Quaternary Glacial, Glacimarine and Glacilacustrine History

2

Norm Catto, Dori J. Kovanen, and Olav Slaymaker

Abstract

Eastern Canada was almost completely glaciated from four major and several lesser ice centres on multiple occasions during the Quaternary. Most of the geomorphology relates to Marine Isotope Stage 2. Areas of resistant bedrock are dominated by glacial erosional features, such as roches mountonées. Glacial depositional landforms are prominent in southern Ontario, Québec, and the Maritime provinces. In Arctic Canada, glaciation had lesser effects on geomorphology, with the exception of the mountainous areas of Baffin and Ellesmere islands. Glacial retreat exposed the isostatically depressed coastlines to marine incursions. Champlain Sea glacimarine sediments cover the St. Lawrence and Ottawa Valleys. In the Great Lakes Lowlands and southern Canadian Shield, blockage of northward and eastward drainage led to the formation of successions of proglacial lakes and other paraglacial landforms during the transition from MIS 2 to the Holocene.

Keywords

MIS 2 • Laurentide ice sheet complex • Innuitian ice sheet complex • Glacimarine • Champlain sea • Glacilacustrine • Great lakes • Lake Barlow-Ojibway

2.1 Introduction to Glacial History

The Quaternary record of eastern Canada is dominated by glaciation. With the exception of nunataks in alpine regions, and limited areas in the Arctic Lowlands and Innuitia, all parts of eastern Canada appear to have undergone multiple glaciations during the Quaternary, particularly during Marine Isotope Stage (MIS) 2. Erosional and depositional landforms are generally used to recognize past glaciations although some areas of cold-based glaciation have been proposed. This chapter outlines the glacial, glacimarine and glacilacustrine events and landscapes of eastern Canada. Paraglacial, periglacial and Holocene landscapes are discussed in Chap. 3 (Table 2.1).

2.2 Pre-MIS 2 Events

The sedimentary record of pre-MIS 2 Quaternary events in eastern Canada is somewhat limited, and the geomorphic record more so. The earliest continental glaciation in Atlantic Canada (Bridgewater deposits, Nova Scotia) is tentatively attributed to either MIS 16 or MIS 22, as there is no numerical dating. Although the available evidence suggests that intensive glaciation occurred at several times in the Quaternary prior to MIS 2, glacial deposits older than MIS 5 have been identified only in isolated locations, including southern Ontario (Karrow 1989), southern Québec (Occhietti 1989), Qikiqtaaluk (Baffin Island; Andrews 1989), New Brunswick (Rampton et al. 1984), Nova Scotia (Grant 1989) and Newfoundland. The deposits are exposed only in sections, without associated surface landforms (Fig. 2.1).

Scattered distributions of glacial sediments and computer-generated ice sheet modelling suggest that extensive glacial ice cover existed throughout Nunavut, Nunavik (northern Québec) and in the Torngat Mountains during MIS 5 (Clark 1988; England et al. 2006; Stokes et al. 2012, 2015; Catto, Chap. 7, this volume; van Wychen et al., this volume). Expansion of continental glaciation from centres in Labrador–Québec and Kivalliq (mainland Nunavut) commenced during MIS 4, and c. 65 ka all of eastern Canada (aside from nunataks) appears to have been ice covered. Along the southern margin, retreat during

N. Catto (✉)
Department of Geography, Memorial University of Newfoundland and Labrador, St. John's, NL A1B 3X9, Canada
e-mail: ncatto@mun.ca

D. J. Kovanen · O. Slaymaker
Department of Geography, University of British Columbia, 1984 West Mall, Vancouver, BC V6T 1Z2, Canada

O. Slaymaker and N. Catto (eds.), *Landscapes and Landforms of Eastern Canada*, World Geomorphological Landscapes, https://doi.org/10.1007/978-3-030-35137-3_2

Table 2.1 Marine isotope stages

Marine isotope stage	Time (ka)	Events in eastern Canada
1	0–11.7	Holocene, see Chap. 3
2	11.7–29	Widespread glaciation; majority of glacial geomorphology formed; glacimarine and glacilacustrine events
3	29–57	Glacial retreat from southern Ontario and Québec, Maritime provinces, Newfoundland
4	57–71	Glacial advances covering most of eastern Canada
5	71–123 (MIS 5.5, 109–123)	Local preservation of interglacial (MIS 5.5) deposits; scattered MIS 5.1 deposits preserved in southern Ontario and Québec; readvances of Laurentide ISC begin c. 100 ka
6	123–191	Widespread glaciation; local preservation of deposits

Fig. 2.1 MIS 3 deposits preserved in karst developed in Carboniferous gypsum, Cape Anguille area, NL. MIS 2 glacial deposits cap the succession. *Photograph* N. Catto

MIS 3 exposed the western and central Great Lakes–St. Lawrence Lowlands, and much of the Maritime provinces. Newfoundland and Labrador remained glaciated at this time. Subsequent readvances began during the latter part of MIS 3, culminating in the Last Glacial Maximum (LGM) of MIS 2, c. 25 ka (e.g. Gosse et al. 2004; Grant 1989; Karrow 1989; Occhietti 1989; Pico et al. 2018; Vincent 1989).

2.3 MIS 2 Glaciation

MIS 2 glaciation resulted in the complete ice cover of eastern Canada, aside from mountain nunataks. The Laurentide Ice Sheet Complex (LISC) expanded to cover all of Ontario, Québec, Kivalliq, and southern Nunavut, and interacted with alpine glaciers in northern Qikiqtaaluk and the Torngat Mountains. In Atlantic Canada, the southern boundary of the LISC fluctuated due to shifting flow directions and coalescence with local ice caps developed in New Brunswick, Nova Scotia, the Gulf of St. Lawrence, and Newfoundland. The Innuitian Ice Sheet Complex (IISC) developed in northern Nunavut, interacting with Laurentide ice along its southern margin, and with alpine glaciation in Tatlurutit (Devon Island) and Umingmak Nuna (Ellesmere Island; see van Wychen et al., this volume).

2.3.1 Laurentide Ice Sheet Complex (LISC)

The Laurentides (Laurentian Mountains) form the southeastern margin of the Grenville Structural Province across Ontario and Québec. Initially, glacial flow to the Great Lakes–St. Lawrence Lowlands to the south was recognized by the presence of granitic and gneissic clasts derived from the Precambrian rocks, and the term 'Laurentide' applied to the event. Subsequently, Laurentide has been applied to all continental glaciation in eastern Canada which originates from any area of the Canadian Shield, and dates to MIS 2, with final deglaciation during the initial phases of MIS 1 (Dyke 2004; Dyke et al. 2002, 2003; Dyke and Prest 1987; Tarasov et al. 2012; Figs. 2.2 and 2.3). Laurentide origin is commonly attributed to glacial deposits that contain some clasts derived from the Canadian Shield, particularly granitic, mafic, ultramafic, or high-grade metamorphic clasts of distal origin.

The limits of Laurentide glaciation correspond to the most distal occurrence of MIS 2 glacigenic sediments containing Canadian Shield clasts, marked either by transitions into non-glacial Quaternary deposits or coalescence with other ice masses. In eastern Canada, the southeastern boundary of Laurentide glaciation is marked by coalescence with local ice masses in Atlantic Canada and Appalachian Québec (e.g. Stea et al. 2011; see Morissette et al., this volume). Laurentide glacial deposits extend across the entire southern boundary of Ontario, including the Great Lakes basins, and westward into Prairie Canada and mainland Northwest Territories (e.g. Dredge and Cowan 1989; England et al. 2009; Mahaney et al. 2014; Stokes, this volume; Veillette et al. 2017; Zaniewski et al., this volume). The northern limit is marked by areas covered by the IISC and with local alpine glaciation in Nunavut. To the east, Laurentide glaciation extended to the MIS 2 marine shoreline, except in the highest parts of the Torngat Mountains.

The LISC has been divided into several 'centres', 'domes', 'sectors' and ice sheets (the terminology varies greatly amongst authors), which coalesced to produce the Ice Sheet Complex. Several time-transgressive changes in configuration have been noted, designated as different sectors by different authors. In broad strokes, the chief areas of accumulation and expansion were (1) an area centred east of Hudson Bay in western Labrador and adjacent Québec; (2) an area centred west and north of Hudson Bay in Kivalliq and western Nunavut; and (3) an area in Foxe Basin and southern Qikiqtaaluk.

2.3.1.1 Labrador—Western Québec

This accumulation centre is commonly designated the Labrador or Labradorean. The eastern part of the source area is at the current location of the Smallwood Reservoir. The source area of the Laurentide Ice Sheet Complex in westernmost Labrador and adjacent Nouveau-Québec was further confirmed through the work of Hughes (1964; also see Klassen et al. 1992; Klassen and Thompson 1993; Occhietti et al. 2004, 2011). Ice extended eastward into the Labrador Sea (Clark and Fitzhugh 1990), northward to block Hudson Strait and coalescing with ice over Qikiqtaaluk and Foxe Basin (Andrews and MacLean 2003; DeAngelis and Kleman 2007; Stokes 2018; Winsborrow et al. 2004, 2010), westward across Québec and Hudson Bay (Figs. 2.4 and 2.5) to coalesce with ice in eastern Kivalliq and northern Manitoba (Roy et al. 2009; Dredge and Dyke, this volume) and southward to Ontario (Figs. 2.6 and 2.7), Maritime Canada, the Northern Peninsula of Newfoundland and the eastern and midwest USA (Beaupre et al., this volume; Desloges et al., this volume; Normandeau et al., this volume; Nutz et al., this volume; Zaniewski et al., this volume).

The core region of the accumulation centre is well defined by the orientations of striated and sculpted bedrock, and by the distribution of distinctive erratics, including high-grade metamorphic gneiss, iron-bearing units from the Labrador City–Wabush area, and ultrabasic rocks such as anorthosite. Several phases of activity, involving shifting ice divides and variations in coalescence zones with adjacent ice masses, are indicated by erratic distributions in sequential deposits, and by cross-cutting landforms.

Glacial features characteristic of western Labrador include drumlins, flutings and eskers. Eskers serve as passage routes for animals through the taiga, and are commonly used as sources of gravel and sand aggregate for road construction. Although esker systems can extend for hundreds of kilometres, all but the shortest are composed of segments, rather than a continuous ridge. Individual segments of eskers

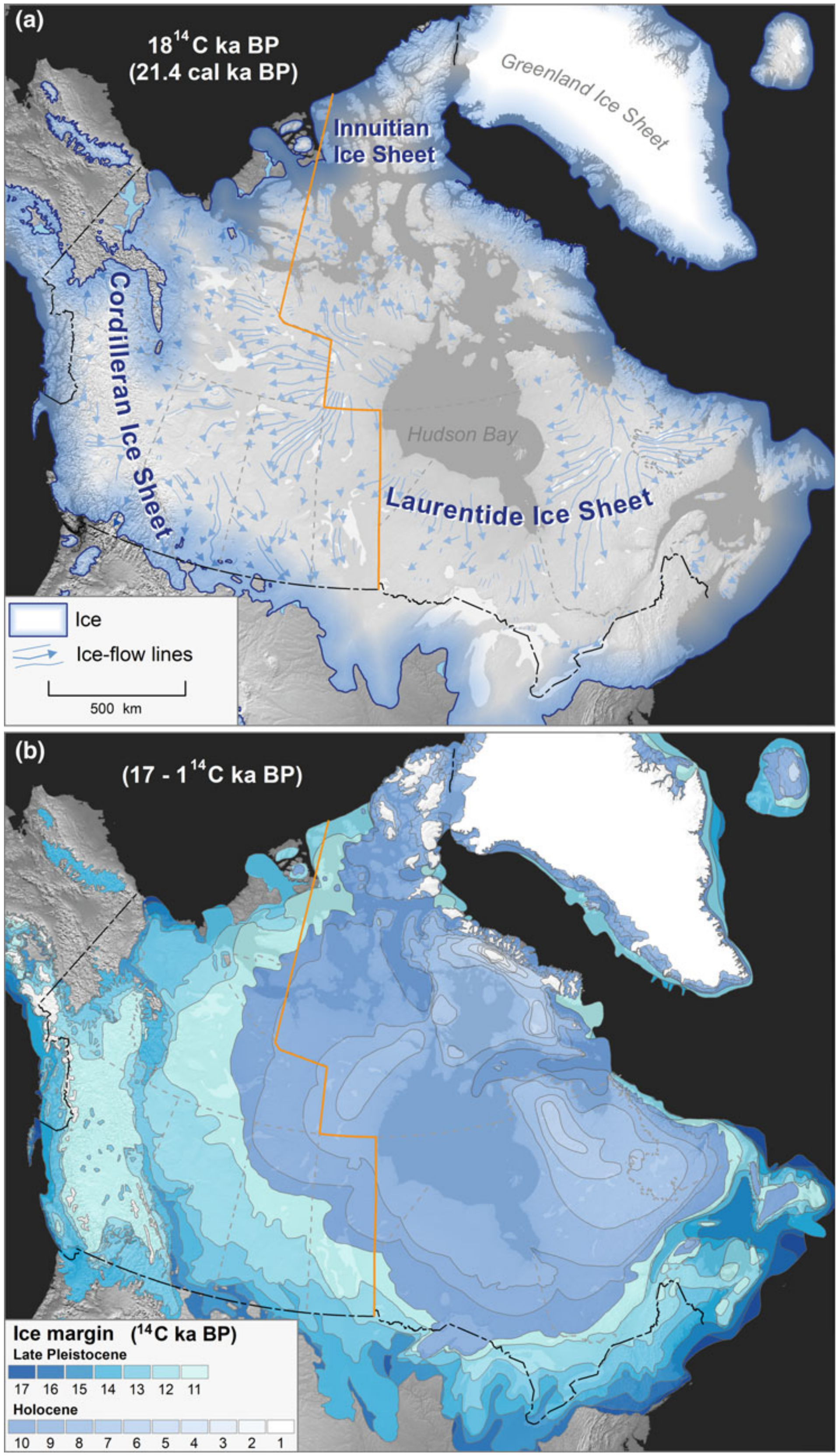


Fig. 2.2 Ice masses in Canada. **a** Distribution of Cordilleran, montane, plateau and continental ice coverage and generalized ice flow direction (modified from Shaw et al. 2000) of MIS 2 (Late Wisconsinan) Glaciation. **b** Extent of ice coverage at various stages of deglaciation. Ice margins from Dyke et al. (2003)

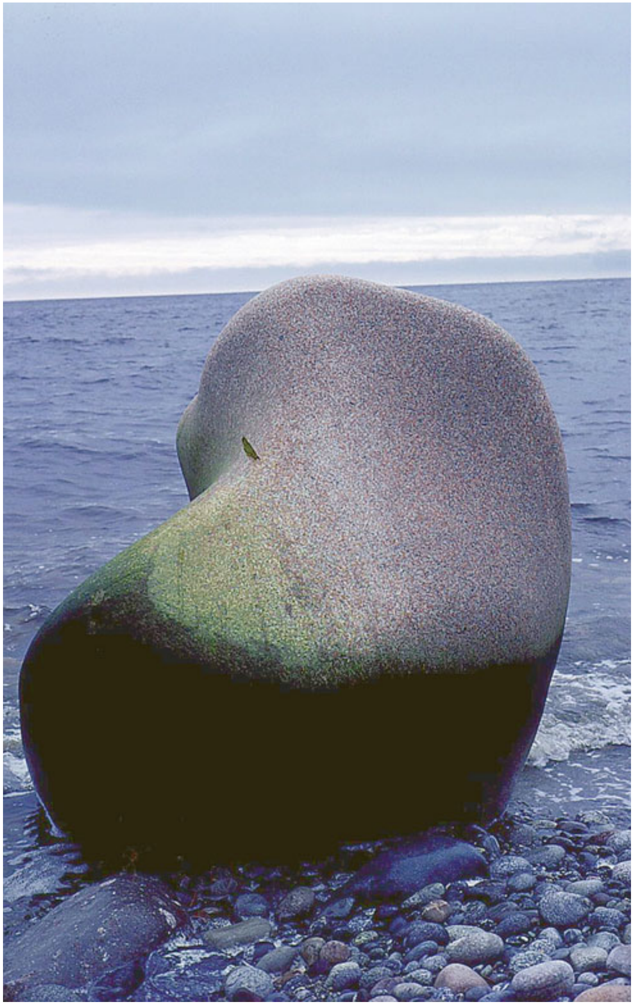


Fig. 2.3 Granitic and gneissic erratics derived from the Canadian Shield indicate Laurentide glaciation. *Photograph* N. Catto

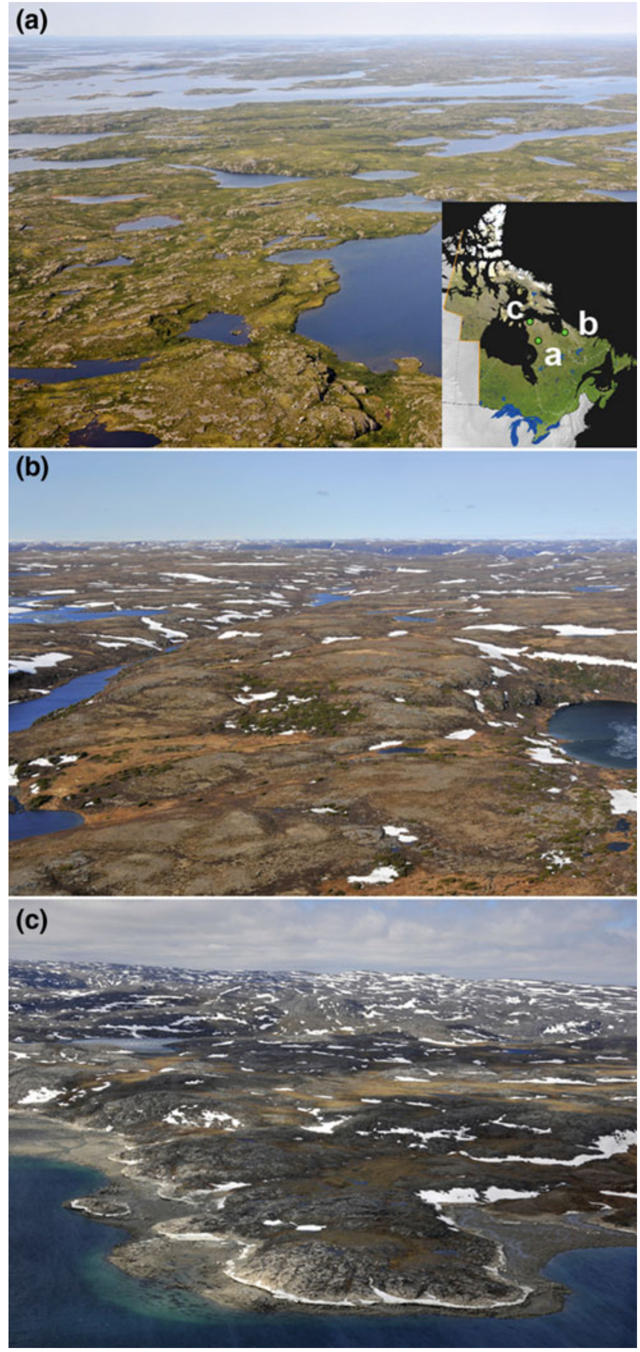


Fig. 2.4 Shield bedrock landscape. **a** Low relief, **b** Low to moderate relief and **c** Moderate to high relief. *Photographs* DER8594, ADD_8922, _ADD0820—Government of Québec, MFFP (2017), CC BY 4.0

may exceed 20 m in height and 20 km in length although most segments are much shorter. They are most commonly single ridges but may be aligned in a braided or reticulate pattern. The eskers of Labrador are attributed to subglacial formation.

Western Labrador remained a source area for glacial ice throughout the Quaternary. It was the last area of continental North America to be deglaciated, approximately 6800 BP (Dyke and Prest 1987; Vincent 1989; Dyke et al. 2002).

2.3.1.2 Kivalliq and Western Nunavut

A succession of glacial accumulation areas developed west and north of Hudson Bay in Kivalliq and western Nunavut. Terms used to describe this accumulation area include ‘Keewatin’ (the former political name for part of Kivalliq) and ‘M’Clintock’ (after M’Clintock Channel, east of Victoria Island). Ice expanded to the south and west to cover mainland Northwest Territories, Victoria and Banks islands, and most of the western prairies. To the east and north, zones of coalescence developed with the other Laurentide centres and with the IISC. The exact configuration of the accumulation centre is somewhat controversial, with evidence of shifting divides and positions.

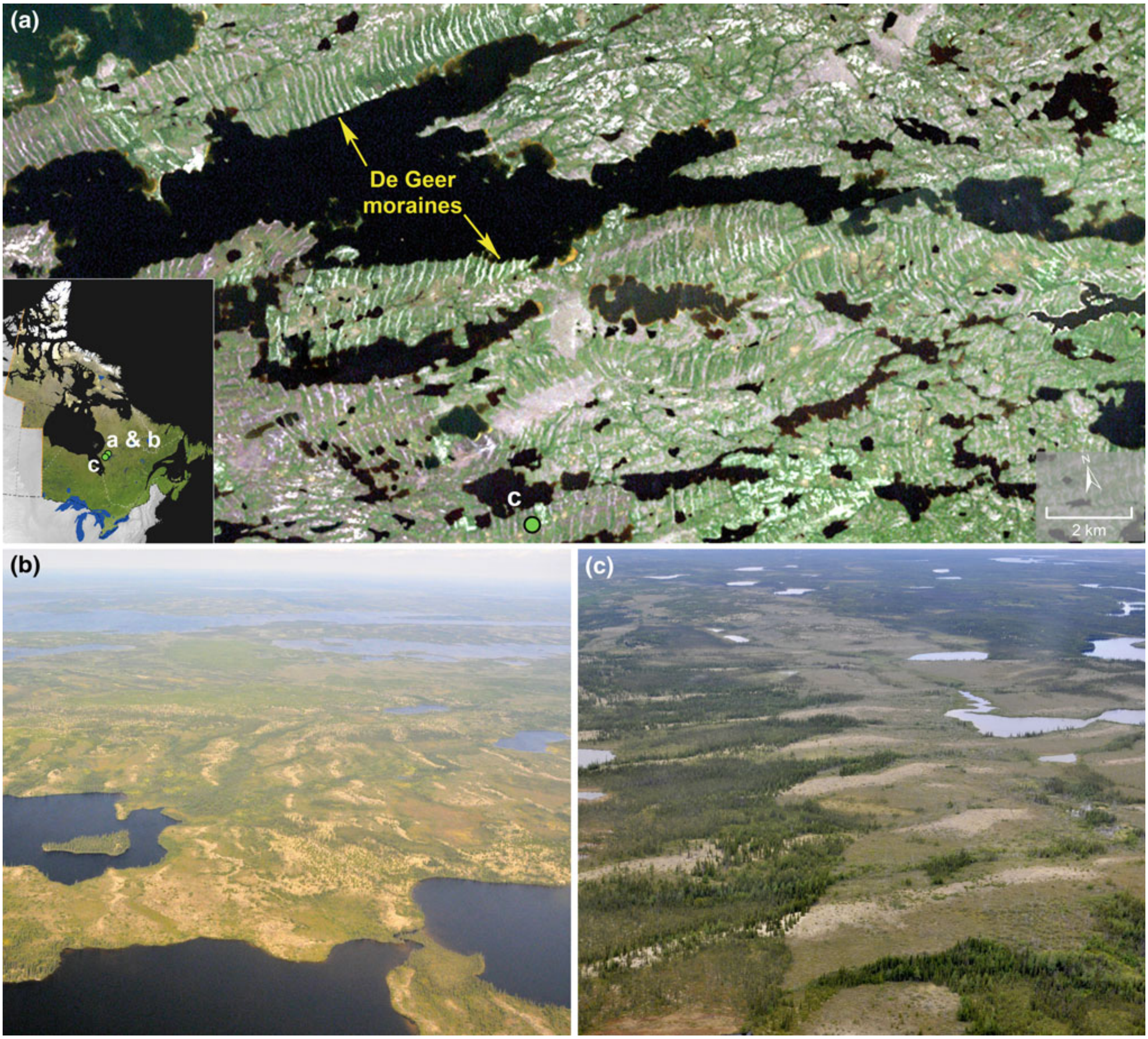
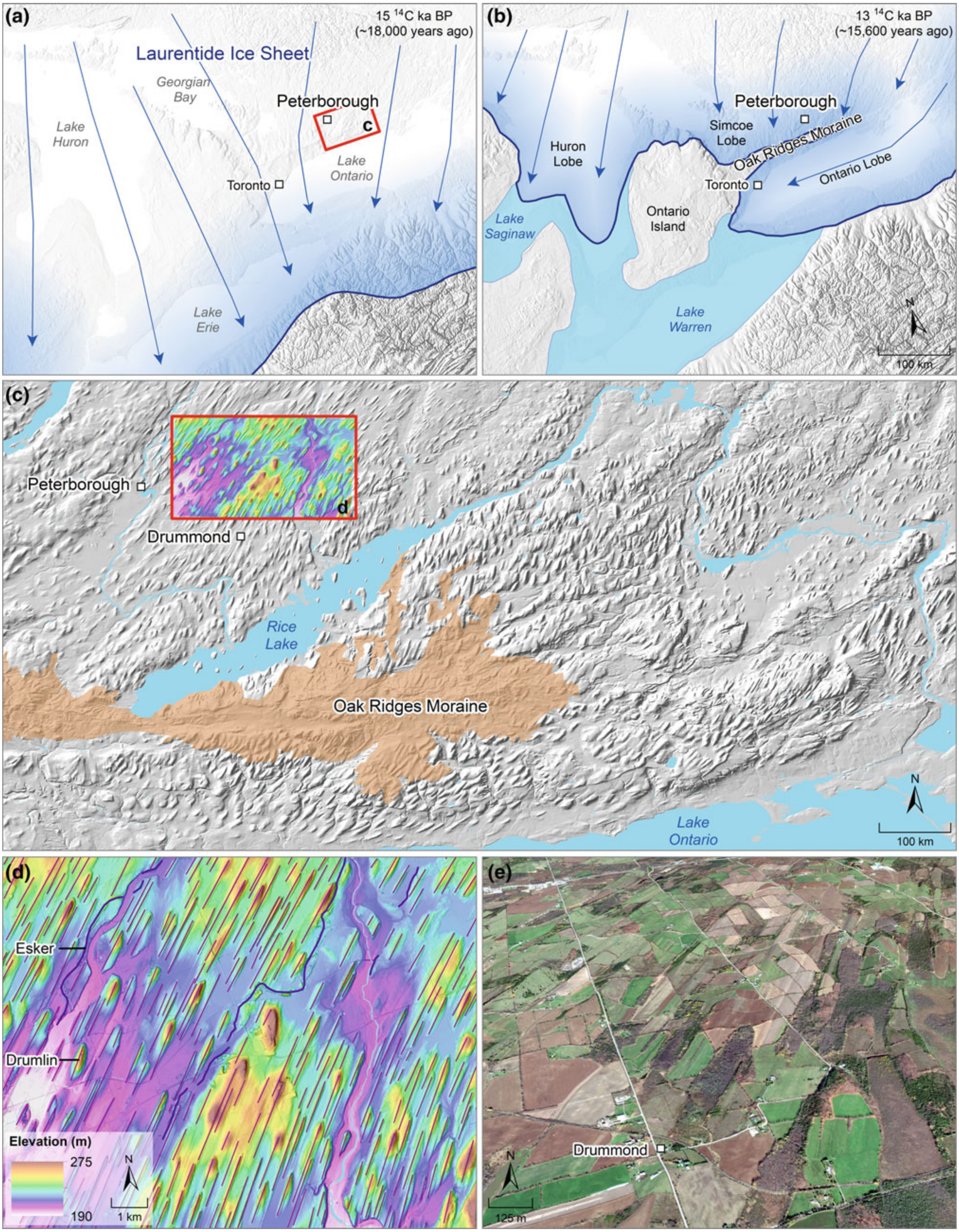


Fig. 2.5 De Geer moraines. **a** Landsat image showing classic De Geer moraines on the lowlands east of Hudson Bay, Québec. **b** and **c** Oblique photographs of fairly regularly spaced ridges of De Geer moraines in the area north of La Grande River, east of Sakami moraine. *Source* a—Government of Canada; Natural Resources Canada (2007). b—DER7018, c—DDDD2408, Government of Québec, MFFP (2017), CC BY 4.0

Flow directions in the marginal areas of this sector are generally well defined (see Stokes, this volume; Figs. 2.8 and 2.9). On Victoria Island, ice from the M'Clintock Dome moved across Victoria Island, diverging into two streams. The northern stream flowed westward through M'Clure Strait, impinging on northern Victoria, northern Banks Island, and southern Melville Island. The southeastern ice stream flowed across southern Victoria Island towards the east-southeast, into the Amundsen Gulf. Drumlins, flutings and accumulations of till mark the areas influenced by the ice streams. Retreat of the ice began approximately 14 ka. Deglaciation of the eastern shore, adjacent to the M'Clintock Dome source area, occurred approximately 9 ka. The isostatic depression produced marine limits of 160–200 m asl along the eastern shores, marked by raised gravel beaches, eroded terraces and fossils of bowhead whales and other marine species (Dyke et al. 1992).

Somerset Island was glaciated by Laurentide ice flowing eastward from the M'Clintock centre, combined with radially flowing local glaciers on the Lancaster Plateau. During MIS 2, the Laurentide ice was prevented from spreading to the northeast by the escarpment separating the Boothia Arch



(a)
15 ¹⁴C ka BP (~18,000 years ago)
Laurentide Ice Sheet
Georgian Bay
Lake Huron
Peterborough
c
Lake Ontario
Toronto
Lake Erie
(b)
13 ¹⁴C ka BP (~15,600 years ago)
Peterborough
Simcoe Lobe
Huron Lobe
Oak Ridges Moraine
Ontario Lobe
Toronto
Lake Saginaw
Ontario Island
Lake Warren
N
100 km
(c)
Peterborough
d
Drummond
Rice Lake
Oak Ridges Moraine
Lake Ontario
N
100 km
(d)
Esker
Drumlin
Elevation (m)
275
190
N
1 km
(e)
Drummond
N
125 m

Fig. 2.6 The Peterborough Drumlin Field is an example of a Laurentide glaciated landscape in southern Ontario. The field's approximately 3000 drumlins cover the region from Lake Ontario to the north of Peterborough. **a** and **b** Landforms created by glacial advance, retreat, stagnation and final melting of the Simcoe, Ontario and Huron Lobes of the Laurentide Ice Sheet (adapted from Maclachland and Eyles 2013). **c** Drumlin orientations in the northern and eastern parts of the drumlin field record southward flow of the Simcoe lobe. The southern part of the field records northwestward movement of the Ontario lobe from the Lake Ontario basin. *Source* shaded relief image from MRD128-REV; © Queen's Printer for Ontario 2010. **d** and **e** Drumlins can range from approximately 45 m to greater than 5 km in length, a few metres to 500 m wide, and from a few metres to greater than 40 m relief. Also see Sookhan et al. (2018) and Marich (2016) for detailed discussions. *Source* d—Lidar from Ontario Geological Survey (2010). e—Google Earth: Landsat/ Copernicus, DigitalGlobe 2019. Centreed on about 44°16′12″ N, 78°12′36″ W

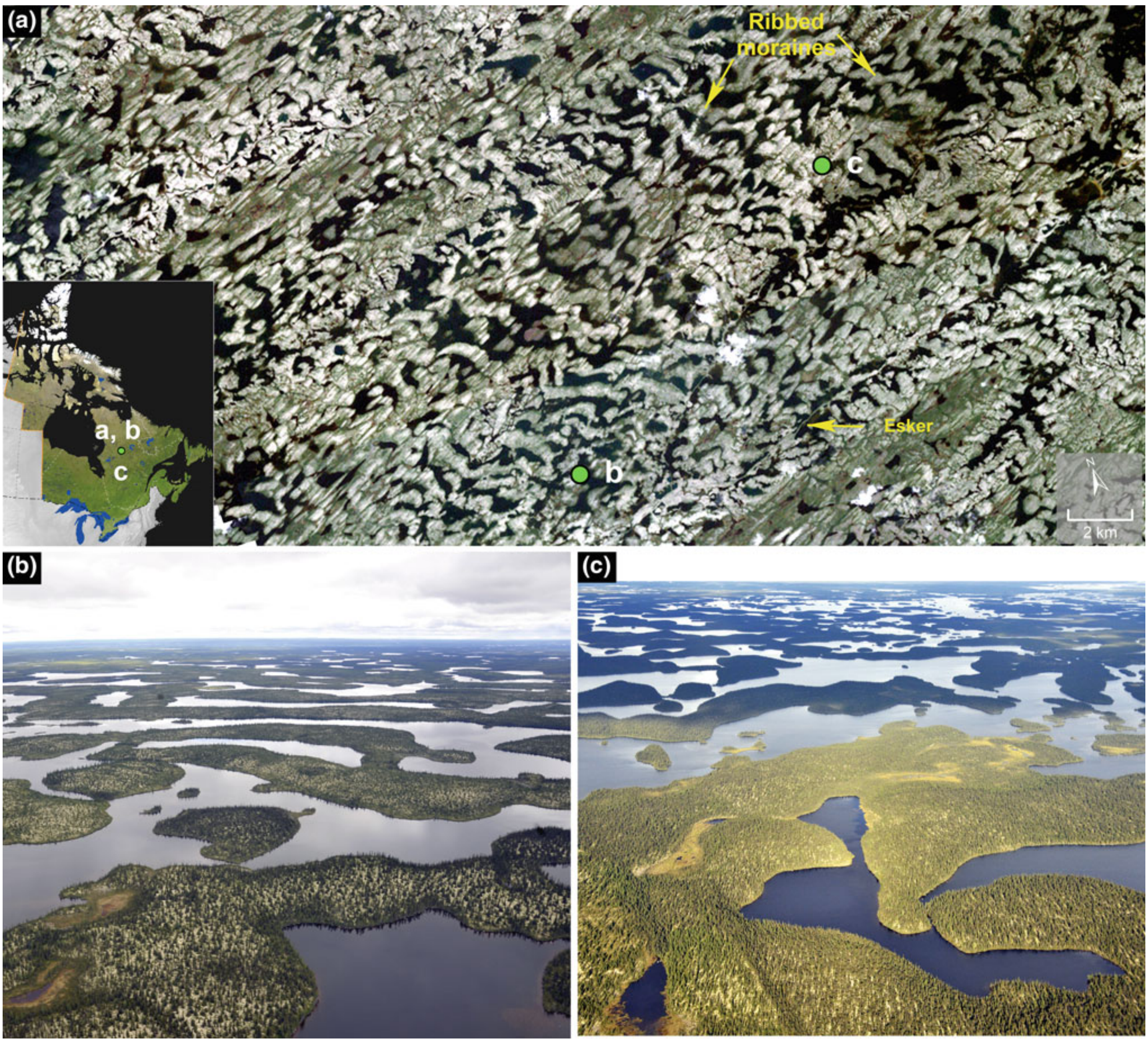


Fig. 2.7 **a** Landsat image showing ribbed terrain (Rogen moraine) northeast of Lake Mistassini. *Source* Government of Canada; Natural Resources Canada (2007). **b** and **c** Oblique photographs of ribbed moraine ridges. *Photographs* b—DIF_1764, c—DER0231, Government of Québec, MFFP (2017), CC BY 4.0

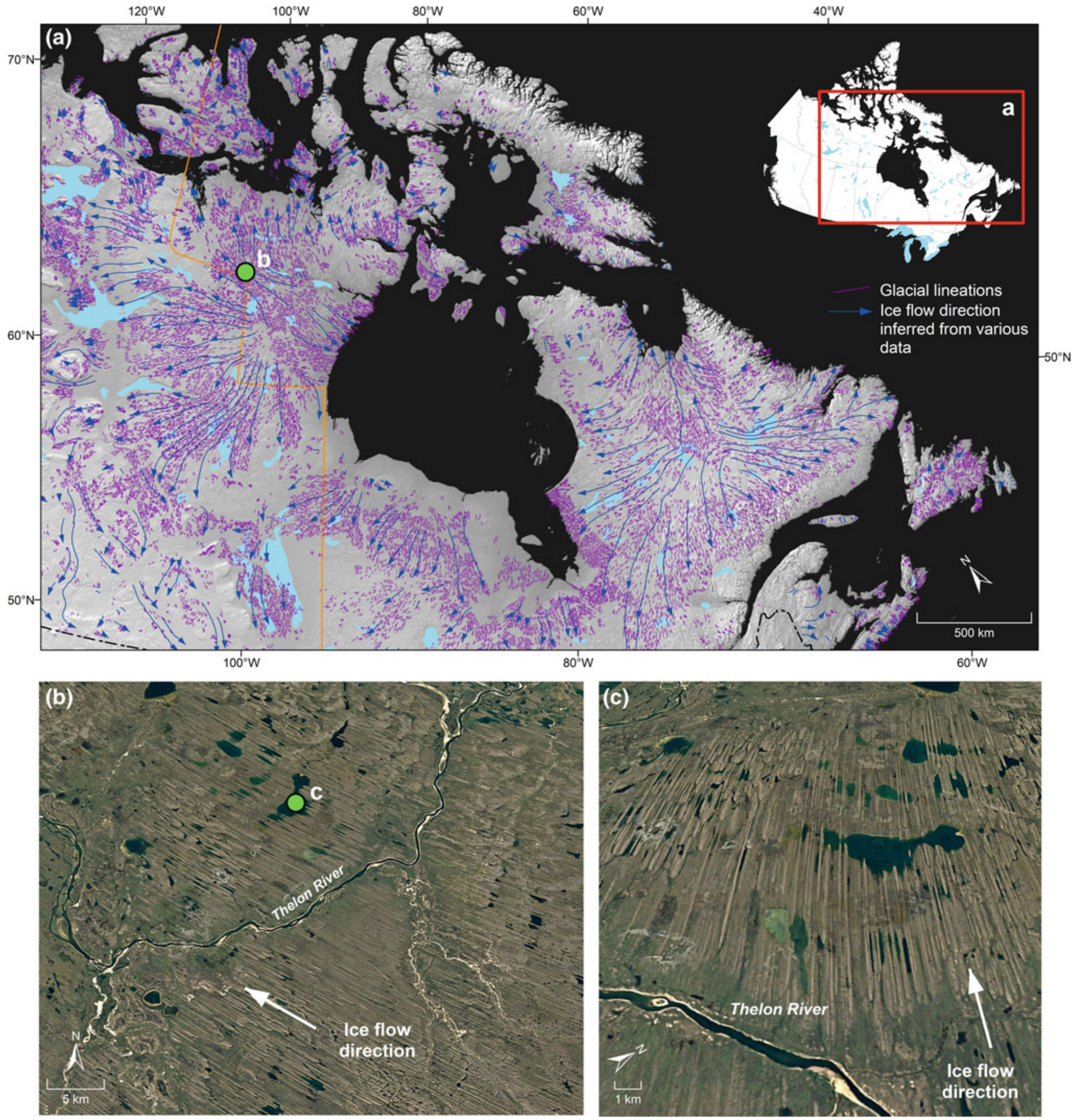


Fig. 2.8 Streamlined bedrock-dominated features are common in glaciated shield regions. **a** Distributions and orientation of streamlined features. *Source* Glacial lineations and ice flow direction from Shaw et al. (2010). **b** Landsat image showing examples of mega-scale (>5 km long) glacial lineations with long axis aligned with ice flow direction; part of the Dubawnt Lake Ice Stream, northwest of Dubawnt Lake in the vicinity of Thelon River, Kivalliq. *Source* Google Earth: Landsat/Copernicus; centred on about 64°15′ N, 102°06′ W. **c** Close-up, oblique view of features looking northwest across the field of mega-scale glacial lineations. *Source* Google Earth: Landsat/Copernicus; centred on about 64°19′ N, 102°09′ W. Also see Stokes et al. (2015)

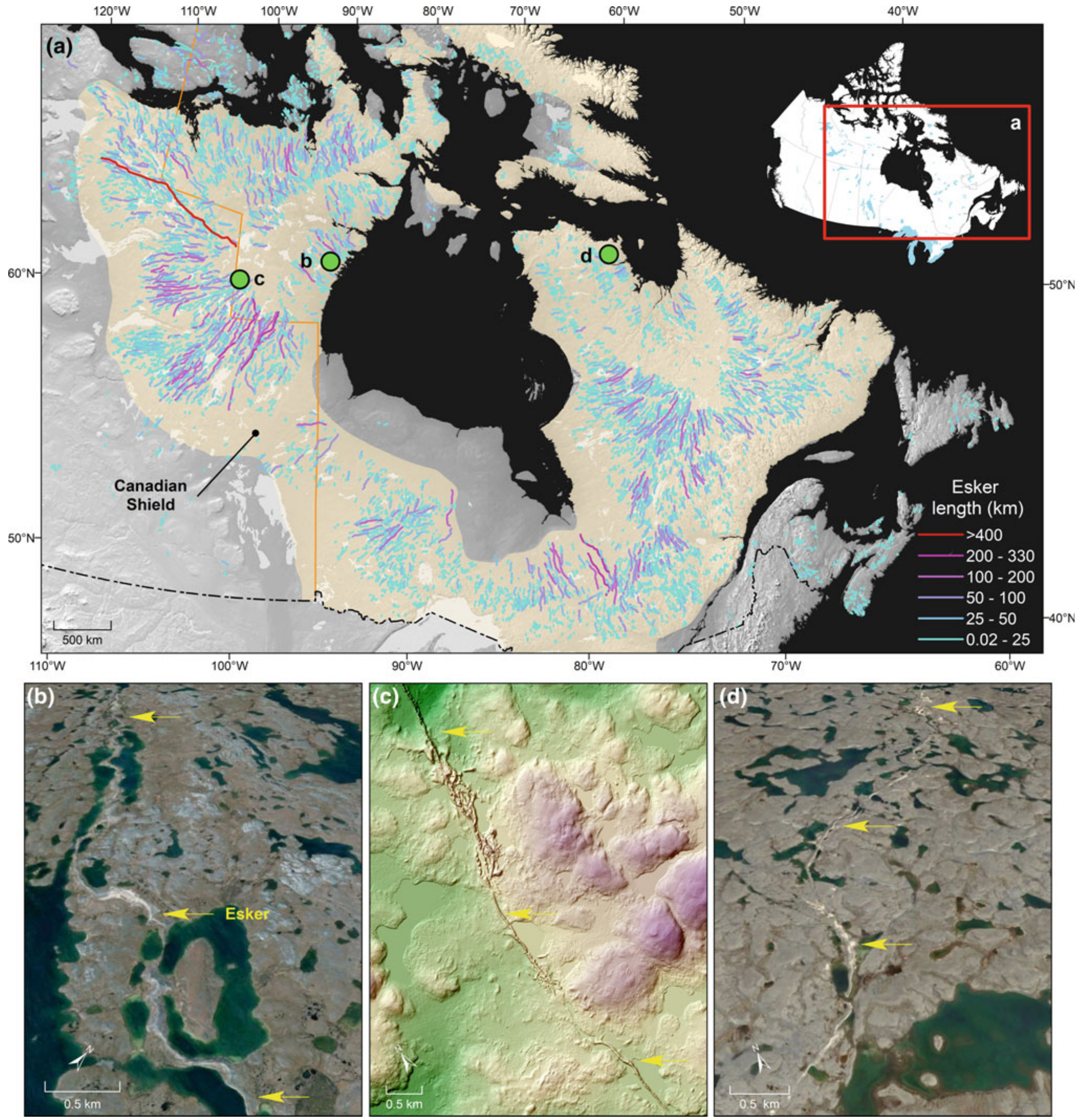


Fig. 2.9 **a** Map showing esker segments associated with deglaciation of the LIS concentrated mainly on the Precambrian Canadian Shield area. The red coloured interpolated esker (i.e. tracing gaps between individual esker segments), the Thelon esker, may be the longest esker in the world (about 750 km; Storrar et al. 2014, 2013). **b** and **c** Typical eskers associated with the Keewatin dome of the LIS. **d** Esker associated with the Labrador dome of the LIS. *Source* a—esker segments modified from Shaw et al. (2010), after Prest et al. (1968). b—Google Earth: Landsat/ Copernicus, DigitalGlobe 2019. c—colour hillshade dsm_5m_polarstereo_23_14_2_2; Government of Canada; Open Government License. d—Google Earth: Landsat/ Copernicus, DigitalGlobe 2019

from the Lancaster Plateau. As a result, a northwest-southeast trending nunatak on the eastern flank of the Boothia Arch, extending from Aston Bay to Creswell Bay, remained unglaciated during MIS 2. An earlier glaciation appears to have covered the entire island (Dyke 1983, 1984).

Marine waters inundated Somerset Island to 120 m asl following deglaciation. Local ice fields persisted in the highest parts of the Lancaster Plateau, and expanded during the Neoglacial c. 1500–1850 A.D. At present, no actively flowing glaciers exist on Somerset Island although remnant bodies of stagnant glacial ice up to 30 m thick are present on the Lancaster Plateau. Today, the landscape is dominated by periglacial features, including tors, cryoturbation hummocks, bedrock felsenmeer, gelifluction stone stripes, and tundra polygons.

2.3.1.3 Foxe Basin

A third Laurentide accumulation centre developed in Foxe Basin (an accumulation area in Foxe Basin and southern Baffin Island (the 'Foxe' or 'Foxe-Baffin') flowed eastward and northward across Qikiqtaaluk, westward to coalesce with the Kivalliq sector, and southward to meet the Labrador sector ice in Hudson Strait (see Dyke 2004; De Angelis and Kleman 2007; Margreth et al. 2016). Palaeozoic carbonate and shale erratics transported by Foxe Basin ice are conspicuous across the areas of exposed Canadian Shield granites and gneisses. Carbonate detritus from the glacial outflow through Hudson Strait has contributed to the distinctive Heinrich and Dansgaard–Oeschger event layers preserved in North Atlantic sedimentary successions (Andrews and MacLean 2003; Andrews and Voelker 2018). Isolated patches of continental glacial ice, the Barnes and Penny ice caps, persist today on Qikiqtaaluk.

Southampton Island was glaciated by Laurentide ice from the Foxe centre to the northeast during MIS 2 (see Hefter et al. 2017). Flow varied from southeastward (east) to southwestward (centre and southwest coast) to westward (west coast). Coats Island was also glaciated by Foxe Dome ice. Mansel Island was successively glaciated by ice from the Foxe Basin to the northwest and by northwest-moving Labrador ice. All of the islands were affected by the last major phase of Laurentide glaciation, the Cockburn event. A powerful flow southeastward towards Hudson Strait modified the terrain of Southampton Island extensively. As seawater flooded Hudson Strait, the Cockburn event came to an end, and the sea flooded in rapidly. The destabilized ice masses in Foxe Basin and Hudson Bay broke up, and Southampton was deglaciated by 8 ka (Ross et al. 2011, 2012).

2.3.2 Innuitian Ice Sheet Complex (IISC)

In northern Nunavut, many areas outside the alpine-glaciated high mountains (see van Wychen et al., this volume) show relatively little evidence of glaciation. However, the presence of erratic and scattered small glacial landforms indicates that most areas, if not all, were covered by glacial ice at some time during MIS 2 (Lamoureux and Rudy, this volume; Fig. 2.10). Cold-based conditions were extensive in areas such as Ellef Ringnes Island and the Sverdrup Basin. The IISC expanded westward across northern Nunavut, reaching the continental shelf of the Beaufort Sea (see Maclean et al. 2010; Lakeman and England 2012; Nixon et al. 2014). To the south, Innuitian ice coalesced and interacted with Laurentide glaciation (England et al. 2006, 2009).

Bathurst Island, in common with most high arctic areas, also shows little evidence of glaciation apart from scattered erratic boulders across the surface. During MIS 2, the island was covered by locally generated cold-based ice caps, which coalesced and appear to have expanded to blanket the entire island sometime before 20 ka. Glacial deposition influences the landscape along the southeastern and northeasternmost shores. In other localities, bare rocks protrude above the thin soil. Deglaciation occurred c. 9 ka and was followed by a marine incursion into the isostatically depressed coastal areas to approximately 90 m above present sea level. Gravel beaches and erosional marine benches mark the elevated positions.

2.3.3 Atlantic Canada

During MIS 2, local ice caps grew and coalesced throughout Atlantic Canada (Prest 1973; Catto 1998a, b, this volume; Hétu et al., this volume; Morissette et al., this volume; Shaw et al. 2002, 2006; Stea and Mott 2005; Stea et al. 2011; Figs. 2.11 and 2.12). Expansion of the local ice centres blocked intrusion of the Laurentide ice from the north. Laurentide ice coalesced with local ice caps to form ice streams through the Gulf of St. Lawrence, which was glaciated due to marine drawdown to −120 m asl. Offshore, the Grand Banks, Scotian Shelf, and Georges Bank were exposed by lower sea level (Miller 1999; see Normandeau et al., this volume). Periglacial features, environmentally modified clasts, and poorly developed regosols and cryosols indicate subaerial exposure. Locally ice streams extended along the major embayments to the continental shelf. Glacial flow patterns and deglaciation were complex, but after

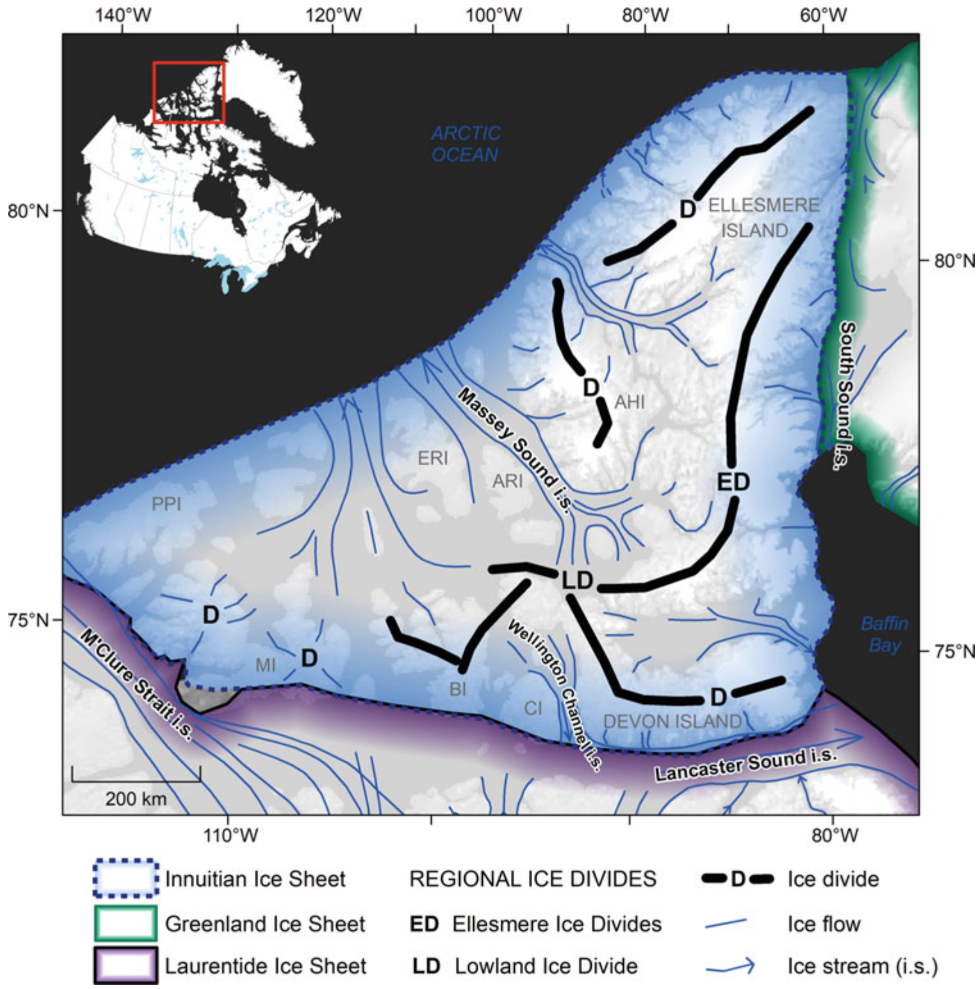


Fig. 2.10 Reconstruction of the Innuitian Ice Sheet over parts of the Canadian High Arctic (Queen Elizabeth Islands) during the LGM, showing ice divides and ice streams (modified from England et al. 2006, 2009; Stokes et al. 2015). AHI—Axel Heiberg Island, ARI—Amund Ringnes Island, BI—Bathurst Island, CI—Cornwallis Island, ERI—Ellef Ringnes Island, MI—Melville Island, PPI—Prince Patrick Island

Younger Dryas readvances throughout the region, rising sea level resulted in rapid destabilization of the ice centres. Deglaciation of the Maritime provinces was complete by 12 ka, and in Newfoundland by 9 ka.

Cape Breton Island displays typical landscapes formed by local glaciation (Grant 1994). Striations and erratics indicate that the island was affected by several glacial events involving ice originating from the west and southwest early in the Quaternary, and all areas were covered by ice at some time. The upland areas of Cape Breton Highlands National Park (above 350 m asl) were largely covered by cold-based ice during MIS 2. Some exposures of weathered bedrock that were formerly considered to represent exposed nunataks have been shown to have developed more recently, and scattered glacial erratics have been found in others. Ice from the Bras d'Or Lakes area was confined to the region south of Mabou Harbour and Wreck Cove, producing a drumlin-dominated coastline along the southeastern coast between Louisbourg and St. Peters.

In southwest mainland Nova Scotia, the current location of Kejimkujik National Park was the source area for ice caps which expanded northward to cover all of the Annapolis Valley, westward to Yarmouth, and southward to the Southern Shore during MIS 2.

The most distinctive glacial features on the Kejimkujik and Southern Shore landscape are its drumlins. From the Halifax Regional Municipality southwest to Bridgewater, almost 2500 drumlins of various shapes are present, including several which have been subject to differing degrees of coastal and/or anthropogenic erosion and modification (Jones 1996). Dimensions of intact drumlins distant from the coastline vary in the range 200–600 m length, 70–400 m width and 8–25 m height. In plan view, the majority are oval or egg shaped although spindle drumlins occur.

Halifax, established as a naval base in 1749, was laid out on the flanks of the steeply sloping Citadel Hill drumlin. Halifax's grid pattern contrasts sharply with the agglomerated patterns characteristic of towns without an initial

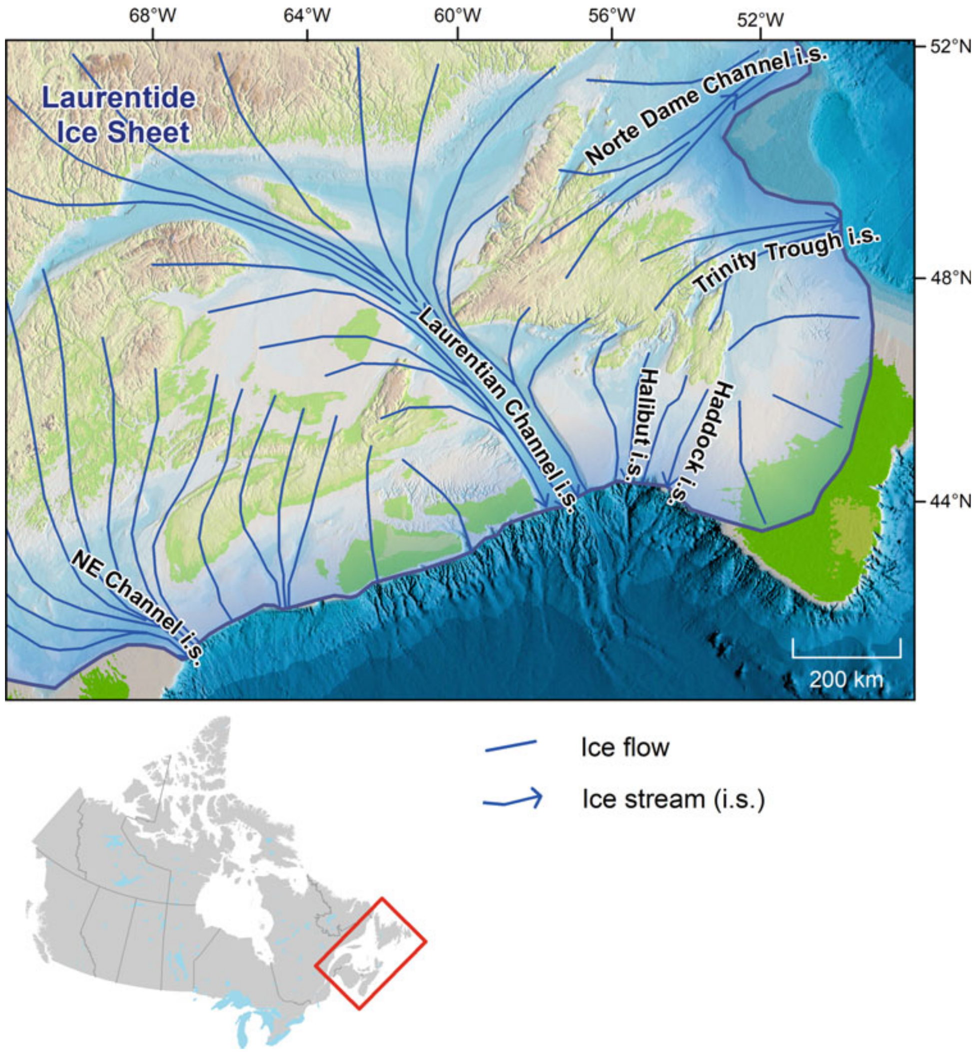


Fig. 2.11 Maximum MIS 2 glacial limits in Appalachian–Acadian region. *Data* background image from Shaw et al. (2002), maximum ice margin from Dyke et al. (2003), and ice flows and streams from Shaw et al. (2006), Stea et al. (2011) and sources cited therein

military presence, such as Boston, also built in a similar topographical setting. Lunenburg, established in 1753 and designated as a World Heritage Site, also displays a grid pattern, with long streets parallel to the drumlin axis and short, extremely steep cross streets.

The 600 drumlins of the Lunenburg field were the subject of research by Jones (1996). The direction of ice flow, as indicated by clast lithology and other adjacent glacial features, was towards the southeast open Atlantic Coast. Jones (1996) noted that 30% of the drumlins had steeper lee slopes than stoss slopes, which would indicate that slope angle is not a reliable guide to flow direction, as has been documented elsewhere (e.g. Spagnolo et al. 2010). Differences between adjacent drumlins in the same field are common, both in relative slope angles and overall shape. In the Lunenburg field and elsewhere in Nova Scotia, many drumlins are essentially symmetrical in form. Many Nova Scotia drumlins show stratified interior successions, with two or more diamicton layers of distinct texture, mineralogy and clast lithology, indicating alternating phases of erosion and deposition and differences in flow direction.

After retreat from the coastlines c. 12 ka, ice persisted for approximately 1,000 more years in Kejimkujik, producing an irregular hummocky topography of glacial diamicton. Remnant glaciers may have persisted through the Younger Dryas, but did not readvance, and final ablation occurred prior to 10 ka.

2.3.4 Alpine Glaciation

Alpine glaciers developed in the Chic-Choc Mountains (QC) and Long Range Mountains (NL; Spooner et al., this volume) of Appalachia–Acadia; in the Mealy (Gray 1969) and Torngat Mountains of Labrador (Way et al. 2014; Catto, Chap. 7, this volume); throughout the High Relief Eastern

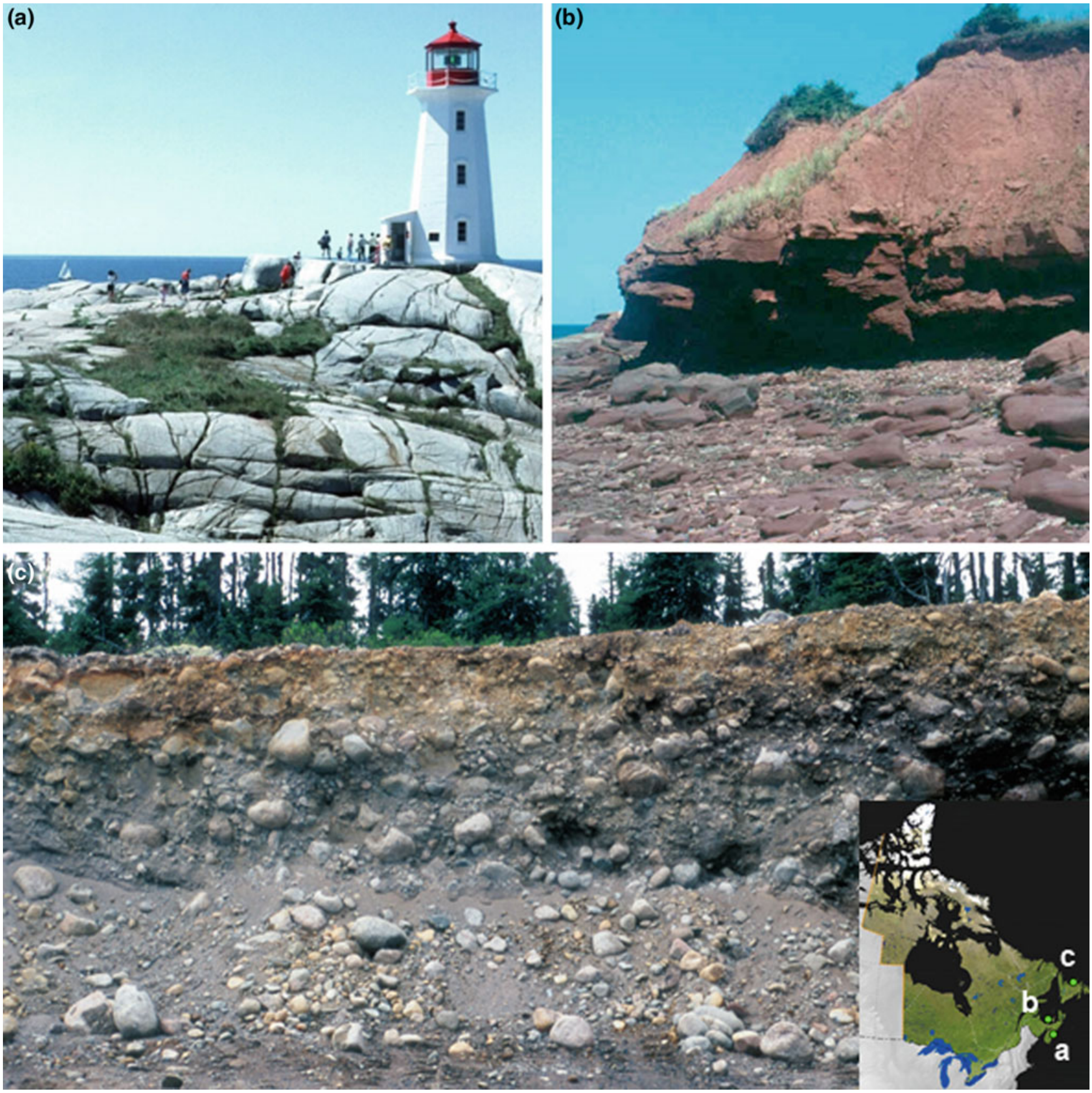


Fig. 2.12 Glacial features, Atlantic Canada. **a** Glacially eroded Devonian granite further modified by wave action, Peggy's Cove NS. **b** Glacial till lithology and mineralogy commonly reflects the underlying bedrock. MIS 2 till developed over Permian sandstone, Malpeque Bay PEI. **c** Glacifluvial esker and kame deposits are common. Carmanville, NL. *Photographs* N. Catto

Shield areas of Qikiqtaaluk (Baffin Island; van Wychen et al., this volume; Figs. 2.13 and 2.14) and Tatlurutit (Devon Island); and in Umingmak Nuna (Ellesmere Island; van Wychen et al., this volume). Glaciers disappeared from all areas south of the Torngat Mountains during the early Holocene.

The Chic-Choc Mountains, extending along the spine of the Gaspé Peninsula, include Gaspésie Provincial Park west of Murdochville, surrounding Mont Jacques-Cartier (1268 m asl) and Forillon National Park along the north shore of Baie de Gaspé (Bédard and David 1991). In Forillon, two cirques represent source areas for alpine

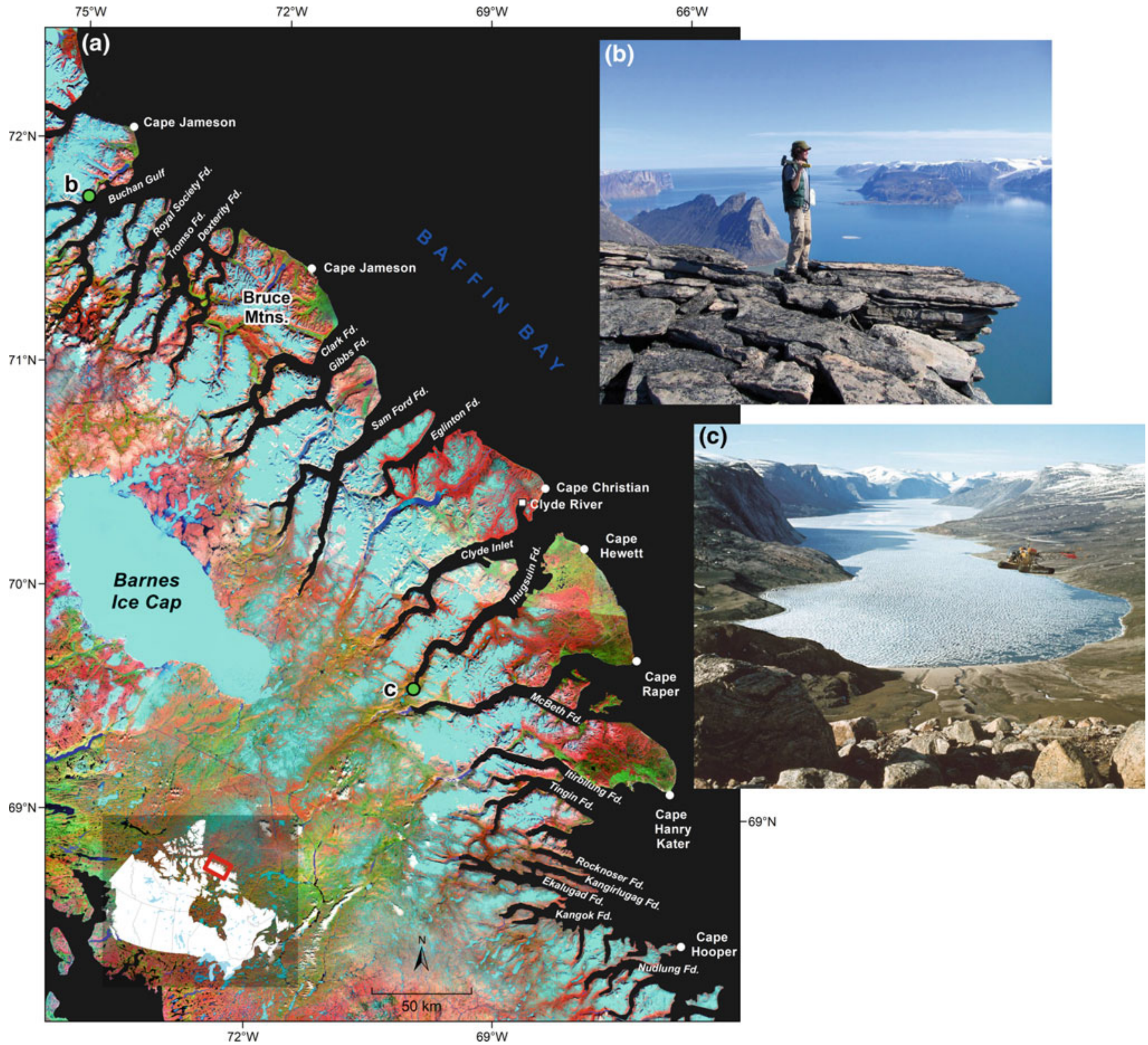


Fig. 2.13 Fjord landscapes. **a**. Landsat image of fjords, Baffin Island. *Source* MDA Federal (2004). **b** A researcher standing on the soaring cliffs above the Buchan Gulf in northeastern Baffin Island, Nunavut. *Source:* NRCan 4524 by J. Boles/ Natural Resources Canada, http://open.canada.ca/en/open-government-licence-canada. **c** Inugsuin Fjord, Baffin Island. *Photograph* reproduced with permission of J. D. Ives (also see Ives 2016)

glaciers, and many others are evident throughout Gaspé. Local alpine glaciers covered the Gaspé Peninsula throughout MIS 2, receding from the coastal areas about 13 ka. The last glaciers ablated from the Chic-Choc Mountains prior to 10 ka, after a Younger Dryas readvance. Along the margins of the glaciers, belts of permafrost terrain developed, and traces of the ice wedge casts and frost heave structures are evident today.

2.4 Glacimarine Geomorphology

Changes in sea level throughout the 2.588 million years of the Quaternary, coupled with glaciations, have resulted in the formation of glacimarine deposits and landforms at elevations from more than −120 m to more than 300 m asl in the coastal areas of eastern Canada. Typical coastal

Fig. 2.14 Cirque landscapes. **a** and **b** Cirques, Bruce Mountains, near Dexterity Fiord, on northern Baffin Island, Nunavut. *Source* Government of Canada; Natural Resources Canada (2007). *Photograph* NRCan 4528 by D. Utting/Natural Resources Canada http://open.canada.ca/en/open-government-licence-canada

glacimarine assemblages involve transitions from glacial landforms and sediments inland, to glacimarine terraces, deltas and fan deltas along the constantly shifting coast, to fine-grained laminated or structureless silts and clays, locally with scattered dropstones, offshore. With the exception of isolated exposures of MIS 5 (or older) marine sediments along the shorelines of Qikiqtaaluk and Atlantic Canada (e.g. Langlade sediments, Newfoundland and St-Pierre-et-Miquelon), glacimarine deposits date from the most recent deglaciation.

2.4.1 Atlantic Canada

Following MIS 2 deglaciation, glaci-isostatic depression resulted in a succession of marine incursions in Atlantic Canada (Fig. 2.15). A series of marine incursions occurred along the open Atlantic coast of Newfoundland and Labrador (Liverman 1994), including beaches and deposits at Terra Nova National Park and the Eastport Peninsula (35 m asl), Carmanville (~60 m asl), Brown's Arm (~65 m asl), Springdale (75 m asl), southern White Bay (75–80 m asl; McCuaig 2003), Roddickton (~100 m) and Port Hope Simpson (150 m asl; McCuaig 2002). Along the Gulf of St. Lawrence coast of Newfoundland, the maximum level of marine inundation declines to the southwest, from 150 m asl at Burnt Cape, along the Strait of Belle Isle (Grant 1989, 1992), to 140 m asl at Watts Point, 135 m asl at St. Barbe (Grant 1989), 110–120 m asl between Port au Choix and The Arches (Bell et al. 2005), 100 m asl at Cow Head, Gros Morne National Park (Grant 1989), 75 m asl at Bonne Bay (Grant 1989; Fig. 2.16), 50 m asl at Deer Lake and Corner Brook (Batterson 1998) and 27 m asl in St. Georges Bay (Bell et al. 2001, 2003). At Cape Ray, an eroded rock platform indicates that the maximum postglacial sea level was less than 10 m asl. Marine incursions also occurred from the Bay of Fundy north along the Saint John River Valley (NB; DeGeer Sea) to 60 m asl at Fredericton (Broster and Dickinson 2015); and from the southern Gulf of St. Lawrence across Kouchibouguac National Park (NB) to 45 m asl (Rampton et al. 1984), rising to 60 m asl further north.

Prince Edward Island (PEI; maximum relief 142 m) underwent a complex sequence of sea level changes following MIS 2 glaciation (Prest 1973; also see Hétu et al., this volume). Eastern and central PEI were covered by MIS 2 ice which advanced northwards from Nova Scotia, crossing the then dry Northumberland Strait. Western PEI was influenced by glacial ice which formed to the north of the present coastline, in the area which is now submerged by the Gulf of St. Lawrence. Glacial ice of the Escuminac Ice Centre expanded southeast from the Gulf of St. Lawrence, covering western PEI (Catto 1998b). The ice sheets fluctuated in extent several times, finally departing from the north coast approximately 12.5 ka (see Shaw et al. 2002, 2006).

Following deglaciation, the area adjacent to the Escuminac Ice Centre was isostatically depressed. Sea level rose throughout this region, flooding the terrain below approximately 15–20 m asl. The rise in sea level was sufficient to flood the land between Malpeque and Bedeque Bays, covering Summerside, and also flooded the low terrain between Egmont and Cascumpec Bays. Western PEI consisted of two islands at this time, one extending from North Cape to O'Leary and a second surrounding Mount Pleasant and Wellington, in addition to small areas of land surrounding Kensington and Kinkora. The period of raised sea level was short, with the sea having dropped to its present position approximately 10 ka. Sea levels did not rise above the present values east of New London Bay. Prince Edward Island National Park and the coastline to the east were not submerged by glacimarine waters.

Throughout the early and mid-Holocene, sea level fell steadily along the entire Gulf of St. Lawrence coast of PEI (Shaw et al. 2002). Drowned stumps of deciduous trees mark former forested areas developed at this time (Prest 1973). Sea level began to rise at the beginning of the late Holocene. Currently, sea levels are rising between 3 mm and 4 mm/y at Charlottetown (Shaw et al. 1998; McCulloch et al. 2002; Vasseur and Catto 2008), and transgression has marked the PEI north coast throughout the late Holocene.

Along the eastern shore of New Brunswick, the Gaspé Peninsula, and the St. Lawrence Estuary, glacimarine deposits are attributed to the Goldthwait Sea (Dietrich et al., this volume; Catto, this volume). Elevations range from 60 m asl along the Baie des Chaleurs, 25 m asl at Forillon National Park, more than 100 m asl at Cap-Chat, and 135 m asl at Mingan National Park, to more than 170 m asl along the Strait of Belle Isle. Goldthwait glacimarine silt and clay are subject to periodic slope failure.

2.4.2 Champlain Sea

Continued glacial retreat allowed marine waters to penetrate along the Saguenay and St. Lawrence Valleys. These marine incursions are designed as the Golfe Laflamme and Champlain Sea, respectively (Fig. 2.17). The Golfe Laflamme extended northwestward along the Saguenay River Valley to 50 km north of the present Lac-St-Jean (Dietrich et al., this volume; Nutz et al., this volume).

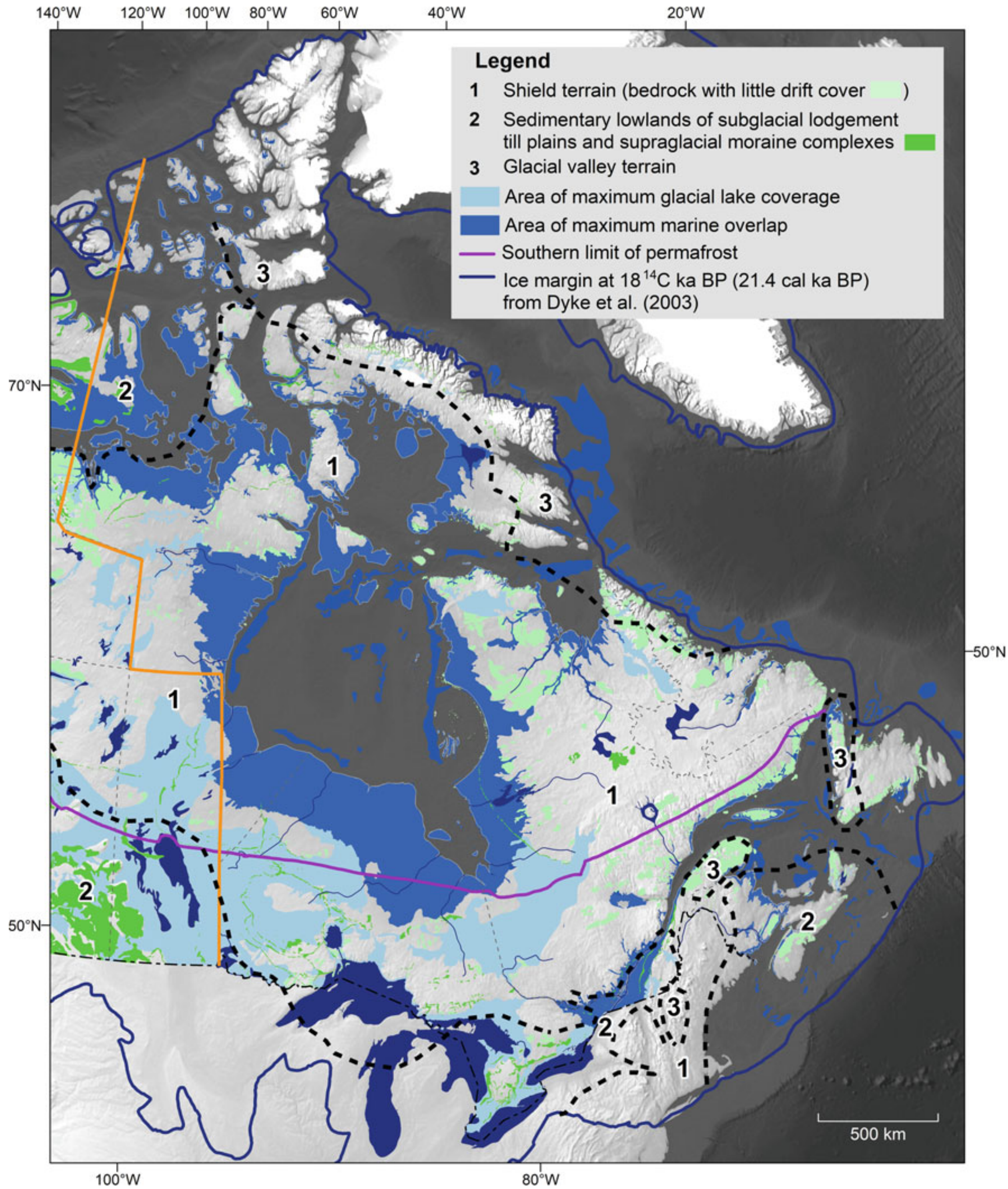


Fig. 2.15 Glacimarine, glacilacustrine and glacial land systems in eastern Canada. Three glacial land systems were defined by Eyles (1983): (1) Shield terrain, dominated by subglacial processes; (2) Sedimentary lowlands, dominated by supraglacial processes and landforms which were draped over the former glacier bed during ice retreat; and (3) glacial valley terrain, which is characteristic of mountain areas (Benn and Evans 2010). *Source* sediment distribution after Prest et al. (1968) and Fulton (1995). Also see Eyles et al. (1983)

Approximately 12 ka, deglaciation at Québec City allowed marine waters to flood the central and western St. Lawrence Lowlands. The resulting Champlain Sea extended along the St. Lawrence Lowlands southwestward to the present day Lake Champlain and Brockville, and northwestward along the Ottawa Valley to Chalk River (Catto et al. 1981; Occhietti 1989; Occhietti et al. 2001). In Gatineau National Park, north of Ottawa, marine deposits and landforms are present to 213 m asl.

A short, sharp readvance of glacial ice c. 11 ka constructed the large frontal St-Narcisse moraine north of the St. Lawrence and Ottawa Valleys from Saint-Siméon near the Saguenay

Fig. 2.16 Glacimarine features, western Newfoundland. **a** and **b** Trout River. Glacimarine terrace and sea stack indicate relative sea level of 70 m asl, c. 12 ka. **c** Distorted glacimarine sediment, Bonne Bay NL, was deposited c. 12 ka. *Photographs* N. Catto

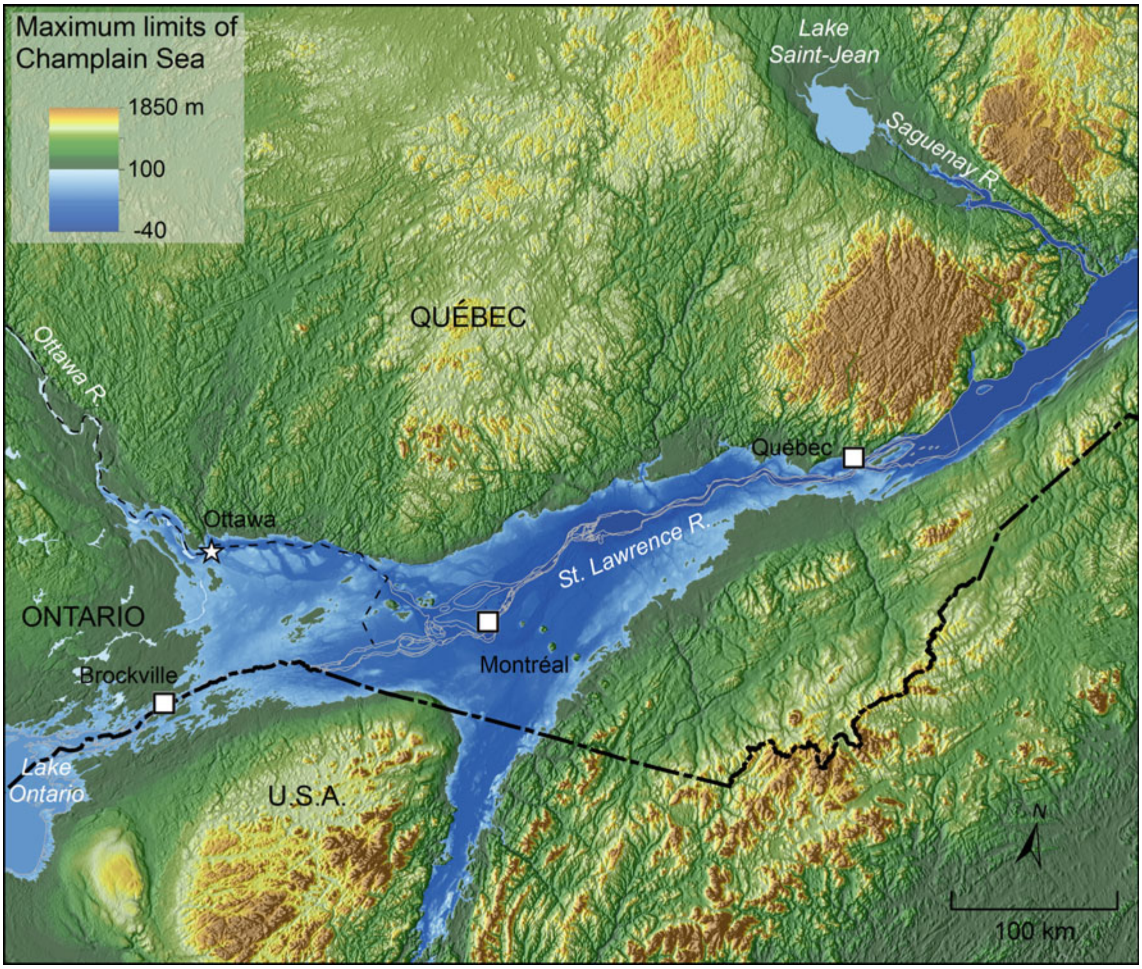


Fig. 2.17 The Champlain Sea was a body of saline to brackish water that occupied the depressed land of the St. Lawrence Lowland between Québec City and Brockville and extended up the Ottawa River Valley from 12 to 10 ka. The modern Ottawa River evolved as the ancestral river and its tributaries adjusted to the retreat of the Champlain Sea

River mouth west to Thurso, east of Ottawa (LaSalle and Shilts 1993; Occhietti 2007). A correlative feature is present near Pembroke, near the western limit of the Champlain Sea. The short duration of this event and its widespread areal extent marks it as a significant episode in the deglacial history of Canada, correlated to the Younger Dryas event.

As the land underwent isostatic recovery, the Champlain Sea was forced to contract from northwest and southwest to northeast. Simultaneously, areas in the southwest (first deglaciated) rebounded, forcing the sea to retreat towards Québec and causing the future tributary streams of the Ottawa River to flow north, down the newly developing slope and away from the St. Lawrence River. By approximately 10 ka, the former Champlain Sea was reduced to a small body of water (Lampsilis Lake, 75–80 m asl) which was isolated from the marine Gulf of St. Lawrence. Continued rebound forced the lake to dissipate completely, and by 9 ka, the ancestral Ottawa and St. Lawrence Rivers flowed through the lowland.

2.4.3 Tyrrell Sea

Glacimarine deposits flank Hudson and James Bays, throughout the Hudson Bay Lowlands and in the Kivalliq region of Nunavut, along the western shore of the permafrost-dominated shield (Dredge and Dyke, this volume). In Wapusk National Park, Polar Bear Provincial Park, and other locations in the Hudson Bay Lowlands, older glacimarine deposits have been identified and assigned to the Bell Sea (MIS 5.5) and the Prest Sea (MIS 5.3).

Following deglaciation and opening of Hudson Strait, the glaci-isostatically depressed Hudson Bay Lowland and adjacent Kivalliq were rapidly flooded by the Tyrrell Sea.

Along southwestern Hudson Bay, the Tyrrell Sea inundated all terrain below approximately 180 m asl. Tyrrell Sea marine clays formed a thick blanket over all of the pre-existing Quaternary deposits and Silurian bedrock, covering everything in the Hudson Bay Lowlands except the elevated (290 m asl) Precambrian Sutton Inlier. South of James Bay and in Kivalliq, maximum Tyrrell Sea levels exceeded 200 m. Withdrawal of the marine waters began shortly after the Tyrrell Sea reached its maximum extent, producing flights of raised beaches. Along the eastern shore line, DeGeer moraines built into the Tyrrell Sea show the progress of the systematic retreat of the Laurentide glacier into Québec.

Isostatic recovery is ongoing, and Hudson Bay can be considered as a remnant of the Tyrrell Sea. As Hudson Bay has a mean depth of 93 m, continued isostatic recovery will cause the bay to shrink significantly through the next 5,000 years, countering the effects of global sea level rise.

2.5 Glacilacustrine Geomorphology

Glacilacustrine landforms dominate much of the landscape of the western Great Lakes Lowlands and the Forested Shield of northern and central Ontario. Smaller glacial lakes formed in Appalachia–Acadia, the Maritime Plain, and the shield areas of Québec and Labrador.

Most glacial lakes in eastern Canada resulted from glacial blockage, interruption or shifting of drainage routes, either by ice impoundment, glaci-isotatic deformation or both in combination. Laurentide ice advancing from western Labrador moved against the topographic gradient as it crossed Québec and Ontario, blocking pre-existing drainage to the Atlantic Ocean. Southward glacial movement from Kivalliq similarly blocked pre-existing drainage routes into the Hudson Bay (Teller 1995; Dredge and Dyke, this volume). Local impoundments resulted as the ice moved upslope into the Appalachian Mountains and other topographic features.

During glacial retreat, ice continued to block drainage into Hudson Bay and the Atlantic Ocean. Glaci-isostatic depression augmented the flow of water towards the retreating ice fronts, causing deep and extensive impoundments in the Great Lakes region and northeastern Ontario. As deglaciation progressed, glaci-isostatic uplift resulted in changes in the configurations of glacilacustrine basins. As areas distant from the ice front were uplifted, the zone of isostatic depression was displaced towards the ice. Glacial retreat exposes new isostatically depressed terrain. A glacial lake thus gradually changes position in synchronization with the retreating ice front. Isolines, contour lines connecting points of equal amounts of isostatic uplift, indicate the gradual progress of glaci-isostatic adjustment. In the lifetime of a large glacial lake, successive outlets may be active, as ice retreat exposes new routes and isostatic recovery closes southern ones. In Manitoba, at various times between 13 and 8 ka, Glacial Lake Agassiz drained southward, into the Mississippi River; southeastward into the Lake Superior basin at Duluth, Minnesota; eastward into Lake of the Woods through Whiteshell Provincial Park; eastward into the Lake Nipigon basin, and thence via the Ottawa River into the Gulf of St. Lawrence; and northwestward via the Clearwater River of Saskatchewan into the Athabasca at Fort McMurray, Alberta, and thence via the Mackenzie Valley to the Beaufort Sea (Teller 1995; Teller et al. 2005, 2018; Leydet et al. 2018). Eventually, continued northward retreat allowed Lake Agassiz to drain directly into Hudson Bay.

2.5.1 Great Lakes

The glacilacustrine history of the Great Lakes is complex, marked by multiple configurations and outlets. Locally, chronological difficulties have led to disputes in interpretation and correlation amongst the basins. A general synopsis, considering each lake basin in turn, is presented as follows: readers seeking more detail are referred to Karrow and Calkin (1985), Karrow (1989) and Desloges et al. (this volume). Figure 2.18 indicates the progressive development of glacilacustrine bodies.

2.5.1.1 Lake Erie Basin

Early in MIS 2, the Lake Erie lobe of the Laurentide Ice Sheet Complex advanced to the southwest c. 27 ka, covering the entire Lake Erie basin and extending southwest into Ohio. The ice retreated in stages, beginning approximately 19 ka. Point Pélée National Park was initially deglaciated c. 16.5 ka, but a subsequent readvance buried the area to the east and built the Pélée moraine system, approximately 16 ka. The ice finally left the Pélée moraine approximately 15.5 ka.

As the ice stood at the Pélée moraine, Lake Erie could not drain eastward via Niagara Falls. Glacial Lake Maumee ponded against the ice front, flooded the Toledo (OH) area, and drained southwestward through several channels into the Ohio River and eventually into the Mississippi. As the ice gradually retreated northwards, progressively lower lakes (Whittlesey, Warren, Wayne, and Arkona) were formed, each one being dammed at its eastern end by the retreating ice. The later stages of this sequence extended north into the southern part of the Lake Huron basin, which had also been deglaciated. These lakes drained to the west via the Grand River of Michigan into Lake Michigan, and thence south through Chicago into the Mississippi system.

When Niagara Falls became ice free, about 13.5 ka, the rapid retreat of the ice in the Lake Ontario basin and in northern Lake Huron opened new eastern outlets for the

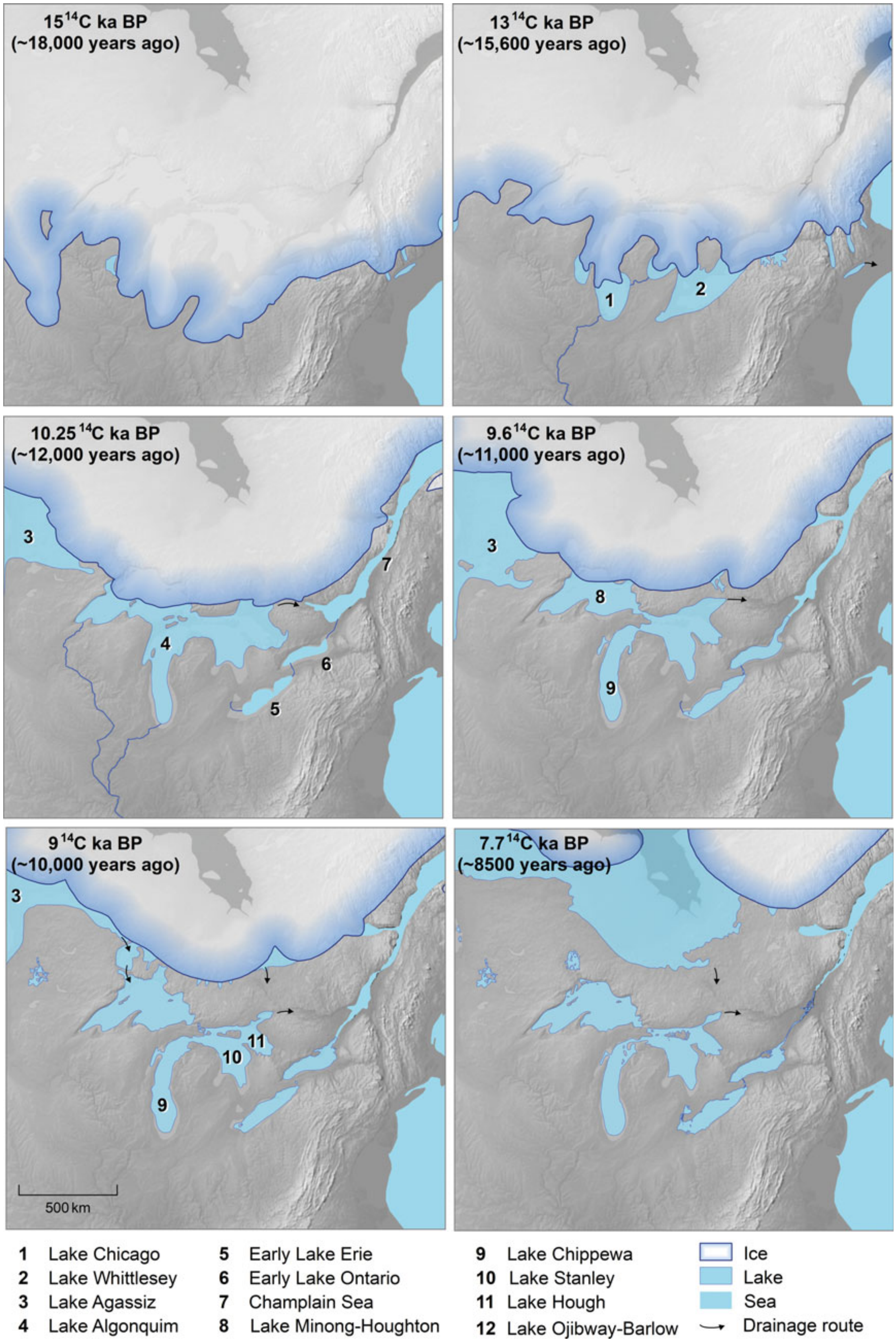


Fig. 2.18 Stages of development of the Great Lakes. Ice margins from Dyke et al. (2003). See text for discussion

upper Great Lakes. Waters drained directly east to Lake Ontario and the Ottawa Valley, thus completely bypassing Lake Erie and causing it to be reduced to several small bodies of water. The Pélée moraine isolated the shallow basin to the west from the main part of the Lake Erie basin to the east. The lake remained at levels much lower than those of the present until approximately 8 ka, when isostatic rebound started to affect the North Bay Outlet and large amounts of water began once again to flow south from Lake Huron via Sarnia into Lake Erie. By approximately 4.5 ka, the modern drainage pattern was completely established, and Lake Erie resembled its present configuration. Point Pélée developed as the lake level rose 11 m over the past 4300 years, causing the sediment to gradually migrate to the northwest. The spit attained its present configuration less than 700 years ago.

2.5.1.2 Lake Huron Basin

The Lake Huron basin was glaciated by Laurentide ice from western Labrador. Glacial ice remained in the lake basin throughout most of the last glaciation (MIS 2).

Retreat began approximately 15 ka with the withdrawal of ice from the southern Lake Huron basin. This part of the basin was occupied by the northern arms of Lakes Whittlesey, Wayne, Warren, and Arkona, which extended north from the Lake Erie basin and drained to the west via the Grand River of Michigan into Lake Michigan. Several glacial advances and retreats occurred throughout the period between 15 and 13 ka, with the ice front standing alternately in the southern part of the Huron basin and as far north of the Straits of Mackinac, joining Lakes Huron and Michigan.

After a readvance, the glaciers again retreated through the Huron Basin, and Glacial Lake Algonquin developed south of the ice front. Lake Algonquin drained alternately to the west (via Lake Michigan) and to the east, via the outlet at Kirkfield, through the Trent River system and into Lake Ontario. The main period of drainage through the Kirkfield outlet into the Lake Ontario basin occurred between 12 and 11.7 ka. As the ice retreated northwards, lower outlets were opened, initially through Algonquin Park and subsequently through North Bay, into the Ottawa Valley. Throughout these events, Lake Algonquin remained present in the Huron basin. High-level shorelines are present along the margins of the Lake Huron basin.

By 11 ka, the North Bay Outlet carried the entire discharge of the Lake Huron and Michigan basins, and the deglaciated part of Lake Superior. Water levels dropped in the Huron and Michigan basins, and the Georgian Bay basin became isolated from the main body of Lake Huron. These low-level lakes, termed 'Lake Hough' (Georgian Bay), 'Lake Stanley' (Huron) and 'Lake Chippewa' (Michigan), remained in the basins as the outlet at North Bay gradually rose. By approximately 8.4 ka, the water level in the Lake Huron basin stood at 176 m asl (at the present elevation of the lake), and Georgian Bay and Lake Huron were joined together again.

Water levels continued to rise as the North Bay Outlet rebounded. By 8 ka, the water level in the Huron, Michigan and Superior Basins stood at the same level, approximately 186 m asl. A single large lake, the 'Nipissing Great Lakes', developed in the basins. Shorelines developed during the Nipissing Great Lakes phase are present at approximately 10 m above the present level of the lake in Georgian Bay Islands and Bruce Peninsula National Park. As the North Bay Outlet continued to rise isostatically, new outlets for the Nipissing Great Lakes developed at Chicago and Sarnia, and all three outlets were functioning simultaneously about 6 ka.

Eventually, the combination of isostatic recovery at North Bay and enhanced downcutting at Sarnia caused the gradual abandonment of the outlets at North Bay (c. 5.5 ka) and Chicago (c. 4.5 ka). The Lake Huron basin drained southward through Sarnia, and became isolated from the Lake Superior basin at Sault Ste. Marie about 3.5 ka.

2.5.1.3 Lake Ontario Basin

Glacilacustrine sediments border much of the Lake Ontario basin. After deglaciation, approximately 13 ka, the ice front remained in the Thousand Islands area, blocking the eastern outlet of Lake Ontario. Waters in the basin were ponded against the ice front to the east, forming Lake Iroquois in the basin, ±140 m above modern Lake Ontario. Lake Iroquois sediment underlies most of the part of Toronto south of Eglinton Avenue. As Lake Iroquois was prevented from draining to the northeast along the St. Lawrence Valley by the retreating glacial ice, it drained to the east through an outlet at Rome (NY). From Rome, the waters followed the Mohawk River valley, and then flowed south along the Hudson River.

As the ice front retreated northeastwards, lower lake levels formed in the Lake Ontario basin as new outlets opened to the northeast. The water surface dropped in stages from the Lake Iroquois level to the Lake Frontenac positions (±90–110 m above modern Lake Ontario level), the Lake Belleville position (±30 m above modern lake level) and finally to levels ±45 m below that of the modern Lake Ontario, approximately 30 m asl. Simultaneously, the waters of Glacial Lake Algonquin, covering the area of the upper Great Lakes, were diverted via newly opened spillway outlets in Algonquin Park and North Bay into the Ottawa River, and consequently the Lake Ontario basin was bypassed. The dry areas of the basin were subjected to frost action, and ice-wedge polygons similar to those currently forming in permafrost regions of Canada developed around the margins of the reduced lake. Although Lake Ontario had retreated to a small area in the deepest part of the basin, it continued to

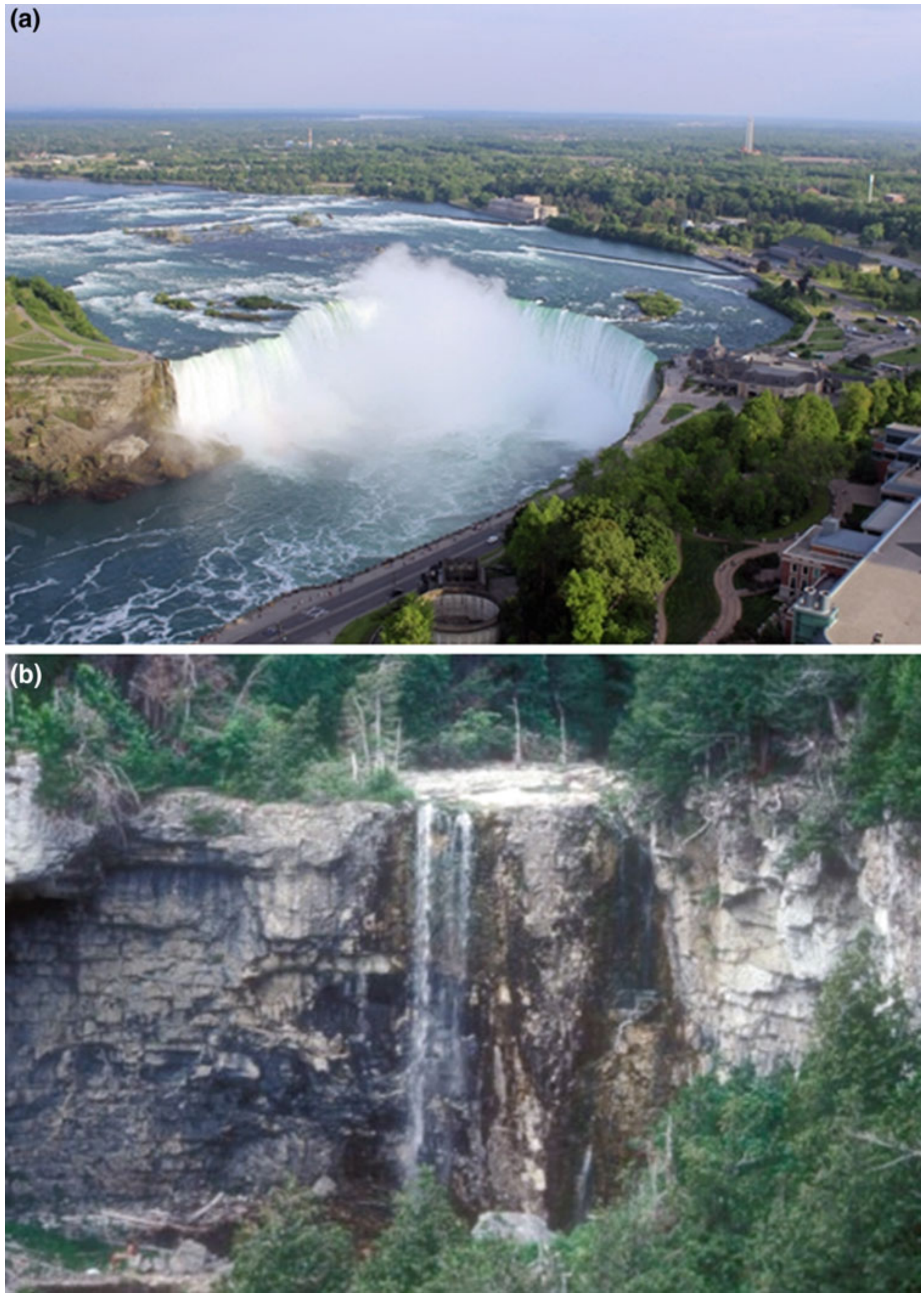


Fig. 2.19 Niagara Falls. **a** Horseshoe Falls lies along the Canada–USA border. *Photograph* Flickr, CC0 1.0. **b** The resistant Silurian Lockport dolomite caps the Niagara Escarpment, underlain successively by the Silurian Rochester shale and Ordovician Grimsby sandstone. *Photograph* N. Catto

drain northeast into the St. Lawrence Valley. Subsequently, levels began to rise in the Lake Ontario basin. By 10 ka, the configuration of Lake Ontario began to resemble what we see today.

2.5.1.4 Niagara Falls

The most recent glaciation to affect Niagara Falls (Fig. 2.19) advanced from the north and northeast, from the Lake Ontario basin, and covered the area approximately 28 ka. Retreat of the ice began about 17 ka, and by 14 ka the glacial front stood midway between Fort Erie and Niagara-on-the-Lake. A small lake was ponded against the retreating ice, but was unable to drain north because the falls and Lake Ontario basin were still ice covered. When the ice did retreat to the escarpment edge c. 13.7 ka, a deep lake quickly developed between the escarpment and the ice, and the resulting production of icebergs by calving caused the glacier to retreat rapidly through the entire Lake Ontario basin. Lake Iroquois developed at this time, eventually extending northeast to the Bay of Quinte.

Progressive glacial retreat opened new, isostatically depressed outlets for Lake Huron at Kirkfield, Algonquin Park, and North Bay. As a result, Lake Huron drained eastward into the Ottawa Valley, rather than southward into Lake Erie. Niagara Falls was thus deprived of most of its water: the modern discharge at Sarnia is approximately 90% of the discharge at Niagara Falls. The falls shrank to a relative trickle, and the rate of erosion at the lip, controlled by the volume of water passing over the Lockport Dolomite, was extremely small. During the period between 13 and 8 ka, when almost all of the drainage from Huron, Superior and Michigan bypassed Niagara Falls, the falls and gorge remained at essentially the same position.

During the mid-Holocene, the Upper Great Lakes outlet at North Bay began to isostatically rise rapidly. By 6 ka, Niagara Falls was receiving approximately 40% of its modern water discharge, with the remainder draining eastward from Lake Huron via North Bay and southward from Lake Michigan via Chicago into the Mississippi River. The closure of the competing outlets at 5.5 ka (North Bay) and 4.5 ka (Chicago) eventually forced all of Lake Huron's discharge to travel south past Sarnia, into Lake Erie and to Niagara Falls.

2.5.1.5 Lake Superior Basin

As the most northerly of the Great Lakes, Lake Superior was the most recently deglaciated. Glacial ice covered the Canadian part of the lake basin until about 12 ka, when glacial retreat from the Sault Ste. Marie area occurred. A small lake was ponded against the ice in the southwestern part of the basin, in the area north of Duluth (MN). Lake Duluth drained southwestwards into the Mississippi River Basin.

After the Younger Dryas, most of Lake Superior remained covered by ice. Lake Duluth remained impounded by ice to the north of Duluth, and was fed by water from Lake Agassiz (which occupied southern Manitoba and the Lake-of-the-Woods area to the northwest). In the eastern part of the basin, Lake Minong was dammed by ice to the northwest and drained eastwards into Lake Algonquin, which occupied the Lake Huron basin (Zaniewski et al. this volume).

Deglaciation of Pukaskwa National Park did not begin until c. 11 ka, when the ice left the northern shore of Lake Superior. The lake basin was occupied by a later phase of Lake Minong, which received water from Lake Agassiz to the west for a short time and drained into the Lake Huron basin to the east. The Superior basin continued to drain east into the Huron basin and through the North Bay Outlet into the Ottawa River.

During the Holocene, water levels gradually dropped from the high Lake Minong levels, as they simultaneously rose in the Huron and Michigan basins to the south. By 8 ka, as the last glacial ice left northernmost Ontario, the three lakes had reached a common level, creating the 'Nipissing Great Lakes' draining through the North Bay Outlet. As the North Bay Outlet isostatically rebounded, the waters of the Nipissing Great Lakes began to drain simultaneously through Chicago and Sarnia. By 4.5 ka, all the drainage of the upper Great Lakes flowed southwards through Sarnia, and over Niagara Falls.

Lake Superior did not become separated from Lake Huron until 3,500 years ago, when the Sault Ste. Marie area had rebounded sufficiently to isolate the northern lake. Water levels in the Superior Basin continued to fall, as rebound along the northern shore continued. Lake Superior did not reach its present shoreline until c. 500 ce.

2.5.2 Lake Barlow-Ojibway

The Clay Belt of northeastern Ontario reflects the region's glacilacustrine history. By 9 ka, ice had retreated northwards along the Ottawa Valley and Lake Temiscaming, allowing a glacial lake to be impounded in the valley. Ice stood in Hudson and James Bays, and across northern Ontario and Québec, blocking drainage and impounding lakes along the margins of the retreating glacier. By 8.5 ka, the lakes had coalesced into two bodies of water. Glacial Lake Barlow developed to the west, and Glacial Lake Ojibway to the east. As the ice continued to retreat, the lakes amalgamated into one body, Lake Barlow-Ojibway. Through long usage by Quaternarists, the double name has stuck. Lake Barlow-Ojibway extended westward to the headwaters of the Albany River.

Initially, the amalgamated Lake Barlow-Ojibway continued to drain south into the Ottawa River system through Lake Temiscaming, as ice blocked the natural drainage northwards to James Bay. The Cochrane glacial readvance event, involving southward-flowing ice between 8.2 ka and 8.0 ka, firmly impounded the lake. Seasonal discharge of meltwater plumes from the ice front allowed the deposition of yearly rhythmites of alternating layers of silt (spring runoff) and clay (summer settling). Some of the varves of Glacial Lake Barlow-Ojibway were disrupted by earthquake disturbances, which can be traced across the lake basin.

After Hudson Strait was deglaciated, calving rapidly exposed Hudson Bay. Lake Barlow-Ojibway rapidly drained northwards, as the Tyrrell Sea flooded southward. The Tyrrell Sea inundated all terrain below 200 m asl, and Barlow-Ojibway clays locally are overlain by Tyrrell Sea clays.

2.6 Conclusion

The geomorphology of eastern Canada is dominated by the landforms from four major and several lesser ice centres, primarily from Marine Isotope Stage 2. The shield regions of resistant bedrock, and the margins of Newfoundland, are dominated by glacial erosional features. Glacial depositional landforms dominate terrain above glacimarine or glacilacustrine limits in southern Ontario, Québec, and the Maritime provinces. In Arctic Canada, alpine glacial features dominate the mountainous areas of Baffin and Ellesmere islands. Arctic Lowlands show little geomorphic input from glaciation.

Glacial retreat exposed the isostatically depressed coastlines to marine incursions. Champlain Sea glacimarine sediments cover the St. Lawrence and Ottawa Valleys, locally to 213 m asl. The western shore of Hudson Bay and mainland Nunavut were inundated by the Tyrell Sea. Other marine incursions occurred in Atlantic Canada. In most regions, isostatic recovery caused relative sea level to drop to 0 m asl by c. 10 ka.

In the Great Lakes Lowlands and southern Canadian Shield, blockage of northward and eastward drainage led to the formation of successions of proglacial lakes and other paraglacial landforms during the transition from MIS 2 to the Holocene. The complicated glacilacustrine history in the Great Lakes Lowlands, involving shifting ice front positions and multiple outlets, resulted in deposition of thick blankets of clay and silt across the terrain flanking Lakes Ontario, Erie and Huron.

The glacial, glacimarine and glacilacustrine terrains throughout southern Ontario, Québec and Maritime Canada are marked by relatively few geomorphic hazards, with the exception of slope failures. In the sparsely populated northern and arctic regions, Quaternary glacial geomorphology has remained largely undisturbed throughout the later Holocene.

References

Andrews JT (1989) Quaternary geology of the Northeastern Canadian Shield. In: Fulton RJ (ed) Quaternary geology of Canada and Greenland. Geology of Canada Series, no. 1. Geological Survey of Canada, Ottawa, pp 276–301

Andrews JT, MacLean B (2003) Hudson Strait ice streams: a review of stratigraphy, chronology and links with North Atlantic Heinrich events. Boreas 32:4–17

Andrews JT, Voelker AHL (2018) "Heinrich events" (and sediments): a history of terminology and recommendations for future usage. Quat Sci Rev 187:31–40

Batterson MJ (1998) Quaternary history, palaeo-geography, and sedimentology of the Humber River Basin and adjacent areas. PhD thesis, Memorial University of Newfoundland

Bédard P, David PP (1991) La météorisation sur les hauts plateaux de la Gaspésie, Québec: Quelques aspects. Géogr Phys Quat 45:195–211

Bell T, Batterson MJ, Liverman DGE, Shaw J (2003) A new Late-Glacial Sea-level record for St. George's Bay, Newfoundland. Can J Earth Sci 40:1053–1070

Bell T, Smith IR, Renouf MAP (2005) Postglacial sea-level history and coastline change at port au Choix, Great Northern Peninsula, Newfoundland. Nfld Labrador Stud 20:9–31

Benn DI, Evans DJA (2010) Glaciers and glaciation. Arnold, London

Broster BE, Dickinson PE (2015) Late Wisconsinan and Holocene development of the Grand Lake Meadows area and southern reaches of the Saint John River Valley, New Brunswick, Canada. Atl Geol 51:206–220

Catto NR (1998a) The pattern of glaciation on the Avalon Peninsula of Newfoundland. Géogr Phys Quat 52:23–45

Catto NR (1998b) Comparative analysis of striations and diamicton fabrics as ice flow direction indicators, Malpeque Bay region, Prince Edward Island. Boreas 27:259–274

Catto NR, Patterson RJ, Gorman WA (1981) Late Quaternary marine sediments at Chalk River, Ontario. Can J Earth Sci 18:1261–1267

Clark PU (1988) Glacial geology of the Torngat Mountains, Labrador. Can J Earth Sci 25:1184–1198

Clark PU, Fitzhugh WW (1990) Late deglaciation of the Central Labrador coast and its implications for the Age of Glacial Lakes Naskaupi and McLean and for Prehistory. Quat Res 34:296–305

De Angelis H, Kleman J (2007) Palaeo-ice streams in the Foxe/Baffin sector of the Laurentide Ice Sheet. Quat Sci Rev 26:1313–1331

Dredge LA, Cowan WR (1989) Quaternary geology of the south-western Canadian Shield. In: Fulton RJ (ed) Quaternary geology of Canada and Greenland. Geology of Canada Series, no. 1. Geological Survey of Canada, Ottawa, pp 214–235

Dyke AS (1983) Quaternary Geology of Somerset Island, District of Franklin, NWT. Geological Survey of Canada Memoir 404

Dyke AS (1984) Quaternary geology of Boothia Peninsula and northern District of Keewatin, central Canadian Arctic. Geological Survey of Canada, Memoir 407

Dyke AS (2004) An outline of North American deglaciation with emphasis on central and northern Canada. In: Ehlers J, Gibbard PL (eds) Quaternary Glaciations—extent and chronology, Part II: North America. Elsevier, Amsterdam, pp 371–424

Dyke AS, Andrews JT, Clark PU, England JH, Miller GH, Shaw J, Veillette JJ (2002) The Laurentide and Innuitian ice sheets during the Last Glacial Maximum. Quat Sci Rev 21:9–31

Dyke AS, Moore A, Robertson L (2003) Deglaciation of North America, Open File 1574. Geological Survey of Canada

Dyke AS, Morris TF, Green DEC, England J (1992) Quaternary geology of Prince of Wales Island, Arctic Canada. Geological Survey of Canada Memoir 433

Dyke AS, Prest VK (1987) Late Wisconsinan history of the Laurentide ice-sheet. Géogr Phys Quatern 41:237–263

England J, Atkinson N, Bednarski J, Dyke AS, Hodgson DA, O'Cofaigh C (2006) The Innuitian Ice Sheet: configuration, dynamics and chronology. Quat Sci Rev 25:689–703

England JH, Furze MFA, Doupe JP (2009) Revision of the NW Laurentide Ice Sheet: implications for paleoclimate, the northwest extremity of Beringia, and Arctic Ocean sedimentation. Quat Sci Rev 28:1573–1596

Eyles N (1983) Glacial geology: a landsystems approach. In: Eyles N (ed) Glacial geology. Pergamon, Oxford, pp 1–18

Eyles N, Dearman WR, Douglas TD (1983) The distribution of glacial landsystems in Britain and North America. In: Eyles N (ed) Glacial Geology. Pergamon, Oxford, pp 213–228

Fulton RJ (1995) Surficial materials of Canada. Geological Survey of Canada Map 1880A, Scale 1:5 000 000

Gosse JC, Bell T, Gray JT, Klein J, Yang G, Finkel R (2004) Interpreting a landscape record of glaciation with cosmogenic isotopes in weathering zone type localities of Newfoundland, Canada. In: Knight PG (ed) Glaciology and earth's changing environment. Blackwell Publishing Ltd., Oxford

Government of Canada; Natural Resources Canada (2007) Canada centre for mapping and earth observation, CanImage—Landsat 7 Orthoimages of Canada, 1:50 000 Tiles: 033i07, 033i10, 033i11, 033k02, 033k07. ftp.geogratis.gc.ca/pub/nrcan_rncan/image/

Government of Québec, Ministry of forests, wildlife and Parks (MFFP) (2017) Bank of photos of Northern Québec. www.donneesquebec.ca/recherche/fr/dataset/photographie-oblique-du-nord-quebecois

Grant DR (1989) Quaternary geology of the Atlantic Appalachian region of Canada. In: Fulton RJ (ed) Quaternary Geology of Canada and Greenland. Geology of Canada Series, no. 1. Geological Survey of Canada, Ottawa, pp 393–440

Grant DR (1994) Quaternary geology, Cape Breton Island. Nova Scotia, Geol Surv Can Bull, p 482

Gray JT (1969) Glacial history of the eastern Mealy Mountains, Southern Labrador. Arctic 22:106–111

Hefter J, Naafs BDA, Zhang S (2017) Tracing the source of ancient reworked organic matter delivered to the North Atlantic Ocean during Heinrich Events. Geochim Cosmochim Ac 205–211–225

Hughes OL (1964) Surficial geology, Nichicun—Kaniapiscau Map-area. Geol Surv Can Bull 106

Ives JD (2016) Baffin Island: field research and high Arctic adventure, 1961–1967. University of Calgary Press

Jones NK (1996) The internal character and formation of the battery point drumlin, Lunenburg County, Nova Scotia. Can Geogr 40:273–280

Karrow PF (1989) Quaternary geology of the Great Lakes sub-region. In: Fulton RJ (ed) Quaternary geology of Canada and Greenland. Geological Survey of Canada Series, no. 1. Geological Survey of Canada, Ottawa, pp 326–350

Karrow PF, Calkin PE (1985) Quaternary evolution of the Great Lakes. Geological Association of Canada, Special Paper 30

Klassen RA, Paradis S, Bolduc AM, Thomas RD (1992) Glacial landforms and deposits, Labrador (Newfoundland) and eastern Québec. Geological Survey of Canada Map 1814A

Klassen RA, Thompson FJ (1993) Glacial history, drift composition, and mineral exploration, central Labrador. Geol Surv Can Bull 435

Lakeman TR, England JH (2012) Paleoglaciological insights from the age and morphology of the Jesse moraine belt, western Canadian Arctic. Quat Sci Rev 47:82–100

LaSalle P, Shilts WW (1993) Younger Dryas-age readvance of Laurentide ice into the Champlain Sea. Boreas 22:25–37

Leydet DJ, Carlson AE, Teller JT, Breckenridge A, Barth AM, Ullman DJ, Sinclair G, Milne GA, Cuzzone JK, Caffee MW (2018) Opening of Glacial Lake Agassiz's eastern outlets by the start of the Younger Dryas cold period. Geology 46:155–158

Liverman DGE (1994) Relative sea-level history and isostatic rebound in Newfoundland, Canada. Boreas 23:217–230

Maclachland JC, Eyles CH (2013) Quantitative geomorphological analysis of drumlins in the Peterborough Drumlin Field, Ontario, Canada. Geogr Anna A 95:125–144

MacLean B, Blasco S, Bennett R, England J, Rainey W, Hughes-Clarke J, Beaudoin J (2010) Ice keel seabed features in marine channels of the central Canadian Arctic Archipelago: evidence for former ice streams and iceberg scouring. Quat Sci Rev 29:2280–2301

Mahaney WC, Hancock RGV, Milan A, Pulleyblank C, Costa PJM, Milner MW (2014) Reconstruction of Wisconsinan-age ice dynamics and compositions of southern Ontario glacial diamictons, glaciofluvial/lacustrine, and deltaic sediment. Geomorphology 206:421–439

Margreth A, Gosse JC, Dyke AS (2016) Quantification of subaerial and episodic subglacial erosion rates on high latitude upland plateaus: Cumberland Peninsula, Baffin Island, Arctic Canada. Quat Sci Rev 133:108–129

Marich AS (2016) Quaternary geology of the Lindsay and Peterborough areas, southern Ontario. Ont Geol Surv Open File Report 6321

McCuaig SJ (2002) Quaternary Geology of the Alexis River area, and the Blanc-Sablon to Mary's Harbour road corridor, southern Labrador. Current Research, Newfoundland Department of Mines and Energy Geological Survey, Report 02-1, 1–20

McCuaig SJ (2003) Glacial history and quaternary geology of the White Bay region. Geological Survey of Newfoundland and Labrador, Report 03-1, 279–292

McCulloch MM, Forbes DL, Shaw RW, CCAF A041 Scientific Team (2002) Coastal impacts of climate change and sea-level rise on Prince Edward Island. Geological Survey of Canada Open File 4261

MDA Federal (2004) Landsat GeoCover TM+ 2000 Edition Mosaics Tiles N-18-65, N-65-70, N-20-70 ETM-EarthSat-MrSID, 1.0, USGS, Sioux Falls, South Dakota, 2000. Data available at the Global Land Cover Facility, www.landcover.org

Miller AAL (1999) The Quaternary sediments and seismostratigraphy of the Grand Banks of Newfoundland and The Northeast Newfoundland Shelf: foraminiferal refinements and constraints. PhD dissertation, George Washington University

Nixon FC, England JH, Lajeunesse P, Hanson MA (2014) Deciphering patterns of postglacial sea level at the junction of the Laurentide and Innuitian Ice Sheets, western Canadian High Arctic. Quat Sci Rev 91:165–183

Occhietti S (1989) Quaternary Geology of St. Lawrence Valley and Adjacent Appalachian subregion. In: Fulton RJ (ed) Quaternary Geology of Canada and Greenland. Geology of Canada Series, no. 1. Geological Survey of Canada, Ottawa, pp 350–379

Occhietti S (2007) The Saint-Narcisse morainic complex and early Younger Dryas events on the southeastern margin of the Laurentide ice sheet. Géogr Phys Quat 61:89–117

Occhietti S, Govare E, Klassen R, Parent M, Vincent J-S (2004) Late Wisconsinan Early Holocene deglaciation of Québec-Labrador. In: Ehlers J, Gibbard PL (eds) Quaternary glaciations—extent and chronology, Part II: North America. Elsevier, Amsterdam, pp 243–273

Occhietti S, Parent M, Lajeunesse P, Robert F, Govare E (2011) Late Pleistocene-early Holocene decay of the Laurentide ice sheet in Québec-Labrador. In: Ehlers J, Gibbard PL, Hughes PD (eds) Quaternary glaciations—extent and chronology, vol 15. Elsevier, Amsterdam, pp 601–630

Occhietti S, Parent M, Shilts WW, Dionne J-C, Govare E, Harmand D (2001) Late Wisconsinan glacial dynamics, deglaciation, and marine invasion in southern Quebec. Geol Soc Am Special Paper 351:243–270

Ontario Geological Survey (2010) Surficial geology of southern Ontario. Miscellaneous Release—Data 128-REV. ISBN 978-1-4435-2483-4 [DVD] ISBN 978-1-4435-2482-7 [zip file]—Revised

Pico T, Birch L, Weisenberg J, Mitrovica JX (2018) Refining the Laurentide Ice Sheet at Marine Isotope Stage 3: A data-based approach combining glacial isostatic simulations with a dynamic ice model. Quat Sci Rev 195:173–179

Prest VK (1973) Surficial deposits, Prince Edward Island. Geological Survey of Canada Map 1366 A

Rampton N, Gauthier RC, Thibault J, Seaman AA (1984) Quaternary geology of New Brunswick. Geological Survey of Canada Memoir 416

Ross M, Lajeunesse P, Kosar KGA (2011) The subglacial record of northern Hudson Bay: insights into the Hudson Strait Ice Stream catchment. Boreas 40:73–91

Ross M, Utting DJ, Lajeunesse P, Kosar KGA (2012) Early Holocene deglaciation of northern Hudson Bay and Foxe Channel constrained by new radiocarbon ages and marine reservoir correction. Quat Res 78:82–94

Roy M, Hemming SR, Parent M (2009) Sediment sources of northern Quebec and Labrador glacial deposits and the northeastern sector of the Laurentide Ice Sheet during ice-rafting events of the last glacial cycle. Quat Sci Rev 27–28:3236–3245

Shaw J, Gareau P, Courtney RC (2002) Palaeogeography of Atlantic Canada 13–0 ka. Quat Sci Rev 21:1861–1878

Shaw J, Piper DJW, Fader GBJ, King EL, Todd BJ, Bell T, Batterson MJ, Liverman DJE (2006) A conceptual model of the deglaciation of Atlantic Canada. Quat Sci Rev 25:2059–2081

Shaw J, Sharpe DR, Harris J, Lemkow D, Pehleman D (2010) Digital landform patterns for glaciated regions of Canada—a predictive model of flowlines based on topographic and LANDSAT 7 data. Geological Survey of Canada Open File 6190

Shaw J, Faragini DM, Kvill DR, Rains RB (2000) The Athabasca fluting field, Alberta, Canada: implications for the formation of large scale fluting (erosional lineations). Quat Sci Rev 19:959–980

Shaw J, Taylor RB, Forbes DL, Solomon S, Ruz M-H (1998) Sensitivity of the coasts of Canada to Sea-level Rise. Geol Surv Can Bull 505

Sookhan S, Eyles N, Arbelaez-Moreno L (2018) Converging ice streams: a new paradigm for reconstructions of the Laurentide Ice Sheet in southern Ontario and deposition of the Oak Ridges Moraine. Can J Earth Sci 55:373–396

Spagnolo M, Clark CD, Hughes ALC, Dunlop P (2010) The topography of drumlins; assessing their long profile shape. Earth Surf Processes 36:790–804

Stea R, Seaman AA, Pronk, T, Parkhill MA, Allard S, Utting D (2011) The Appalachian glacier complex in Maritime Canada. In: Ehlers J, Gibbard PL, Hughes PD (eds) Quaternary glaciations—extent and chronology, vol 15, pp 631–659. Elsevier, Amsterdam

Stea R, Mott RJ (2005) Younger Dryas glacial advance in the southern Gulf of St. Lawrence: analogue for ice inception? Boreas 34:345–362

Stokes CR (2018) Geomorphology under ice streams: moving from form to process. Earth Surf Process 43:85–123

Stokes CR, Tarasov L, Blomdin R, Cronin TM, Fisher TG, Gyllencreutz R, Hättestrand C, Heyman J, Hindmarsh RCA, Hughes ALC, Jakobsson M, Kirchner N, Livingstone SJ, Margold M, Murton JB, Noormets R, Peltier WR, Peteet DM, Piper DJW, Preusser F, Renssen R, Roberts DH, Roche DM, Saint-Ange F, Stroeven AP, Teller JT (2015) On the reconstruction of palaeo-ice sheets: recent advances and future challenges. Quat Sci Rev 125:15–49

Stokes CR, Tarasov L, Dyke AS (2012) Dynamics of the North American Ice Sheet Complex during its inception and build-up to the Last Glacial Maximum. Quat Sci Rev 50:86–104

Storrar RD, Stokes CR, Evans DJA (2014) Morphometry and pattern of a large sample (>20,000) of Canadian eskers and implications for subglacial drainage beneath ice sheets. Quat Sci Rev 105:1–15

Tarasov L, Dyke AS, Neal RM, Peltier WR (2012) A data-calibrated distribution of deglacial chronologies for the North American ice complex from glaciological modelling. Earth Planet Sci Lett 315–316:30–40

Teller JT (1995) History and drainage of large ice-dammed lakes along the Laurentide Ice Sheet. Quat Int 28:83–92

Teller JT, Boyd M, Yang ZR, Kor PSG, Fard AM (2005) Alternative routing of Lake Agassiz overflow during the Younger Dryas: new dates, paleotopography, and a re-evaluation. Quat Sci Rev 24:1890–1905

Teller JT, McGinn RA, Rajaparac HM, Shuklac AD, Singhvi AK (2018) Optically stimulated luminescence ages from the Lake Agassiz basin in Manitoba. Quat Res 89:478–493

Vasseur L, Catto N (2008) Atlantic Canada. In: Lemmen DS, Warren FJ, Lacroix J, Bush E (eds) From impacts to adaptation: Canada in a changing climate 2007. Government of Canada, Ottawa, pp 119–170

Veillette JJ, Roy M, Paulen RC, Ménard M, St-Jacques G (2017) Uncovering the hidden part of a large ice stream of the Laurentide Ice Sheet, northern Ontario, Canada. Quat Sci Rev 155:136–158

Vincent JS (1989) Quaternary geology of the southeastern Canadian Shield. In: Fulton RJ (ed) Quaternary Geology of Canada and Greenland. Geology of Canada Series, no. 1. Geological Survey of Canada, Ottawa, pp 249–275

Way RG, Bell T, Barrand NE (2014) An inventory and topographic analysis of glaciers in the Torngat Mountains, northern Labrador, Canada. J Glaciol 60:945–956

Winsborrow M, Clark CD, Stokes CR (2004) Ice streams of the Laurentide Ice Sheet. Géogr Phys Quat 58:269–280

Winsborrow M, Clark CD, Stokes CR (2010) What controls the location of ice streams? Earth-Sci Rev 103:45–59

Norm Catto joined Memorial University in July 1989 and is now the Head and Professor of Geography at that university. His research and teaching interests include the following: coastal landforms, natural hazards, sea level change and impacts in coastal environments; response of river systems to climate and weather events, and flood risk assessment; aeolian geomorphology and response to climate and human factors in boreal and coastal environments; mass movements and slope failures; loess deposition; palaeosol formation; emergency measures, policies and effectiveness human adaptations to climate and weather events; the impacts of climate and weather events on agriculture, transportation, fisheries and communities; and the relationships among landscapes and people. His research has included projects and investigations in landscapes and environments in 16 countries, and in all Canadian provinces and territories, particularly in eastern Canada. For 18 years, he served as Editor-in-Chief for *Quaternary International,* a professional international journal dedicated to the study of landscape evolution and climate variation throughout the past 3 million years. He has taught more than 50 different undergraduate and graduate courses focused on numerous aspects of geomorphology, landscape analysis, Quaternary research, natural hazards, ocean sciences, environmental science, climate and climate change, soil science, geoarchaeology and palaeontology. Study of landscapes forms his central focus for the understanding of the various areas of eastern Canada, the combination of physical and cultural constituents that contribute to its identities. For most species, and for all human occupants, life in eastern Canada has been heavily influenced by geomorphology since deglaciation.

Dori J. Kovanen is a professional engineering geologist and Research Associate in the Department of Geography at the University of British Columbia, Vancouver, BC. With an M.Sc. from Western Washington University in Bellingham and a Ph.D. in Quaternary geology from the University of British Columbia, she is a specialist in Quaternary geomorphology. She has written extensively on late glacial and Holocene history of the Pacific Northwest as well as contemporary environmental changes in the region and was a significant contributor to 'Landscapes and Landforms of Western Canada' (Slaymaker 2017).

Olav Slaymaker is a Member of the Order of Canada, and professor emeritus of geography in the Department of Geography at the University of British Columbia, Vancouver, B.C. His 20+ co-authored and edited monographs and 160+ refereed papers reflect three different styles of work. First, he has pursued original field research for 40 years on sediment systems in the Canadian Cordillera and the European Alps, strongly supported and enhanced by his stellar doctoral and postdoctoral students and international colleagues. Second, he has produced papers and books summarizing trends in land use and environmental change in mountain regions worldwide. Third, he has edited monographs with invited international contributions on major environmental and geomorphological themes. He is Former President of the Canadian Association of Geographers and Former President of the International Association of Geomorphologists.