arch, the top of the Cabot Head Formation appears to be cut by a regional angular unconformity at the base of the Fossil Hill or Merritton formations (formerly referred to, incorrectly, as the Reynales Formation; *see* Brunton and Brintnell 2020). From Cabot Head to south of Owen Sound, regularly spaced boreholes reveal the systematic removal of the middle and lower Fossil Hill, St. Edmund, Wingfield and Dyer Bay formations, which resulted in the Fossil Hill or Merritton formations resting disconformably on the Cabot Head Formation or Thorold Formation or Grimsby Formation (Brintnell et al. 2009; Brunton and Brintnell 2020). This is arguably the most significant disconformity in the Silurian succession of southern Ontario, representing millions of years of erosion in strata from Guelph to Niagara Falls. The Cabot Head Formation requires stratigraphic revisions to better integrate the tectonostratigraphic history of the eastern Michigan and northwestern Appalachian basins. The Cabot Head Formation forms the subregional aquitard across Manitoulin Island that enabled the development of the deep lakes in the interior of Manitoulin Island (*see* Figure 3; Enyedy-Goldner 1994; Brunton and Dodge 2008).

DYER BAY, WINGFIELD AND ST. EDMUND FORMATIONS

The type locality for the Dyer Bay Formation is at Dyer’s Bay, just south of Cabot Head on the east coast of the northern Bruce Peninsula. The type section for the Cabot Head, Wingfield and St. Edmund formations is a cliff exposure to the west of Rocky Bay (also called Clay Cliffs), located approximately 3.5 km west of Cabot Head at the north end of the Bruce Peninsula (Grabau 1913; Bolton 1953, 1957; Liberty and Bolton 1971). The Dyer Bay Formation is also exposed in this outcrop.

The designation of discrete formational rankings for some of these rock units is problematic because greenish shales of Cabot Head Formation character recur above these dolostones (e.g., Dyer Bay and St. Edmund formations) as well as mixed green shale and dolostones (Wingfield Formation). From Clappison’s Corners in the Hamilton to Niagara Falls area, upper Cabot Head Formation lithofacies are overlain by various sandstones and shaly siltstones of the Thorold and Grimsby formations. The regional lithofacies change from siliciclastic-dominated lithofacies to mixed calcareous and noncalcareous shales in the southern Niagara Escarpment region of Ontario to mixed dolostones and shales with much less terrigenous influence in the northern Bruce Peninsula area is also observed in the younger Silurian strata that lie above the Irondequoit Formation (*see* Gasport Formation section below regarding the Rochester Formation and its equivalency to the Lions Head Member of the former Amabel Formation). Both the Lions Head Formation and Rochester Formation sit disconformably on the crinoidal grainstones of the

Irondequoit Formation—a very resistant dolostone unit that can be traced in core from southwestern Ontario through Kincardine to Tobermory and down through the Guelph–Cambridge areas to Niagara Falls, New York (*see* discussions in Rowell and Brunton 2012; Brunton and Brintnell 2020).

Dyer Bay Formation

The Dyer Bay Formation was named by Williams (1919) and is largely known from the Bruce Peninsula to Manitoulin Island region of the Niagara Escarpment. The upper contact of the Dyer Bay Formation is gradational to sharp with the Wingfield Formation (diamond-drill cores reveal varied contacts; Brintnell et al. 2009; Brintnell 2010), and sharp and disconformable with other units (e.g., Fossil Hill or Merritton formations), although overlying units may be shaly and therefore difficult to distinguish using geophysics. The distinctive medium to dark blue-grey, medium-crystalline texture of the Dyer Bay Formation distinguishes it from the tan to brown dolostones of the overlying carbonates or green shales of the Wingfield Formation. It possesses a low diversity coral and brachiopod fauna, is extensively horizontally bioturbated and displays well-developed ripple marks. This rock unit is not well exposed across Manitoulin Island and is not seen on this field trip.

Wingfield Formation

The first formal usage of Wingfield Formation as a rock unit was by Williams (1937) for strata that are best exposed from Cabot Head to the designated type section to west of Rocky Bay on the northern Bruce Peninsula. The Wingfield Formation has either a gradational to sharp upper contact with dolostones of the overlying St. Edmund Formation or a sharp disconformable contact with dolostones of the Fossil Hill Formation. The Wingfield Formation is more argillaceous than either the St. Edmund Formation or Fossil Hill Formation and, therefore it can be picked using geophysical logs in the subsurface. It is typically a greenish-grey shaly unit with typically darker brown dolostone beds than the overlying St. Edmund Formation. It is generally poorly fossiliferous and displays horizontal bioturbation. This rock unit is not well exposed across Manitoulin Island and is not seen on this field trip.

St. Edmund Formation

The St. Edmund Formation was first described as a dolostone lentille (lens) of the Cabot Head Formation by Williams (1919). It has a sharp upper contact with the overlying Fossil Hill Formation, but possesses a similar dolostone lithology and, therefore, is difficult to pick in borehole geophysical logs. The formation top is reported to be sometimes marked by a thin green shale bed that may be represented by a small gamma-ray spike in geophysical logs. This rock unit was designated as a formation by Sanford (1978) and is equivalent to the Mindemoya Formation described by Liberty (1968). The St. Edmund Formation is a finely crystalline dolostone, also described as sublithographic or lithographic in older field description sense. It is generally poorly fossiliferous. It has a disconformable contact with the overlying Fossil Hill Formation and, on the Bruce Peninsula, has greenish shales of Cabot Head Formation character separating it from the overlying Fossil Hill Formation (Brintnell et al. 2009; Rowell and Brunton 2012; Brunton and Brintnell 2020). The upper part of the formation possesses rare very Early Silurian Aeronian (440.8–438.5 Ma) stromatoporoid biostromal beds in the vicinity of the Cup and Saucer Trail (trail not part of the field trip).

Clinton Group

FOSSIL HILL FORMATION (UPPER INFORMAL MEMBER ≍ MERRITTON FORMATION)

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 (Stop 9) (Bolton 1953, 1957; Winder 1961). Williams (1919, 1937) referred to this rock unit as being part of the Lockport Formation. The Fossil Hill Formation consists of 4 informal members at the type section on Manitoulin Island (Brunton, Turner and Armstrong 2009; Brintnell et al. 2009; Brintnell 2010). The formation consists of thinly bedded, very cherty, sparsely fossiliferous, argillaceous dolostones and relatively pure, fossiliferous, nonchert–bearing dolostones, and is well indurated (Eley 1977; Eley and Jull 1982; Eley and von Bitter 1989), 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; Brunton and Brintnell 2020; *see also* discussion below). Other good exposures of the Fossil Hill Formation are located on the Bruce Peninsula on the shore of Isthmus Bay, just north of the village of Lions Head and in a roadcut near Inglis Falls, just south of Owen Sound (Bolton 1957; Liberty and Bolton 1971; Stott and von Bitter 1999; Armstrong, Goodman and Coniglio 2002; Armstrong and Carter 2006, 2010; Armstrong and Dodge 2007; Brintnell et al. 2009). Diamond-drill cores collected systematically along the spine of the Bruce Peninsula and southward (from south of Tobermory to Corbetton) display the systematic cut out of the middle and lower Fossil Hill Formation and the underlying St. Edmund, Wingfield and Dyer Bay formations, and the upper portions of the Cabot Head Formation.

The lower third to middle portion of the formation, as revealed in the type section on Highway 6 (*see* Stops 8A and 8B), possesses a poorly fossiliferous lime mudstone to wackestone succession and superficially resembles the underlying St. Edmund or Mindemoya formations (this succession is informally referred to as the “false Mindemoya”). The upper third of the formation shows a return to richly fossiliferous brachiopod beds of *Pentameroides* instead of *Pentamerus* and a rich megafauna of corals and calcified sponges and related faunas. No bioherms have been described from this unit. The condensed nature and taphonomic character of the fauna in core and select outcrops indicate palimpsest conditions and a slow rate of sedimentation, along with several disconformities.

Everywhere, the Fossil Hill Formation is disconformably overlain by the Rockway Formation (*see* discussion in Brunton and Brintnell 2020) from the northern Bruce Peninsula to Niagara Falls. In general, the *Pentameroides*-dominated facies of the upper Fossil Hill Formation seems to be a regionally persistent rock unit. Of equal significance is the fact that the Irondequoit Formation is a persistent, thoroughly bioturbated crinoidal grainstone to packstone lithofacies that is present from Tobermory to Kincardine and in cores from the Chatham Sag area to Niagara Falls (Brunton and Brintnell 2020).

The upper Fossil Hill Formation (≍ Merritton Formation of Brett et al. 1995) rests disconformably above the shales of the Cabot Head Formation in diamond-drill cores from the Guelph area and rests disconformably on the St. Edmund Formation across Manitoulin Island. It was originally named as a member of the Reynales Formation (Kilgour 1963), hence the confusion in nomenclature. It is generally less than a metre thick and appears to thin to the east, toward the present-day cuesta margin. It is thicker in some diamond-drill cores near Guelph than at the type section in Thorold. It possesses the same pentamerid brachiopods and tabulates as the Fossil Hill Formation and, therefore, is correlated with that formation. Previously, the upper Fossil Hill Formation has been incorrectly assigned to the lower Reynales Formation of New York State, which is much older (*see* Brett et al. 1995).

The upper Fossil Hill Formation dolostone is distinctive and comprises up to 3 well-indurated beds of unequal thickness that are separated by dark shaly partings. It has a distinctive, bioturbated, pinkish-brown finely crystalline matrix. It possesses a black, phosphate pebble-bearing hardground unit in the lower beds. The lower beds are wackestones and the upper bed possesses the pentamerid-bearing units (*Pentameroides subrectus*), and halysitid chain corals and favositid corals typical of the Fossil Hill Formation. The uppermost brachiopod-rich beds are rarely evident in diamond-drill core from the Guelph region. The *Planolites*-type burrows may possess glauconite and the lower beds are rich in pyrite.

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 crinoidal limestone of the Irondequoit Formation (Brett et al. 1995). This formation possesses a distinctive, greenish-grey finely crystalline matrix separated by styloseam sets and thin shaly partings. It is an argillaceous dolomicrite to wackestone with no discernible macrofaunal elements. It has a very distinctive and erosional contact with the overlying crinoidal grainstone of the Irondequoit Formation, making it easy to delineate in the core. This contact is best described as "welded", and its distinctive character in every diamond-drill 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 Rockway Formation persists north of Hamilton, across the Algonquin Arch, where it has been termed "Lions Head Member" of the Amabel Formation (*see* Figure 5 for new interpretation). The lack of significant change in the overall thickness of the Merritton and Rockway formations from the northern Appalachian Basin to the eastern Michigan Basin regions suggests that the Algonquin Arch did not influence regional sedimentation patterns during this time interval. A thin Rockway Formation has been observed in the deep core from Cockburn Island, but is absent from northwestern Manitoulin Island core (*see* black dots in Figure 3; Rowell and Brunton 2012; Brunton and Brintnell 2020).

Lockport Group

The Lockport Group comprises 4 formations, which, from base to top, include Gasport, Goat Island, Eramosa and Guelph formations (Brunton and Brintnell 2020). The Gasport and Goat Island formations form the top bedrock units across the southern region of Manitoulin Island (*see* Figure 3).

GASPORT FORMATION

In Ontario, the Gasport Formation has a confusing nomenclatural history (Brunton and Brintnell 2020). Several examples of how the formation has been referred to in the past include the following examples: 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 1969); and Member 3 of the Lockport Formation (Liberty and Bolton 1971). Results of the regional diamond-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. The type section for the formation is in Gasport, New York (Kindle and Taylor 1913; Winder 1961; Brett et al. 1995). *Ozarkodina sagitta* conodonts in the Gasport Formation (LoDuca and Brett 1991) in New York indicate an early Homerian age (430.5–427.4 Ma). Recent conodont data obtained from 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 are Early to Middle Sheinwoodian (433.4–430.5 Ma) (Bancroft, Kleffner and Brunton 2016).

The Gasport Formation consists of a basal cross-bedded crinoidal grainstone–packstone succession with incipient microbial–crinoidal reef mound lithofacies that change upward to rhynchonellid brachiopod–bryozoan–bivalve coquinas and large-scale microbial reef mounds dominated by crinoidal holdfasts and greater than 1 cm diameter *Periechocrinites* sp. and possibly *Eucalyptocrinites* sp. pluricolumnals. It has a characteristic white (encrinitic grainstone units) to dark blue-grey matrix (reef mound microbial matrix) and is known in the subsurface terminology of the Michigan Basin as the "White Niagaran" (Alguire 1962).

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 north of Hamilton and extending from Guelph to the southern Bruce Peninsula differs from the typical Gasport Formation lithofacies in the Niagara Falls area in that it does not possess the interreefal Pekin Member lithofacies that envelope the Gothic Hill Member reef mounds. Gothic Hill Member faunas and reef mound characteristics are reflected in both members of the Amabel Formation as outlined by Bolton (1953, 1957) and modified by Liberty and Bolton (1971) (*see* faunal lists in Williams 1919; Bolton 1957; Zenger 1965; Liberty and Bolton 1971). It also differs from Pekin Member and Gothic Hill Member facies in New York State, whereby large gypsum nodules are evident in the Pekin Member beds (this compares favourably with the lithofacies in the Cambridge area of Ontario).

The sources of the argillaceous Pekin Member lithofacies presumably were cut off by the migrating forebulge. This tectonically induced phenomenon enabled increased accommodation space and resultant thicker reef mound development on the leading edge of the forebulge in what is now referred to as the eastern Michigan Basin (north Cambridge to Guelph regions; Brunton and Brintnell 2020). In the Manitoulin Island region, the Gasport Formation has a generally unknown thickness because of poor subsurface well control and outcrop accessibility. Cores and outcrops on the northwest side of the island suggest up to 15 m of thickness.

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 varies 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 (Brett et al. 1995). This unit commonly has a distinctive pinstriped 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 commonly 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 commonly has 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. 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 and along the southern region of Manitoulin Island. 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.

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 2). 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 (Brintnell 2012; Brunton et al. 2012; Brunton and Brintnell 2020).

Road Logs

Note: Caution should be taken when parking vehicles on the shoulders of the road or highways and when examining outcrops located along the field trip route. All Universal Transverse Mercator (UTM) co-ordinates are provided using North American Datum 1983 (NAD83) in Zone 17.

DAY 1. ORDOVICIAN OUTCROPS (FROM SUDBURY TO LITTLE CURRENT)

The first day focusses on the Ordovician outcrops on Birch Island, La Cloche Island, Goat Island and the Sheguiandah site.

0.0 km	Leave Laurentian University and head toward Highway 17W from Ramsey Lake Road and Regional Road 80 south (Paris Street).
7.9 km	Continue on Highway 17W.
72.8 km	Turn left onto Highway 6 toward Espanola and Manitoulin Island.
106.0 km	Stop 1 is on the right side of Highway 6, just past the community of Whitefish River, Birch Island.

Stop 1. Roadside outcrop of Shadow Lake, Gull River and Bobcaygeon formations

UTM 440357E 5101193N

Potential hazards:

- Steep and/or slippery slopes; loose rocks
- Busy road with high-speed traffic; stay off road shoulder and remain downflow of parked vehicles if possible; high-visibility vests, hard hats and safety glasses required
- Vertical outcrops with loose debris; rockfall hazard, hard hats must be worn

This outcrop exposure displays a partially covered interval of the upper Gull River Formation and lower Bobcaygeon Formation. These strata correlate with the upper Black River Group and possibly basal portion of the Trenton Group. A new finding within this outcrop is the possible presence of a bentonite bed in the upper Gull River Formation (Photo 1). This bed was sampled for U/Pb zircon geochronology.

The red beds observed at the base of the outcrop have been attributed to the Shadow Lake Formation. However, these beds show some affinity with the overlying greenish tabular beds recognized as the Gull River Formation. It is possible that the Shadow Lake Formation represents the first phase of deposition of carbonates and siliciclastic rocks on the Precambrian basement (Paleoproterozoic Huronian Supergroup of the Lorrain Formation strata). Barnes, Telford and Tarrant (1978) described a Black River Group neurodont conodont fauna from this succession, along with other conodont genera that are characteristic of faunas from the type Lowville and lower Chaumont formations of New York State and southern and eastern Ontario (Barnes 1967). It is important to note that the red beds exposed here, believed to represent the oldest Paleozoic carbonate rocks found in the area and in south-central Ontario, are not identical to the red beds present at Stop 2 (*see* discussions of faunas in Foerste 1912, 1913a, 1913b, 1924; Copper et al. 1995). Look for a restricted marine fauna of digitate bryozoans, and broken strophomenids and small rhynchonelloid brachiopods in the upper beds of the outcrop. The contact relationships of the basal Paleozoic strata and the Lorrain Formation quartzites (2.3 Ga) vary in the Birch Island area, with Paleozoic strata ranging from reddish, intertidal burrowed and mud-cracked units with *Trypanites*-like borings in sharp contact with the Lorrain Formation quartzites to paleosol-like textures of reddish units with wind-facetted pebbles and sand-blasted clasts overlying reworked Proterozoic conglomeratic and sandy units of the Lorrain Formation (*see* discussions in Copper and Long 1993; Copper, Jin and Armstrong 1995).

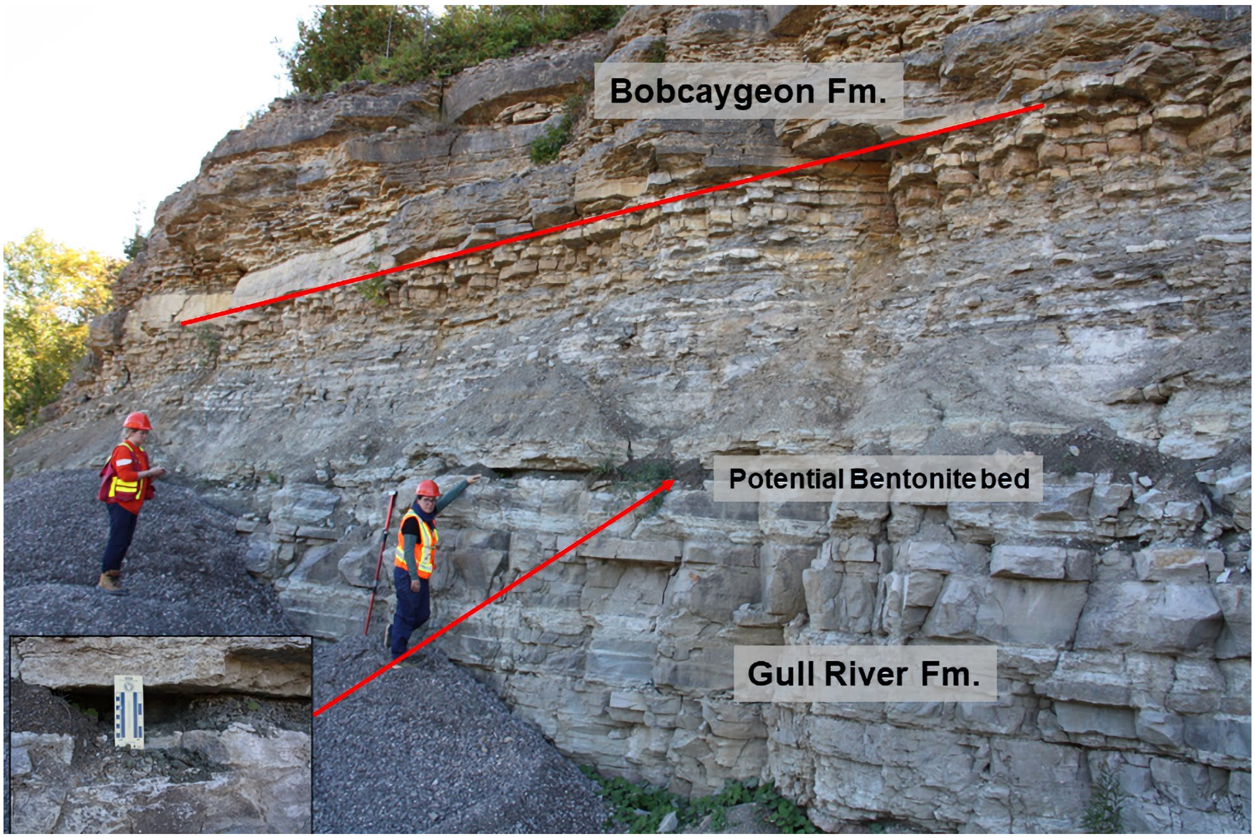

Photo 1. Gull River and lower Bobcaygeon formations at Stop 1. Section includes the Shadow Lake Formation at the base (not in photo); the greenish tabular beds of the Gull River Formation marked by an increase of shale content near the top of the unit; and the lower Bobcaygeon Formation at the top of the outcrop. A possible bentonite bed has been found within the Gull River Formation. Red Jacob's staff, for scale, is 1.5 m high.

Return to vehicles and continue driving on Highway 6 toward Manitoulin Island for 7.6 km.

113.6 km Pull over on the right side of the road (there is room to park just south of the first portion of the outcrop).

Stop 2. Roadside outcrop of Paleozoic–Proterozoic disconformity

UTM 437986E 5095905N

Potential hazards:

- Steep and/or slippery slopes; loose rocks
- Busy road with high-speed traffic; stay off road shoulder and remain downflow of parked vehicles if possible; high-visibility vests required

This outcrop exposure shows the unconformity between Paleoproterozoic Huronian Supergroup Lorrain Formation quartzites of the Lorrain Formation and overlying Paleozoic boulder conglomerates and mixed carbonates, shales and sandstones. The amount of time represented by this unconformity is approximately 1.8 billion years (age of Lorrain Formation quartzite is approximately 2.3 billion years old; Hill, Davis and Corcoran 2018; Young 2013, 2014, 2018), and the Shadow Lake Formation is approximately 450 million years old. Note the undulatory and varied dip of the Paleozoic strata over quartzitic knobs of the Lorrain Formation. The highly irregular paleotopography of the Huronian Supergroup metasedimentary quartzites in the North Channel region has influenced the Paleozoic stratigraphic unit sitting on the unconformity (e.g., Shadow Lake versus Gull River versus Bobcaygeon formations).

The red and green basal beds at this outcrop were previously attributed to the Shadow Lake Formation (Photo 2; *see* also Brunton et al. 2009). The overlying contact with the Gull River Formation was thought to be gradational and, in the outcrop belt in central Ontario, has been placed at different levels depending on which criterion is used (*see* discussion in Melchin et al. 1994). Generally, there is a rapid upward lithologic transition from basal, coarse sand grade, arkosic sandstone, to poorly sorted, very argillaceous sandstone, to sandy shale, to argillaceous and sandy dolostone to finely crystalline limestone. These rock types are also commonly interbedded and green or red colouration can extend upward into the carbonate-dominated strata of the lower Gull River Formation (*see* Photo 2). The contact may appear to be sharp where most lithologic characteristics (i.e., colour, argillaceous content, and carbonate content) change together.

Look for boulders and cobbles of the underlying Paleoproterozoic Lorrain Formation quartzites intermixed with the Paleozoic siliciclastic and mixed carbonate and shale strata. Although the basal red beds at this stop somewhat resemble the rocks observed at the base of Stop 1, the fauna suggests a younger Blackriveran (e.g., upper Gull River Formation or basal Bobcaygeon Formation ≍ Coboconk Formation) to Trenton Group fauna (Copper 1978; Barnes et al. 1978; Copper, Jin and Armstrong 1995). The strata flatten out to the south away from the quartzite knob and represent the Bobcaygeon Formation.

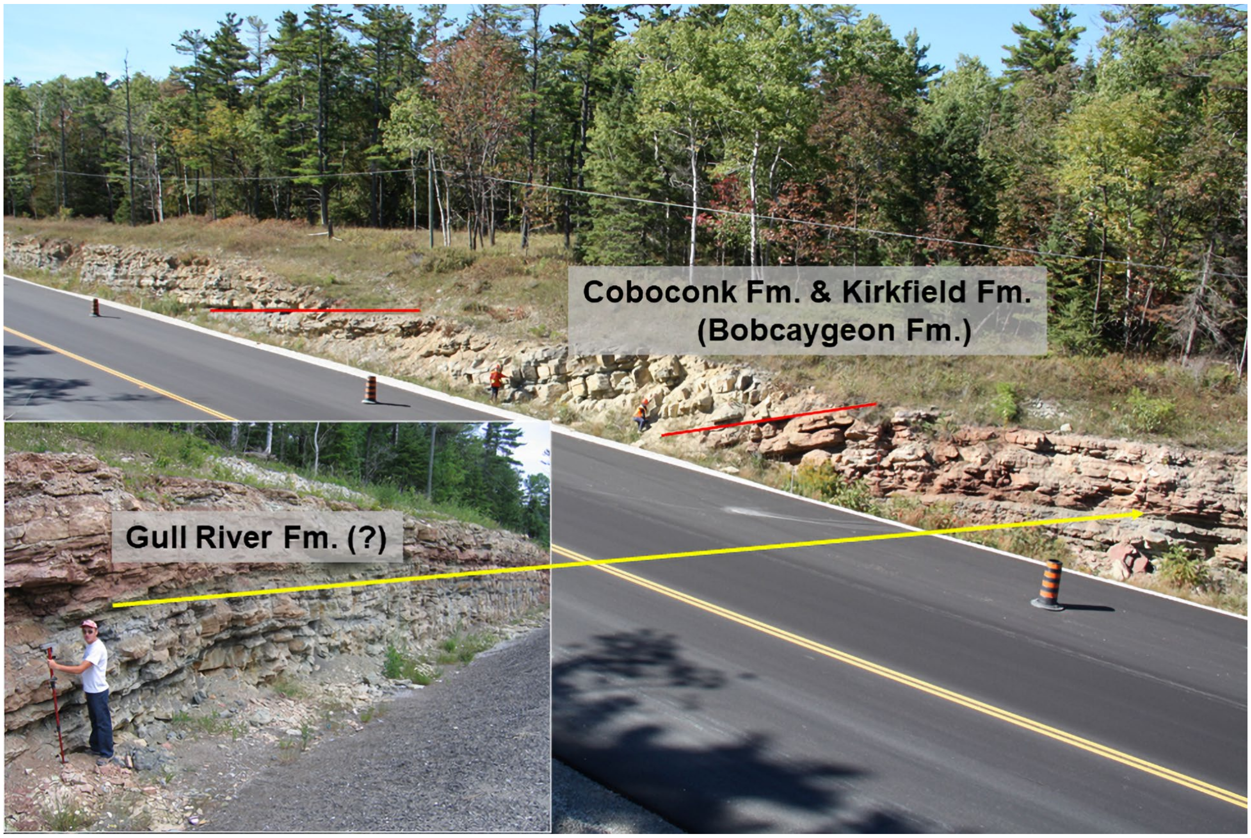

Photo 1. Ordovician outcrop along Highway 6 on Birch Island at Stop 2. Previous interpretations of the outcrop suggested that the lower red beds correlate to the Shadow Lake Formation, but the sparse fauna in the lower red beds and the absence of Shadow Lake and/or Gull River formations at this location may suggest a younger age. The red lines represent the possible upper contact of the Shadow Lake and Gull River formations as previously interpreted. Red Jacob's staff, for scale, is 1.5 m high.

Return to vehicles and continue on Highway 6 toward Manitoulin Island.

115.8 km Turn left at the Fisher Wavy Inc. Quarry entrance

116.5 km Pull over at the scale house and wait until the field trip group is admitted into the quarry by aco-ordinator. Once granted entry, drive on the main quarry road (generally southeast) to the quarry. Note the quarry is on private property, and prior permission is required to access the site.

120.6 km Pull over in the quarry.

Stop 3: Fisher Wavy Inc. Quarry, Great La Cloche Island: Coboconk and Bobcaygeon formations

UTM 440774E 5093323N

Note: This stop includes an active quarry. Prior permission is required to access this location.

Potential hazards:

- Steep and/or slippery slopes; loose rocks
- Vertical outcrops with loose debris; rockfall hazard, hard hats must be worn
- Stay away from machinery

The ringing rocks are 3 large rocks that were used to sound warning alarms to the local community members who lived along the shores from Whitefish River First Nation to Sheguiandah First Nation. When struck against one another, these large rocks rang out like a bell. The ringing of the rocks was the inspiration that led the French voyageurs to name the islands and area La Cloche, meaning “The Bell”. The remaining pieces of the ringing rocks, which are Huronian Supergroup Lorrain Formation quartzites, are located to west of the active quarry. If time permits, the ringing rocks can be viewed more closely before looking at the Ordovician outcrops.

This quarry face displays variably fossiliferous beds of both the Coboconk Formation (≍ lower Bobcaygeon Formation) and the Kirkfield Formation (≍ middle to upper Bobcaygeon Formation). The field trip visits the active quarry area (Photo 3) and an abandoned quarry area on the eastern coast of Great La Cloche Island, where sand and salt are stockpiled for winter road maintenance. Very large labechiid stromatoporoids, assorted brachiopods, trilobites, tabulate corals, large gastropods, bryozoans and algae can be observed at this site. Faunas at this site have been illustrated and described in Copper (1978) and Copper, Jin and Armstrong (1995).

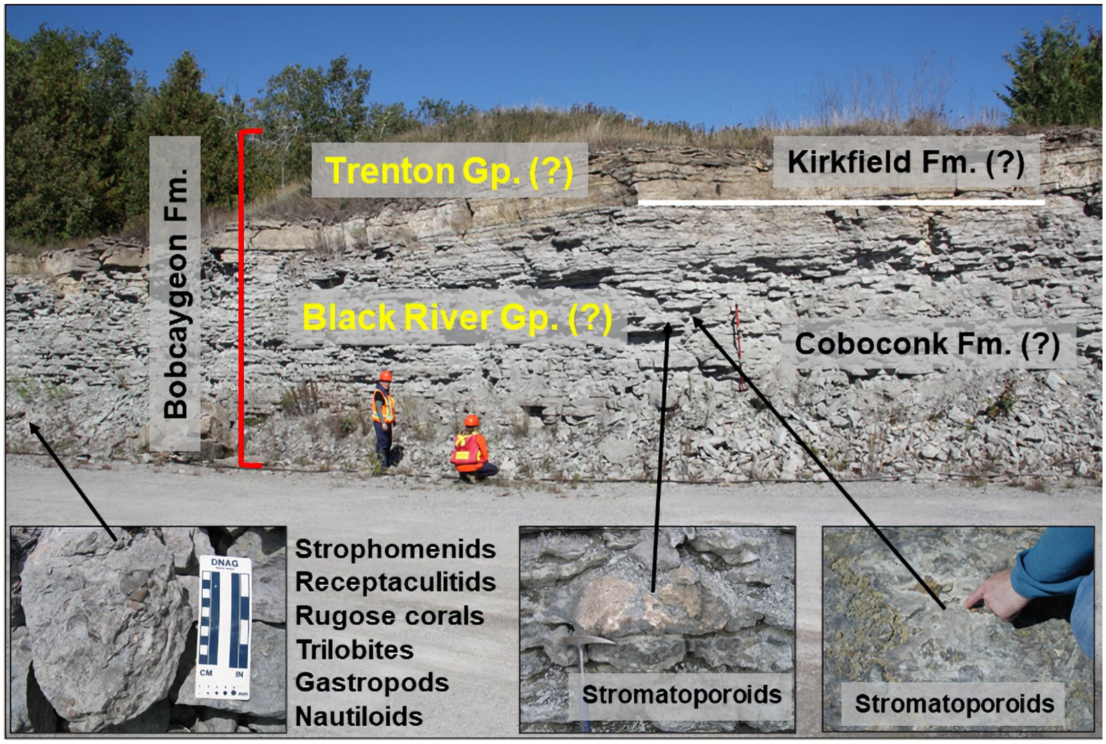

Photo 2. The Coboconk and Kirkfield formations (= the lower Bobcaygeon Formation) in the Fisher Wavy Inc. Quarry at Stop 3. The upper and lower contacts of the Bobcaygeon Formation are not observed here. The authors believe that the contact between the Black River and Trenton groups is present at the base of the brownish beds (base of the Kirkfield Formation of the Trenton Group) and is represented by the white line. Red Jacob's staff, for scale, is 1.5 m high.

Return to vehicles and exit the quarry.

125.4 km	Turn left on Highway 6 toward Manitoulin Island.
133.1 km	Pull over at the power station on the left side of the road, just passed the outcrop, and park vehicle.

Stop 4: Goat Island: Verulam Formation

UTM 430143E 5092840N

Potential hazards:

- Steep and/or slippery slopes; loose rocks
- Busy road with high-speed traffic; stay off road shoulder and remain downflow of parked vehicles if possible; high-visibility vests required

This outcrop exposure displays beds of the Verulam Formation with varying fossil content (Photo 4). Abundant trace fossils, trilobites, crinoid calices and large stromatoporoids characterize this succession (Copper 1978; Copper, Jin and Armstrong 1995). If time is limited on Day 1, this stop may be visited on Day 2.

In the Manitoulin area, the Verulam Formation rock unit is richly fossiliferous and displays storm event-style sedimentation, cross-laminated crinoidal grainstones, and winnowing and rapid pulses of muddy sedimentation. The exposures on Goat Island display lower units rich in *Rafinesquina* brachiopods, encrinite storm beds, branching bryozoans, *Solenopora* red algae, *Paratetradium* colonies, solitary rugosans, clusters of the calcified stromatoporoids *Stromatocerium*, and giant ripple marks. *Isotelus* and other trilobites may be found in some micritic beds.

Photo 3. Fossiliferous beds of the Verulam Formation on Goat Island along Highway 6 at Stop 4.

Return to vehicles and head toward Manitoulin Island on Highway 6.

135.0 km	Turn left on Manitowaning Rd to stay on Highway 6.

145.0 km	Park on the left side of the road, the outcrop is on the right side.

Stop 5A: Sheguiandah Paleozoic Island: Lindsay Formation dolostones and overlying shales on Bar River Formation quartzites

UTM 428264E 5082696N

Potential hazards:

- Busy road with high-speed traffic; stay off road shoulder and remain downflow of parked vehicles if possible; high-visibility vests required

This outcrop exposure displays the unconformity between Paleoproterozoic Huronian Supergroup quartzites of the Bar River Formation and overlying intraformational quartz cobble and boulder, and pebble conglomerates within grainstone lithofacies of the lower Lindsay Formation (Photo 5). The "Sheguiandah Paleozoic island" was a topographic high of Bar River Formation quartzites that formed an island when surrounded by the Lindsay Formation carbonates being deposited in an inland sea. Suggested readings relating to the upper Lindsay Formation and rocky shorelines on Manitoulin Island and on nearby islands include Sproule (1936), Sanford (1957, 1971), Sanford and Mosher (1978), Johnson and Rong (1989, 1990), Robertson (1990), von Bitter (2002) and Maheen (2015). If time permits, a few additional bedding plane exposures on the other side of the highway can be examined.

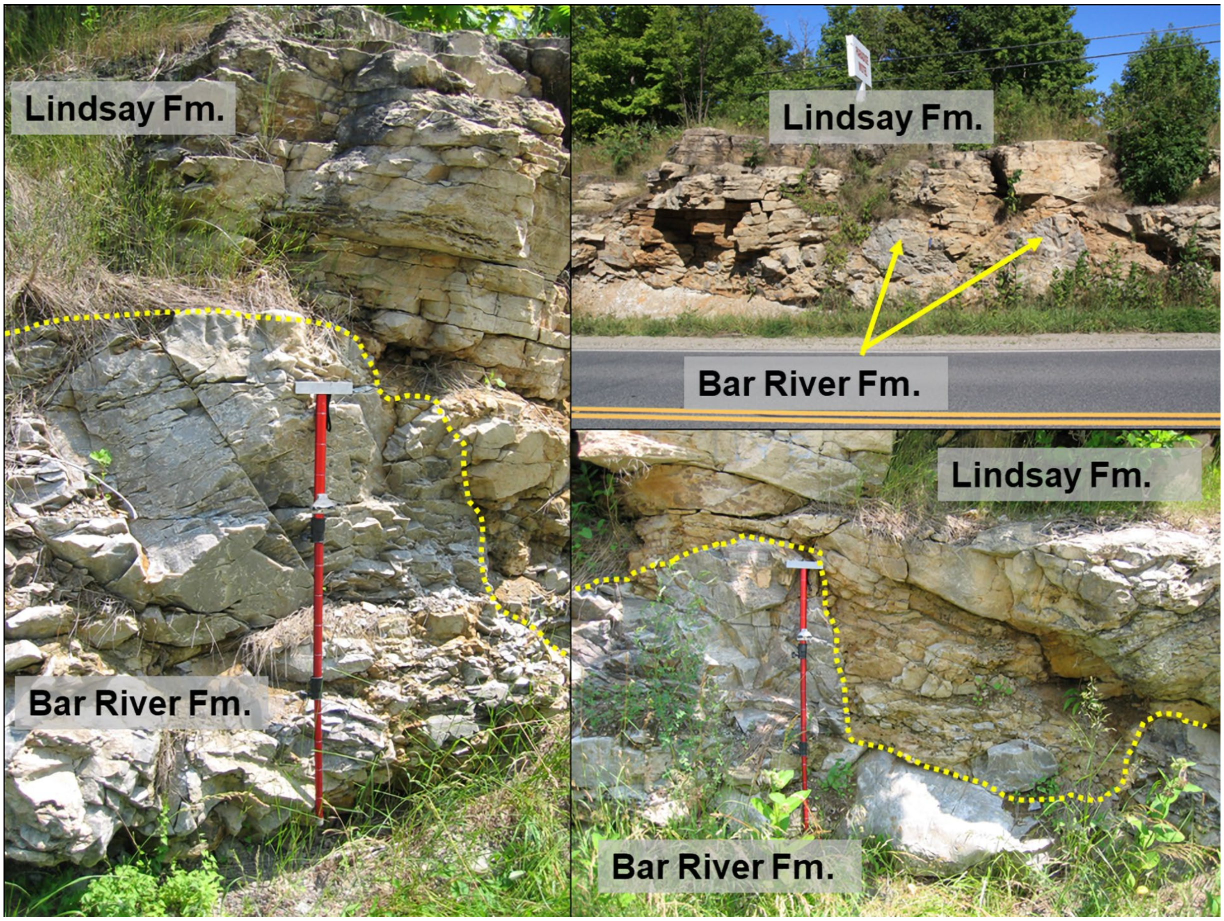

Photo 4. Unconformity at Stop 5A (dashed yellow line) between the youngest of the Paleoproterozoic quartzites of the Huronian Supergroup (Bar River Formation) and the overlying Upper Ordovician Lindsay Formation (uppermost stratigraphic units of Trenton Group). Key features to observe at this outcrop include imbricated quartz pebble conglomerates in basal portions of surge channels between Proterozoic bedrock knobs; chemical weathering of quartzite surfaces; orientation of orthocone nautiloids; and composition and bedforms in the Lindsay Formation. Red Jacob's staff, for scale, is 1.5 m high.

Stop 5B: Sheguiandah: Upper Lindsay Formation (Collingwood Member) and overlying Blue Mountain Formation (Rouge River Member)

UTM 428257E 5082674N

This outcrop exposure displays the Collingwood Member strata of the upper Lindsay Formation and overlying shale and carbonate beds of Rouge River Member of Blue Mountain Formation (Photo 6). The outcrop is across the highway from the Sheguiandah Museum.

In southern Ontario, the contact between the Collingwood Member (Lindsay Formation) and the Rouge River Member (Blue Mountain Formation) is generally easily identifiable because the former is a micritic limestone (finely crystalline, muddy carbonate) and the overlying Rouge River Member comprises noncalcareous shales with thin carbonate beds.

There are known hydrocarbon seeps from this stratigraphic interval on Manitoulin Island. These probably originate from the Collingwood Member as suggested by preliminary OGS drill-core data (Manitoulin core OGS 83-5) that show that this unit has the greatest hydrocarbon source potential (Béland Otis 2015). If time permits, some of the bedding planes at the Batman Sawmill in the village of Sheguiandah can be examined to look for pyritized nautiloids and graptolites.

Photo 5. Contact at Stop 5B (yellow line) between the micritic beds of the Collingwood Member of the Lindsay Formation and the overlying Rouge River Member of the Blue Mountain Formation. Trip leaders K. Hahn and C. Béland Otis provide scale. Red Jacob's staff, for scale, is 1.5 m high.

Stop 5C: Sheguiandah archeological site visit – Mystic Ridge

Potential hazards:

- Steep and/or slippery slopes; loose rocks
- In the forested area, be mindful of low branches and wet ground conditions
- Poison ivy

The remainder of the afternoon is spent at the Sheguiandah Museum participating on a hiking tour of the Sheguiandah site with P. Julig (Photo 7). The Sheguiandah site is a rare upper Great Lakes stratified Paleoindian and Archaic site (for more information, *see* Julig 2002; Anderson 2002; Anderson and Lewis 2002; Barnett 1991, 2002; Julig and Mahaney 2002; Julig and Storck 2002; Karrow 1987; Lee 2002; Long, Julig and Hancock 2002; Sanford 1957, 1971; Storck 2002; von Bitter 2002). This site is stratified in both vertical and horizontal senses, with long-term multiple occupations and archeological deposits from modern lake levels in Sheguiandah Bay to the top of the hill, with Middle Woodland at the Algoma water level, Archaic below the Nipissing beach level, and Paleoindian and later occupations stratified (and mixed) at the Korah level in the "Habitation Area" (von Bitter 2002; Julig 2002) (*see* Ordovician rocky shoreline studies: Johnson and Rong 1989; Johnson 1988a, 1988b, 1992; Robertson 1990; Maheen 2015).

Photo 6. Stone tool demonstration by P. Julig at Sheguiandah National Historic Site on Manitoulin Island at Stop 5C.

Return to vehicles and head back toward Little Current on Highway 6.

158.2 km Turn right on Meredith Street East to stay on Highway 6.

158.8 km Turn left at the Manitoulin Hotel and Conference Centre (accommodations for the night).

DAY 2. ORDOVICIAN AND SILURIAN OUTCROPS

The second day focusses on the Ordovician Georgian Bay Formation and Silurian units. Head south on Highway 6 from the Manitoulin Hotel and Conference Centre.

159.4 km	Turn left on Manitowaning Road to stay on Highway 6.
184.6 km	Turn left at High Falls Road.

Stop 6: High Falls: Georgian Bay Formation (≍ Kagawong Formation)

UTM 433722E 5072240N

Potential hazards:

- Steep and/or slippery slopes; loose rocks
- Vertical outcrops with loose debris; rockfall hazard, hard hats must be worn
- Poison ivy and/or wild parsnip; , long pants and socks advised

This outcrop exposure displays shaly lithofacies grading upward into dolomitic limestones of the Georgian Bay Formation (Photo 8; Foerste 1912, 1916; Caley 1936; Copper 1978; Copper, Jin and Armstrong 1995).

These strata form a prominent cuesta with associated waterfalls (Bridal Veil Falls in Kagawong and Pula Falls in Gore Bay) (*see* Photo 8). In southern Ontario, the Georgian Bay Formation is overlain by the Ordovician Queenston Formation. However, on the island, the latter is absent, and the Manitoulin Formation overlies the Georgian Bay Formation. The base of the Manitoulin Formation was thought to represent the Ordovician–Silurian boundary. However, recent isotopic work suggests that the Manitoulin Formation is latest Ordovician rather than earliest Silurian in age (Bergström et al. 2011) and that the Georgian Bay Formation is not the youngest Ordovician unit on the island.

This formation is approximately 25 m thick on Manitoulin Island and comprises coral and stromatoporoid biostromes, and low diversity brachiopod and eurypterid assemblages (Foerste 1912; Caley 1936; Copper 1981; Copper and Grawberger 1978; Copper and Morrison 1978; Stott, Glasser and Devereux 2001; Stott et al. 2005; Stott and Jin 2007b). This is a brief stop to show the nature of lithofacies in the uppermost Georgian Bay Formation and the prominent scarp that it forms with the only significant waterfalls on Manitoulin Island.

Return to vehicles and continue south on Highway 6.

196.5 km	Park on the left shoulder, just past the outcrop.

Photo 7. Georgian Bay Formation at High Falls at Stop 6. Red Jacob's staff, for scale, is 1.5 m high.

Stops 7A and 7B: Manitowaning barrier reef and nearby patch reefs, Manitoulin Formation

UTM 435694E 5063633N (Back barrier reef mounds);
UTM 435272E 5062633N (Barrier reef structure on Highway 6)

Potential hazards:

- Steep and/or slippery slopes; loose rocks
- Busy road with high-speed traffic; stay off road shoulder and remain downflow of parked vehicles if possible; high-visibility vests required
- Vertical outcrops with loose debris; rockfall hazard, hard hats must be worn

This outcrop exposure displays the core of a barrier reef mound complex with overturned scattered megafaunal invertebrates (e.g., tabulate corals) and evidence of paleokarst surfaces (Photo 9). It may have formed a barrier with abundant patch reefs (30–50 m across and 4–6 m thick) situated to north and forming a linear cluster subparallel to the La Cloche Mountains that formed a paleoshoreline (*see* faunal descriptions in Williams 1919; Copper 1978, 1982; Fay 1983; Fay and Copper 1982; Copper and Fay 1989; Cuffey and Copper 1989; Copper and Brunton 1991; Copper and Long 1993; Copper, Jin and Armstrong 1995).

More than 300 patch reefs have been estimated to be present across the Manitoulin Formation outcrop belt on Manitoulin Island (Fay 1983; Copper and Fay 1989; Copper and Brunton 1991). It appears that large fasciculate rugose corals are more abundant in the easterly patch reefs with stromatoporoids dominant in the reef mounds to the west. Patch reefs are uncommon or absent in the central parts of the island and on the Bruce Peninsula, with only very small bryozoan reef mounds observed (*see* faunal and sedimentological observations in Anastas 1992; Anastas and Coniglio 1992, 1993). The patch reefs or reef mounds extend for approximately 80 km from Tamarack Point on the east coast of Manitoulin Island to west of Green Bay, in Manitoulin Lake, with small bryozoan-dominant reef mounds at Honora Bay. The patch reefs observed on the field trip are approximately 30 to 40 m across by 5 to 6 m in thickness (Fay 1983). Large colonial rugosans and tabulate corals represent the larger mega invertebrates with scattered clathrodictyid stromatoporoids and bryozoans.

Carbon and oxygen isotopic curves suggest that the Manitoulin Formation on Manitoulin Island is older than the Manitoulin Formation present on the Bruce Peninsula and Georgian Bay (*see* discussion in Bergström et al. 2011). Some of these more recent studies (e.g., Bergström, Finney et al. 2006;Bergström, Kleffner et al. 2006; Bergström et al. 2011; Stott, Glasser and Devereux 2001, Stott et al. 2001, 2005)) suggest that the placement of the Ordovician and Silurian boundary should be higher up into the Manitoulin Formation. This is not a new idea and is discussed at the High Falls and Manitoulin Formation stops.

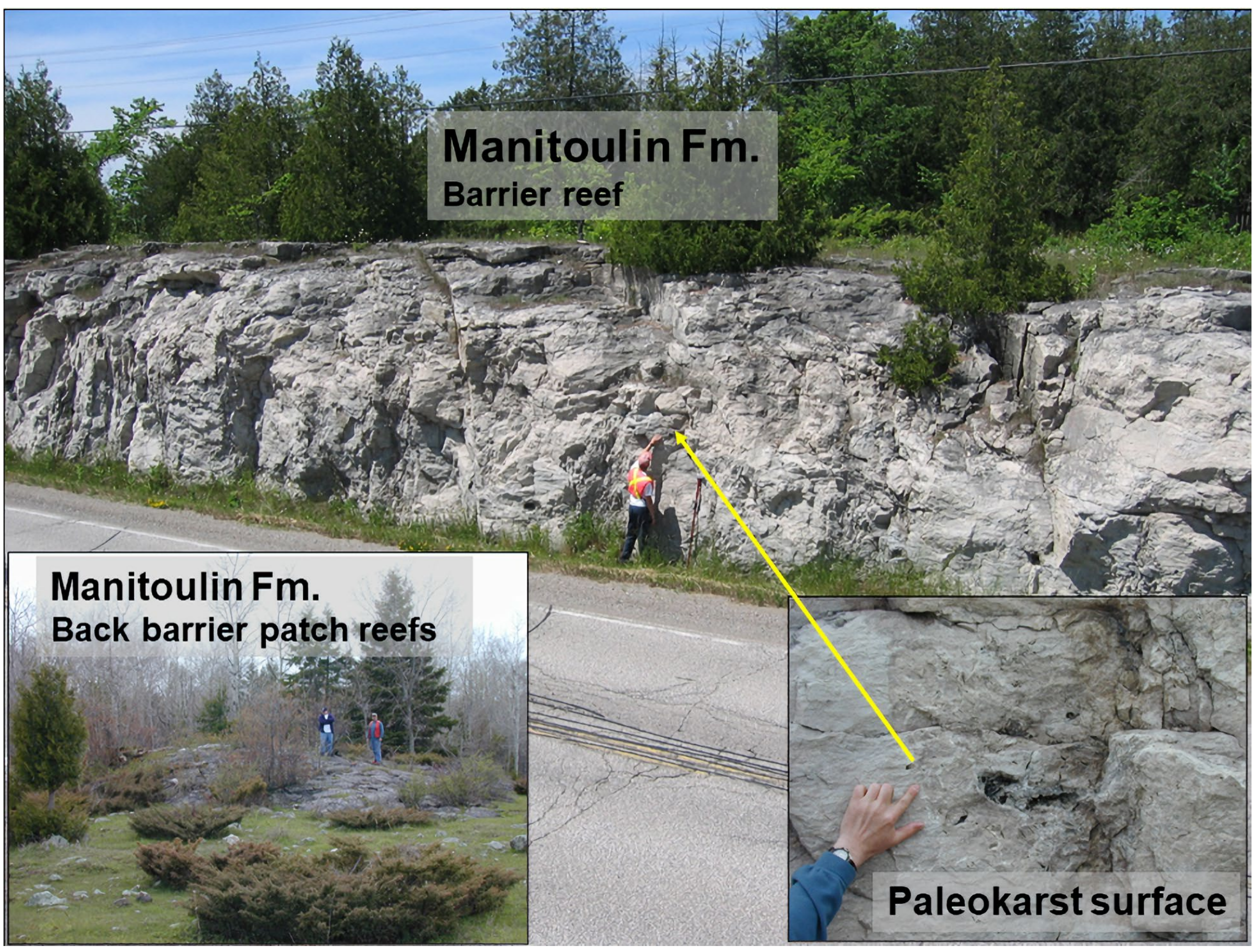

Photo 8. Manitoulin Formation barrier reef complex (main photo) and patch reefs (inset photo in the lower left) at Stops 7A and 7B. The patch reefs are located north of the barrier reef outcrop. Red Jacob's staff, for scale, is 1.5 m high.

Return to vehicles and continue south on Highway 6.

204.0 km Turn left on New England Road. Parking is available just passed the intersection on the left.

Stops 8A and 8B: Fossil Hill Formation type section

UTM 429736:5058540 (type section)
UTM 426203:5057705 (upper fossiliferous Fossil Hill Formation)

Potential hazards:

- Steep and/or slippery slopes; loose rocks
- Busy road with high-speed traffic; stay off road shoulder and remain downflow of parked vehicles if possible; high-visibility vests required
- Vertical outcrops with loose debris; rockfall hazard, hard hats must be worn

This outcrop exposure, along Highway 6 at the intersection with New England Road, displays the key units that make up the Fossil Hill Formation and is the type locality for this rock unit (Photo 10). A second outcrop farther to the south on Highway 6 displays extremely rich coral and sponge lithofacies and some *Pentameroides*-rich beds of the upper Fossil Hill Formation (Photo 11). If time permits, an additional outcrop farther south that contains upper pentamerid brachiopod-bearing Fossil Hill Formation strata can be visited. The contact between the Fossil Hill and disconformably overlying Rockway Formation and thin Irondequoit Formation below the Lions Head Formation (former member of the now invalid Amabel Formation; *see* Brunton 2009; Brunton and Brintnell 2020) is covered, which is generally the case across Manitoulin Island. The type section displays a unit informally referred to as the "false Mindemoya" (Liberty 1968). It comprises a largely faunally barren sublithographic limestone that resembles the underlying poorly fossiliferous units of the upper St. Edmund Formation (Liberty 1968; Copper 1978). *Pentamerus* brachiopod and coralliferous beds are evident below this thinly bedded unit.

The Fossil Hill Formation requires revision as a formational rank unit because there are significant time breaks or disconformities within the formation from Manitoulin Island to Niagara Falls (Stop 8B; *see* stratigraphic data and discussions in Brintnell et al. 2009; Brintnell 2010; Brett et al. 1995; Stott and von Bitter 1999; Brunton and Brintnell 2020). The upper beds of the Fossil Hill Formation may be dominated by pentamerid brachiopods (*Pentameroides*) with lesser atrypids and thin tabulate corals (favositid and heliolitid faunas) and platy stromatoporoids in specific interbeds. The pentamerid shells are highly concentrated and predominantly disarticulated hinge elements, suggesting palimpsest conditions and winnowed, comminuted skeletal and muddy sediments.

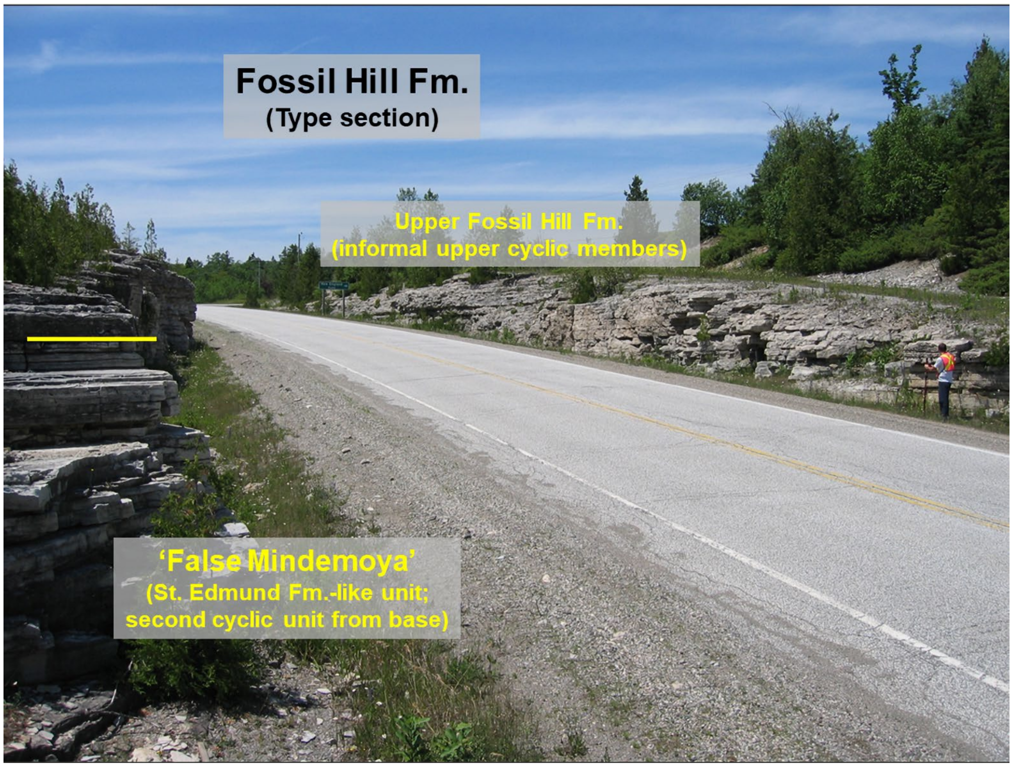

Photo 9. Type locality and section of early Silurian Fossil Hill Formation at Stop 8A located along New England Road, Manitoulin Island. Red Jacob's staff, for scale, is 1.5 m high.

Photo 10. Upper Fossil Hill Formation units located to the south of type section at Stop 8B on New England Road, Manitoulin Island. These units have scattered corals, stromatoporoids and abundant *Pentameroides* brachiopods (= Merritton Formation of Niagara Falls region; Brett et al. 1995; Brintnell et al. 2009; Brunton and Brintnell 2020).

Return to vehicles and head north on Highway 6 to Sudbury (Laurentian University).

248.5 km	Turn right on Meredith Street East to stay on Highway 6 North.
300.2 km	Turn right onto Highway 17 heading east.
365.9 km	Take the Long Lake Road South (Regional Road 80S) exit.
374.0 km	Turn right onto Ramsey Lake Road.
377.0 km	Turn right onto University Road.

End of road log.

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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.*

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