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N. Eyles, R.P.M. Mulligan, R.C. Paulen, and S. Sookhan
(Field trip leaders)

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Leaders: Nick Eyles, Riley Mulligan, Roger Paulen, and Shane Sookhan

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FOREWORD

This publication is a compilation of descriptions of field localities in southern Ontario that were visited during the CANQUA/AMQUA 2018 (joint meeting of the Canadian and American Quaternary Associations: Crossing borders in the Quaternary) post-conference field trip, August 11th to 13th, 2018.

The field trip focused on the geomorphic record of former ice stream tracts within the Laurentide Ice Sheet (LIS) between Lake Simcoe and Lake Ontario, which have been resolved and mapped using high-resolution DEM (digital elevation model) and LiDAR (light detection and ranging) imagery. This exercise showed that deglaciation of the LIS in the eastern Great Lakes sector after ca. 14,400 yrs BP resulted in the onset of several fast-flowing ice streams in southern Ontario and adjacent parts of New York State (NYS). This event postdates the deposition of the Valley Heads Moraine at the southern Finger Lakes in NYS, is coeval with the previously recognized St. Lawrence Ice Stream, and it records region-wide reorganisation of flow within the ice sheet. Topographic confinement and the presence of large ice frontal lakes that formed during the regional warming of the Bölling-Alleröd interstadial appear to have been keys to the onset of fast ice flow. Megascale glacial lineations on rock and sediment indicate a common erosional origin along ice stream corridors. These lineations are part of a bedform continuum with drumlins: 'channeled drumlins' are an intermediate morphotype recording lowering of high-standing asperities (drumlins) to form a lower relief megalineated bed. The 160 km-long Oak Ridges Moraine (ORM) was formed between the convergence of the Simcoe and Halton ice streams just after ca. 13,300 yrs BP, preceding the formation of glacial Lake Iroquois. New subsurface data from deep drilling of the ORM also inspires a review of past models and supports the new paradigm of LIS deglacial history. For additional context, a long list of supplemental references is also provided for the reader.

The original CANQUA/AMQUA field trip guidebook has undergone review and editing by the Geological Survey of Canada. The authors would like to acknowledge all the reviewers, especially Alain Plouffe who provided a final review of this entire guidebook. Elizabeth Ambrose is thanked for a thorough grammatical review and the digital page layout. We trust this collection of field stops and an examination of the surficial geology of southern Ontario under a new palaeo-ice stream paradigm will be of interest and use to active and future Quaternary and related activities in the glaciated terrain of southern Ontario. This publication is also available as Ontario Geological Survey Open File 6348.

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Subglacial bedforms in southern Ontario —from flood paths to flow sets: CANQUA/AMQUA Post-Conference Field Trip

Trip Leaders: Nick Eyles (University of Toronto), Riley Mulligan (Ontario Geological Survey),
Roger Paulen (Geological Survey of Canada), and Shane Sookhan (University of Toronto)

ADVANCES IN PALEOGLACIOLOGY

The last 25 years has seen a profound change in understanding of the paleoglaciology of Pleistocene and pre-Pleistocene ice sheets. What were originally modelled as simple domes are now recognized to have resulted from a more complex structure and topography with very fast-flowing (<10 km/yr) low-profile 'ice streams' based on the distinct geomorphology of their beds (megascale glacial lineations: MSGLs; Clark, 1993; Stokes and Clark, 2002a; King et al., 2009; LeHeron, 2018; Fig. 1) that were inset within more sluggish flowing parts of the ice sheet. The role of these ice streams has been likened to arteries within organisms transporting large volumes of ice, water and sediment (e.g. Bennett, 2003; Dowdeswell et al., 2016).

In North America, the glacially megalineated flow paths of almost 220 paleo-ice streams have been identified across the beds of the former Late Wisconsin Laurentide Ice Sheet (LIS: Fig. 2) and the Cordilleran Ice Sheet (CIS: Fig. 3) (e.g. Clark, 1993; Patterson, 1997; Dredge, 2001; Mickelson and Colgan, 2003; De Angelis and Kleman, 2005, 2007; Ross et al., 2006, 2009; Dyke, 2008; Evans et al., 2008; MacLean et al., 2010, 2015, 2017; Margold et al., 2015a,b, 2018; Dowdeswell et al., 2016; Eyles and Doughty, 2016; Putkinen et al., 2017; Shaw and Longva, 2017; Stokes, 2017; Veillette et al., 2017; Sookhan et al., 2018a,b; Eyles et al., 2018). Several 'ice stream landsystem' models have been proposed to portray their depositional and geomorphic record (e.g. Stokes and Clark, 1999, 2002a,b; Evans et al., 2008, 2014; Stokes, 2011) and there is corresponding interest in implications of the ice stream paradigm for mineral exploration (e.g. Dyke and Morris, 1988; Ross et al., 2011; McMartin et al., 2015a,b, 2017, 2018; McMartin, 2017; Paulen et al., 2017). A pressing priority is to complete a full inventory of ice streams at different stages within the life cycles of the LIS and CIS, and to identify pathways in areas of hard bed, especially within the Canadian Shield where bare smooth rock may have had an analogous role in promoting fast flow that deforming sediments have within soft beds (e.g. Krabbendam et al., 2016). The critical importance of high-resolution imagery is apparent in mapping former ice stream beds.

OBJECTIVES AND OVERVIEW OF THE FIELD TRIP ROUTE

This field trip will examine the hard (rock) and soft (sediment) beds of several ice streams that developed during deglaciation of the Ontario Basin (Figs. 4, 5). Deep drilling, geophysical surveys, field mapping, and integration with detailed outcrop studies, especially by the Ontario Geological Survey, has provided greater understanding of the thickness, distribution, and character of glacial sediments and regional groundwater resources in southern Ontario (Figs. 6–10). This information has revealed much of the early history and paleogeography of pre-Last Glacial Maximum (LGM) ice margins and lake bodies recorded by the infill of a major buried valley (Laurentian Valley: Figs. 10–13).

In southern Ontario during the LGM, regional ice-flow directions were generally southward and southwestward (Fig. 14A); however, during deglaciation, ice flow was strongly topographically controlled and more than 10 Late Wisconsin paleo-ice streams can be identified across the Lake Ontario Basin, extending as far south as the Finger Lakes in New York State (Sookhan et al., 2018a; Figs. 4, 14B). The onset of ice streaming is marked by deposition of the Valley Heads Moraine in central New York State at ca. 14,500 ybp (uncalibrated age) along the margin of the Seneca-Cayuga Ice Stream (Fig. 4). The largest of these ice streams (the Ontario-Erie Ice Stream: OEIS) flowed southwest along the St. Lawrence Valley from the southern Quebec sector of LIS, along the axis of the present-day Lake Ontario Basin (Eyles and Doughty, 2016; Sookhan et al., 2018b). This was the mirror-image of a long-recognized ice stream that flowed *eastward* from southern Quebec along the confines of the St. Lawrence Valley to terminate at a marine-based ice margin in the Gulf of St. Lawrence (the St. Lawrence Ice Stream of Occhietti et al., 2001, 2011; Ross et al., 2006). In contrast to earlier phases of flow, these large ice streams were controlled by topography (Figs. 5, 10); cross-cutting bedforms are widespread and indicate dynamic changes in ice-flow direction and the importance of 'flow switching' (e.g. Ross et al., 2006). The presence of a former ice stream flowing along the axis of the Ontario Basin had been suggested by Taylor (1913) based on the then contemporary identification of modern ice streams in Arctic Canada (*see* Brookes, 2007). Fast ice flow through parts of the New York State Drumlin Field was initially proposed by White (1985), Mullins et al. (1996) and Hart (1999), and subsequently confirmed by Briner (2007) and Hess and Briner (2009) on the basis of so-called highly elongated 'megaflutes'—now confirmed as megascale glacial lineations (MSGL) by LiDAR-based mapping (Sookhan et al., 2018a). Current discussion focusses on the timing and duration of fast ice flow in the life cycle of the LIS and the nature of the triggers on streaming, e.g., deep ice-frontal lakes and 'topographically constrained' flow during deglaciation (*see* Stokes et al., 2016; Stokes, 2017).

This three-day field trip starts and finishes in Ottawa, Ontario and extends as far south as Niagara Falls, along the border between the USA and Canada (Fig. 5). The 'hard' (rock) and 'soft' (sediment) beds of three lateglacial ice streams (Ontario-Erie, Halton and Simcoe: Figs. 4, 15) are well exposed and have been recently mapped using high-resolution digital imagery. We will discuss formative models for drumlins and MSGLs on rock and sediment, and speculate on their relationship to ice-flow velocity. In addition, the trip will review recent developments in the understanding of the earlier (pre-Late Wisconsin) glacial history of the region, which is being revealed by drilling of deep buried valleys such as the Laurentian Valley. The trip will also include reference to the geology and origin of the region's largest glacial landform, the Oak Ridges Moraine (ORM), which is 160 km in length with an estimated volume of 70 km^3 and is now recognized to have formed between converging ice streams (Sookhan et al., 2018b; Figs. 4, 14B).

On Saturday August 11th (and the morning of Sunday August 12th), we will examine the geomorphology of the upstream hard bed of the OEIS in the Kingston area, which consists primarily of glacially streamlined Paleozoic carbonates and clastics, and the drumlins and MSGLs on its downstream soft bed, which can be seen near Peterborough (Figs. 15, 16). The geomorphology of these two subglacial terrain types is directly analogous to the upstream and downstream beds of Antarctic ice streams (e.g. Livingstone et al., 2012; Fernandez et al., 2018).

The OEIS flowed southwest into the Ontario Basin from source areas in southern Quebec and moved across a low-relief arch of ca. 1 billion-year-old Proterozoic metasediments and gneisses of the Canadian Shield near the city of Kingston (Frontenac Arch: Fig. 10). This separates the overdeepened basin of Lake Ontario (246 m below sea level at its deepest in the Rochester Basin) from the narrow fault-controlled St. Lawrence Valley. As was first recognized by Gilbert (1899), ice flowed across the Frontenac Arch onto offlapping gently dipping and commonly faulted Cambro-Ordovician carbonate and sandstone strata (Fig. 17), which comprise a glacially streamlined hard bed present over an extensive area that can be traced from southern Ontario across the floor of Lake Ontario into upper New York State (Figs. 18–21). North-facing escarpments, which mark the outcrop of more resistant carbonate units, are extensively drumlinized by fast ice flow, with dip-slopes marked by megagrooves akin to mega-scale glacial lineations (Eyles, 2012; Eyles and Doughty, 2016; Krabbendam et al., 2016). The associated flow of turbulent, sediment-laden subglacial meltwaters within bedrock channels is also recorded on the hard bed (e.g. Shaw, 1988; Pair, 1997).

The hard bed of OEIS is partially covered by hummocky spreads of locally derived morainal debris of carbonate breccias with large angular blocks and slabs of limestone, reflecting extensive subglacial plucking and quarrying of well jointed carbonates from north-facing escarpments (Fig. 15). Historically, this material has been mapped as the so-called 'Dummer Moraine', however, it is not a moraine *sensu stricto* but comprises subglacially transported limestone rubble of varying thicknesses. The chaotic hummocky topography is suggestive of passive melt-out of englacial debris but new imagery reveals some local organization into distinct small moraines that may be ice frontal or Rogen moraines; discrimination awaits a detailed study. Representative exposures occur on Highway 41 en route from Kingston to Peterborough, where we will move on to the soft bed to examine 'drift drumlins' (i.e. those composed of sediment) and accompanying (and demonstrably transitional) megascale glacial lineations of the Peterborough Drumlin Field (PDF: Fig. 22). The PDF is in fact, part of a broad regional belt of streamlined till that extends west to the Niagara Escarpment and beyond, and south into upper New York State (Figs. 6, 7), with an estimated 20,000 individual bedforms that have long been studied by glacial geologists (Fairchild, 1900, 1929; Sookhan et al., 2018a,b and cited references therein). Recent study of these bedforms reveals drumlins that are transitional to MSGLs, indicating that they are part of a bedform continuum (Figs. 22–24).

Sunday morning we will drive south from Peterborough toward the ORM and discuss the implications for its origin in the context of converging ice streams that have been identified north and south of the ORM by MSGLs (Figs. 14B, 25–31). Those to the south record the fast flow of the Halton Ice Stream (HIS) at about 13,000 ybp, whereas those to the north were left by the southward-flowing Simcoe Ice Stream (SIS). The ORM accumulated rapidly (in several hundred years) as a series of *en echelon* subaqueous ice-contact fans in a narrow lacustrine basin trapped between the HIS and the SIS. By analogy with modern ice streams and their margins, fast ice flow is known to move very large volumes of ice, water and sediment, which is reflected in the formation of large 'morainal banks' at their margins. We will discuss the origin of valleys cut into the streamlined bed of the SIS south of Lake Simcoe, which channeled water and sediment to the ORM (Figs. 32–33).

As we drive from Peterborough to Toronto there is a marked increase in the thickness of glacial sediments associated with a prominent buried bedrock valley system (Laurentian Valley: Figs. 10, 11). These deposits locally reach thicknesses of >250 m. Deep drilling and geophysical studies of its infill are providing new insights into the pre-Wisconsin history of southern Ontario and the origins of subsequent Wisconsin sediments that predate the LGM and subsequent deglacial phase of ice streaming (Figs. 11–13). The infill records a long history of Illinoian glacial, Sangamon interglacial and Wisconsin glacial environments, and the corresponding changes in drainage from the upper Great Lakes to the Ontario Basin (Mulligan and Bajc, 2018). Early and Middle Wisconsin glaciolacustrine sequences are exposed at the Scarborough Bluffs along the Lake Ontario shoreline (Fig. 13B). There, we will discuss the broader regional 'cross border' significance of these units. If time permits we will visit the Don Valley Brickyard in Toronto where Sangamon and underlying Illinoian deposits (York Till) were discovered by A.P. Coleman during quarrying operations in the 1890s.

Leaving Toronto, we will drive west to the city of Hamilton along the floor of lateglacial Lake Iroquois to see the Niagara Escarpment en route to Niagara Falls (Fig. 5) There we will explore the origin and history of the Niagara Gorge (Figs. 34–36) in the light of new work on the postglacial history of the Great Lakes.

On a historical note and in keeping with the theme of the joint CANQUA/AMQUA meeting ('Crossing Borders'), the region covered by the field trip lies along the Canada-US border, which is one of the longest settled in Canada. Southern Ontario saw an influx of Loyalist settlers from the US at the time of the American War of Independence (1775–1783) and was the site of numerous conflicts during the War of 1812 between the British and their Canadian allies and the USA, and later during cross-border raids by the Fenian Brotherhood (1866–1871), which strengthened political support for Canadian confederation in 1867.

DETAILED ITINERARY

Note: The sites described in this field guide can be found on a website that describes more than 600 sites of geological interest across Ontario (https://planetrocks.utsc.utoronto.ca/). This website supports both Street-View and Google Maps.

Day 1: Saturday August 11th

We will leave Ottawa at 12:30 pm on Saturday August 11th to drive to the Kingston area via Perth. We will examine the hard bed of the OEIS that developed on the Shield and offlapping Paleozoics before crossing onto the soft bed near Peterborough, which is characterized by drumlins and megalineations. We will stay in Peterborough Saturday night.

Much of the city of Ottawa is built on the floor of the lateglacial (ca. 11,500 ybp) Champlain Sea, which flooded the newly deglaciated and still glacio-isostatically depressed St. Lawrence Lowlands. This created good farmland but left unstable 'quick clays' (Leda Clay) that is prone to landsliding, resulting in evacuation of communities (e.g. the Lemieux slide: Brooks et al., 1994). Ongoing work by the Geological Survey of Canada indicates many large pre-historic landslides along the Ottawa Valley may have been triggered by earthquakes.

At the close of the last ice age (ca. 11,000 ybp), the Ottawa River carried meltwaters from extensive proglacial lakes (Agassiz, Algonquin) ponded in the upper lake basins by the retreating margin of the LIS. An exit for rivers, this part of Ontario has also been a doorway from Montreal to the interior of the continent coveted at various times by First Nations, French, Americans and British, whose conflicts have played a crucial role in Canadian history. In November 1813, the decisive battle of the War of 1812 (the 'battle that saved Canada') was fought between the USA and Britain at Crysler's Farm near Morrisburg, along the shores of the St. Lawrence River. It confounded those in Washington, such as former President Thomas Jefferson who remarked in August 1812 that the conquest of Canada would be a "mere matter of marching".

Ottawa lies within the so-called Ottawa Embayment, underlain by Paleozoic carbonates and clastic rocks that accumulated within a complex failed rift system of a triple junction within the margin of Proterozoic North America (Laurentia) as Rodinia broke up after 750 Ma. Both the Ottawa and St. Lawrence rivers follow failed rifts, similar to other large rivers worldwide. This complex structure (and its Paleozoic fill) was reactivated during the subsequent breakup of Pangea and the nation's capital is underlain by numerous faults that define the Ottawa-Bonnechere graben. The sharp northern margin of the graben is best seen from the Champlain Lookout in the Gatineau Hills and faults are well exposed at Hogs Back Falls. The area lies within the Western Quebec Seismic Zone (Fig. 17B), where an 'intraplate' earthquake occurs on average every five days; in 1732, Montreal received significant damage when it was shaken by an earthquake estimated to have had a magnitude of 5.8. In 1935, the Temiskaming area, at the western end of the rift, experienced an earthquake of magnitude 6.2, and is associated with ongoing neotectonic activity; the provinces of Ontario and Quebec, whose border lies along the rift, are separating. The 1944, magnitude 5.6 temblor at Cornwall, Ontario is Canada's most costly earthquake to date. These events are related to deep-seated (>10 km depth) structures, such as terrane boundaries in the Shield, undergoing ductile reactivation, resulting in brittle failure of overlying crust.

There is a distinct association between kimberlite pipes and the graben system in the upper (northern) part of the Ottawa Valley near New Liskeard and Lake Timiskaming. Several faults cross the floor of Lake Ontario into upper New York State. Well defined southwest-trending shear zones, faults and other less well known 'lineaments' occur at the margins of 'terranes' (or 'domains'), as a result of repeated obduction of crustal blocks during prolonged collision of ancestral North America and northern South America (Amazonas craton) during the Mesoproterozoic ca. 1.5–1.0 Ga Grenville Orogeny. The most prominent structure is a ~5 km-wide seismogenic shear zone, the Central Metasedimentary Belt Boundary Zone (CMBBZ: Fig. 3), between the Central Gneiss Belt (CGB) to the west and the Central Metasedimentary Belt (CMB). This structure lies below the nuclear generating facility at Pickering on the northern shore of Lake Ontario and crosses the lake to pass under the Niagara Peninsula into Pennsylvania. Reactivation of old deep structures, and propagation through younger overlying Paleozoic rocks, a common theme in southern Ontario, exerted a strong control on the depth of Quaternary glacial erosion; most lake basins and buried valley networks are structurally controlled (e.g. Doughty et al., 2014; Fig. 17).

Hard bed

Southward from Ottawa near Perth on Highway 10, the irregular surface of the Canadian Shield rises from under the cover of Paleozoic strata and glacial sediments of the Ottawa Embayment, resulting in a dramatic change in landscape and land use of exposed Shield, forests and lakes—best described as 'cottage country'. Glacially scoured monadnock-like knobs of granite, granulite, gneiss and mylonites together with a wide variety of much softer metasedimentary rocks, such as marbles and metaturbidites of the Precambrian (Mesoproterozoic) Grenville Province are ubiquitous. Differential weathering and glacial erosion of weaker strata, such as marble, has created thousands of ice-scoured lake basins.

At Westport on Highway 10, we will cross the Rideau Canal that connects Ottawa and Kingston (which was founded in 1673 as the French trading post, Fort Frontenac, and was briefly the capital of the Province of Upper Canada from 1841 to 1844). Kingston is known as 'the limestone city' because of the widespread use of Ordovician limestone as a building material. The Rideau Canal, which was completed in 1832, was constructed to be a safe inland route from Lake Ontario to the Ottawa River and then to Montreal if US forces invaded across the St. Lawrence River. It is the longest continuously operating canal system in North America. It terminates in Ottawa, which became the capital of the new nation of Canada in 1867. The location was purposely sited at the boundary of the Shield to the north and the Paleozoics to the south, and at the boundary of the former colonies of Upper and Lower Canada that were established in 1791 to accommodate Loyalist refugees from the USA.

The so-called 'Great Unconformity' between the Shield (gneisses of the Central Metasedimentary Belt of the Grenville Province) and overlying Paleozoic carbonates (Ordovician Shadow Lake Formation) can be seen at numerous sites around Kingston, where the buried Shield slowly rises eastward to be exposed as the Frontenac Arch. The best example can be seen in a road cut at Inverary (**Stop 1**). The 600 Ma-old Holleford Meteorite Impact Crater occurs on the Shield 15 km to the northwest and is infilled with the Lower Paleozoic Shadow Lake Formation.

Southwestward-dipping Paleozoic strata display multiple glacially streamlined escarpments that form a stepped topography across an area of at least 500 km^2 and which are cut by fault-controlled 'through valleys' occupied by lakes (Camden, Varty, Odessa, Loughborough, Collins, Cataraqui, etc.). These valleys separate drumlinized interfluves of varying width, from bullet-shaped upglacier noses that are repeated down dip on other escarpments on the limestone plains (Figs. 16–21). The through valleys and lakes seen on the field trip are representative, albeit on a small scale, of the many large lakes found along the margins of the Shield in Canada (Great Slave, Great Bear, etc.) and record enhanced glacial erosion of offlapping Paleozoic strata by ice streaming off the Shield. Large erratics of Proterozoic gneiss can been seen scattered across the limestone plains (**Stop 2**).

Meltwater-cut scours ('flutes', 'scallops' and potholes) are a common feature on 'hard beds' where recharge of subglacial meltwater into the bed was limited. An abandoned quarry along Wilton Creek (**Stop 3**) exposes erosional scours cut in limestone along the floor of a bedrock valley in the megagrooved limestone plain of the Middle Ordovician Bobcaygeon Formation. The former quarry consists of a series of bedrock steps that reflect alternations of limestone and shale within the Ordovician Bobcaygeon Formation. The site lies on the northern margin of a large flow set of megagrooves that were cut into the limestone and that extend for 15 km from Highway 401 to the northern end of Odessa Lake. Straight 'spindle-shaped', curved and braided flutes (erosional scallops) with sharply defined rims occur in large numbers in conjunction with striations. These subglacial fluvially cut forms are of some significance as they were used by Shaw (1988) and Gilbert and Shaw (1994) to develop a model of regionally extensive catastrophic subglacial sheet floods (but *see* Pair, 1997).

Note: The site at Stop 3 is on gated private land and permission must be obtained from the owner to enter the site.

A road cut on Highway 6 north of Odessa (**Stop 4**) provides a cross-section through a megagrooved limestone plain that is underlain by the Middle Ordovician Bobcaygeon Formation (Fig. 19A). The grooved plain is bounded to the north by an escarpment that shows numerous 'conjoined' rock drumlins. This is the northern end of a 15 km-long flow set of megagrooved limestone plains that extends from Loughborough Lake through Odessa Lake to Wilton Creek. The grooved and drumlinized plain extends into New York State (Figs. 18–21). See Eyles and Doughty (2016), Krabbendam et al. (2016), and Newton et al. (2018) for recent descriptions of bedrock megagrooves and their relationship to fast ice flow.

The southwest flow direction of the OEIS during deglaciation reflects the important control the deep bedrock basin (now occupied by Lake Ontario) had on ice flow. During deglaciation around 13,000 ybp when the western part of the Ontario Basin was ice free, part of the ice mass occupying the remainder of the basin surged northwestward toward the Niagara Escarpment as the Halton Ice Stream (HIS). An exposed surface of Bobcaygeon limestone south of Highway 401 at the end of Shane Street (Fig. 19B: **Stop 5**) shows several sets of crossing striations on glacially grooved surfaces, reflecting complex flow switching.

Note: The site at Stop 5 is on gated private land and permission must be obtained from the owner to enter.

Large volumes of bouldery limestone rubble (a.k.a. 'Dummer Moraine': Fig. 15) were plucked from the flanks and fronts of drumlinized interfluves along the escarpment of the Shadow Lake and overlying Gull River formations. Highway 41, between Grieves Corners and Roblindale Station, exposes representative facies of the Dummer Moraine (**Stop 6**). The railway track immediately to the north follows low ground along the Salmon River fault. The outcrop lies on the footwall block, which can be traced southwest across the floor of Lake Ontario into New York State. The same plucking process occurred widely across the hard bed, generating a very large flux of coarse debris downglacier. Subglacial mixing of this debris with overridden fine-grained glaciolacustrine sediment was a very effective till-generating mechanism that resulted in the typical carbonate-rich tills of southern Ontario and the dilution of crystalline lithologies derived from the Shield.

Tracts of Dummer Moraine were a major obstacle to mid-nineteenth century European settlers faced with the prospect of 'farming rocks' on the limestone plains south of the Shield (popularly known as '*the land in between*'). Today, it is a strangely attractive landscape of bare limestone plain: hummocks of bouldery rubble with large slabs of limestone, farms that have gone back to bush, lakes and forest, with the odd small patch of glacial sediment that can be grazed. One of Canada's most acclaimed poets, A. Purdy (1918–2000) (known as the 'Voice of the Land'), who was born in Wooler, just north of Trenton, wrote about the area in his most famous poem, *The Country North of Belleville*, contrasting the "*fat south*" of rich farms and deep soils with the "*country of our defeat*" and the many hills that "*picknicking glaciers have left strewn with centuries' rubble*".

Soft bed

As we drive west from Kingston along Highway 401, Paleozoic strata are progressively buried by glacial sediments that comprise the 'soft bed' of the OEIS, HIS and SIS (Fig. 4). As noted by Gravenor (1957) and Eyles and Doughty (2016), the margin between the two is very irregular and is marked by closely juxtaposed rock drumlins carved into Paleozoic carbonates of the underlying 'hard bed' and 'drift drumlins' (sediment-cored); this relationship was used by Gravenor (1957) to argue that both types were erosional in origin, an idea supported by much prior work elsewhere in drumlin fields (*see* Eyles et al., 2016 for a review).

Highways 1 and 14 will take us north from Highway 401 to Highway 7 where we will drive west through the community of Marmora, which has a long history of mining (iron, talc) Proterozoic metasediments along the southern edge of the Canadian Shield. Ontario's first gold mine (the Richardson Mine) opened (briefly) in 1866. Paleozoic limestones exposed in road cuts immediately west of Marmora contain thin (~10 cm) bentonite layers from unknown volcanoes dated at ca. 447 Ma, marking the onset of the Taconic Orogeny when the African plate began to collide against eastern North America (to create Pangea). On Highway 7 west of the community of Havelock, the landscape changes once again with the appearance of large farms accompanying thickening of the glacial sediment cover along the eastern edge of the Peterborough Drumlin Field. Highway 7 crosses a large esker system at Norwood, which originates on the hard bed to the north. Ongoing work shows the widespread presence of MSGLs among drumlins, which is an emerging theme in the international literature, as 'drumlin' fields are increasingly re-examined and re-mapped using new high-resolution imagery.

Peterborough Drumlin Field

Drilling and observation of quarry exposures and road cuts shows that the 'drift' drumlins around Peterborough are composed of a wide variety of sediments; including poorly sorted, coarse-grained, ice-contact glaciofluvial sediments and fine-grained glaciolacustrine facies. These often account for the entire volume of individual drumlins that lack any surficial till drape (Maclachlan 2011; Maclachlan and Eyles, 2013; Marich, 2016), confirming that the drumlin form cross-cuts and that drumlinization was genetically unrelated to underlying sediments (Gravenor, 1957; cf. Sharpe, 1987). The importance of erosion in the formation of drumlins (and the common presence of coarse-grained sediment in their cores) conflicts with the proposed theory that drumlins form as wave-like 'bumps' that grow upward from the bed as a result of deformation of soft till (i.e. the 'instability theory' of Stokes et al., 2013).

Many drumlin cores show a dense and very coarse-grained till rich in angular carbonate debris, akin to Dummer facies, mixed with outwash. This unit thickens to the south to a maximum of ~70 m near Lake Ontario, where it is mapped as Northern Till (and locally as Newmarket Till). Geophysical, outcrop, and core data show that the Northern Till is an accretionary till sheet composed of distinct beds reflecting 'incremental aggradation' of deforming subglacial debris (Boyce and Eyles, 2000; Evans and Hiemstra, 2005). Quarrying of large volumes of carbonate debris from the hard bed, the presence of large ice frontal lakes, and the overriding and remobilization of fine facies were important factors in generating thick till. We will see outcrops at Peterborough of what can be called 'immature' Northern Till and discuss till-forming mechanisms.

The Peterborough area shows numerous examples of large northeast/southwest-oriented drumlins that are 'grooved', 'bisected' or 'channeled' to form more elongate bedforms and MSGLs (defined as having an elongation ratio of length/width of >10). Many have a comet-like appearance with distinct tails that are, in places, oriented oblique to the original drumlin form, pointing to multiple phases of ice flow. 'Channeled' bedform morphologies, which were first identified in New York State by Fairchild (1900), are very common and have been mapped at Peterborough as 'complex drumlins' (Crozier, 1975). They are a recurring feature of drumlin fields in general and provide strong evidence that drumlins and MSGLs are transitional within a subglacial bedform continuum (*see also* Barchyn et al., 2016; Fig. 22). The transition points to the key role of subglacial erosion in reducing the height of bed asperities (drumlins) formed under relatively low-velocity steady-state ice flows, to reduce friction and create a 'low drag' bed of MSGLs under streaming ice (Sookhan et al., 2018a). The same grooves and ridges occur on fault traces (from micro to macro at sizes comparable to that of subglacial forms), at the base of large landslides and debris flows, on man-made surfaces undergoing frictional wear, and notably in the biological realm; they indicate a commonality of processes and form. This is the subject of the science of 'tribology', which recognizes the erosive role of 'a third body' composed of eroded debris between two surfaces undergoing wear. A thin deforming till layer immediately below the ice base is in effect a third body (what Eyles et al. (2016) term an 'erodent layer') capable of shaping underlying non-deforming sediments into streamlined residuals.

Figure 22A can be used as a basis for an extended self-guided tour of the principal subglacial bedform types in the Peterborough Drumlin Field. A good starting point is the Coffee Time store at the intersection of Highway 7 (Trans-Canada) and Highway 34 (Heritage Line) - Highway 28. Drive north on Highway 28 and turn left (west) on Old Norwood Road for a splendid view of a drumlin on the left (south), about 750 m from Highway 28. Proceed west, crossing the railway track, and drive through narrow ridges that are the tails of a large 'comet-like' drumlin (location A). Note the well developed MSGL ridge at location B. Cross over Providence Line and continue to Drummond Line; turn right and drive north to Division Road and take a right (east). In about 1 km, the road crosses the summit of a large drumlin with a great view over the drumlin field.

Note the high plateau area on the skyline to the southeast; these are higher elevation parts of the field underlain by thick antecedent sediments into which drumlins have been carved; most of the drumlin field occurs at lower elevation having been lowered by subglacial erosion. In general, the most elongated bedforms occur at the lowest elevation, the least elongated on the higher parts. Bedrock is close to the surface over large areas between drumlins, likely resulting from the complete removal of sediment, exposing successively larger areas of the hard bed below.

Continue east on Division, cross Highway 28, turn left (north) on 5th Line, and immediately on the right is a remarkable view of paired drumlins, apparently carved from an initially larger drumlin bedform (location C). Continue north on 5th Line to turn right (east) onto Highway 8. At Douro 4th Line - Jermyn Line turn right (south) to return to Highway 7. Note an excellent example of 'channeled' drumlin ridges that can be seen 1 km north of Highway 7.

Urban development and construction in Peterborough has exposed temporary outcrops through MSGLs; these show a thin (~1.5 m) surface drape of a clast- and boulder-rich till, which is possibly a preserved erodent layer (e.g. location D). Other drumlins lack surface till drape and are composed entirely of antecedent sediment, commonly glaciolacustrine and proglacial outwash facies.

From Coffee Time Donuts at the intersection of highways 28, 34, and 7, turn left (south) drive 3 km on Highway 34 (Heritage Line). Turn left (east) onto Esson Line and follow this gravel road back to Highway 7, noting numerous examples of bisected drumlins. Turn right (east)on Highway 7 and proceed to Villiers Line, turn right and drive south for 3 km and turn left (east) on Elmhirst Road, where more channeled drumlins can be seen, especially at the intersection of Elmhirst Road and Villiers Line. Turn right (south) on Villiers Line to Highway 2. Turn right (west) and proceed across the Indian River to Highway 34 and right (north) back to Highway 7, noting the many examples of channeled drumlins en route.

We will stay in Peterborough Saturday night. The city is located on the Trent-Severn Canal that connects Trenton on Lake Ontario to Port Severn on Georgian Bay; the first lock was built in 1833 and the entire system took 87 years to complete. It was a financial disaster (until the advent of recreational boating in the 1950s) but the hydraulically operated lift lock at Peterborough is an engineering marvel not to be missed.

Day 2: SUNDAY August 12th

On Sunday morning we will drive south from Peterborough into the northern part of the Greater Toronto Area to cross the ORM deposited between the Simcoe and Halton ice streams (Figs. 14B, 25, 26). The ORM is the largest glacial landform in southern Ontario and sits on a broad high on the Late Wisconsin subglacial bed, composed of bedrock in the west and thick pre-Late Wisconsin sediments in the central and eastern parts, stretching from the Niagara Escarpment in the west to the Trenton area, some 160 km to the east. Along its length, the ORM occurs as 4 distinct 12–20 km-wide beds that are separated by much thinner (3–5 km-wide) zones (the 'wedges' of Barnett et al., 1998; Fig. 25). These are large fan-delta complexes, which are composed of stacked cross-cutting successions of sand, gravel, silt, and diamict facies, which were deposited subaqueously in a complex depocentre trapped between the Simcoe and Halton ice streams. Most of the water was fed across the bed of the Simcoe Ice Stream (Figs. 32, 33). Some 70 km^3 of sediment was likely deposited in 1000 years if not less (Gilbert, 1997), which underscores the importance of ice streams in moving large volumes of ice, water and sediment to their margins.

Streamlined bed of the Simcoe Ice Stream north of the Oak Ridges Moraine

We will stop near the town of Greenbank on Marsh Hill Road (**Stop 8**), just north of the Oak Ridges Moraine, to examine the broader glacial landscape of streamlined bedforms and valleys on the bed of the Simcoe Ice Stream (Figs. 25–27, 32–34). This entire landscape has been previously attributed to subglacial meltwater erosion by one or more catastrophic sheet floods that is thought to have flowed across the entire region, from southern Ontario into New York State, lifting the LIS from its bed (Sharpe et al., 2013, 2018; *see* End Note *below*). Valleys have long axes oriented NE–SW and NNW–SE, and fed meltwaters and sediment under and from the SIS to the evolving ORM depocentre trapped against the northwest-flowing Halton Ice Stream. Some are >7 km wide and the largest, such as that occupied by Holland Marsh, are >200 m deep and >30 km long, and display highly varying widths along their lengths. We will discuss the characteristics of these complex valleys as established by analysis of geophysical data, including land-based (Pugin et al., 2018) and waterborne (Mulligan, 2018) seismic reflection surveys and surficial mapping and drilling (Mulligan and Bajc, 2012, 2018; Bajc et al., 2015; Mulligan, 2017a,b,c, 2018; Mulligan et al., 2018a,b). Collectively, these data point to multiple episodes of cutting and filling rather than a single flood event. Mulligan et al. (2018a) identify the importance of valley cutting by subglacial meltwater discharge(s) in combination with piping from pressurized confined aquifers and direct glacial erosion below the Simcoe Ice Stream, similar to other modern and Pleistocene subglacial valleys cut into thick groundwater-bearing sediments and bedrock (e.g. Bjornsson, 1996; Janszen et al., 2012).

Streamlined bed of the Halton Ice Stream south of the Oak Ridges Moraine

We will drive over the crest of the ORM noting the characteristic high-relief hummocky topography created by the melting of ice trapped and buried below sediment deposited in the water body between the SIS and HIS. On the northern flank of the ORM, abandoned lateglacial lake shoreline features occur at consistent elevations (300 masl near Newmarket, 320 masl near Uxbridge, up to 360 masl east of Lake Scugog; Chapman, 1985; Barnett et al., 1998; Mulligan et al., 2015) and record the development of lakes impounded between the retreating margins of the SIS and HIS (Sookhan et al., 2018b). HIS records short-lived ‘flow switching’ of part of the northern margin of OEIS during final deglaciation, which left a thin spatially discontinuous and variable deposit called the Halton Till. The megalineated bed of the HIS is exposed from Lake Ontario north to the Oak Ridges Moraine and the northward-trending forms are very clearly visible in the Scarborough-Oshawa area where numerous exposures through MSGLs have become available as a result of the construction of Highway 407 and rapid urbanization (Figs. 28–31; **Stops 9, 10**).

New mapping confirms the presence of a large recessional moraine consisting of low-relief hummocky till (the Scarborough Moraine of Taylor, 1913) that marks a pause in the recession of the HIS and the advection of subglacial debris to the margin by fast flow (Fig. 28). The moraine marks the outer limit of the flow sets of MSGLs on the bed of the HIS. Several stops near the Metro Toronto Zoo, adjacent to the Rouge National Urban Park, will allow discussion of their origin and geology. Outcrop and geophysical data indicates MSGLs are erosional in origin and cut across a wide range of sediments, including LGM Northern Till. Much of the northern part of the Toronto urban area has been built across MSGLs left by HIS. These characteristic landforms can still be recognized in urbanized areas, notably along hydro corridors and along roads that run west-east, perpendicular to ice flow direction, e.g., Sheppard Avenue east of Markham Road just north of Highway 401.

Scarborough Bluffs and the infill of the Laurentian Valley

Leaving the Toronto Zoo we will drive south, crossing the shoreline bluff of former glacial Lake Iroquois to stop along the Lake Ontario shoreline at Scarborough Bluffs (**Stop 11**). In the nearby Don Valley Brickyard, we will briefly view Early and Mid-Wisconsin glaciolacustrine sequences (Fig. 13B) that immediately postdate the last interglacial facies. Well studied lakeshore exposures, up to 100 m high (most of which have now been lost to urban development designed to prevent erosion), record the complex fluctuation in depth and extent of deep (<100 m) very large ice frontal lakes across the Ontario-Erie basins as the LIS grew in volume and entered the Great Lakes basins. Discussion has hitherto focused on the origin(s) of pebbly silty-clays (‘diamicts’) interbedded with rhythmically laminated silty clays (tills versus subaqueous rain-out and debris flows) and the corresponding geographic positions of the LIS margin prior to maximum regional expansion sometime after 30,000 ybp when the area was completely overrun (Northern Till). There is agreement that the succession records ice marginal sedimentation in a very deep evolving water body (*see* summary in Eyles et al., 2005; Mulligan and Bajc, 2018). The succession includes muddy deep-water diamict facies that contain in situ crustaceans (*ostracods*) whose changing isotopic composition has been used as a chemostratigraphic tool that records successive influxes of O^{16}-rich meltwaters from an expanding ice sheet (Schwarcz and Eyles, 1991). Diamict facies are interbedded with shallow-water fan-delta and shoreface sediments of the Thorncliffe Formation with abundant ice-rafted debris in hummocky and swaley cross-stratified sands deposited by large storm waves and cut by iceberg scours.

The stop at Scarborough Bluffs will provide an opportunity to review what is known of the pre-Late Wisconsin chronology and paleogeography of southern Ontario in the light of new information from more than 100 continuously cored boreholes through the fill of the Laurentian Valley drilled by the Ontario Geological Survey, many of which penetrate the entire sediment succession (Figs. 10–13). New subsurface data provide insights into the paleogeography of the eastern Great Lakes region at various times prior to the Late Wisconsin (Mulligan and Bajc, 2018) and a better understanding of regional groundwater systems hosted within the Laurentian Valley and overlying ORM (*see also* Gerber et al. (2018) and Sharpe et al. (2018)).

Don Valley Brickyard

If time/traffic permits, we will visit the Don Valley Brickyard (**Stop 12**) near downtown Toronto, which was in operation between 1893 and 1985 using shale from the Late Ordovician Georgian Bay Formation; although now badly slumped, penultimate glaciation (Illinoian) and last interglacial (Sangamon) sediments were formerly exposed above bedrock on the Brickyard's 'North Slope'. An exhibit details work by A.P. Coleman in the Brickyard in the late 1800s, which was instrumental in demonstrating multiple ice ages (later predicted by several astronomical theorists —most notably Milankovitch) at a time when many believed that only a single ice age occurred. The succession is noteworthy among North American interglacial sites because it retains a paleontological record of climate cooling toward the end of the last interglacial (but which is still inadequately dated) at a time of dramatic increases in the depth of an ancestral Lake Ontario, and which includes the remains (teeth) of the giant beaver *Castoroides ohioensis*. A complete skeleton is on display in the Field Museum of Natural History in Chicago.

Coleman, who produced the first Quaternary geological map of Toronto in 1912, is also remembered for his discovery of the Gowganda Formation glacial deposits (now established at 2.4 Ga ybp) in Northern Ontario, his mapping of the nickel deposits of the Sudbury Basin, his surveying and exploration of the eastern Canadian Rockies, and the 1926 book *Ice Ages; Recent and Ancient*.

We will leave Toronto by driving west along the Lake Ontario shoreline, along the Queen Elizabeth Way (QEW) toward Hamilton. As we leave downtown Toronto the original Fort York can be seen to the north. In 1793, it was constructed on the then shoreline of Lake Ontario by Upper Canada's first governor, John Graves Simcoe; it is now inland as a consequence of extensive landfilling. The garrison was attacked and overrun by American troops in April 1813; many US soldiers, including the commanding officer Zebulon Pike (after whom Pikes Peak is named in Colorado), were killed by flying glacial erratic boulders when the main magazine was set afire. In 1834, the community that developed around the fort was named Toronto.

Hamilton

The QEW was the first intercity divided highway in North America when it opened in 1937 and was based on the German autobahn. Part of the original highway is preserved near Hamilton as York Boulevard; it was built atop the raised spit (Burlington Heights; **Stop 13**) of glacial Lake Iroquois (Fig. 36), which now separates Hamilton Harbour from the waters of Cootes Paradise, which drained at ca. 12,000 ybp. This area lies above the buried Dundas Valley, which is cut into the face of the Niagara Escarpment (Fig. 37). Data from drilling suggests the glacial fill is >195 m thick; the bedrock surface within the re-entrant valley is more than 120 m below sea level (Burt, 2017).

We will visit the Jolley Cut in the Sam Lawrence Park at Hamilton (**Stop 14**), which affords a fine view of the modern-day Dundas Valley and Niagara Escarpment, with its hard cap rock of Silurian Lockport Dolostone. Eastward from Hamilton, the QEW follows the shoreline of glacial Lake Iroquois, at the foot of the Niagara

Escarpment. The route crosses the Welland Canal near the city of St. Catherines, which lies above another major buried valley that may have formerly carried drainage from the Erie Basin into the Ontario Basin (e.g. Gao, 2011; Fig. 10). It has been postulated that the Laurentian Valley and the Dundas Valley may be part of an ancestral St. Lawrence system pre-dating the Great Lakes (Spencer, 1890).

Immediately south of the crest of the Niagara Escarpment lies a series of low-relief to hummocky moraines left by the retreating Halton Ice Stream (HIS). The southernmost limit of the HIS in the Erie Basin is marked by the Hamburg Moraine near Buffalo, New York and a series of small recessional moraines (Unnamed moraine, Mohawk Bay, Wainfleet, Crystal Beach, Fort Erie, Niagara Falls, Vinemount) that stretch from the Dundas Valley in the west into New York State in the east the position of which were strongly influenced by the position of the Niagara Escarpment (Feenstra, 1981; Burt and Mulligan, 2017). Large exposures in bedrock quarries indicate that the sedimentology of the Vinemount Moraine is dominated by glaciotectonized and subglacially reworked glaciolacustrine silty clays (e.g. Menzies, 2001; Maclachlan and Eyles, 2011), suggesting subglacial reworking of ice-marginal sediments by the HIS, similar to that seen in numerous outcrops of the Halton Till across the south slope of the Oak Ridges Moraine. Below the Niagara Escarpment, the retreating HIS left a series of moraines cored by fine-grained pebble-poor till, such as the Trafalgar and Scarborough moraines, which record submarginal aggradation of fine-grained deforming till being advected toward the ice margin (*see* Eyles et al., 2010). Analogous sediment associations have recently been observed in dozens of continuously cored boreholes, which penetrate the surficial and buried segments of the moraines that stretch across the Niagara Peninsula, (Burt, 2016, 2017). Subglacial remolding and reworking of fine-grained sediment in ice marginal waterbodies aided fast ice flow throughout the eastern Great Lakes sector of the Laurentide Ice Sheet. Flow sets of bedrock megagrooves along escarpments and MSGLs poking through glaciolacustrine sediment in the central and western part of the Niagara Peninsula record the fast ice-flow velocities of the HIS and OEIS (*see* Sookhan et al., 2018b; Fig. 14B). Large glaciolacustrine kame deltas, such as that at Fonthill, which was deposited at the mouth of the 12 Mile re-entrant valley, and that of the Niagara Falls Moraine (Fig. 37), were deposited downflow of re-entrant valleys cut into the face of the Escarpment as the HIS retreated eastward in glacial Lake Whittlesey.

We will stay in Niagara Falls on Sunday night (August 12th).

Day 3: MONDAY August 13th

Niagara Falls and Gorge

After breakfast on Monday, we will stop at the site of the Battle of Lundy's Lane (1814), along the crest of the Niagara Falls Moraine (**Stop 15**). This battle ended in stalemate and brought the war of 1812–1815 to a conclusion. We will then stop at the Niagara Falls overlook, at the intersection of Livingstone Street and Fallsview Boulevard, which affords a fine view of the Horseshoe Falls and American Falls (**Stop 16**), for a discussion of recession rates and processes (Figs. 38–40). We will then drive north along the Niagara Parkway, which Sir Winston Churchill called "*the prettiest Sunday afternoon drive in the world*" during a visit in 1943. We will discuss the geological history of the Niagara Falls and Gorge, stopping at the Whirlpool (**Stop 17**), the Sir Adam Beck Power Plant (opened in 1957; **Stop 18**), and Queenston Heights on the crest of the Niagara Escarpment (**Stop 19**). The last of which was the site of the October 1812 battle—the first major battle of the War of 1812—that repelled US invaders but resulted in the loss of British Army officer, Major General Sir Isaac Brock; he is memorialized by the Brock Monument nearby.

The Niagara Gorge is where the modern view of the great age of planet Earth was first recognized, opening the way to exploration of 'deep time' by geologists. The length of postglacial time was first broadly established by Charles Lyell (in 1841), and later by James Hall, on the basis of the assumed age of the Gorge, which was established from the average annual retreat rate of the Horseshoe Falls in response to undercutting of the Lockport Dolostone cap rock (Fig. 38). The rate of retreat (then approximately 1 m/yr) was compared to the length of the Gorge, measured from the initial postglacial location of Niagara Falls some 12

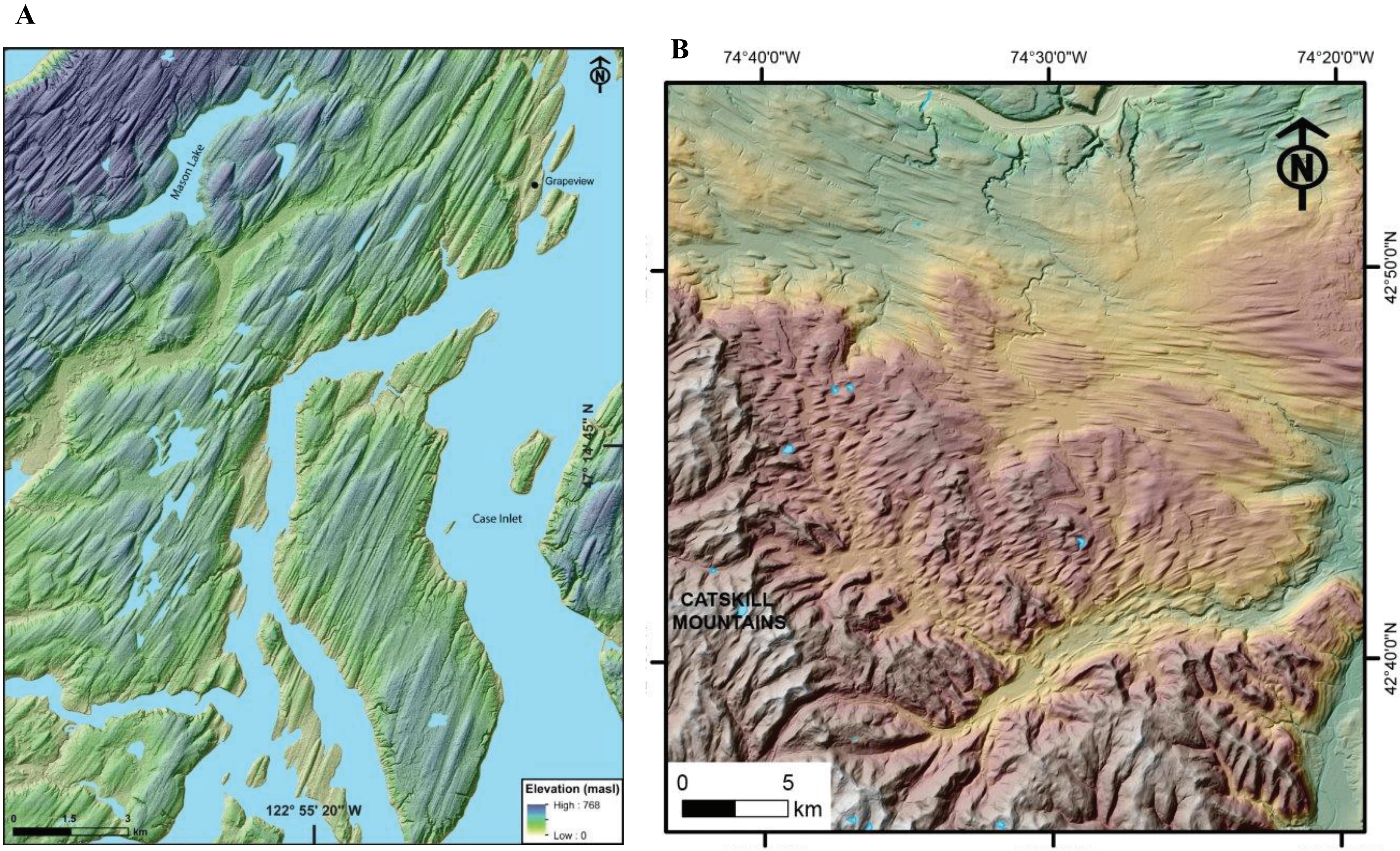


Figure 1 A) LiDAR-generated images of megascale glacial lineations exposed on the bed of the Juan de Fuca paleo-ice stream (*see* Fig. 3) near Seattle, Washington State (from Eyles et al., 2018) and **B)** on the bed of the Mohawk Ice Stream in New York State (*see* Fig. 4; Sookhan et al., 2018a). These bedforms are the characteristic hallmark of fast-flowing ice streams (*see also* Figs. 22, 23).

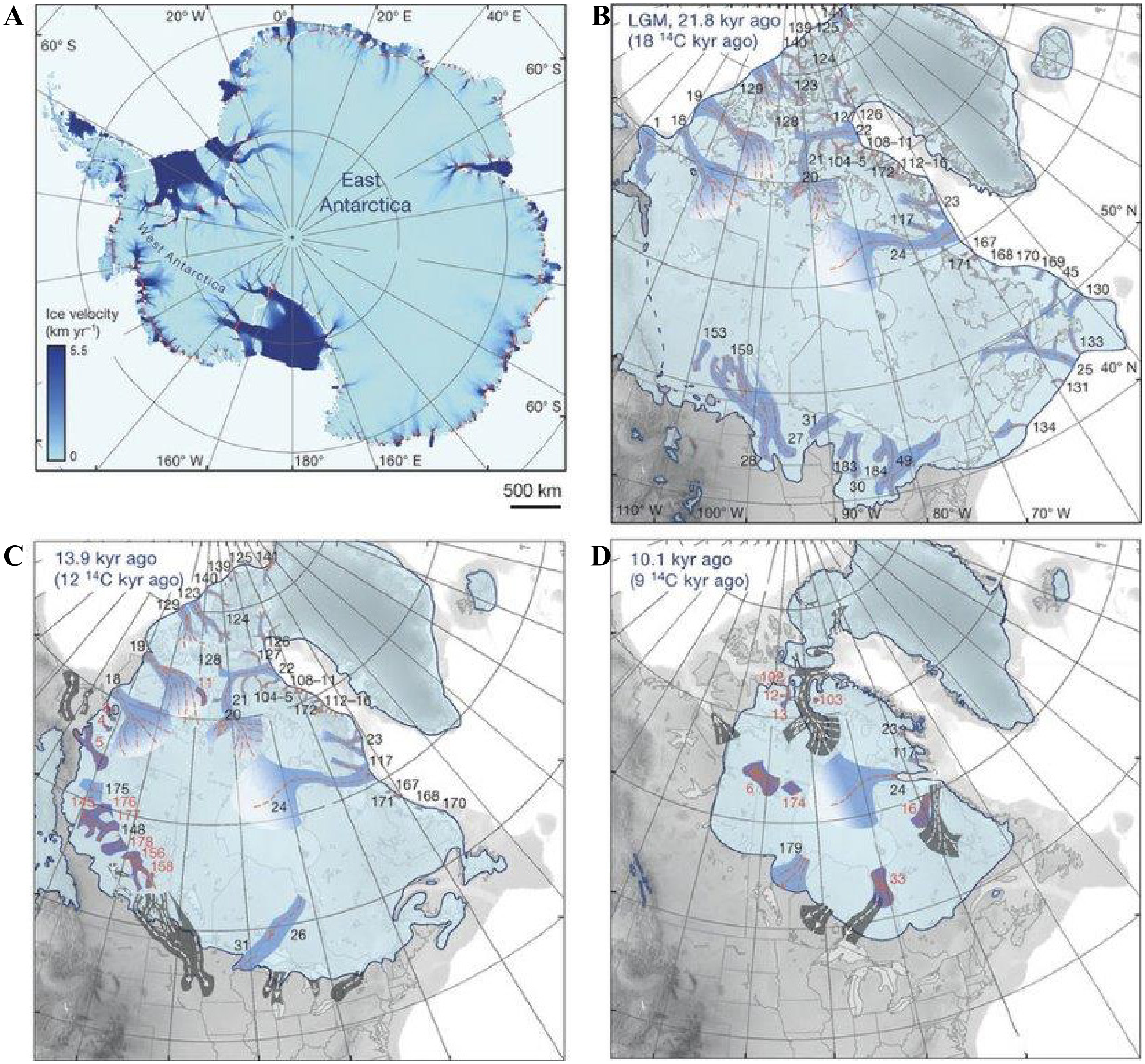
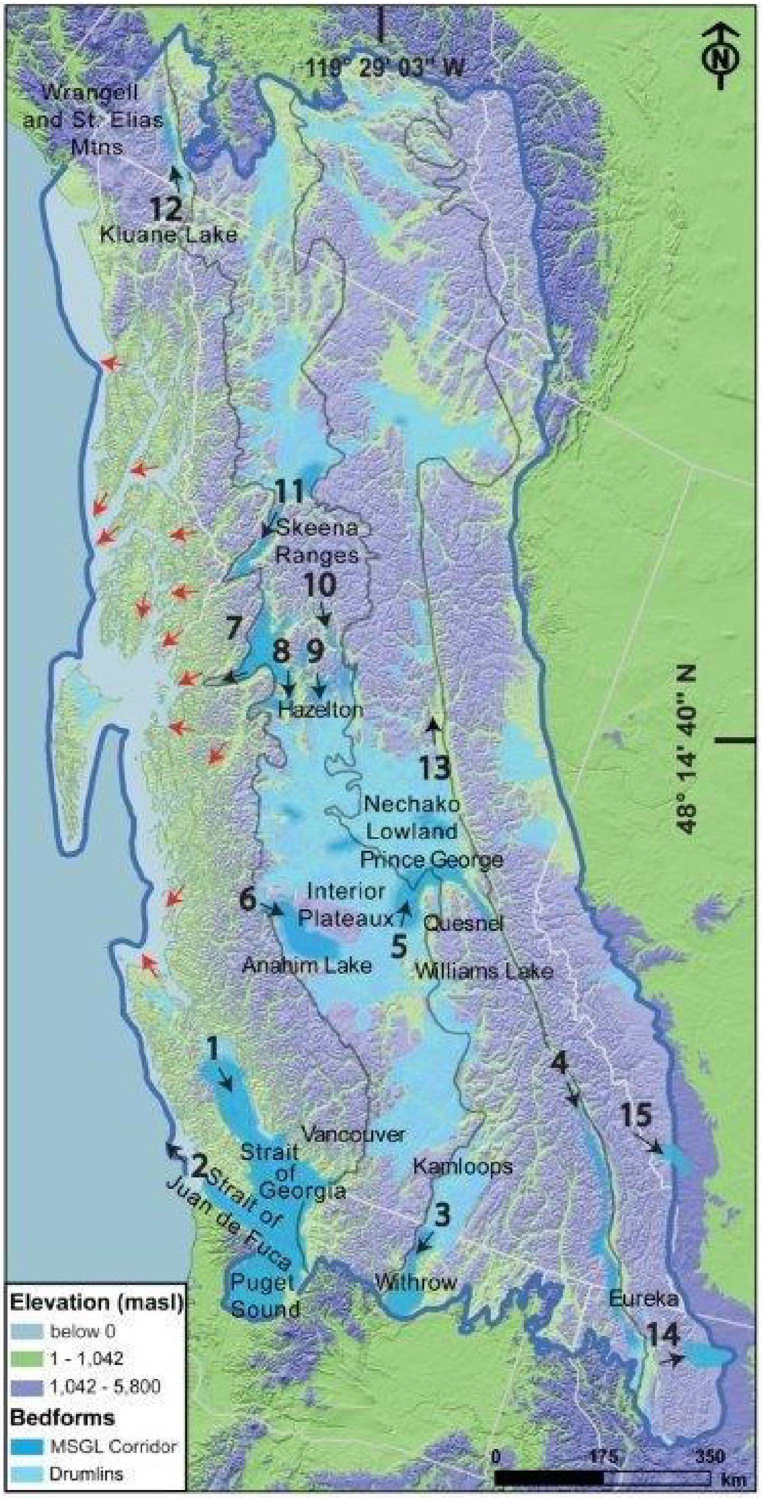


Figure 2. Ice streams within an evolving Laurentide Ice Sheet (reproduced from Margold et al., 2015b, 2018) based on mapped flow paths of megascale glacial lineations. Given the challenges of identifying the geomorphic record of fast flow on hard crystalline rock, this is likely an underestimate of the number of ice streams that were present on the Canadian Shield.



Paleo Ice Streams		
1	**Georgia - Puget**	Strait of Georgia and Puget Sound
2	**Juan de Fuca**	Strait of Juan de Fuca
3	**Okanogan**	Okanogan River
4	**Rocky Mountain Trench**	Rocky Mountain Trench
5	**Fraser**	Fraser River
6	**Anahim**	Anahim Lake
7	**Nass**	Nass River
8	**Skeena**	Skeena River
9	**Babine**	Babine River
10	**Bear**	Bear Lake
11	**Kinaskan**	Kinaskan Lake
12	**Kluane**	Kluane Lake
13	**Nechako**	Nechako Lowland
14	**Two Medicine**	Two Medicine Lakes
15	**Bow River**	Bow River

Figure 3. Ice streams within the Cordilleran Ice Sheet immediately prior to deglaciation (from Eyles et al., 2018).

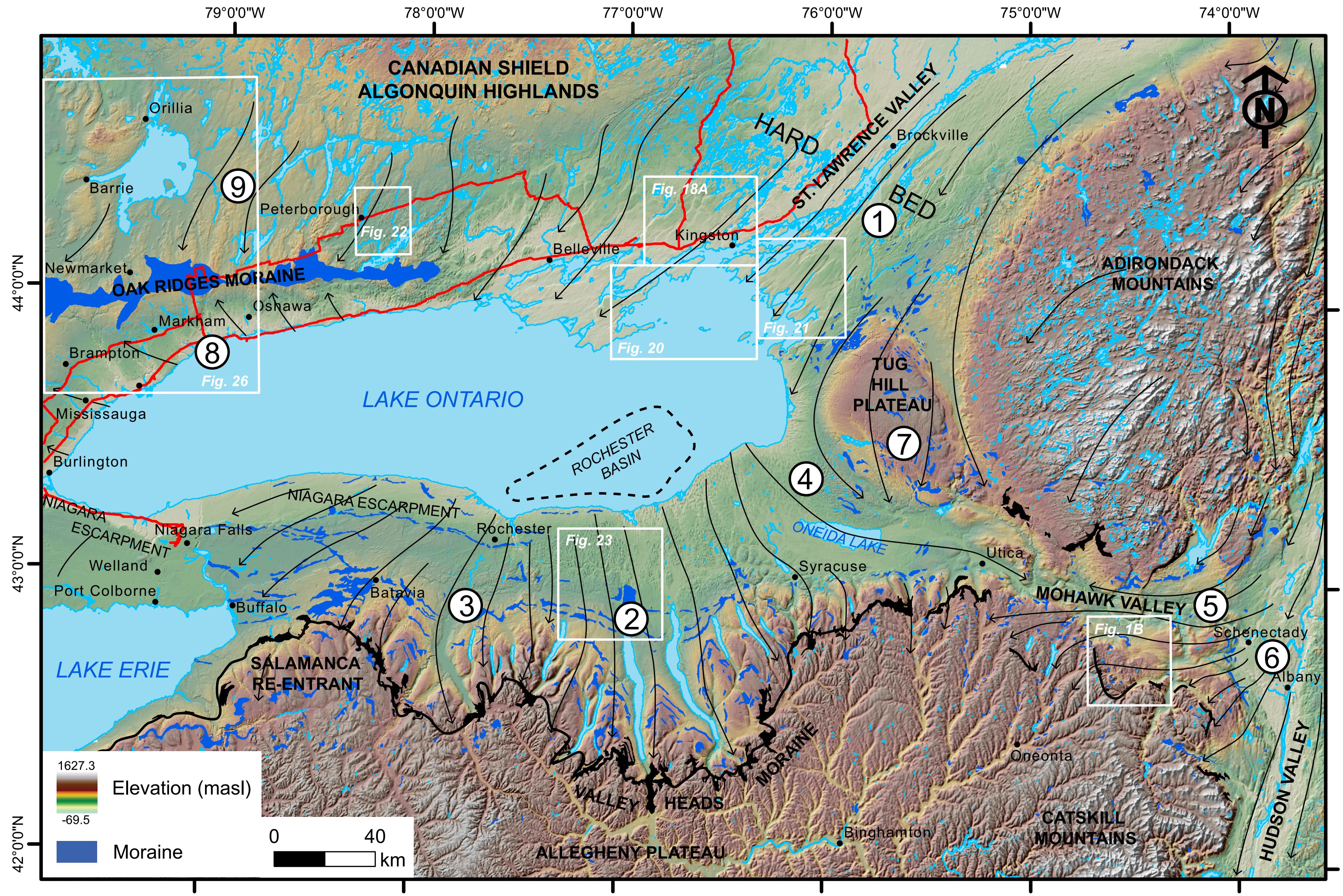


Figure 4. Paleo-ice streams during deglaciation of the Late Wisconsin Laurentide Ice Sheet (LIS) after deposition of the Valley Heads Moraine (VHM in black) at around 14,400 ybp. 1) Ontario-Erie, 2) Seneca-Cayuga, 3) Genesee, 4) Oneida, 5) Mohawk, 6) Hudson, 7) Tug Hill, 8) Halton and 9) Simcoe. Note the close association of ice streams flowing south to the Finger Lakes from the deepest part of the Ontario Basin (Rochester Basin: 244 m below sea level), indicating a strong topographic control on ice flowing through the St. Lawrence Valley into the Ontario basin. From Sookhan et al. (2018a).

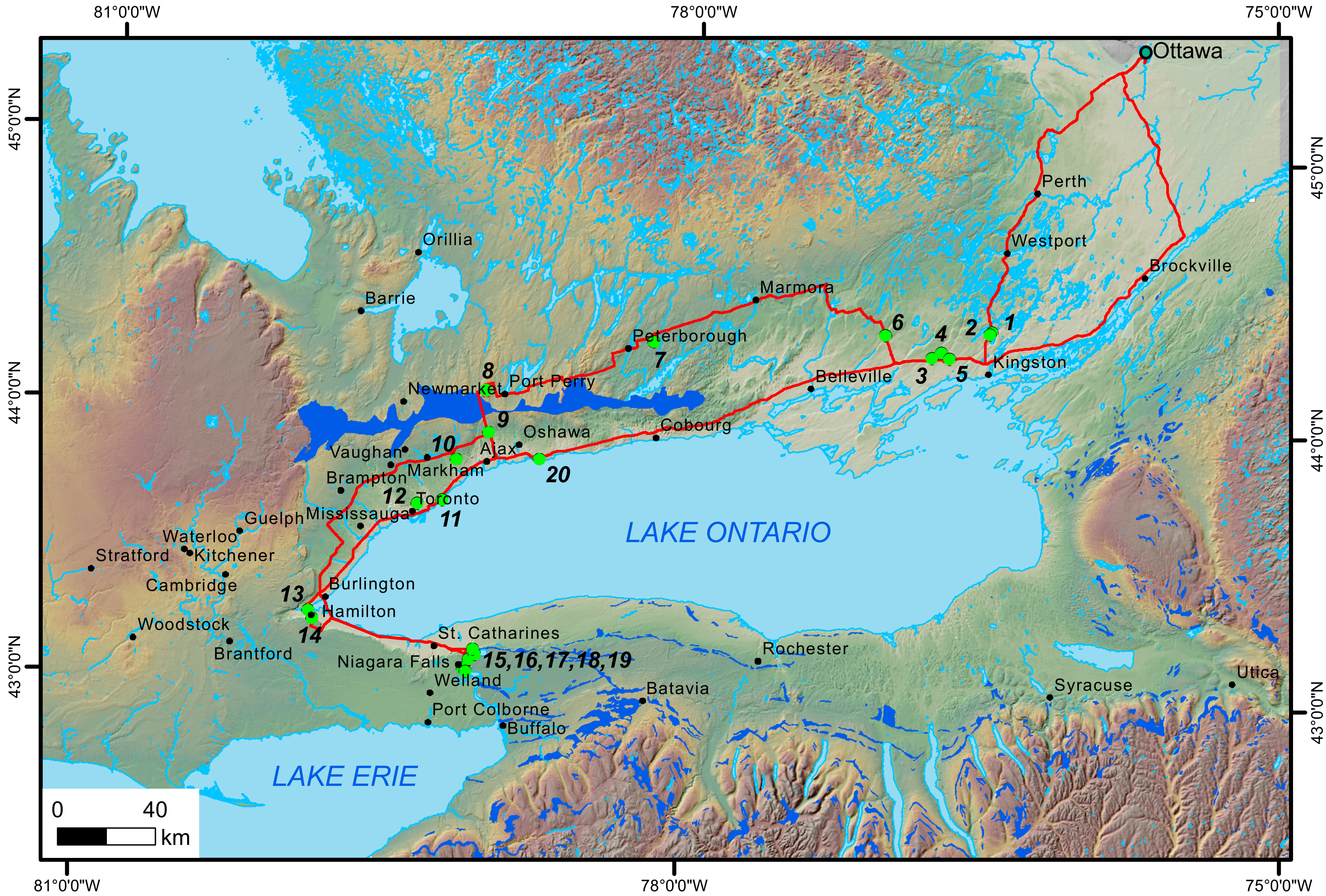


Figure 5. Topography and bathymetry of southern Ontario and northern USA showing the field trip route (red line) and stop locations (numbered green circles).

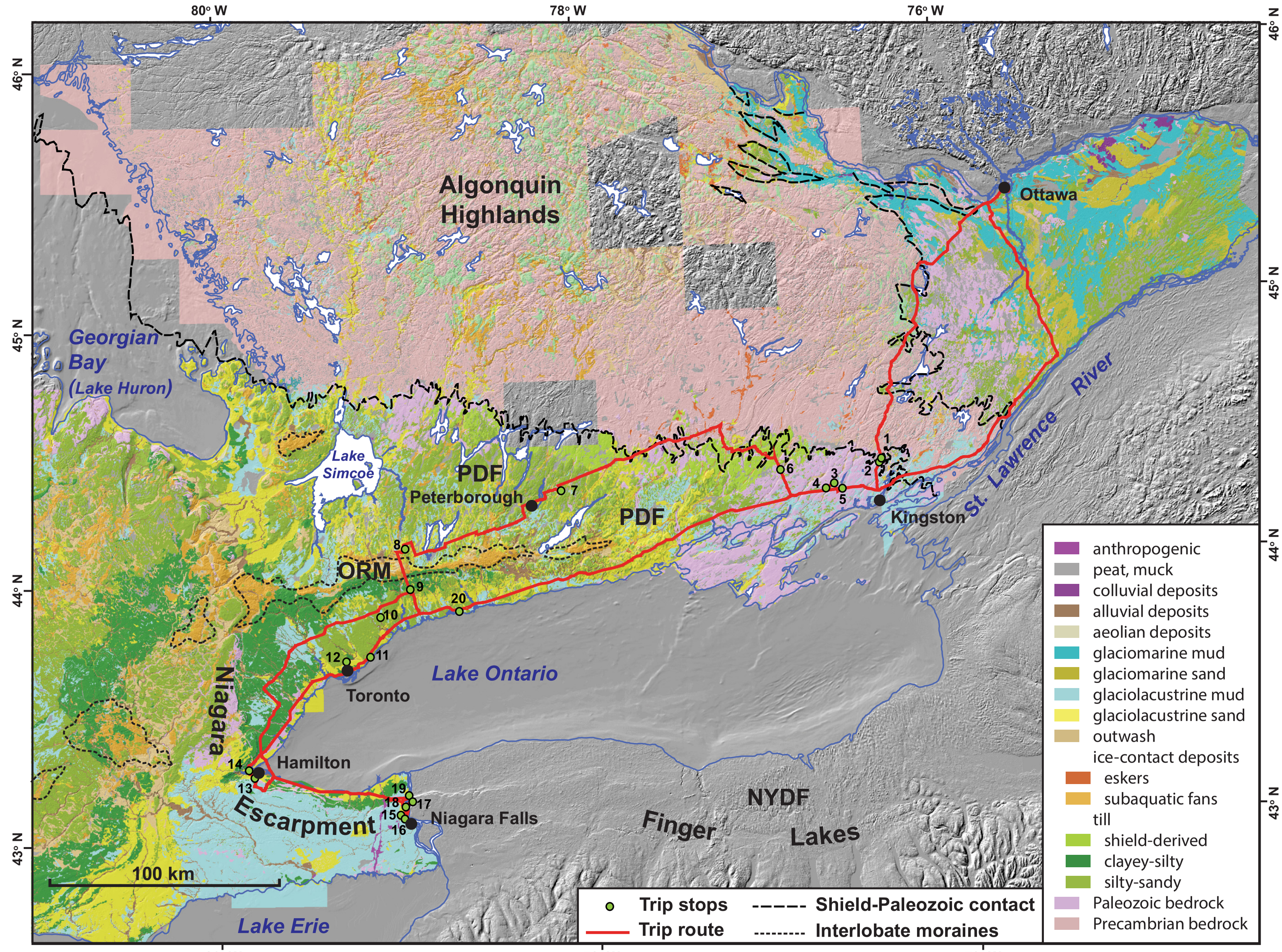


Figure 6. Simplified surficial geology map of southern Ontario (Ontario Geological Survey, 2010) showing the field trip route (red line), stop locations (red circles), and major physiographic features that are discussed in this guide. Abbreviations:: NYDF = New York Drumlin Field; ORM = Oak Ridges Moraine; PDF = Peterborough Drumlin Field.

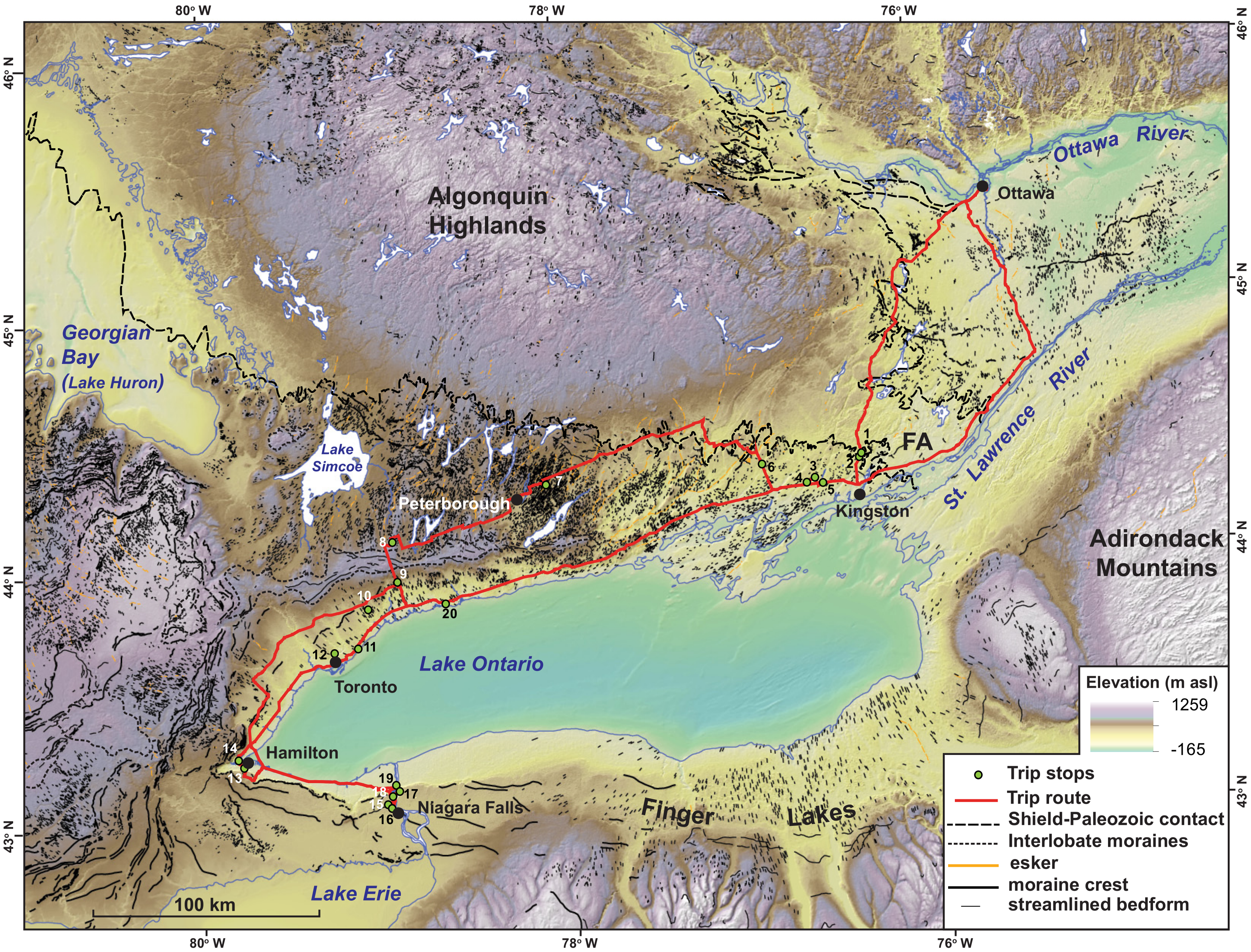


Figure 7. Principal glacial landforms of southern Ontario and adjacent areas of northern USA, showing the field trip route, stop locations, and major physiographic features discussed in this guide. Abbreviation: FA = Frontenac Arch.

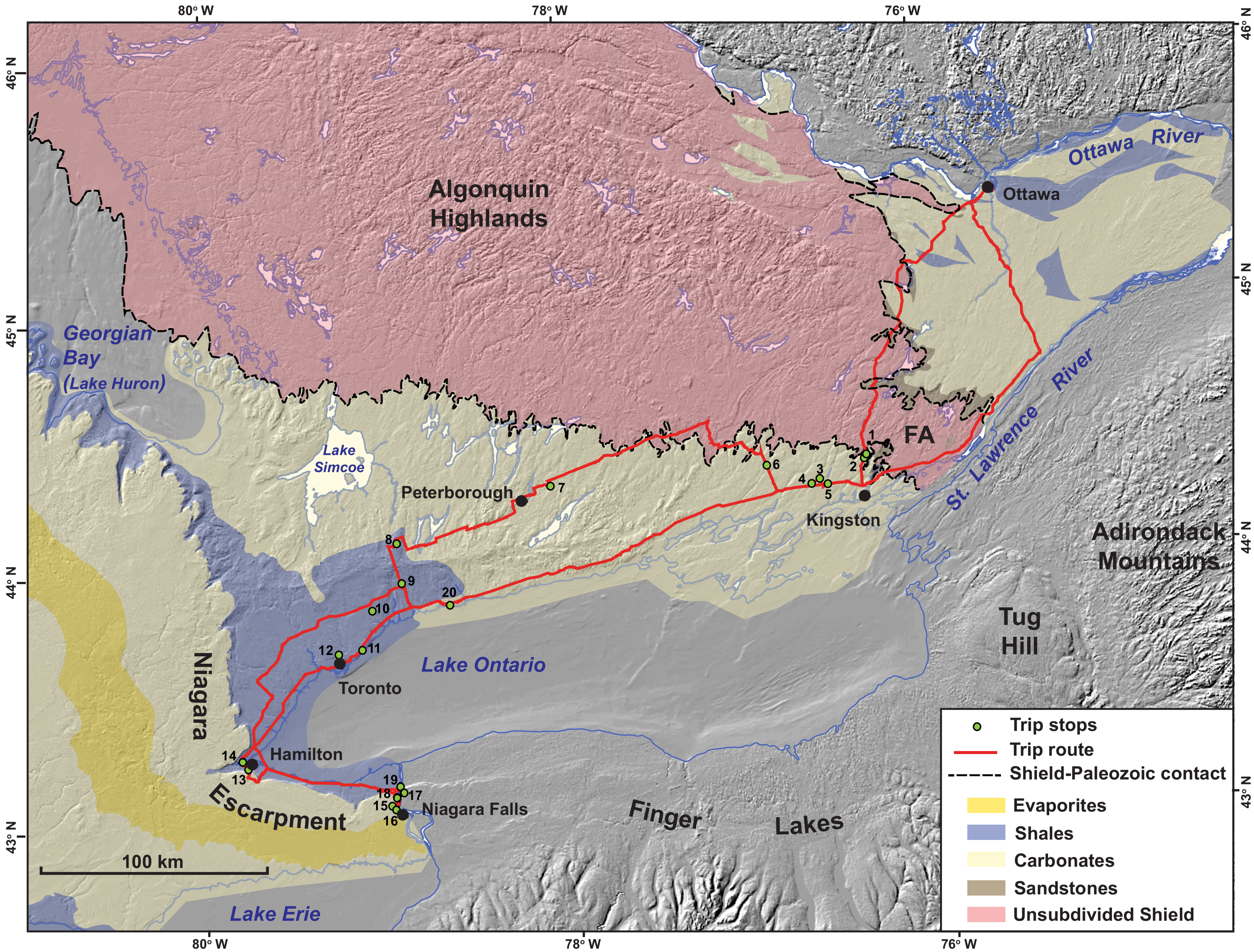


Figure 8. Simplified bedrock geological map showing unsubdivided Shield to the north and the major lithological changes in the offlapping, gently dipping, Paleozoic strata that young to the southwest. Map is modified from Armstrong and Carter (2010). Abbreviation: FA = Frontenac Arch.

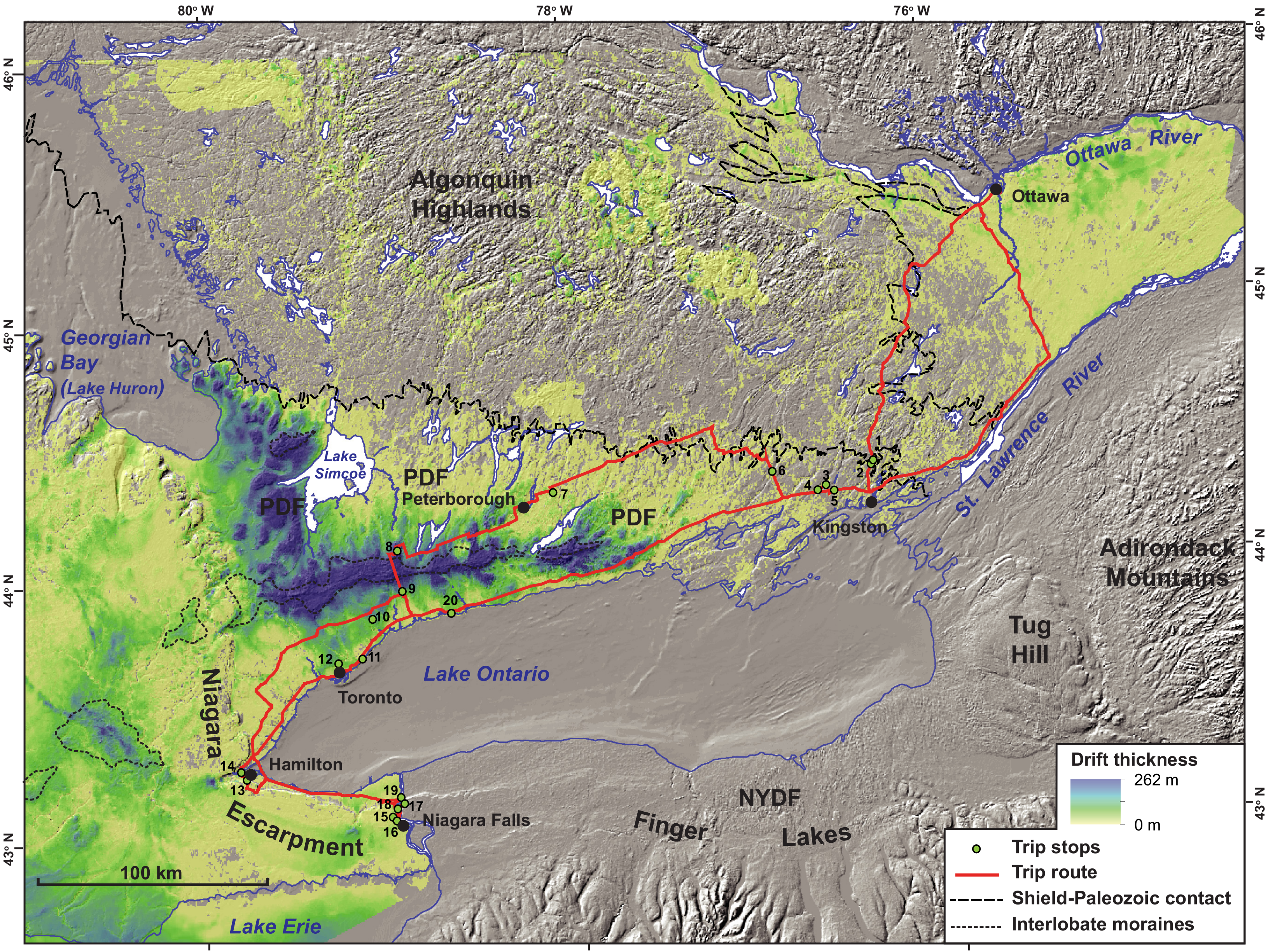


Figure 9. Generalized drift thickness map of southern Ontario (after Gao et al., 2006). Note the significant thickening of drift southward from the Shield contact as well as the areas of very thick drift (as much as 250 m) along the Laurentian Valley (LV: Fig. 10) and within interlobate moraines. Areas of exposed bedrock are not coloured. Abbreviations: NYDF = New York Drumlin Field; PDF = Peterborough Drumlin Field.

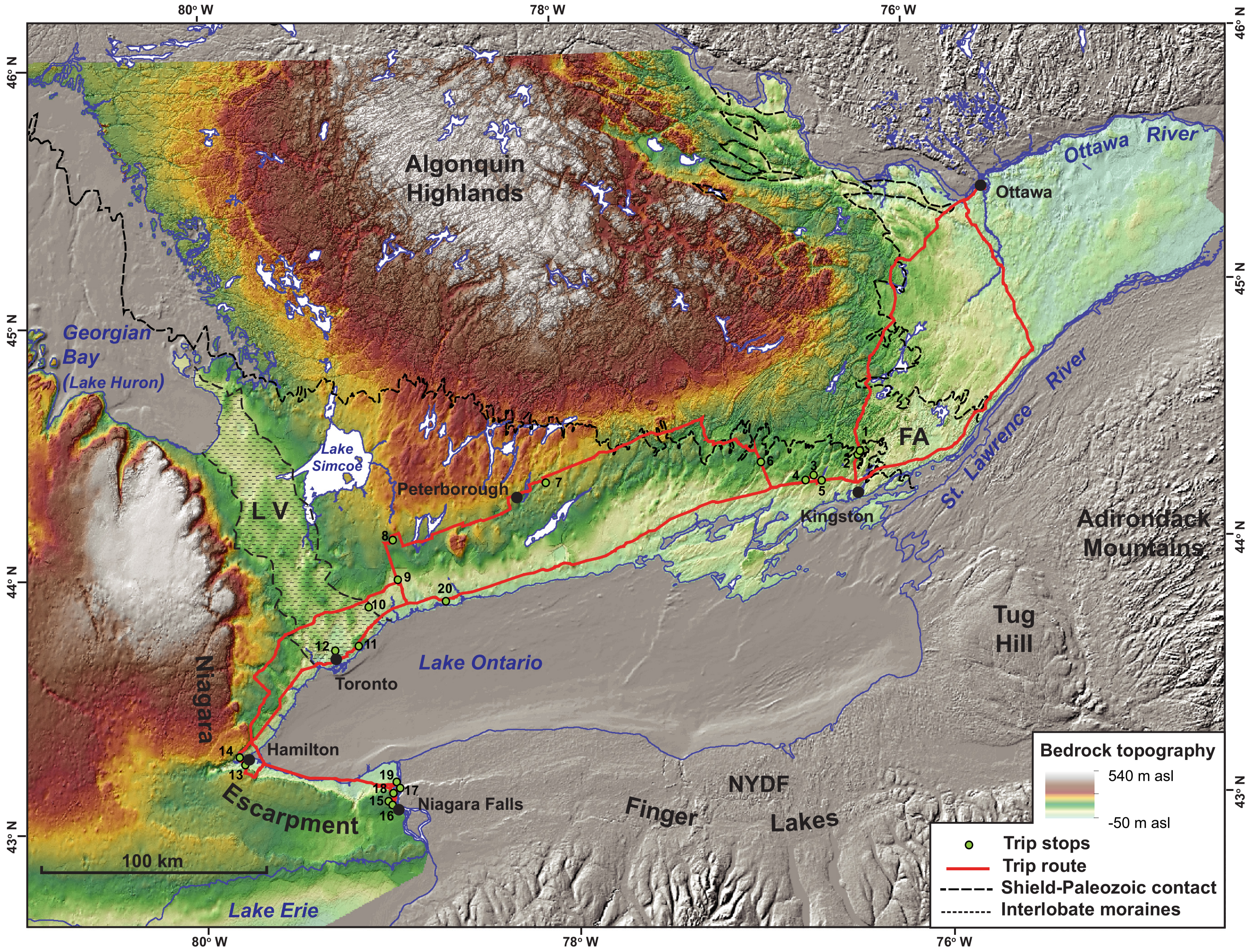


Figure 10. Bedrock topography of southern Ontario (after Gao et al., 2006) with major physiographic features discussed in this guide (FA: Frontenac Arch; LV: Laurentian Valley; NYDF: New York Drumlin Field). The infill of the latter is shown schematically in Figure 11.

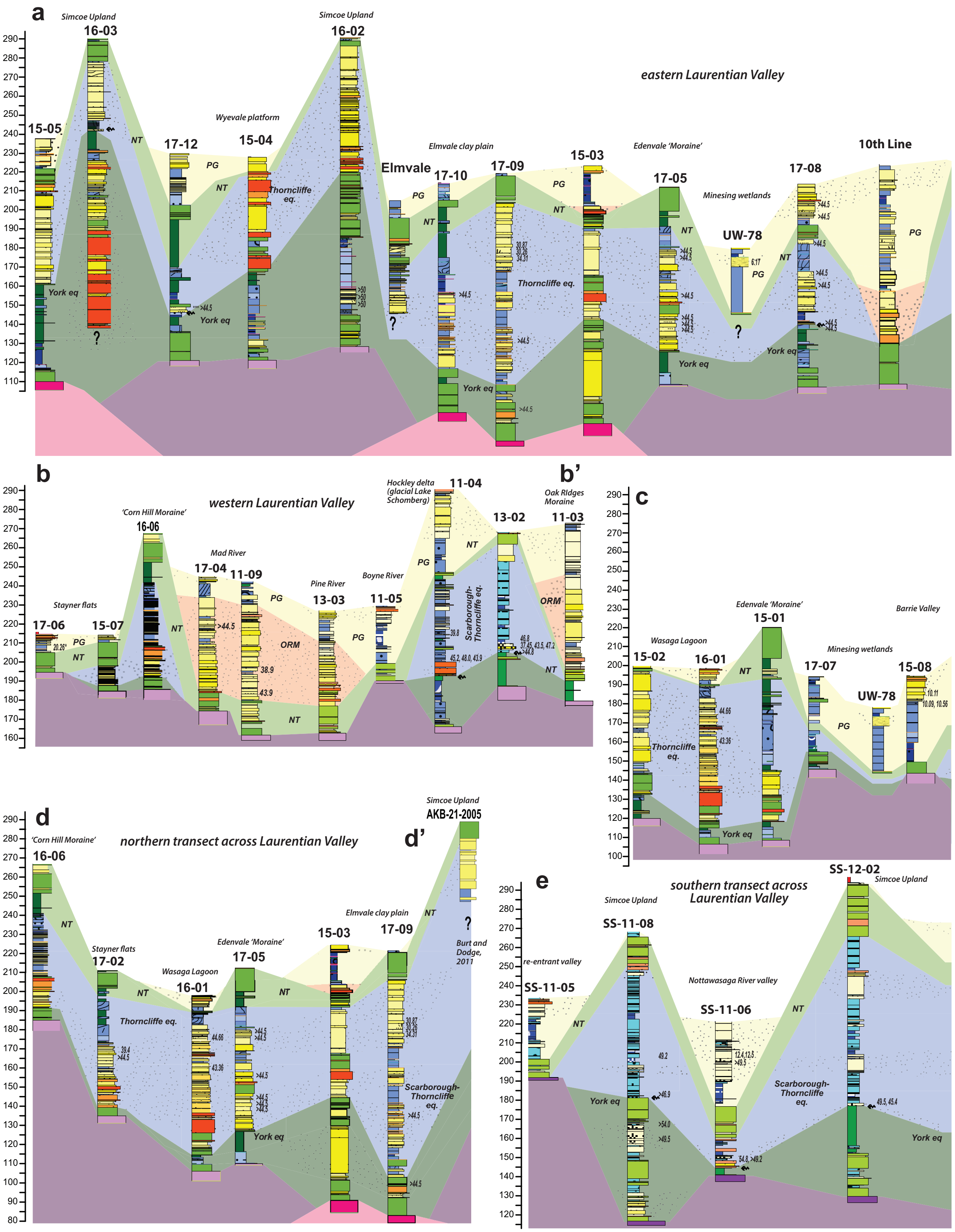
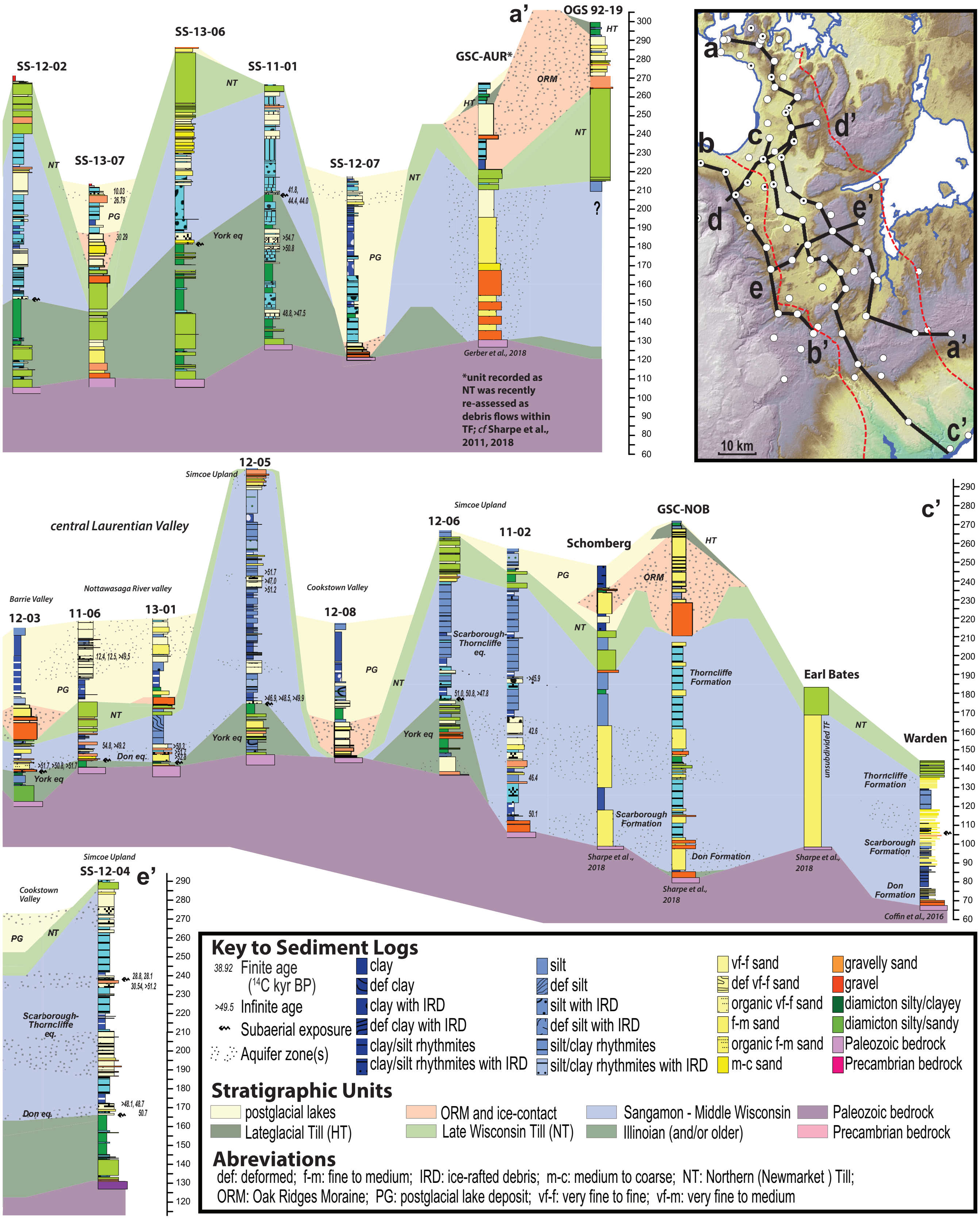


Figure 11. Generalized cross-sectional profiles within the eastern (a-a'), western (b-b'), and central (c-c') parts of the Laurentian Valley (LV: Fig. 10; dashed red line on location map at right) as well as northern (d-d') and southern (e-e') transects. Note the incision down to Precambrian basement rocks in the north and the significantly lower bedrock elevations in the central part of the valley system. Borehole logs are available online (Bajc et al., 2015),



in Mulligan (2016, 2017c), or from cited sources. Elevation is in metres above sea level, but topography between borehole locations is generalized and no horizontal scale is implied. Figure 13B shows the stratigraphy that is exposed at the Scarborough Bluffs (Stop 11).

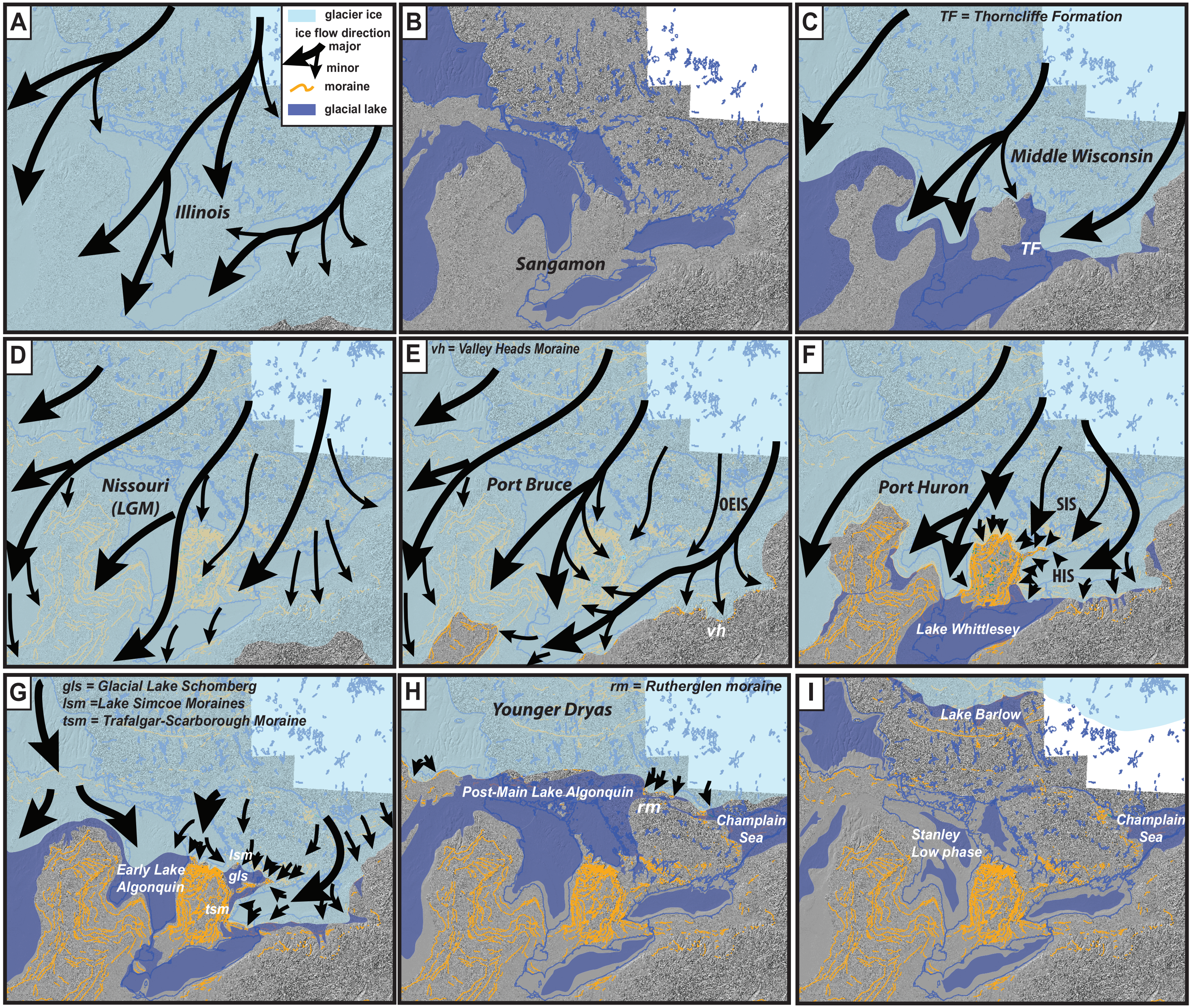


Figure 12. Paleogeographic reconstructions of southern Ontario at from the Illinoian glaciation through the Sangamon interglacial and at various stages of the last glaciation. Abbreviations: HIS = Halton Ice Stream; LGM = last glacial maxiumum LIS = Late Wisconsin Laurentide Ice Sheet; OEIS = Ontario-Erie Ice Stream; SIS = Simcoe Ice Stream.

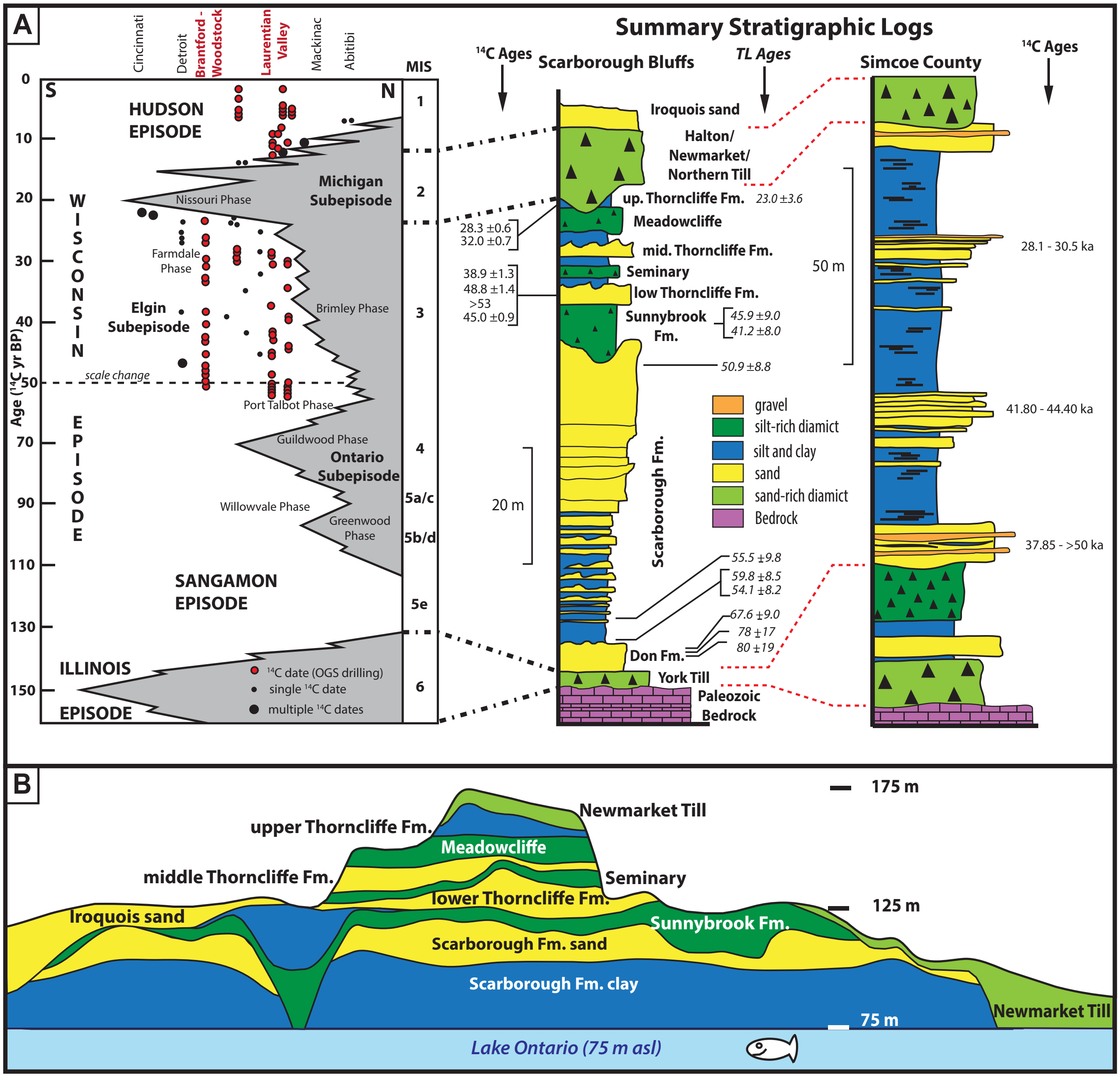


Figure 13. A) Generalized time-distance diagram for the Laurentian Ice Sheet in southern Ontario (modified from Karrow et al., 2000), showing ice extents, past and recent radiocarbon age determinations, and correlations to marine oxygen isotope stages (modified from Mulligan and Bajc, 2018). Generalized stratigraphic columns for the Scarborough Bluffs (centre) and Simcoe County (right) areas are loosely correlated to oxygen isotope stages. **B)** Stratigraphy of the principal units exposed along the Scarborough Bluffs (modified from Karrow, 1967). Abbreviations: Fm = Formation; MIS = Marine isotope stage; TL = thermoluminescence.

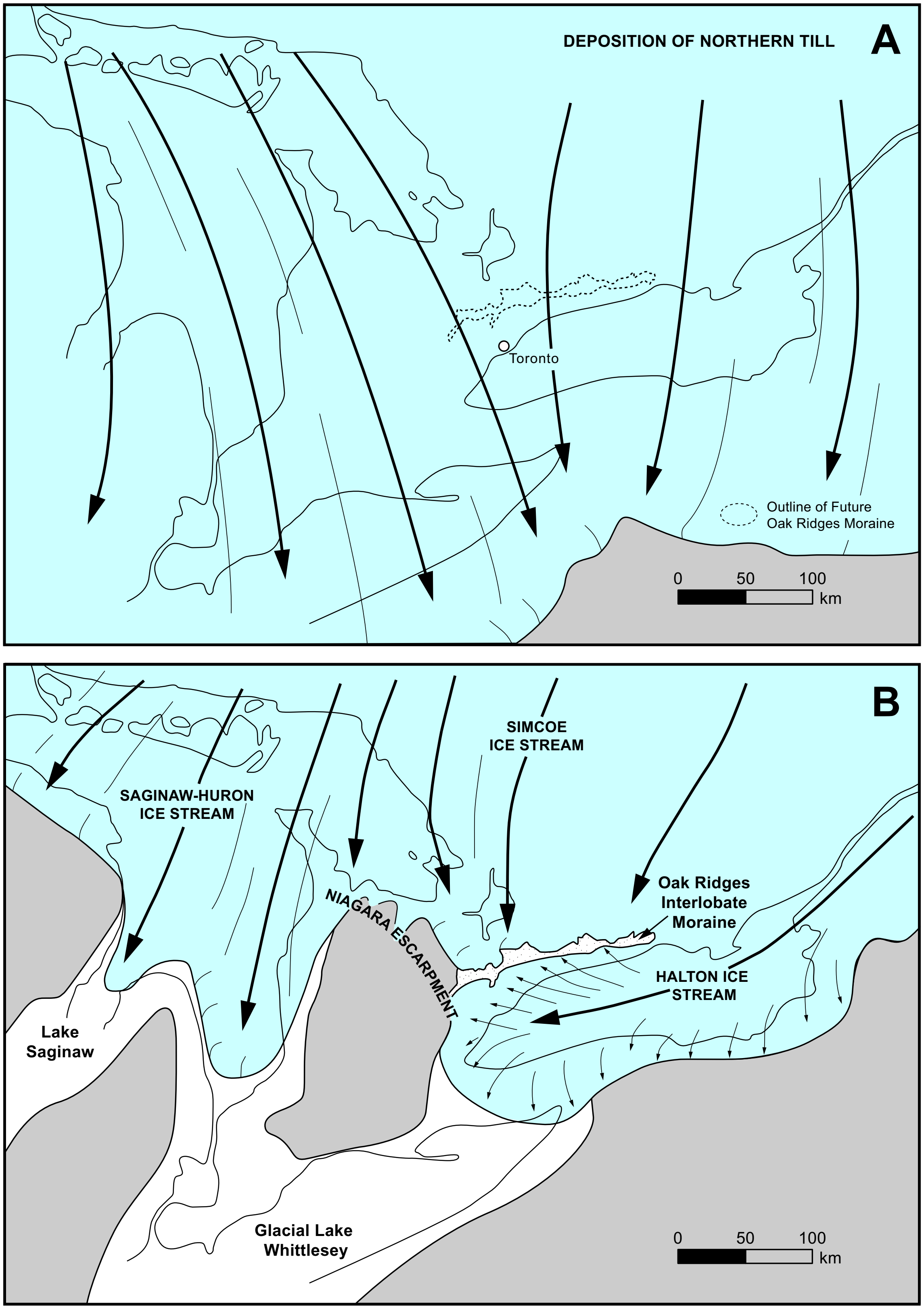


Figure 14. A) Inferred paleoglaciological setting of the field trip area at the time of the last glacial maximum. **B)** Converging ice streams (SIS: Simcoe Ice Stream and HIS: Halton Ice Stream) during the final retreat of the Laurentide Ice Sheet sometime shortly before 13,000 ybp. The Oak Ridges Moraine was deposited in a narrow glaciolacustrine depocentre trapped between the two ice streams and dammed to the west by the Niagara Escarpment (*see* Fig. 26).

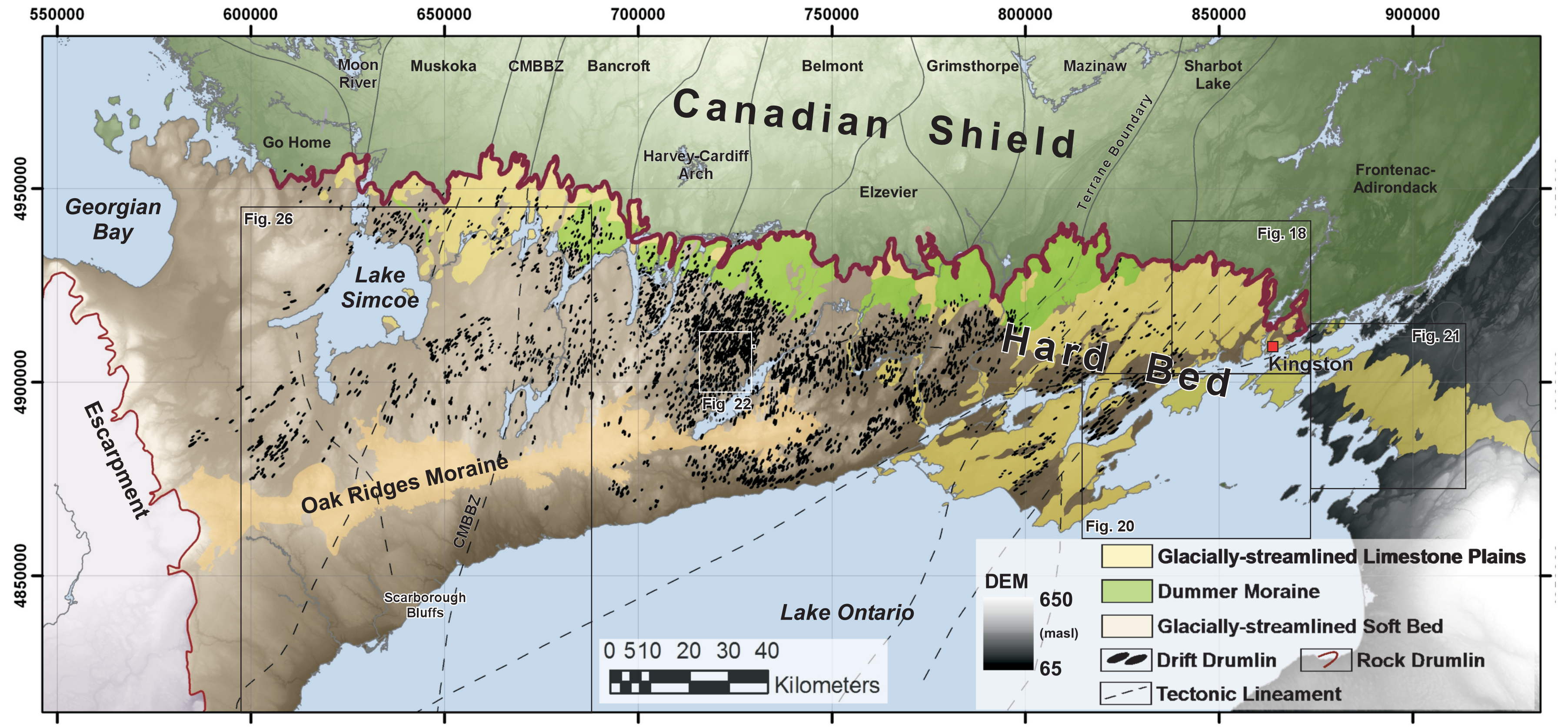


Figure 15. Simplified distribution of hard and soft beds below the principal ice streams in southern Ontario. Glacially streamlined bedrock surfaces are shown in Figures 18, 20, and 21. The hard bed is offset by numerous faults (*see* Fig. 17). Figures 22 and 26 show typical streamlined soft beds with megascale glacial lineations. Note the large expanse of the so-called Dummer Moraine, which is composed of limestone rubble plucked from north-facing escarpments.

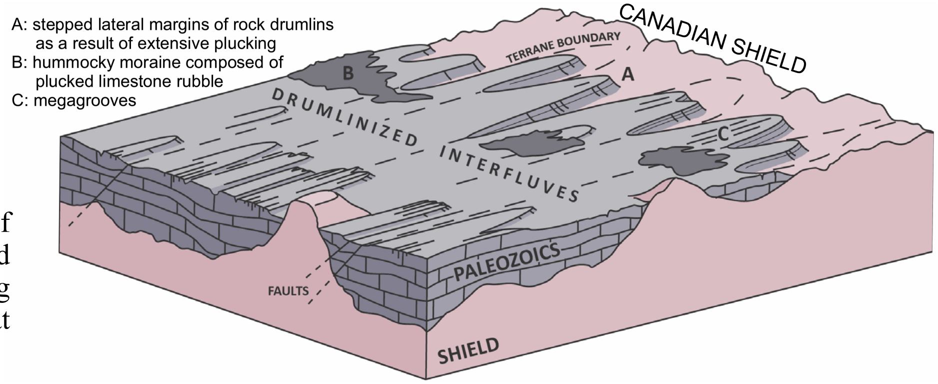
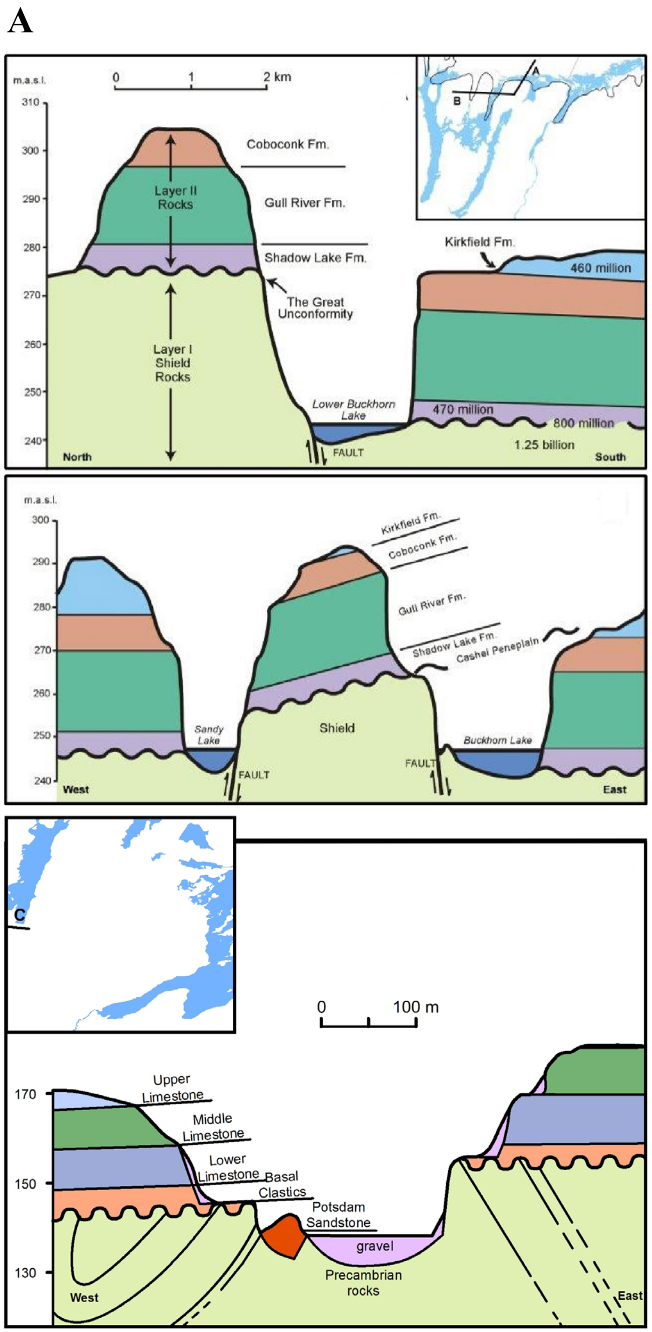


Figure 16. (right). Highly simplified landsystem model of the hard beds of the Ontario-Erie Ice Stream that developed on crystalline strata of the Canadian Shield and offlapping Paleozoics. Not shown are eskers or bedrock channels that carried meltwaters across the hard bed.



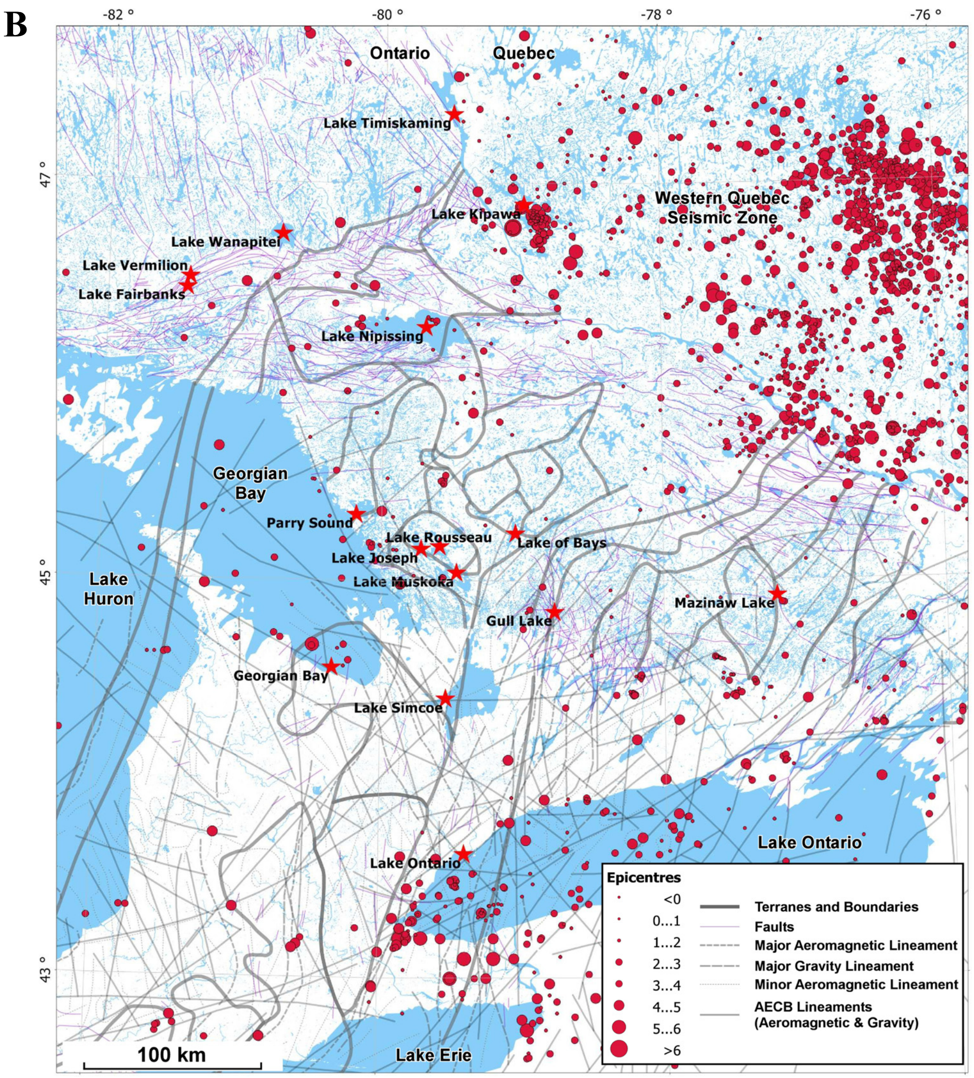


Figure 17. A) Faulted Paleozoic strata across the hard beds that resulted from the propagation of Proterozoic structures, such as terrane boundaries, likely due to distal field stresses associated with the Appalachian orogenies and the building of Pangea. The diagram is redrawn and modified from Sanford (1993) and Doughty et al. (2014). **B)** Structure of the Canadian Shield showing exposed terrane boundaries and other bedrock lineaments to the north and buried sub-Paleozoic structures to the south with locations of earthquake epicenters (after Doughty et al., 2014). Bedrock structure controls the location of major bedrock valleys cut into overlying Paleozoic rocks now filled with thick sediment and guided subglacial meltwater flows across the hard bed (Fig. 10).

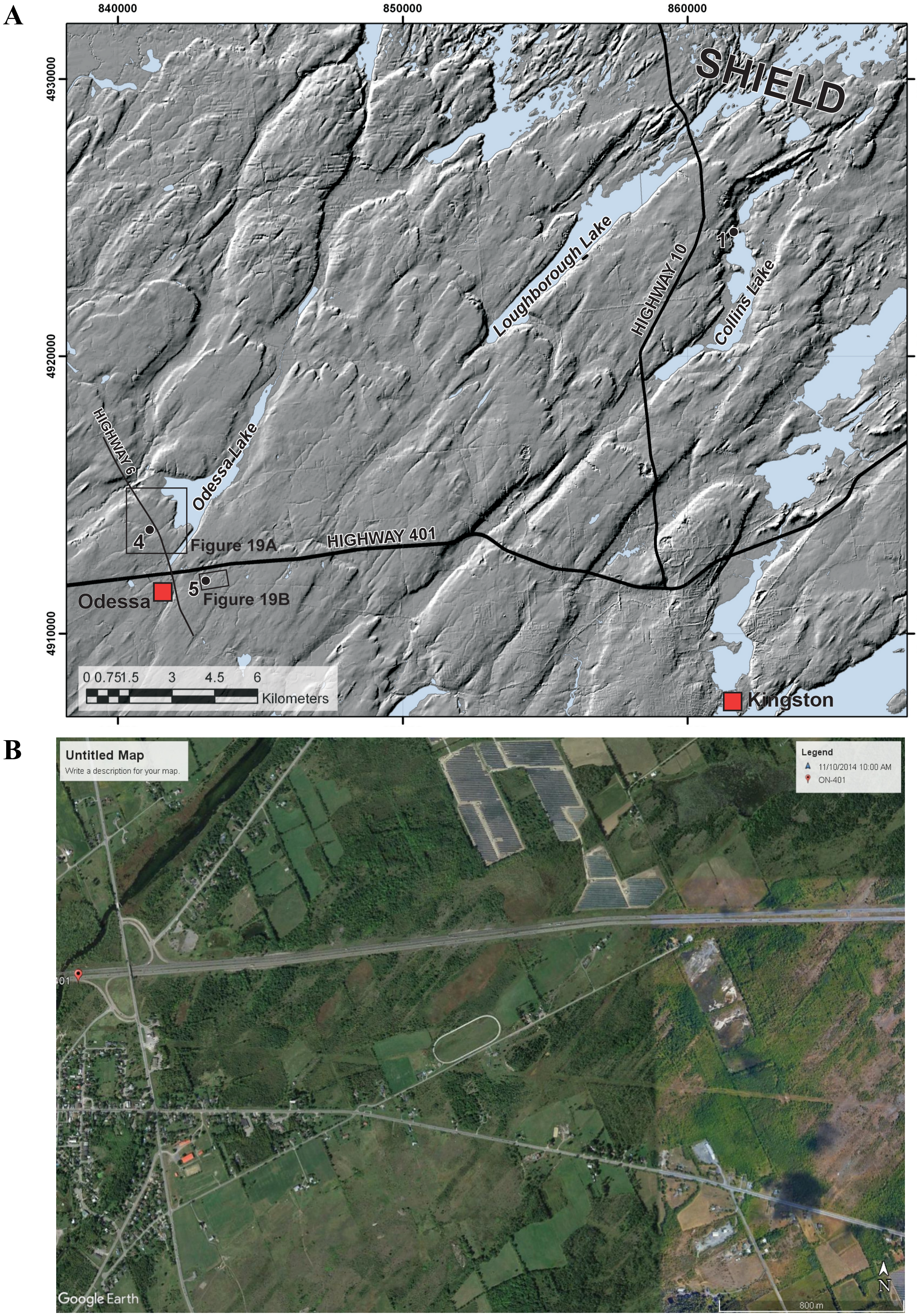


Figure 18. A) Megagrooved and drumlinized limestone surfaces north and west of Kingston (*see* location on Figs. 4 and 15) with locations of Stops 1, 4 (Fig. 19A) and 5 (Fig. 19B). Canadian Shield occurs to the north. **B)** Megagrooved limestone surface near Stop 5 (Fig. 19B).

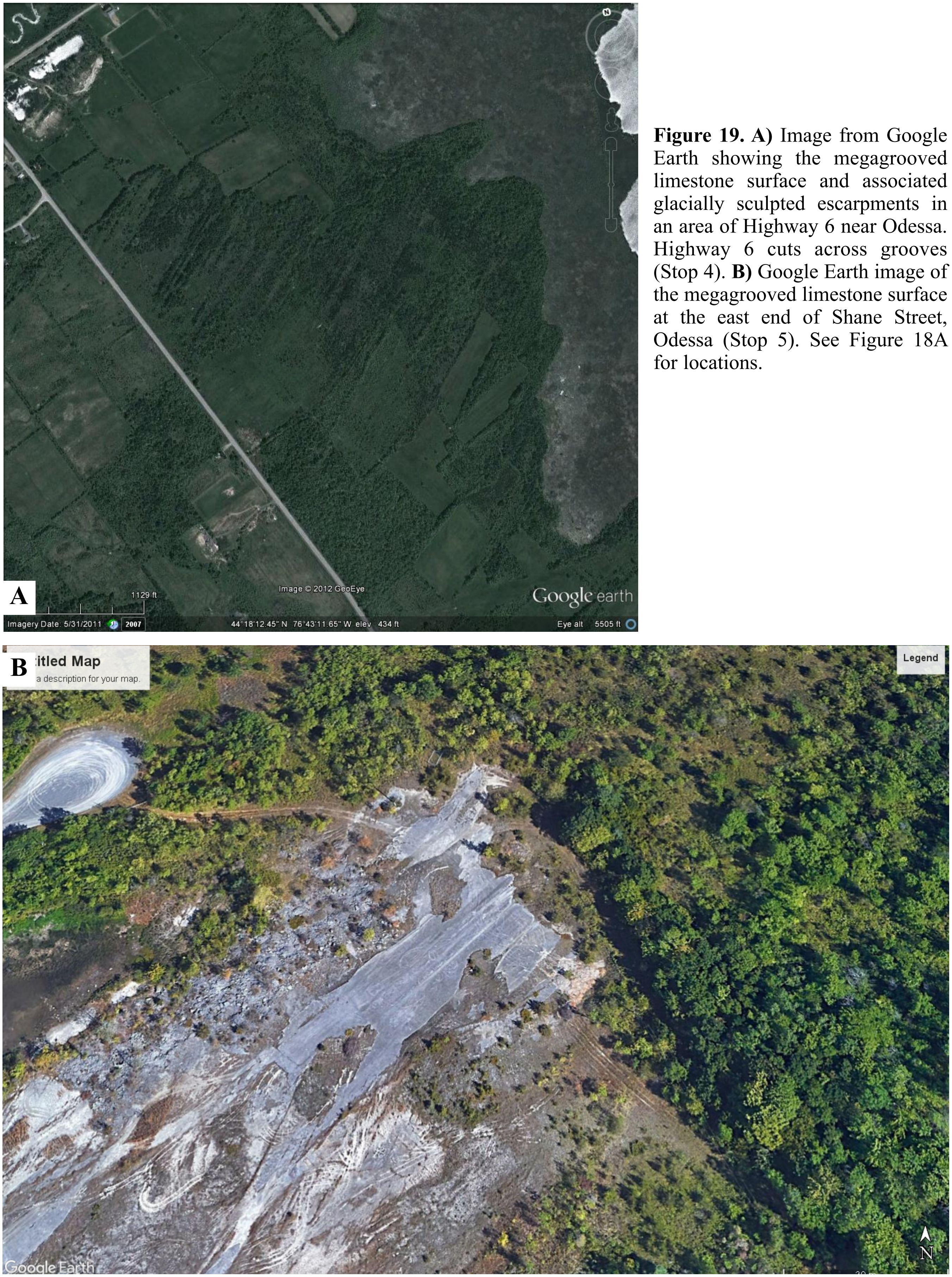


Figure 19. A) Image from Google Earth showing the megagrooved limestone surface and associated glacially sculpted escarpments in an area of Highway 6 near Odessa. Highway 6 cuts across grooves (Stop 4). **B)** Google Earth image of the megagrooved limestone surface at the east end of Shane Street, Odessa (Stop 5). See Figure 18A for locations.

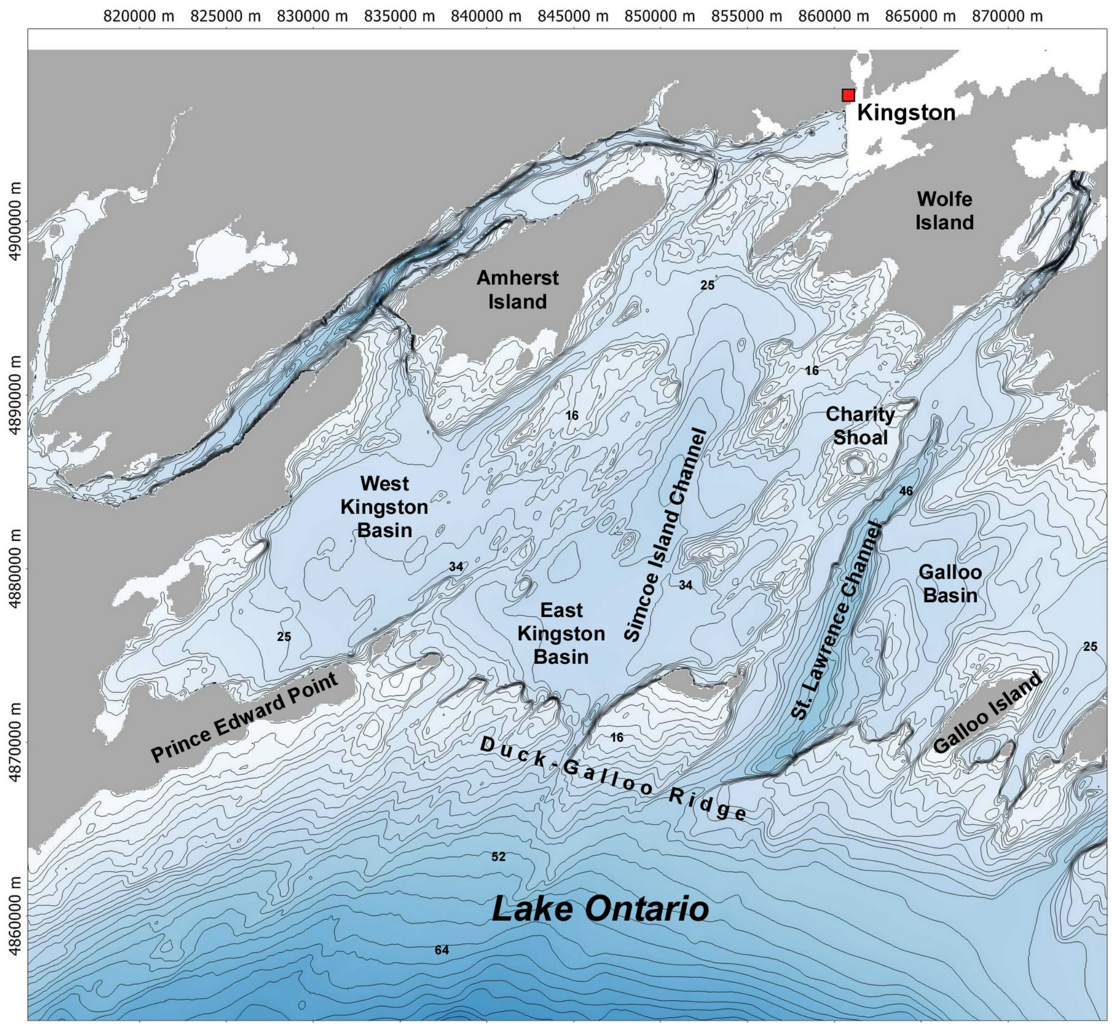


Figure 20. Floor of Lake Ontario between Ontario and New York State with prominent glacially sculpted escarpments (*see* Figs. 4 and 15 for location). From Eyles and Doughty (2016).

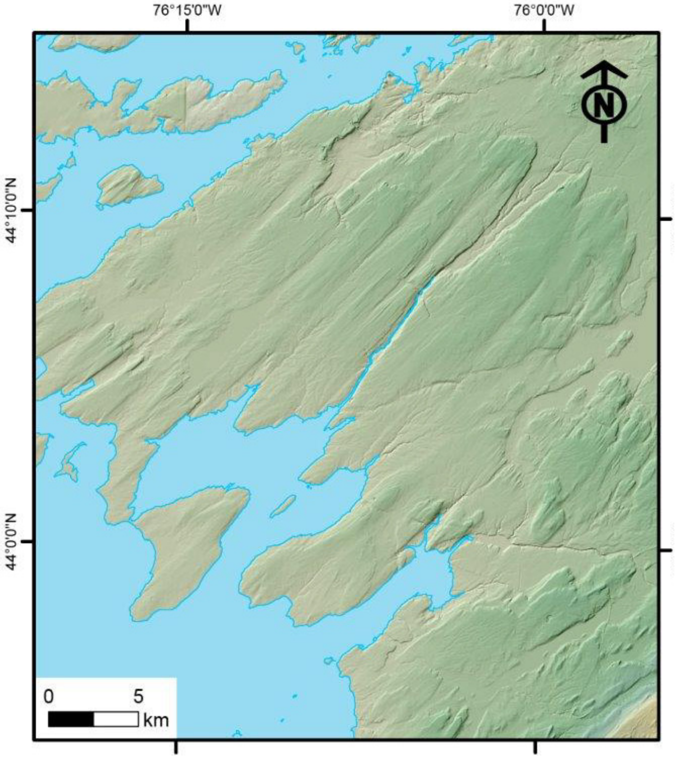
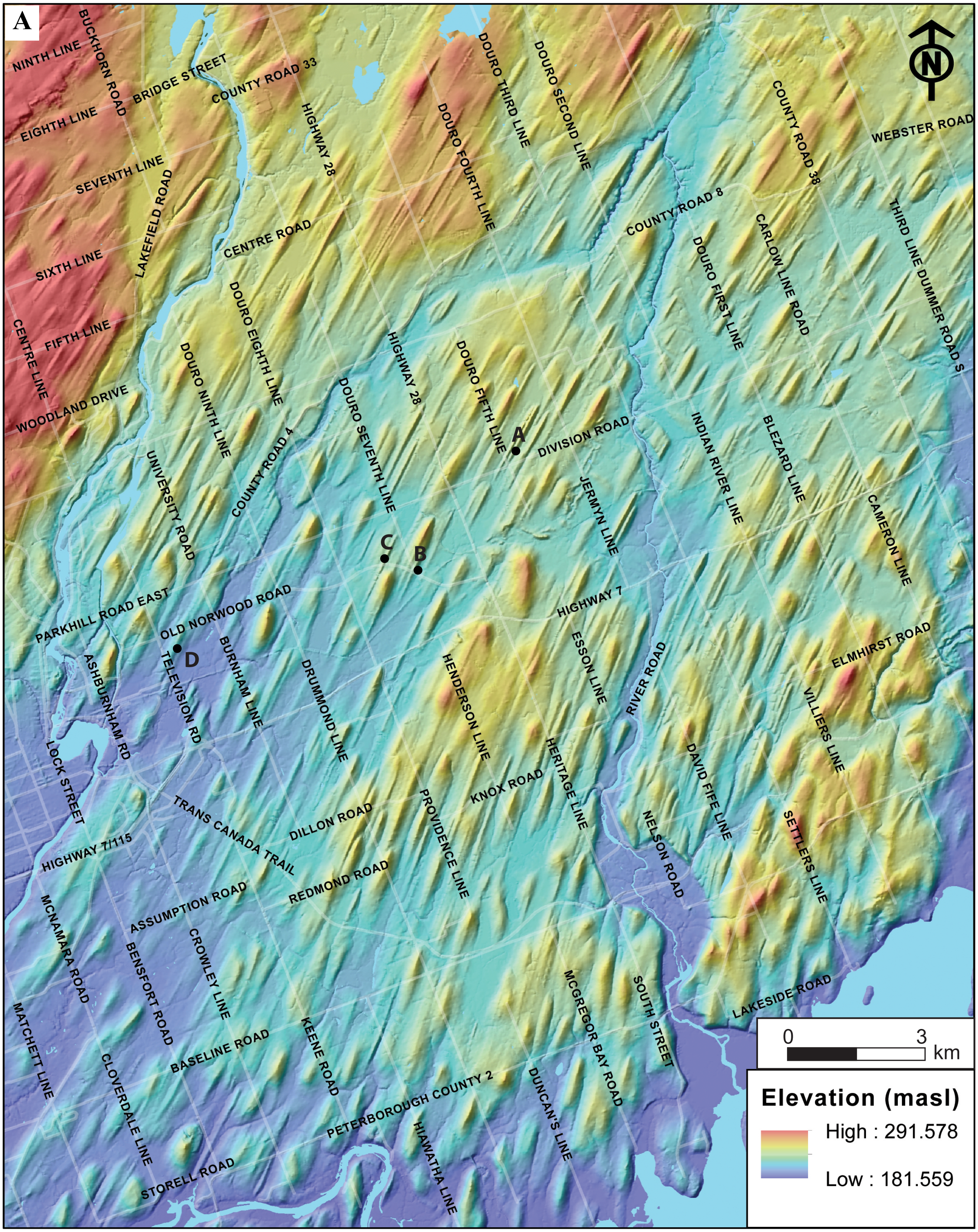


Figure 21. LiDAR-generated topographic surface of the Paleozoic Potsdam Sandstone at the eastern end of Lake Ontario with rock-cut drumlins and megascale glacial lineations recording subglacial erosion below the Ontario-Erie Ice Stream (*see* Fig. 4 and 15 for location). The glacially sculpted bedrock surfaces in New York State were first identified by Gilbert (1899).


A
N
NINTH LINE
BUCKHORN ROAD
EIGHTH LINE
BRIDGE STREET
COUNTY ROAD 33
HIGHWAY 28
DOURO THIRD LINE
DOURO SECOND LINE
DOURO FOURTH LINE
COUNTY ROAD 38
WEBSTER ROAD
SEVENTH LINE
LAKEFIELD ROAD
CENTRE ROAD
COUNTY ROAD 8
DOURO FIRST LINE
CARLOW LINE ROAD
THIRD LINE DUMMER ROAD S
SIXTH LINE
DOURO EIGHTH LINE
FIFTH LINE
CENTRE LINE
DOURO NINTH LINE
HIGHWAY 28
DOURO FIFTH LINE
WOODLAND DRIVE
DOURO SEVENTH LINE
A
DIVISION ROAD
INDIAN RIVER LINE
BLEZARD LINE
UNIVERSITY ROAD
COUNTY ROAD 4
JERMYN LINE
CAMERON LINE
C
B
PARKHILL ROAD EAST
OLD NORWOOD ROAD
HIGHWAY 7
D
ASHBURNHAM RD
TELEVISION RD
BURNHAM LINE
DRUMMOND LINE
HENDERSON LINE
ESSON LINE
RIVER ROAD
ELMHIRST ROAD
VILLIERS LINE
LOCK STREET
HERITAGE LINE
KNOX ROAD
DAVID FIFE LINE
TRANS CANADA TRAIL
DILLON ROAD
PROVIDENCE LINE
NELSON ROAD
SETTLERS LINE
HIGHWAY 7/115
REDMOND ROAD
ASSUMPTION ROAD
MCNAMARA ROAD
CROWLEY LINE
BENSFORT ROAD
MCGREGOR BAY ROAD
SOUTH STREET
LAKESIDE ROAD
0
3
km
MATCHETT LINE
CLOVERDALE LINE
BASELINE ROAD
KEENE ROAD
PETERBOROUGH COUNTY 2
DUNCAN'S LINE
HIAWATHA LINE
STORELL ROAD
Elevation (masl)
High : 291.578
Low : 181.559

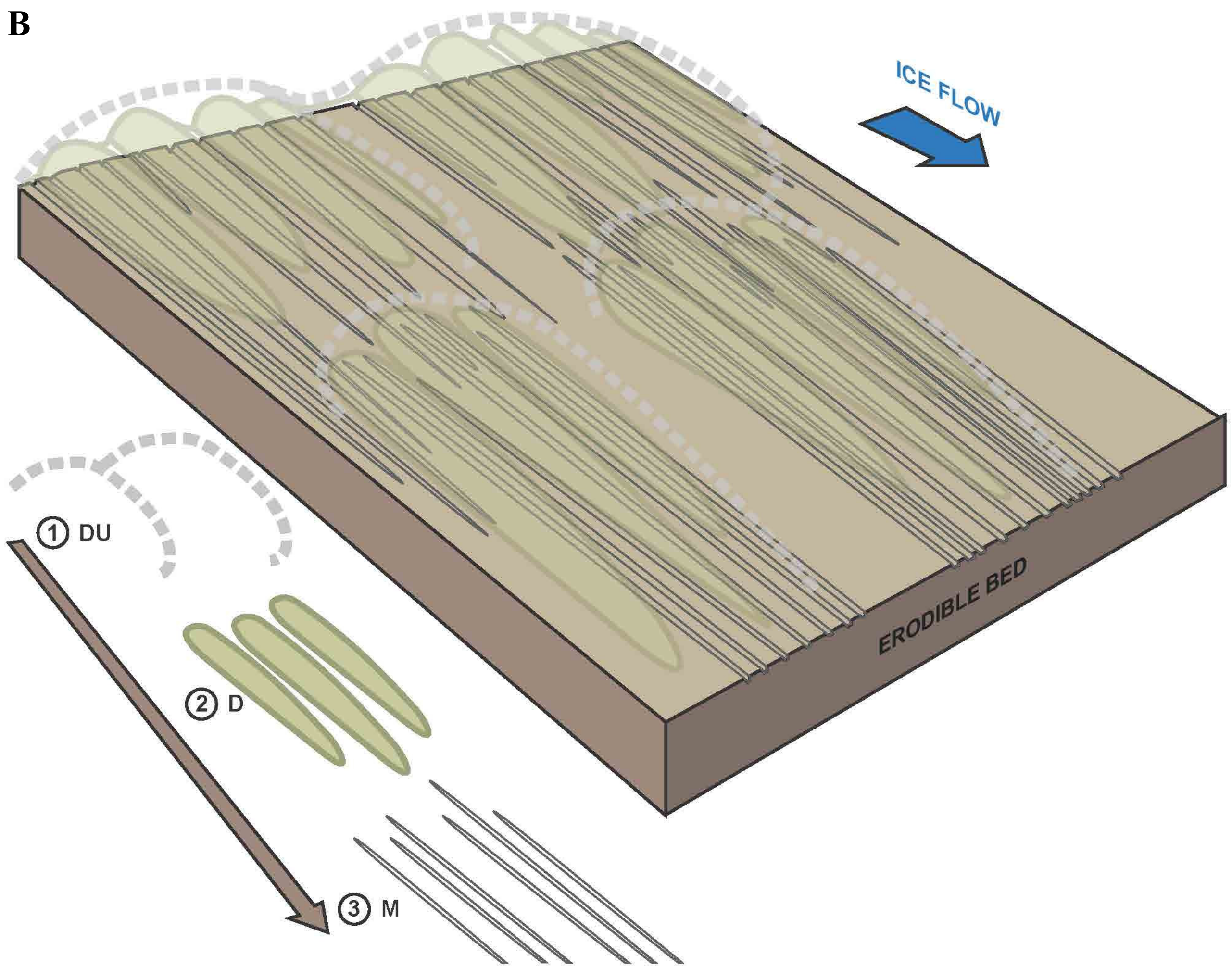


Figure 22. A) (opposite) Topography of the Peterborough Drumlin Field just east of Peterborough showing the locations A to D mentioned in the text (*see* Figs. 4 and 15 for location). Higher standing drumlinized 'uplands' west of the Trent River are cored by antecedent sediment. East of the river, the overall topography is much reduced and residual outliers of the upland surface show consistent downglacier changes from large drumlins into 'channeled drumlins' to megascale glacial lineations (MSGLs) that record erosional lowering of the bed. The same overall downglacier bedform evolution is shown in the beds of ice streams in New York State (*see* Fig. 23) and suggests headward propagation of fast flow and accompanying erosion of the drumlinized bed into MSGLs (*see* Fig. 24). **B)** (above) Suggested evolution of MSGLs from a large drumlin uplands (DU) as a result of progressive bed lowering and smoothing to produce a low-drag surface that enables fast flow.

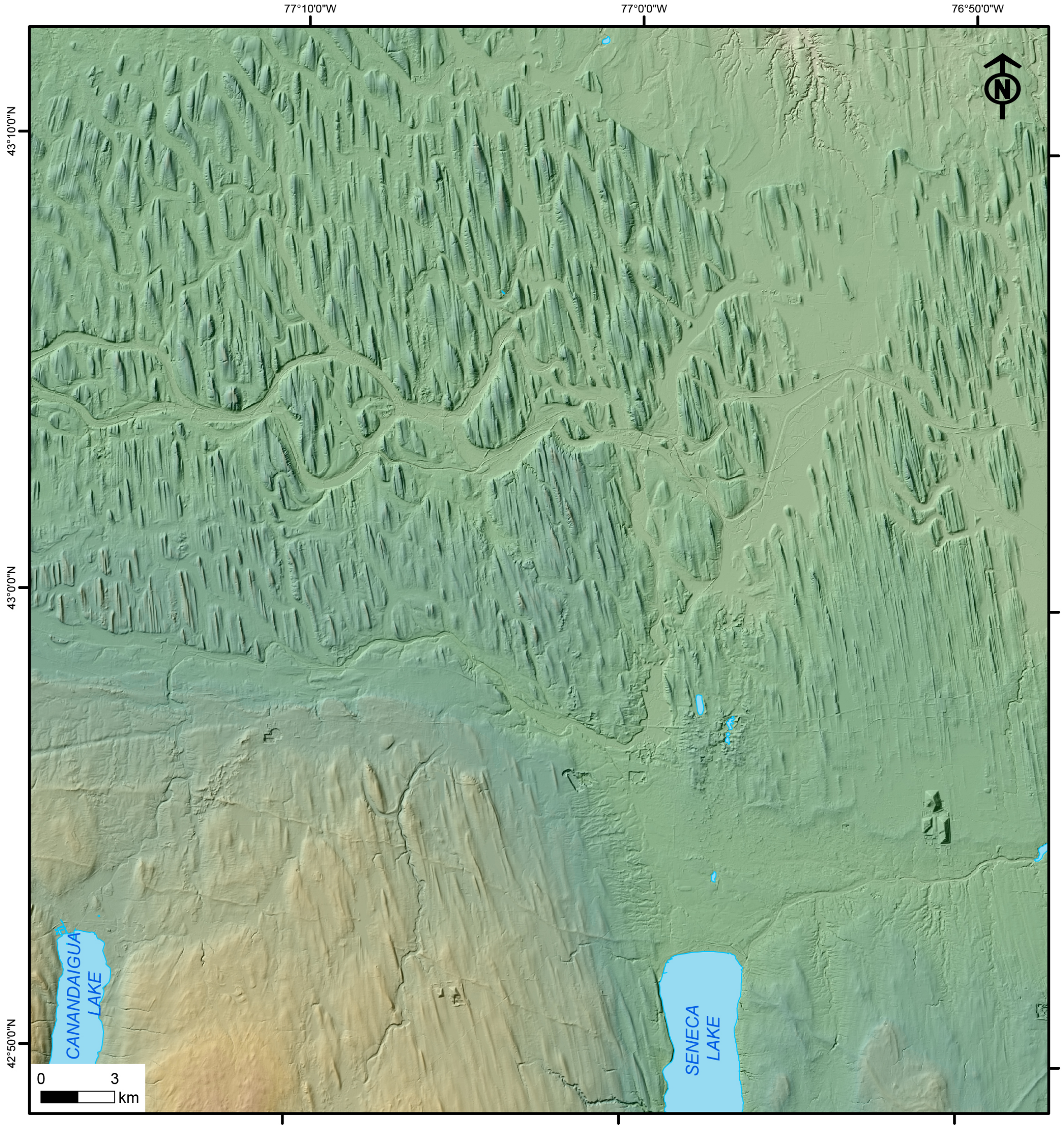


Figure 23. A portion of the bed of the Cayuga Ice Stream (*see* Fig. 4 for location) in upper New York State showing transitions from drumlins through 'dissected drumlins' to megascale glacial lineations, which can also be seen in Peterborough (Fig. 22) as first noted by Fairchild (1900).

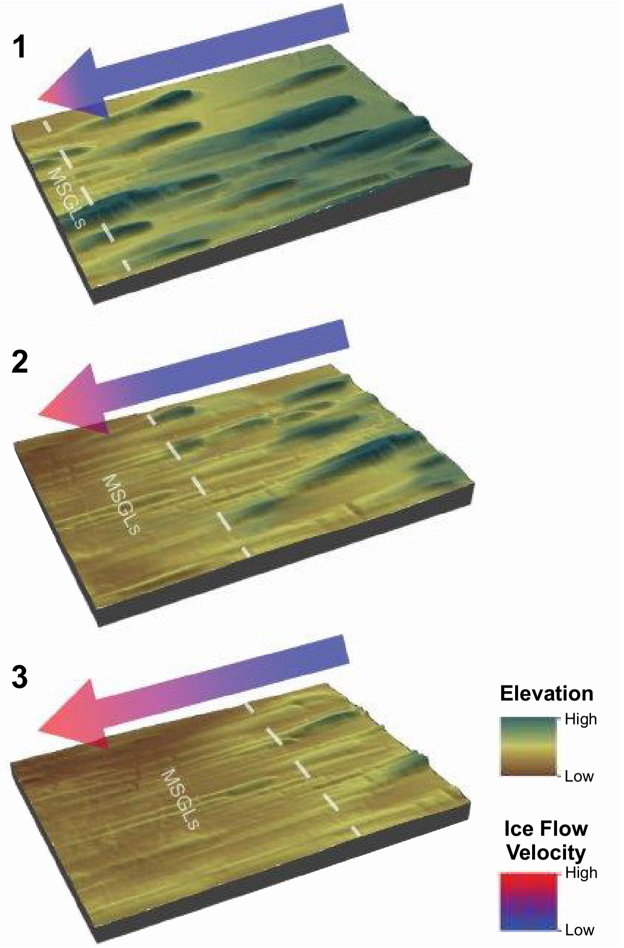


Figure 24. Hypothetical model showing the 'retrograde dissection' of a drumlinized bed to form megascale glacial lineations (MSGLs) to reduce basal shear and facilitate *upglacier propagation* of fast flow from the glacier margin, giving rise to a *downglacier geomorphic continuum* from high-standing, little-modified drumlin bedforms in areas of thicker antecedent sediment to intermediate forms ('channeled drumlins'), to the final stage of MSGLs in areas of thin drift cover (or rock). In this model drumlins and MSGLs form a bedform continuum that is controlled by changing ice velocity.

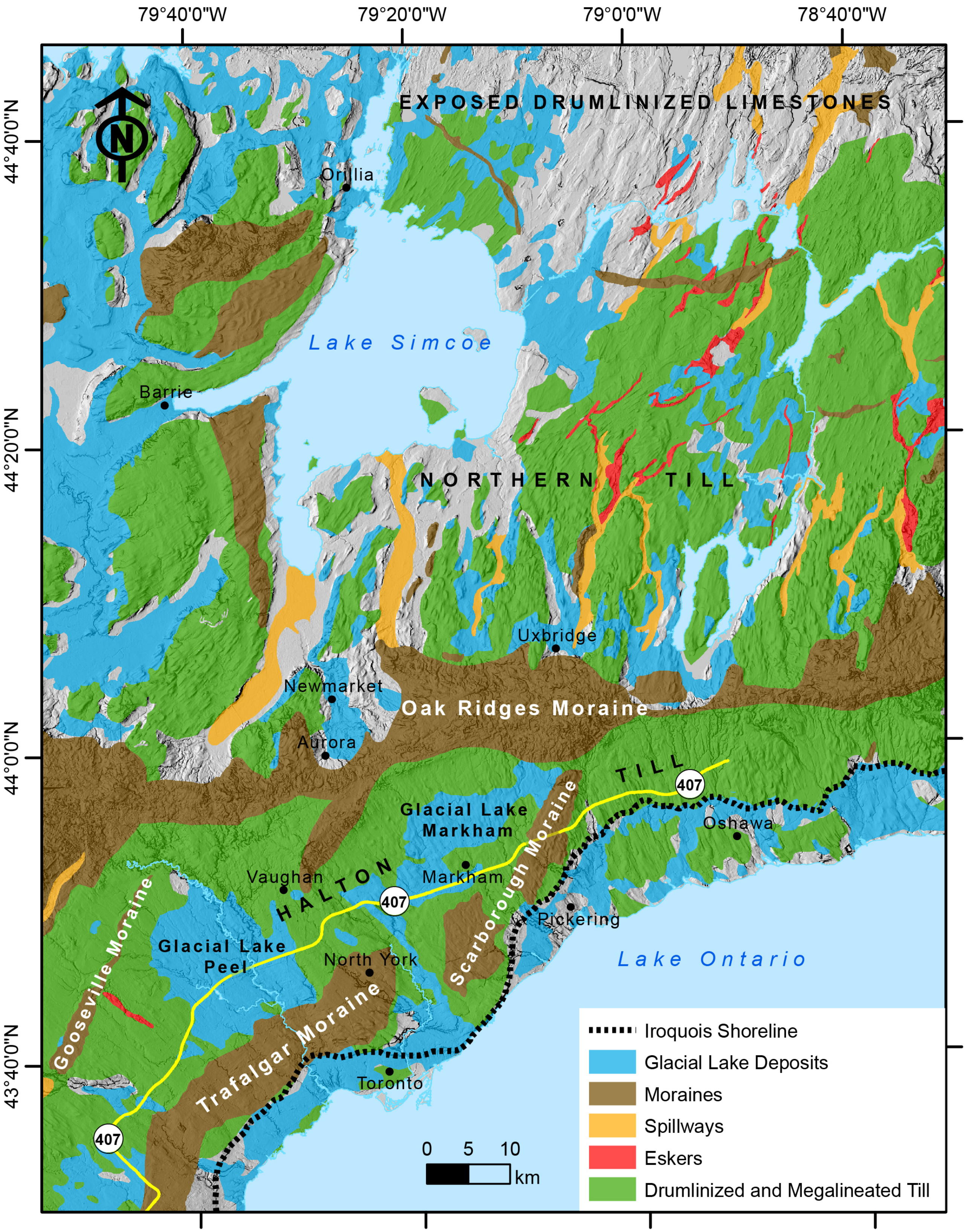


Figure 25. Greatly simplified glacial geology of southern Ontario showing the principal till plains and moraines (based on various authors, principally Barnett, 1992). Note the prominent bulges in width of the Oak Ridges Moraine forming large fan-deltas, which are referred to as the Albion (1), Uxbridge (2), Pontypool (3) and Rice Lake (4) 'wedges' by Barnett et al. (1998). These were deposited in an elongate highly dynamic ice-contact lake basin trapped between two ice streams (Fig. 26). Paleocurrents are dominantly to the west.

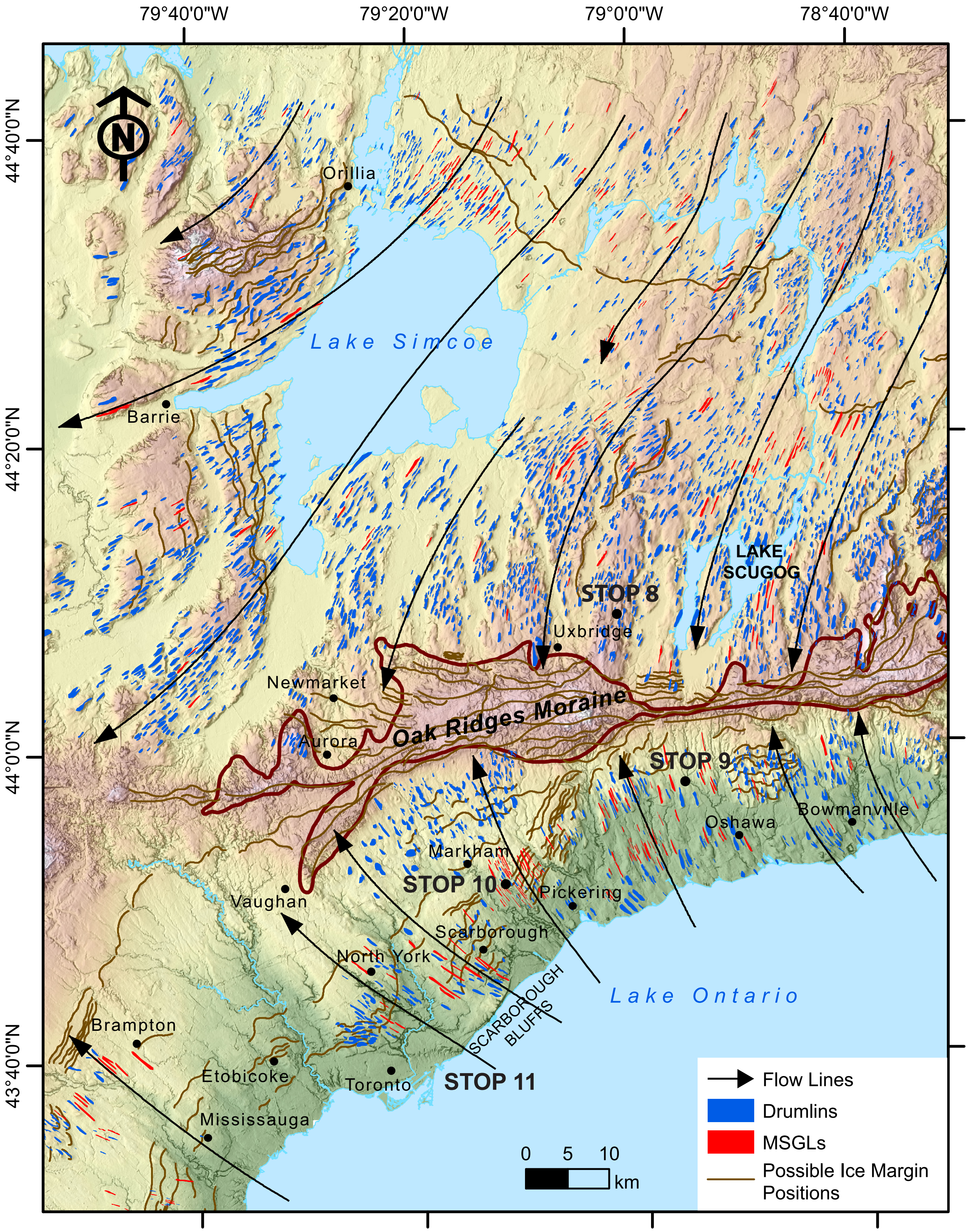


Figure 26. Flow lines of Halton and Simcoe ice streams converging on the Oak Ridges Moraine based on mapping of megascale glacial lineations (*see* Figs. 14 and 5 for location).

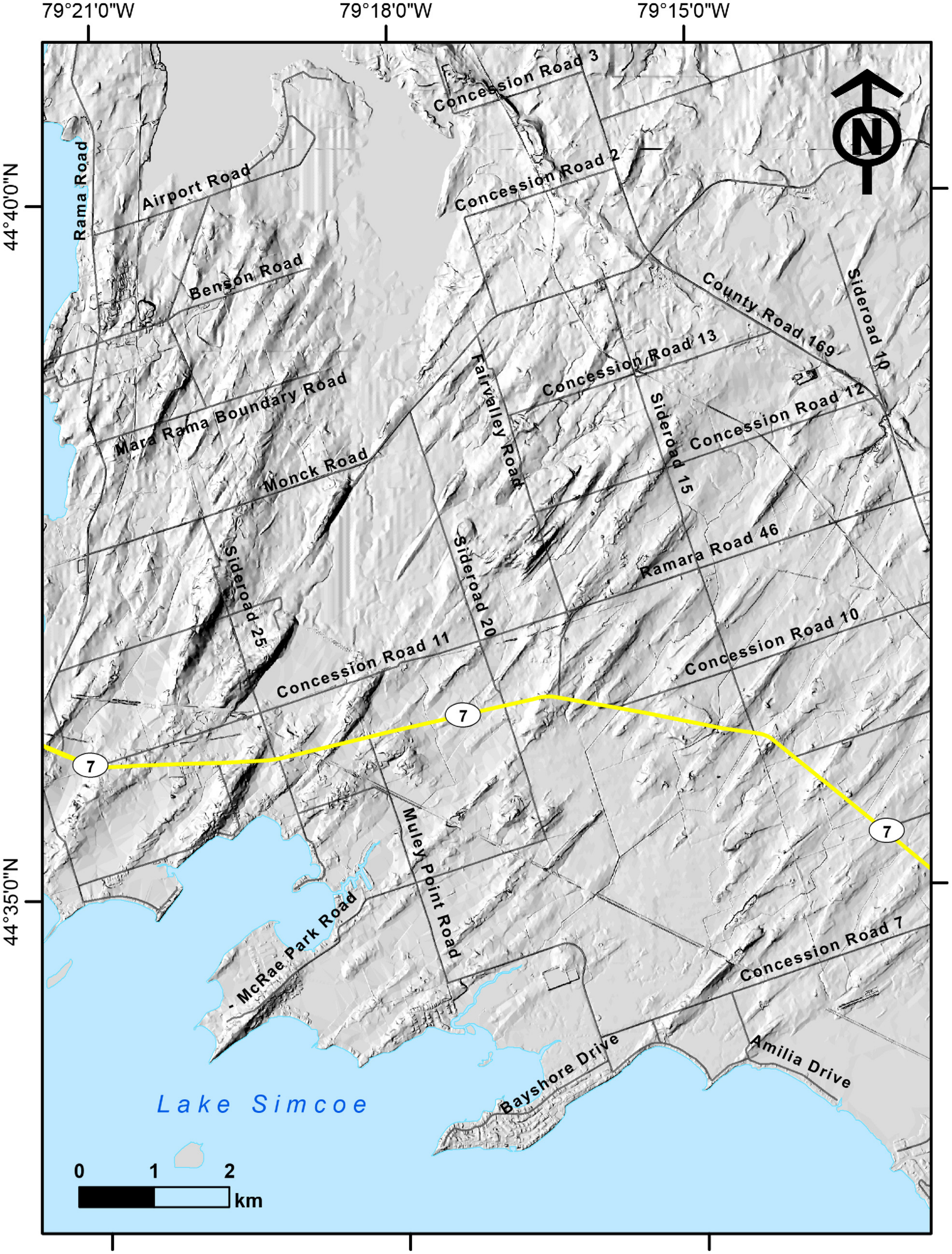


Figure 27. Megascale glacial lineations and drumlins of the soft bed of the Simcoe Ice Stream on the north flank of the Oak Ridges Moraine, northeast of Lake Simcoe.

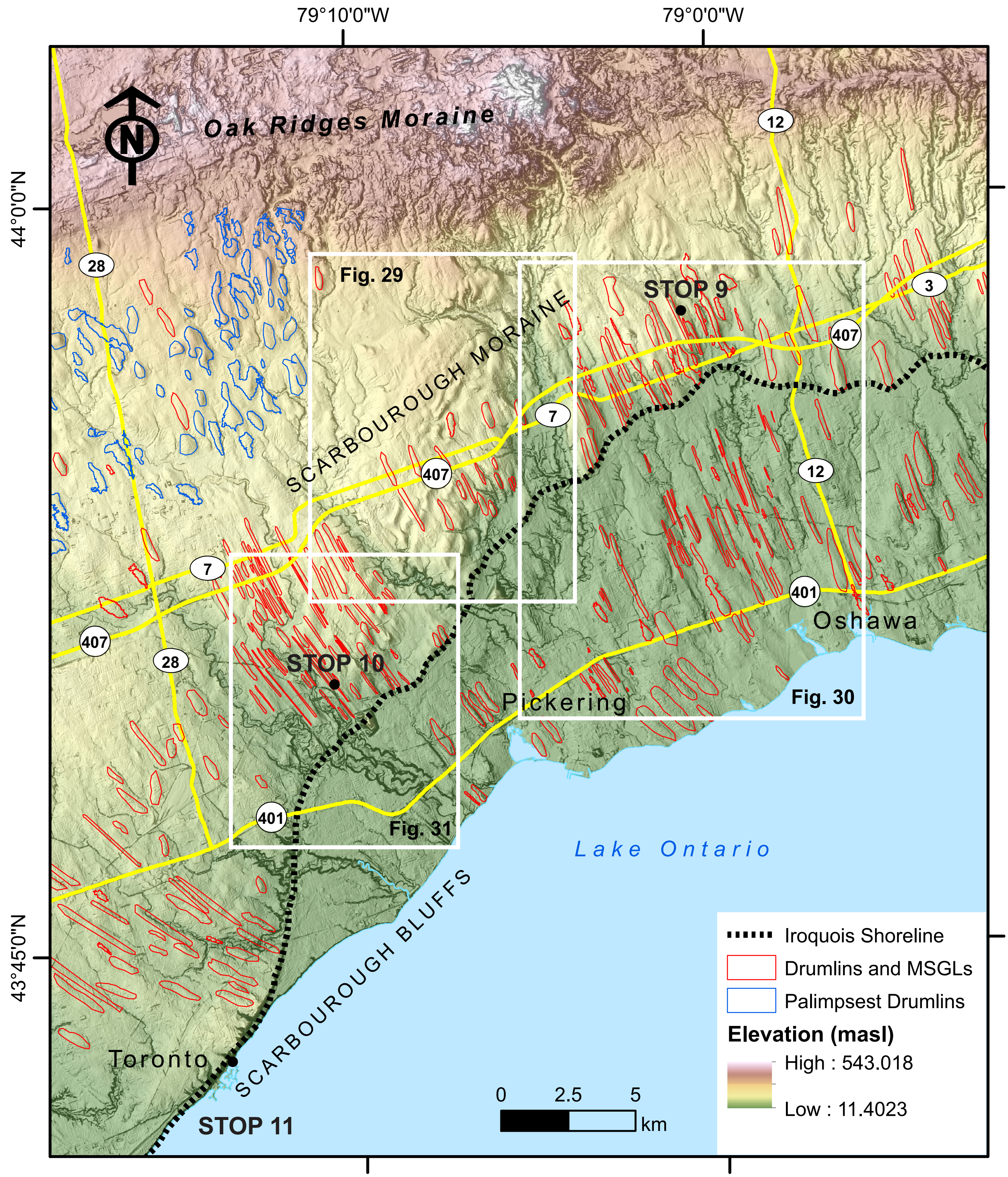


Figure 28. Principal flow sets of megascale glacial lineations (MSGLs) on the bed of the Halton Ice Stream south of the Oak Ridges Moraine; note the overridden and partially reshaped 'palimpsest' drumlins that record the preceding Late Wisconsin maximum flow during the Last Glacial Maximum (Fig. 14A). MSGLs superposed on palimpsest drumlins are commonly seen throughout the Ontario Basin and can still be recognized across the floor of glacial Lake Iroquois. Note the Scarborough Moraine, which is composed of reworked till that has been advected to the ice stream margin.

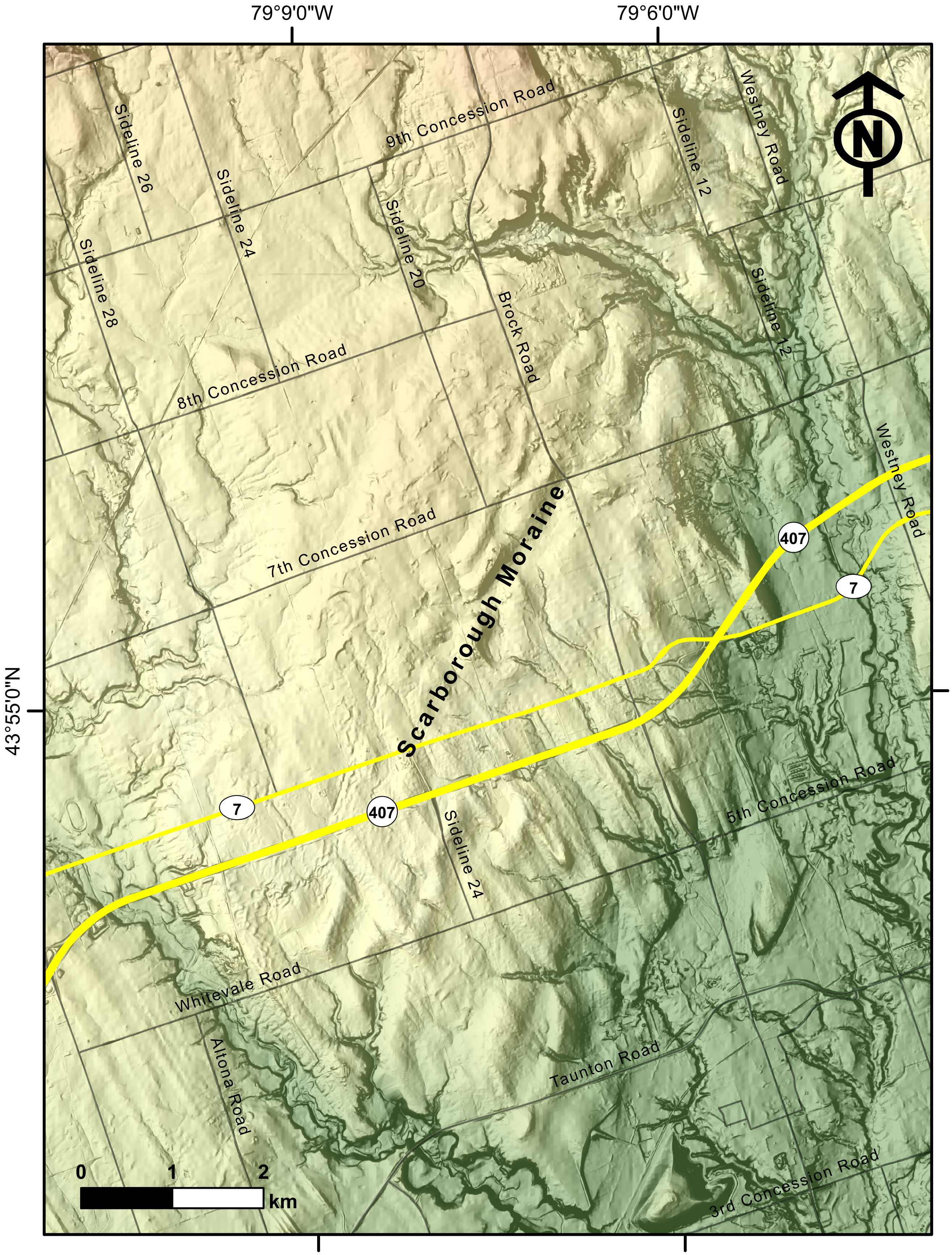


Figure 29. Flow set of the megascale glacial lineations immediately north of Lake Ontario that resulted from northward flow of the Halton Ice Stream from the Lake Ontario basin.

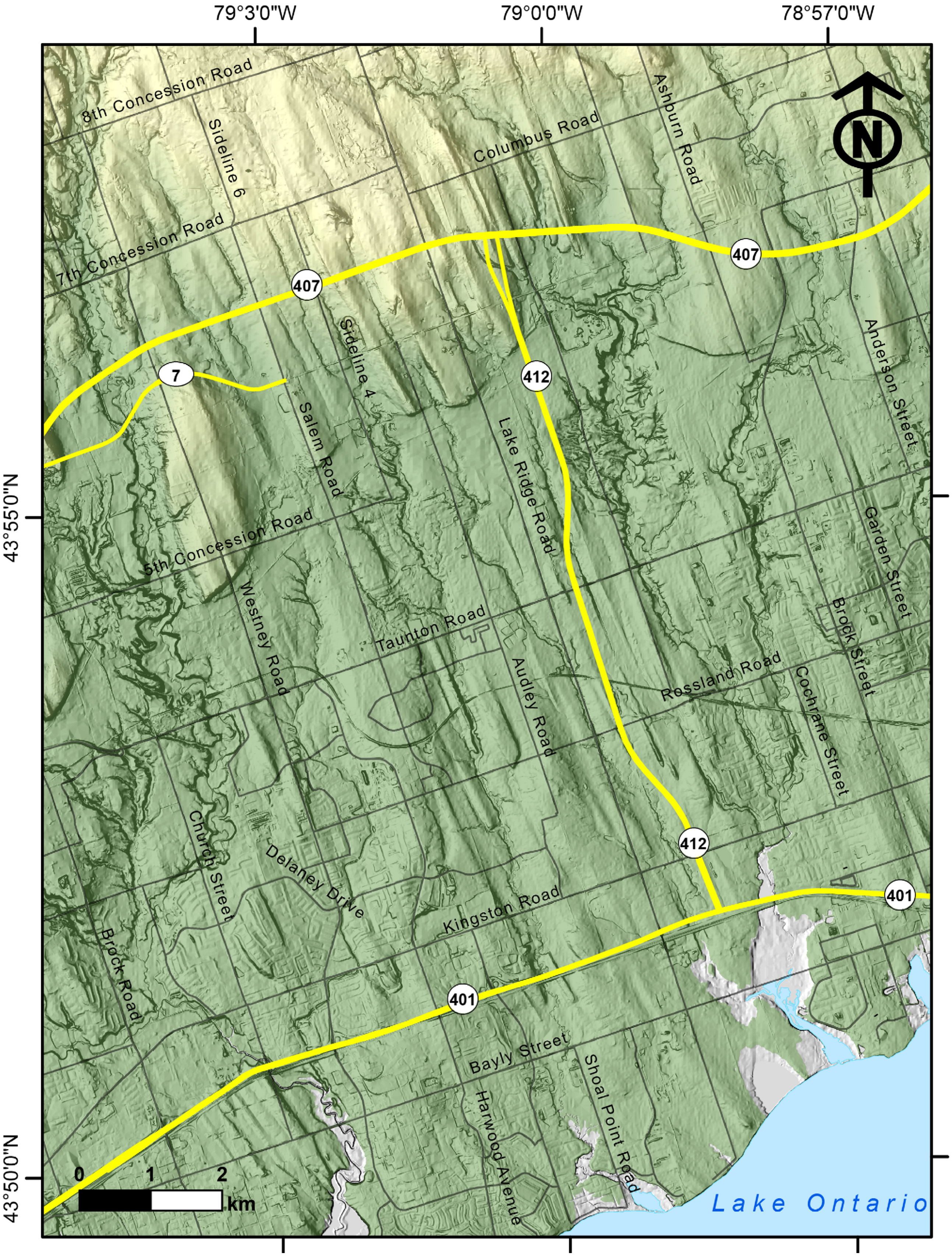


Figure 30. Megascale glacial lineations (MSGLs) on the bed of the Halton Ice Stream on the south flank of the Oak Ridges Moraine, between Highways 407 and 401. Highway construction has provided long exposures through MSGLs, indicating they are erosional and cut across pre-existing till and sediments.

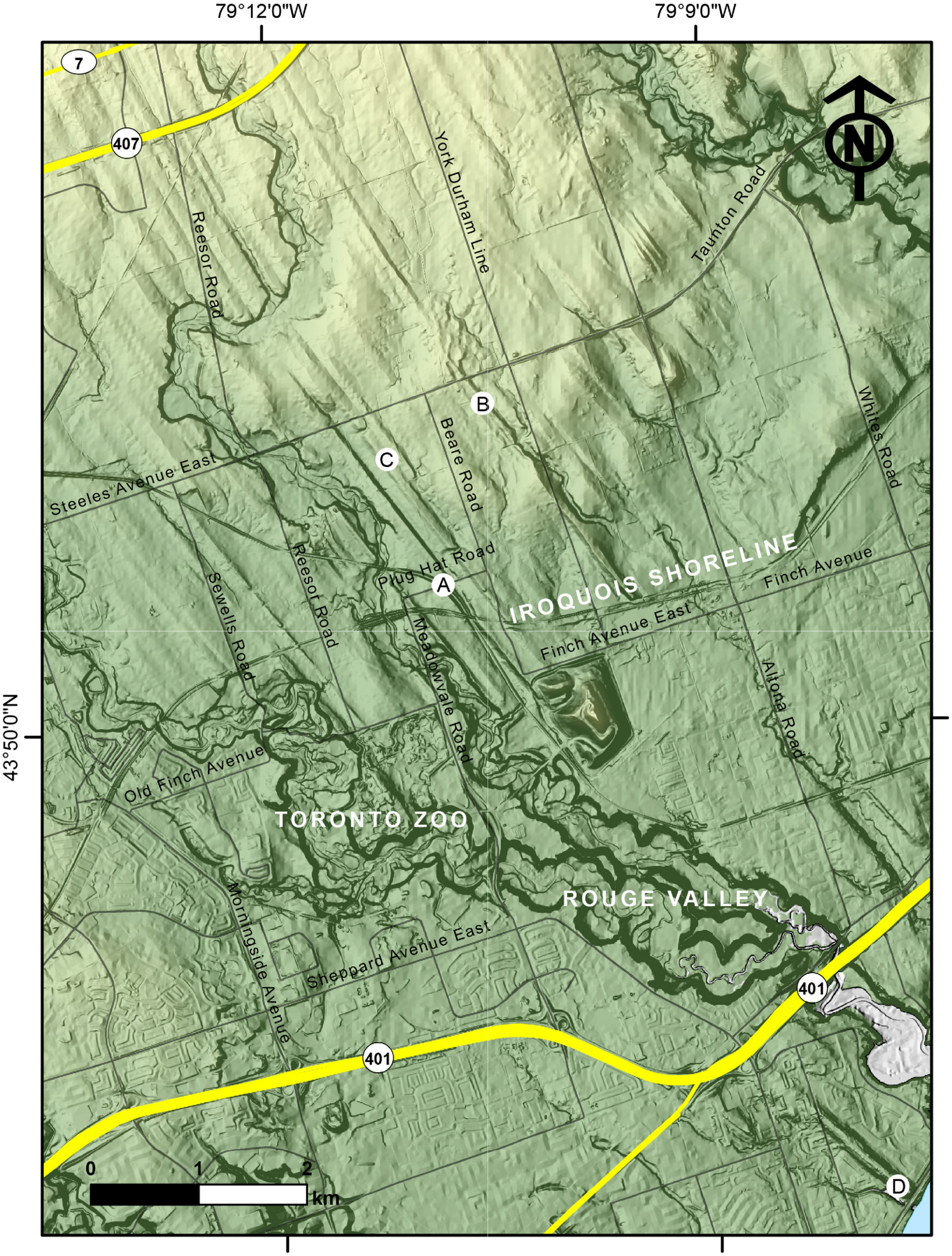
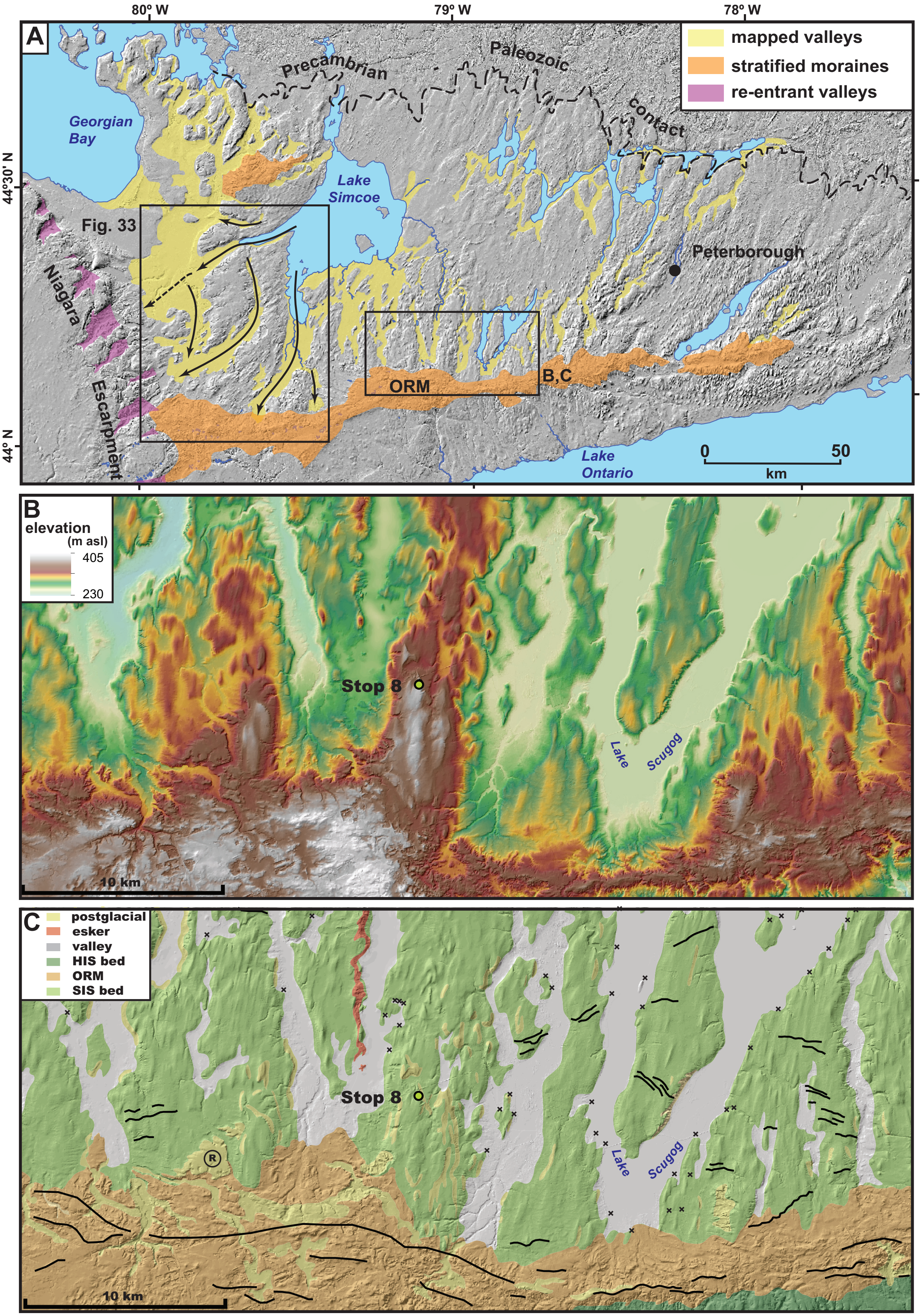


Figure 31. Flow set of megascale glacial lineations (MSGLs) in Scarborough near the Toronto Zoo. Locations A, B, and C are sub-stops at individual MSGLs.


80° W
79° W
78° W
44°30' N
44° N
A
mapped valleys
stratified moraines
re-entrant valleys
Precambrian
Paleozoic
contact
Georgian Bay
Lake Simcoe
Fig. 33
Peterborough
Niagara
Escarpment
ORM
B,C
Lake Ontario
0
50
km
B
elevation
(m asl)
405
230
Stop 8
Lake Scugog
10 km
C
postglacial
esker
valley
HIS bed
ORM
SIS bed
Stop 8
R
Lake Scugog
10 km

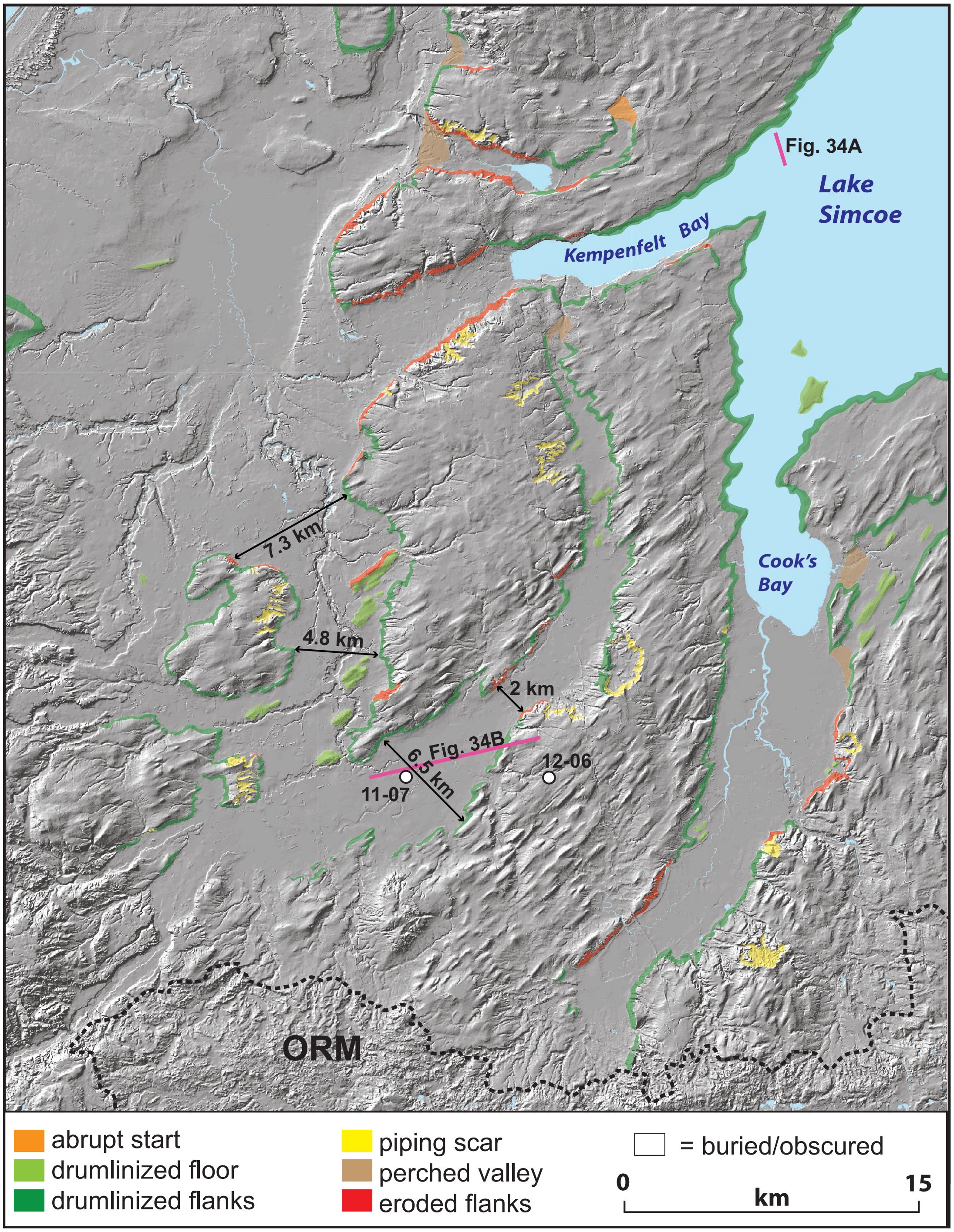


Figure 33. Streamlined bed and prominent valleys beneath the Simcoe Ice Stream (Figs. 14B, 26) southwest of Lake Simcoe (modified from Mulligan et al., 2018a). Location is shown on Figure 32A.

Figure 32 opposite. A) Regional valley networks cut into the drumlinized and megascale glacially lineated till bed north of the Oak Ridges Moraine (ORM), with central axes with drainage directions depicted by black arrows (Mulligan et al., 2018a). The large inset box shows the location of channels on the bed of the Simcoe Ice Stream at the southern end of Lake Simcoe (*see* Fig. 33). **B)** Digital elevation model of the bed of the Simcoe Ice Stream (SIS) showing the location of Stop 8. **C)** Hillshaded relief map of the same area. Drumlins within or along the lower flanks of valleys are highlighted with an 'x' at their stoss (NE) end. Postglacial features, such as shorelines, outwash channels and groundwater piping scars, are shown in yellow; note the glaciofluvial outwash system that originates at a recessional moraine (solid black line) in the south within the ORM, and terminates as a large fan delta (shown as a circled R) north of the ORM (Roseville Delta; Barnett et al., 1998). This likely indicates earlier northward retreat of the Simcoe Ice Stream compared to the Halton Ice Stream (HIS) south of the ORM (*see* Figs. 14B, 26).

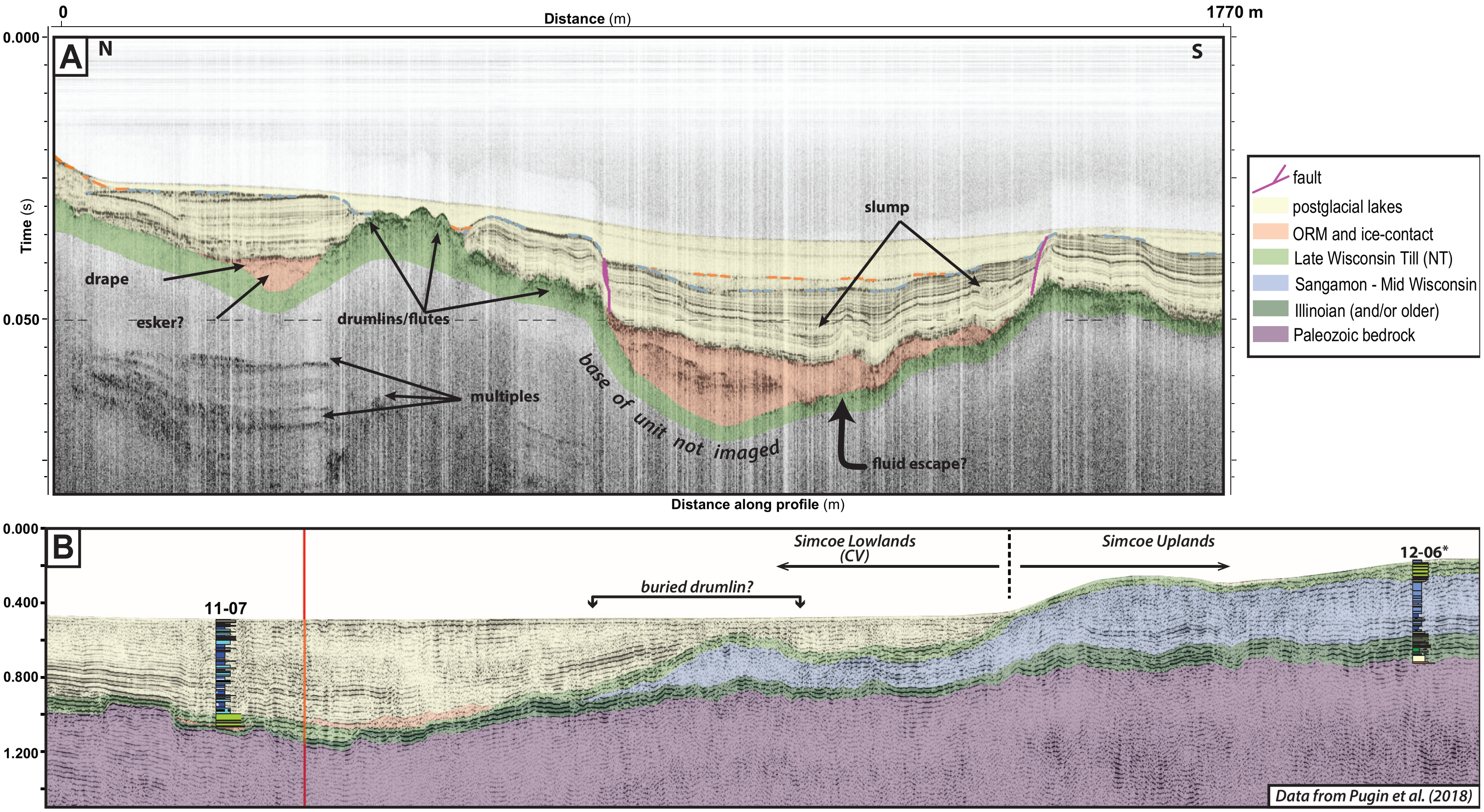


Figure 34. A) High-resolution CHIRP sub-bottom profile of the eastern part of Kempenfelt Bay in Lake Simcoe (*see* Fig. 33 for location) showing multiple valley infill units, including an anticlinal feature interpreted as an esker that overlies a drumlinized valley floor. **B)** High-resolution S-wave seismic reflection survey profile from the Cookstown Valley (from Pugin et al., 2018) showing the drumlinized floor of the valley. Modified from Mulligan et al. (2018a). Abbreviation: ORM = Oak Ridges Moraine. Locations are shown on Figure 33.

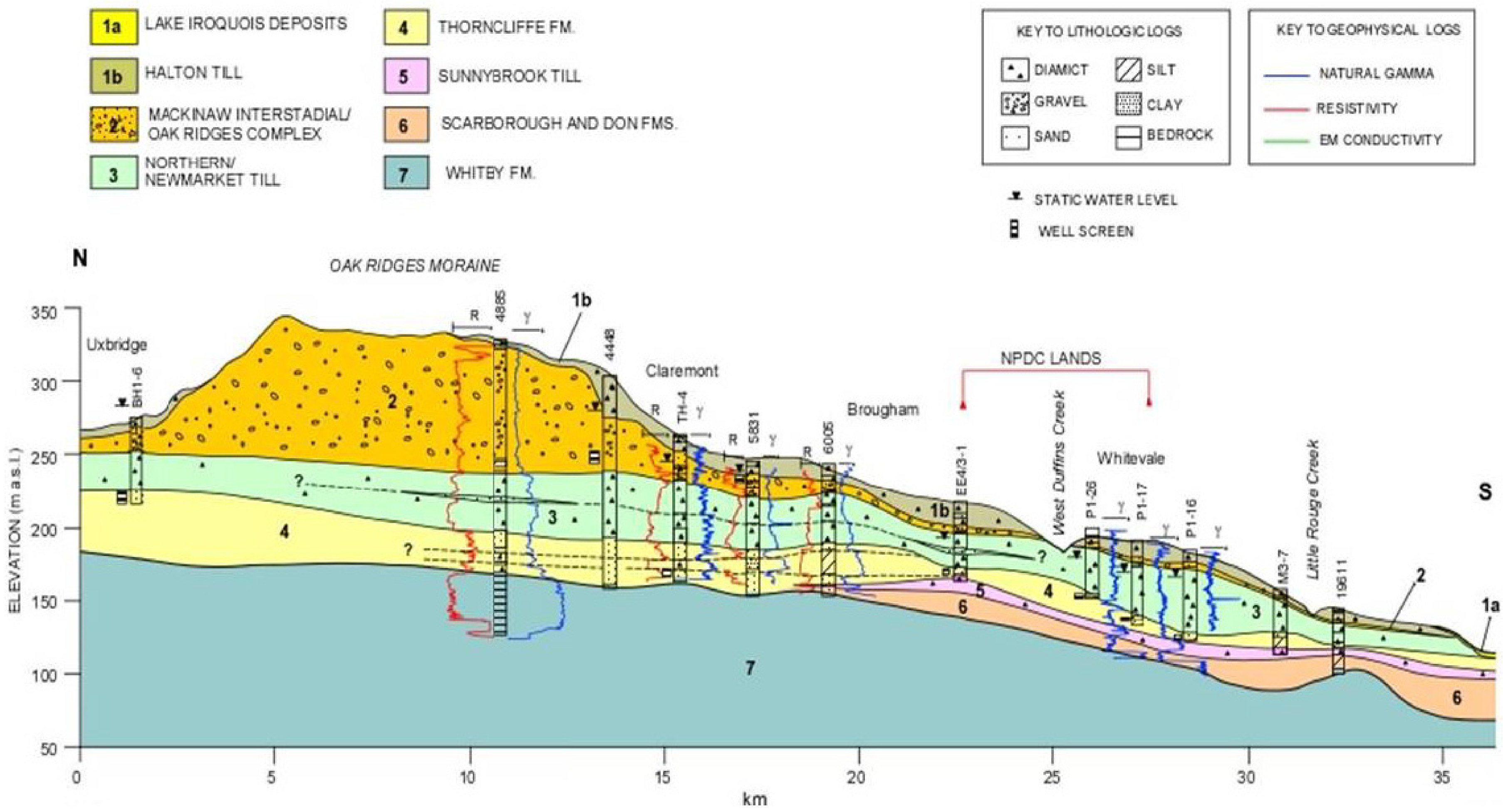


Figure 35. Generalized stratigraphic cross-section through the Oak Ridges Moraine and the so-called 'South Slope' that comprise the megalineated bed of the Halton Ice Stream (after University of Toronto) (Figs. 26–31). This area is rapidly being developed and groundwaters are being severely impacted by urban contaminants, especially road salt.

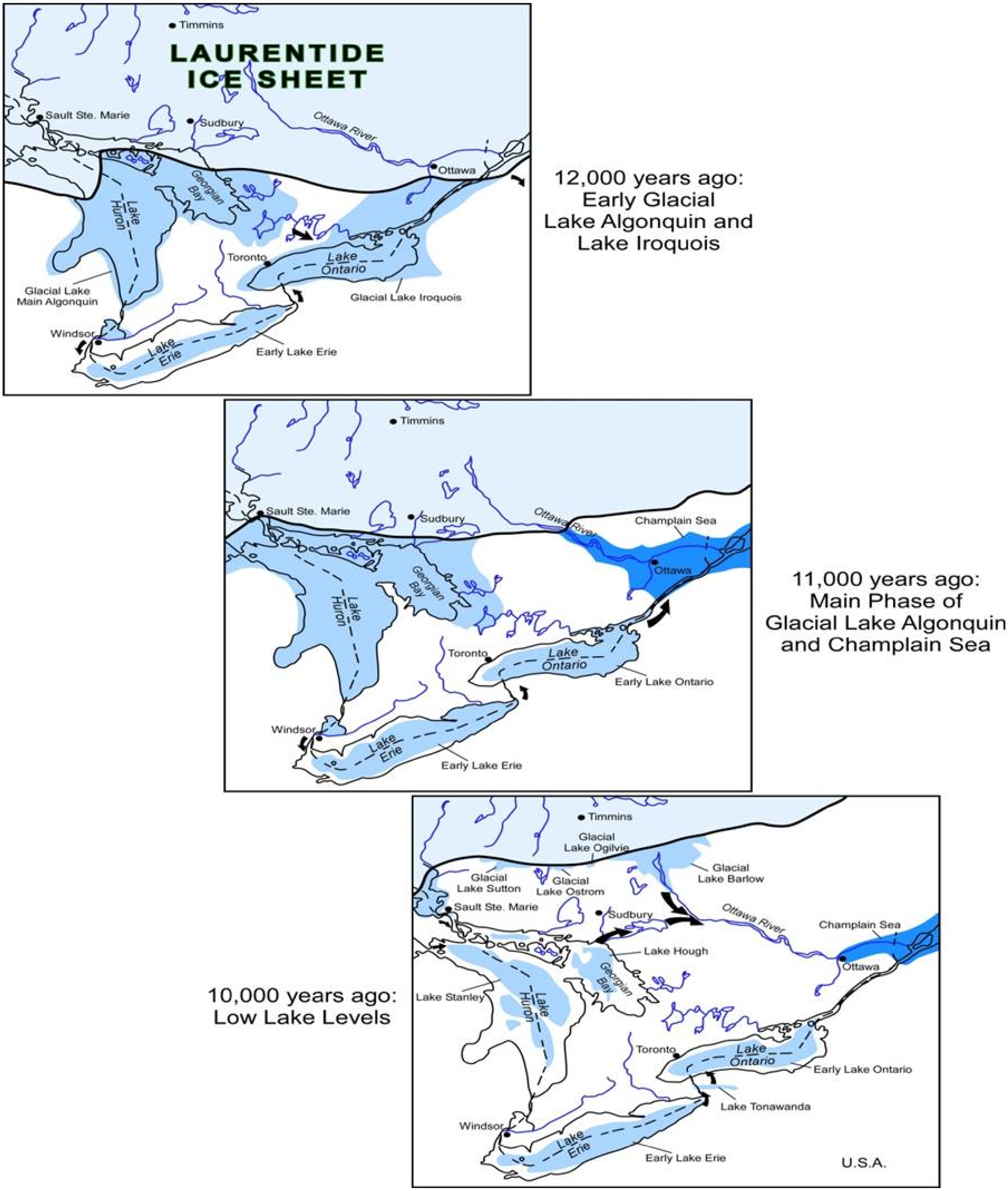


Figure 36. Late stages of deglaciation during the early Holocene; low lake levels persisted until after 7,000 ybp during the Hypsithermal (principally after Donnelly et al. (2005) and McCarthy et al. (2012a)).

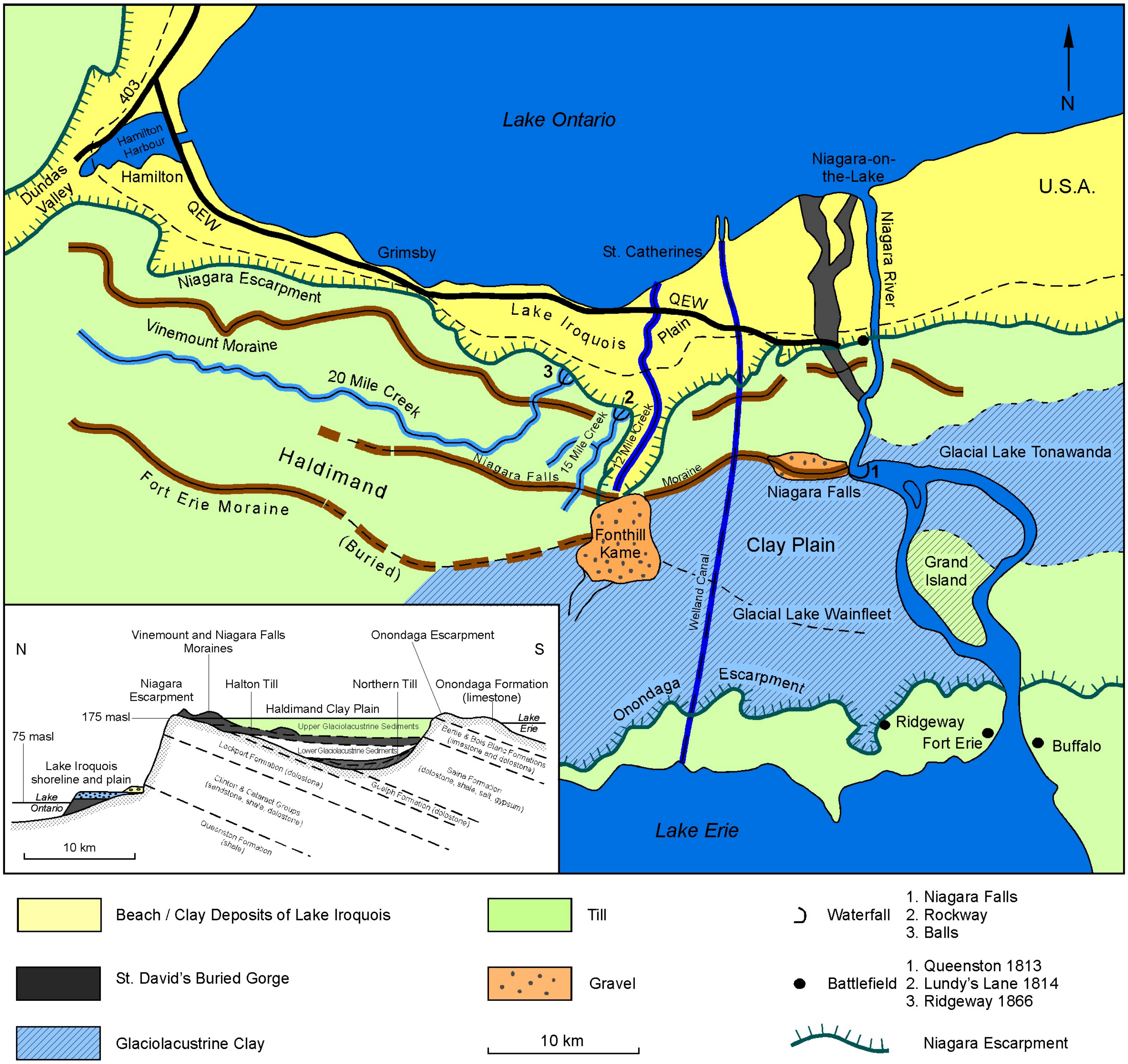


Figure 37. Generalized stratigraphic cross-section through the Niagara Peninsula (after Middleton et al., 2009).

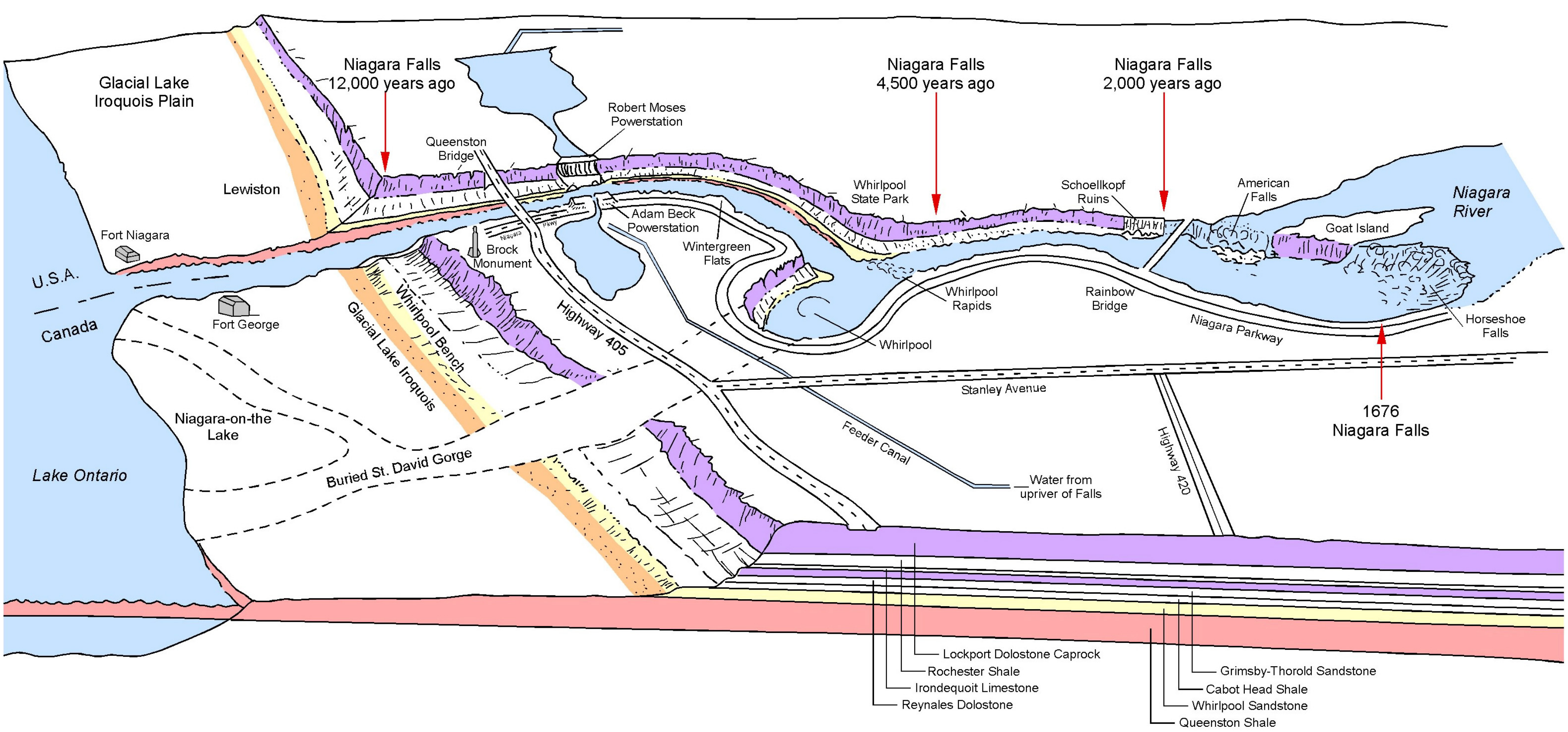


Figure 38. Geology of the Niagara area showing successive positions of the Niagara Falls during the last 12,000 years (after Eyles, 2013).

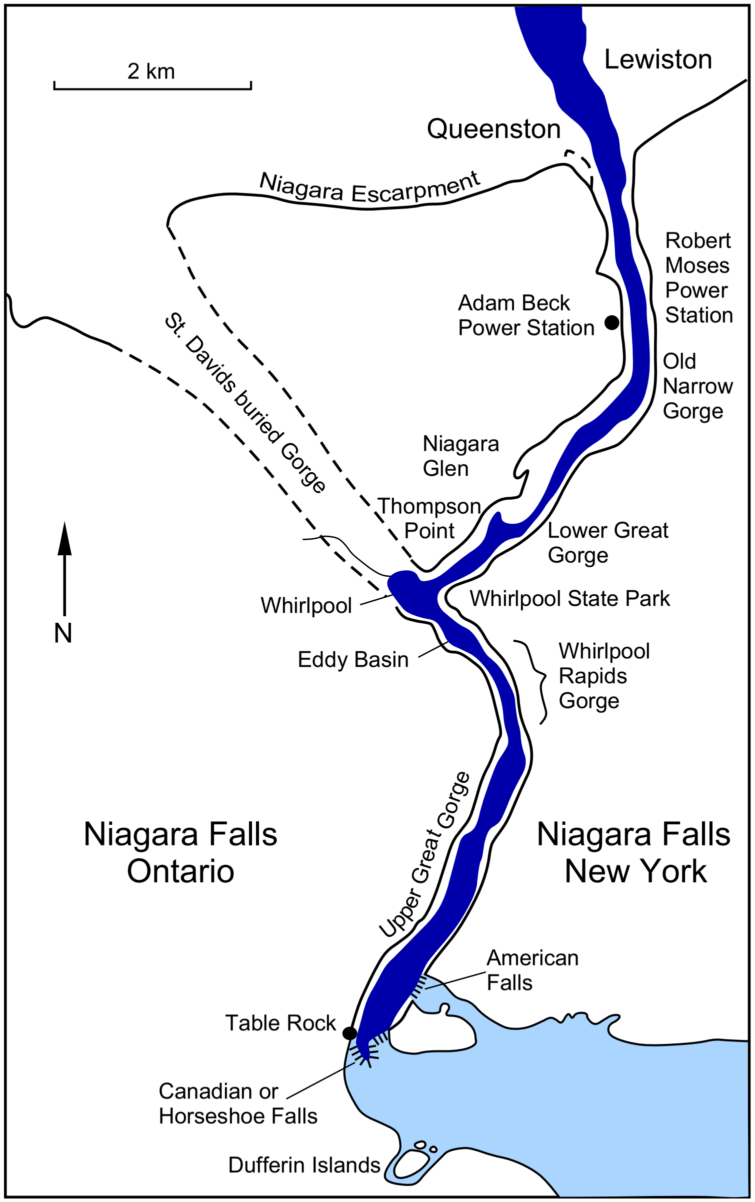


Figure 39. Niagara Gorge showing the location of the buried pre-Wisconsin St. David's Gorge. Part of the Upper Great Gorge, south of the Whirlpool, may result from the re-excavation of the buried gorge (after Middleton et al., 2009).

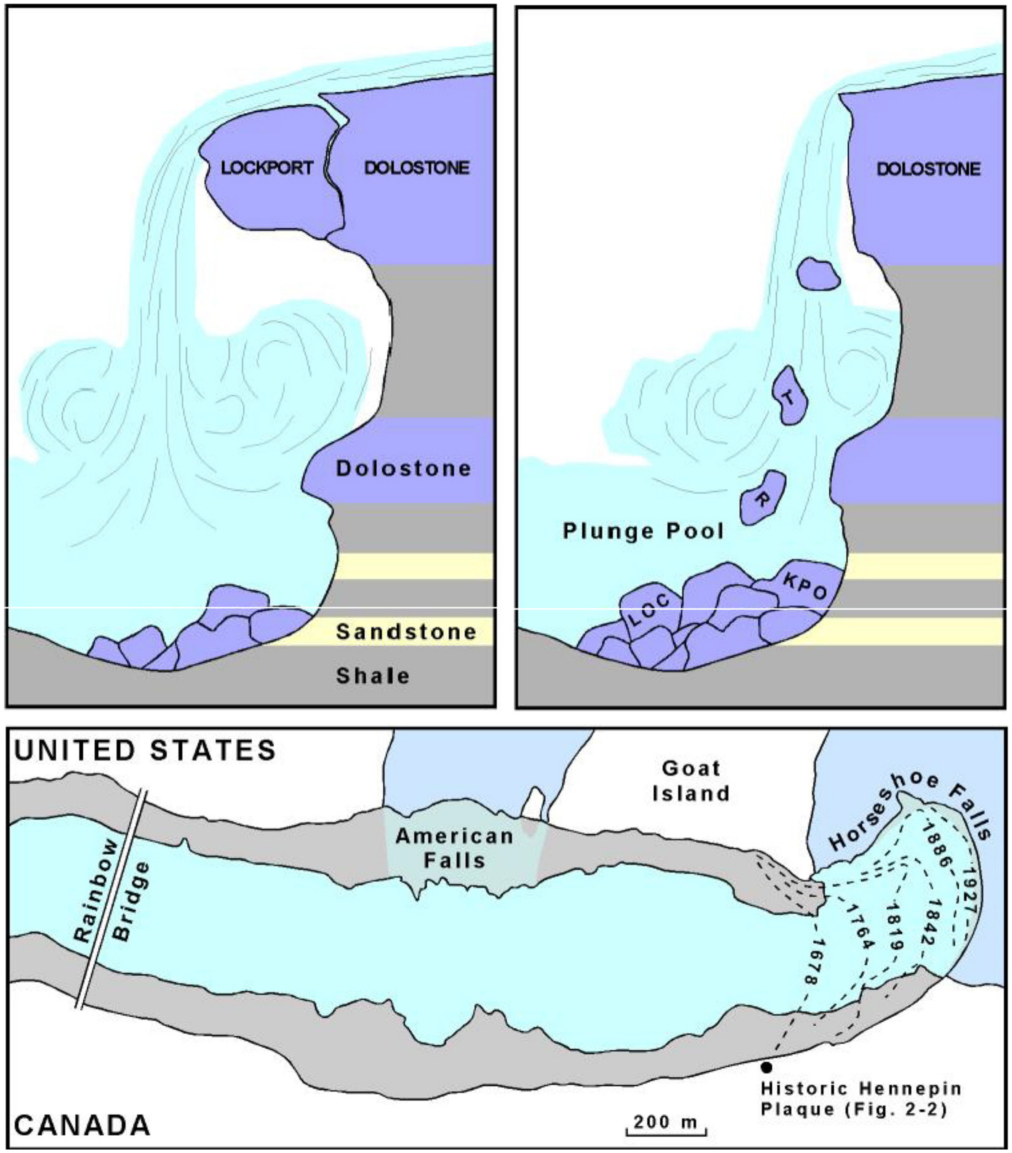


Figure 40. Retreat of Niagara Falls arising from undercutting of the Lockport Dolostone cap rock (after Middleton et al., 2009).

km downstream at Queenston Heights, at a time when the early Niagara River overspilled north from glacial Lake Tonawanda ponded in the Erie Basin. Recent work suggests a much more complex history due to the changing facies and thickness (and thus erodibility) of the cap rock (the Lockport Dolostone) along the length of the Niagara Gorge. There have also been dramatic changes in postglacial flow of the Niagara River, including a long episode of low to non-existent flows from the upper Great Lakes during the Hypsithermal (McCarthy et al., 2012a,b). This was a time of much reduced lake levels in the Great Lakes (e.g. Lake Stanley low stand in the Huron Basin and the equivalent Lake Hough in Georgian Bay). There is also the possibility that parts of the 'modern' Upper Great Gorge results from re-excavation of a relict pre-Wisconsin gorge (St. David's Gorge: Fig. 37). Drilling of the infill of still-buried sections of the relict gorge provides some of the few dates available from southern Ontario, which constrains the age of the Late Wisconsin maximum of LIS to sometime after 22.8 ^{14}C ybp (Hobson and Terasmae, 1969). The gorge was likely in use for an extended period of time, and a recent borehole intersected thick sequences of organic-bearing sand and muds dated to 29,763 to 32,003 ^{14}C ybp (Burt, 2017). The relict gorge can be seen along the walls of the present-day gorge at the Whirlpool, where the Niagara River abruptly widens and changes circulation according to the changing volume of water that is removed upstream of Niagara Falls for hydroelectricity generation; this varies from day (minimum) to the night hours (maximum). The modern rate of retreat is consequently much reduced.

Canada's first parliament was held at Niagara-on-the-Lake (1792–1796) and the various portages that circumvent Niagara Falls have long been of strategic importance. The Escarpment and Peninsula separates Ontario and Erie basins; the Welland Canal connects the two and is part of the 2,300 km-long St. Lawrence Seaway ('Highway H_2O') that opened in 1959. Construction of the Seaway, which links the Atlantic Ocean to the western end of Lake Superior and can accommodate large ocean-going 'Great Lakers', had to deal with highly overconsolidated tills (often requiring explosives), large boulders and cost overruns that were the result of unforeseen paleo channels causing variations in the depth to bedrock. This gave impetus to the study of till-forming processes and the geotechnical properties of glacial sediments.

Development of the Falls ushered in hydroelectric power generation and the birth of the US chemical industry, as well as the ill-fated attempt to build a diversion canal (Love Canal) by A.T. Love on the US side of the Falls (which he abandoned in 1907). The canal was later infilled with chemical wastes impacting the health of local residents in the late 1970s and giving rise to the infamous Love Canal episode that resulted in the creation of the Environmental Protection Agency in the US and the development of the Superfund Act to assess and clean up contaminated sites. This event prompted study of the lateglacial glaciolacustrine clays that cover Paleozoics on both sides of the international border at the eastern end of Lake Erie and the rapid fracture flow of contaminants; understanding of which led to changes to the design of landfills. There are some 250 chemical waste sites in the Niagara-Buffalo area and many are associated with plumes of contaminated groundwater. The biggest dump, Hyde Park, contains the largest known volume of dioxin anywhere in the world.

Along the Niagara Peninsula in Ontario several prominent north-facing bedrock benches (the outcrop of resistant sandstones) along the face of the Niagara Escarpment, together with the shoreline and floor of the former glacial Lake Iroquois, enjoy a less extreme winter climate and host numerous vineyards. The best known product is ice wine, an intensely sweet dessert wine produced from frozen grapes. Simon Haynes of Brock University has written extensively on the geological controls on terroirs and potential sub-appellations of Niagara Peninsula wines (*see* Middleton et al., 2009).

Leaving Queenston Heights, we will then drive back to Ottawa via the QEW, and highways 407, 401 and 416, arriving late evening. If time permits we will make a brief stop along bluffs on the Lake Ontario shoreline at Courtice Road where MSGLs, formed on the bed of the Halton Ice Stream, are cored by Northern Till (**Stop 20**: Fig. 5).

END NOTE

Research on the geomorphic and geological record of paleo-ice streams in southern Ontario and New York State is expanding rapidly. The 'ice stream paradigm' now provides a firm uniformitarian approach to understanding the deglacial stratigraphic and geomorphic record of the region based on modern ice stream analogs (e.g. Antarctica, Greenland) and closely aligns with work on the LIS elsewhere in Canada by many university groups, the Ontario Geological Survey and the Geological Survey of Canada (e.g. Margold et al., 2015a,b; Stokes et al., 2016; Stokes, 2017). This represents a significant departure from previous work in southern Ontario that, following the lead of Shaw (1989) and Shaw and Gilbert (1990), emphasized the supremacy of regionally extensive catastrophic subglacial meltwater floods in shaping the geomorphology and geology of much of Canada. Hitherto, virtually *all* glacial landforms in southern Ontario have been ascribed to subglacial sheet floods that supposedly cut thousands of drumlins (20,000 at the last count) on sediment and rock, not only in Canada but also downstream in adjacent parts of the US *as far south as the Finger Lakes*, along with a notional regional network of tunnel valleys as flood waters subsided and became channeled (*see* Sharpe et al., 2013).

For a wealth of substantive discussions refuting the entire concept of colossal subglacial meltwater floods on the trans-continental scale envisaged by Shaw and Gilbert (1990) and Sharpe et al. (2013), the interested reader is referred to Braun et al. (2003), Fullerton et al. (2003, 2004), Clarke et al. (2005), Evans et al. (2006, 2008), Benn and Evans (2006, 2010, p. 274 et seq.), Ó Cofaigh et al. (2010), Eyles (2012), Kehew et al. (2012, 2017), Stumpf et al. (2014), Livingstone and Clark (2016), and Eyles et al. (2018). Recent investigations of the Peterborough Drumlin Field by the Ontario Geological Survey (Marich, 2016) found no evidence of the subglacial flood invoked by Sharpe (1987), echoing the conclusions of Eyles and Doughty (2016). Superficial mapping and deep drilling of the infills of 'tunnel valleys' cut instantaneously during waning megafloods reveals a protracted history of cutting and filling (Mulligan et al., 2018a). Ross et al. (2006) mapped the glacial geology of the eastern outlet area of the Ontario Basin along the St. Lawrence Valley in the vicinity of Montreal and showed that it is readily explained as the product of an ice stream rather than megaflooding, agreeing with previous work by the Geological Survey of Canada on the importance of topographically constrained fast ice flow from the southern Quebec sector of the LIS during deglaciation (e.g. Parent and Occhietti, 1999; Occhietti et al., 2001, 2011; Margold et al., 2015a,b; Sookhan et al., 2018a,b).

Fullerton et al. (2003) wrote in regard to postulated subglacial megafloods crossing from western Canada into what is now the US (Shaw et al., 1996) that "*morphologic and sedimentologic evidence of a supercolossal, catastrophic, subglacial megaflood has eluded us*", which is an apt summation of the situation along the entire Canada/USA border.

Three dimensional conceptual models (a.k.a. 'facies models') arise from detailed site studies aimed at understanding the origins and stratigraphy of glaciogenic sediments. These models, in turn, provide an essential framework for construction and associated geoengineering projects, in addition to hydrogeological studies and groundwater management across the rapidly urbanizing Greater Toronto Area, where the population is expected to double to 10 million by 2030. This field trip is particularly timely given the recent publication of several articles that employ regional subglacial megaflooding as an appropriate foundation on which to base assessments of the area's glacial geology and to guide groundwater management models (e.g. Sharpe and Russell, 2016; Sharpe et al., 2018). These claims together with the interpretations of subsurface data on which they are based, are entirely at odds with the conclusions of much of the prior and ongoing work on sediment architecture in southern Ontario by the Ontario Geological Survey and university researchers and also run counter to modern approaches elsewhere in North America and Europe that emphasize the importance of ice stream dynamics. Identification of many paleo-ice streams in southern Ontario (Fig. 4) and adjacent parts of New York State confirms and amplifies the importance of fast ice flow within the eastern Great Lakes sector of the Laurentide Ice Sheet as proposed by Briner (2007) and Margold et al. (2015a,b, 2018) (Fig. 2). The hard and soft beds of the paleo-ice streams so far identified in this part of the Laurentide Ice Sheet are moreover directly analogous to those of modern Antarctic ice streams (*see* Fernandez et al., 2018).

In conclusion, the unambiguous and readily verifiable presence of flow sets of megascale glacial lineations around the Ontario Basin on both hard and soft beds in both Canada and the USA is the hallmark of dynamic, fast-flowing ice streams and underscores the importance of re-mapping glacial landforms using new high-resolution digital imagery. Meltwaters played a ubiquitous role in landscape development, as they do in modern-day glacial environments (where glacial outburst floods are common), but there is no evidence of gigantic regional subglacial sheet floods that supposedly lifted the LIS from its bed across the entire eastern Great Lakes region and cut drumlins and regional networks of tunnel valleys in southern Canada and northern USA.

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FIELD TRIP ROUTE

Day 1: SATURDAY August 11th

Leaving Ottawa from Carleton University Campus at 12:30 pm, drive north on Bronson Avenue to Highway 417, west to Highway 7 exit and to Perth. Turn left (southeast) in Perth onto Wilson Street West (Highway #43) then left (northeast) onto North Street and then turn right (southeast) onto Gore Street (Highway 1). Turn right (southwest) onto Highway 10 (Scotch Line) to Westport.

Continue on Highway 10 (Perth Road) south to Inverary and turn left (east) onto Highway 12 (Moreland Dixon Road) and continue 1 km east and stop at unconformity outcrop (44.38292, -76.4685: **Stop 1**).

Turn around and return to Highway 10; turn left (southwest) and stop at a large Proterozoic metasedimentary erratic in the parking lot of the Northway Home Hardware at Davidson Side Road (3832 Perth Road, Inverary; 44.377, -76.4786: **Stop 2**).

Continue south on Highway 10 and then west on Highway 401 to exit #593; turn right (north) on Highway 4. Turn right (east) on Maple Road and proceed 1.5 km to where the road crosses Wilton Creek and stop at the meltwater cut features on the south side of the valley (***Private property***: 44.28578, -76.773: **Stop 3**)

Proceed eastward on Maple Road to Highway 6 and turn south and proceed 250 m, stopping at roadside outcrop through megagrooves (44.3060, -76.727: **Stop 4**).

Proceed south on Highway 6 over Highway 401 and turn left (east) on Highway #2; at 500 m turn left onto Shane Street. Drive to the end of the road. Large grooves can be seen cut into the limestone with several sets of crossing striations (on gated ***private property*** to the south: 44.28392, -76.6843: **Stop 5**).

Return to Highway 401 to Napanee (exit #579) and proceed north on Highway 41, stopping at the roadside outcrops of rubbly Dummer Moraine facies, just north of Grieves Corners (44.3658, -77.0156: **Stop 6**).

Return to 401, drive west to exit #538, and drive north on Wallbridge-Loyalist Road (Highway 1) to Highway 14 toward Stirling and continue north to Marmora. Turn left (west) onto Highway 7 and drive toward Peterborough; turn north on Highway 28 at Coffee Time donuts and the Peterborough Drumlin Field (44.3170, -78.198: **Stop 7**)

Turn right on Division Street to Douro 5th Line to view channeled a drumlin.

Return to Highway 48 and continue south to Old Norwood and drive west to Television Road and new construction site on east side of road immediately south of the junction.

Return north on Television Road to Old Norwood Road and turn left to Ashburnham Drive and proceed south to Lansdowne Street and turn right (east) and proceed to 4.1 km to the hotel, which is on right after the Parkway.

Quality Inn, 1074 Lansdowne St, Peterborough, Ontario (telephone: 705-748-6801)

Day 2: SUNDAY August 12th

Turn right (west) from the motel and proceed along Lansdowne Street to Highway 7; turn left (south) to Highway 115 and drive south to Highway 7A. and proceed west toward Port Perry.

At Highway 12 turn right (north) to and continue to Highway 47. Turn left (west) at the gas station and continue to Marsh Hill Road and turn left. Stop to view the drumlinized till plain and channels in the foreground and Oak Ridges Moraine on southern skyline (44.111, -79.044: **Stop 8**).

Proceed south on Marsh Hill Road to Scugog Line 8 and turn right (west) toward Reach Street. Turn right (west) on Reach Street (Highway 8) and proceed to Lake Ridge Road (Highway 23) and turn left (south) to Columbus Road turning left (east) and stop on dead-end road immediately on the right (south) amid flow set of MSGLs (43.957, -79.019: **Stop 9**).

Back to Lake Ridge Road, turn left (south) and continue past Highway 401 to Taunton Road (Highway 4), and turn right (west). Continue on Taunton Road, which becomes Steeles Avenue East to Beare Road (43.852 -79.179) turning left (south). At Plug Hat Road turn right (west) amid flow set of MSGLs on the bed of the Halton Ice Stream in area of the Toronto Zoo: **Stop 10**).

Continue on Plug Hat Road, which ends at Meadowvale Road and continue south past Highway 401 to Highway 2. Turn right (west) on Kingston Road/Highway 2.

Either: continue on Highway 2 to Brimley Road South and turn left (south) toward Lake Ontario and the Scarborough Bluffs outcrops of Early and Middle Wisconsin sedimentary rocks that are visible on shoreline (43.702, -79.239: **Stop 11**). Return to Highway 2, turn left (west) and proceed onto Gardner Expressway, which continues as Queen Elizabeth Way (QEW) west toward Hamilton.

Or: Proceed to Don Valley Brickyard (43.684, -79.366: **Stop 12**) by continuing on Highway 2 and turn right (west) onto Danforth Road. Just past the Don Valley Parkway, Danforth Road becomes Bloor Street East. Turn right (north) onto Bayview Avenue to the Brickyard. After which proceed south and onto the Gardiner Expressway west either via Bayview Avenue or the Don Valley Parkway. Continue on the Queen Elizabeth Way (QEW) and Highway 403 to Hamilton.

Either: Take Highway 403 westward to Hamilton and turn left onto Main Street West (Highway 8) downtown to James Street. Turn right (south) onto James Street and proceed to St. Joseph's Drive turning left and follow Arkledun Avenue up through Jolley Cut to Concession Street. Turn right on Concession Street to Sam Lawrence Park (43.244, -79.862) where there is a view of the Niagara Escarpment (**Stop 13**).

Or: From QEW turn north on Highway 6 up Escarpment. Exit and turn right on Old York Road and then immediately turn left (south) onto Plains Road West. Continue southeast and turn right (southwest) onto York Boulevard and continue to Burlington Heights (43.272, -79.886: **Stop 14**) and drive along raised spit of glacial Lake Iroquois. Continue south on York Boulevard to Dundurn Castle and turn right on Dundurn Street North. Continue through the intersection with King Street West, where Dundurn Street North becomes Dundurn Street South to Main Street West to John Street South. Turn right (south) onto John Street South and follow to Arkledun Avenue. Turn left (east) onto Arkledun Ave and this through Jolley Cut, above, to Sam Lawrence Park (43.244, -79.862: **Stop 13**).

Turn left (east) onto Concession Street and proceed to Upper Wentworth Street and turn right (south). At the Lincoln Alexander Parkway, turning left (east) and continue to the QEW towards Niagara Falls.

Take QEW east to Casablanca Boulevard (Highway 10) south to Casablanca Service Station. Return to QEW eastbound to General Brock Parkway (Highway 405), Proceed east on Highway 405 to Stanley Avenue exit. Turn left (north) on Stanley Avenue to Portage Road and continue eastward to the roundabout at the Niagara Parkway (Highway 420) and follow the gorge south (upriver).

On the Niagara Parkway, continue south by turning right (west) onto Queen Street and proceed to the end of the street. Turn left (south) onto Victoria Avenue. Proceed west by turning right on Centre Street. The Days Inn & Suites is on the left hand side of the street.

Days Inn & Suites, 5068 Centre Street, Niagara Falls, Ontario (telephone: 905-357-2550).

Day 3: MONDAY August 13th

Exiting the hotel, turn right (southeast) onto Center Street and turn right again (southwest) onto Victoria Avenue. Continue as the street becomes Ferry Street and then Lundy's Lane. Breakfast will be at the Flying Saucer (6768 Lundy's Lane at the corner of Corwin Ave and Lundy's Lane). Return east along Lundy's Lane and stop if time permits on the crest of Niagara Falls Moraine and Battle of Lundy's Lane (43.089, -79.096: **Stop 15**).

Continue east on Lundy's Lane, which becomes Ferry Street, to turn right (south) onto Stanley Avenue. Drive south to turn left onto Livingstone Street and stop at the intersection with Fallsview Boulevard (43.077, -79.082: **Stop 16**).

Proceed north along Fallsview Boulevard to turn right (east) on Murray Street and join Niagara Parkway northwards down the Niagara Gorge.

Traveling north on the Niagara Parkway to the Whirlpool (43.123, -79.068: **Stop 17**), The Sir Adam Beck Generating Station (43.142, -79.039: **Stop 18**), and The Niagara Escarpment overlook at Queenston Heights (43.162, -79.050: **Stop 19**).

Continue northward on the Niagara Parkway and turn left (west) onto York Road (Highway 81). Follow this to rejoin the QEW west to Toronto.

Drive north and east on the QEW and continue driving east on Highway 407. Exit at Highway 412, and drive south to Highway 401. Continue east to Exit #425, Courtice Road. At the top of the exit ramp, turn right (south) toward Lake Ontario to view the outcrops of Northern Till in cores of MSGLs from the Halton Ice Stream (43.868, -78.759: **Stop 20**).

Return to Highway 401 and drive east to Highway 416, taking exit 721A north to Ottawa and return to Carleton University.