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Research Article

Late glacial lake and marine strandlines in the Ontario, St. Lawrence, and Champlain Lowlands, USA and Canada record steadily decreasing water levels interrupted by breakout floods

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Abstract

We report new interpretation of >19,500 beach strandlines from waterbodies in the western St. Lawrence and Champlain Lowlands in northern New York and adjacent areas of Vermont, Quebec, and Ontario from ≤2-m-resolution digital elevation models. Strandline evidence supports a deglaciation model in which proglacial lake and marine shoreline deposits adjusted continuously in response to steady shoreline regression linked to outlet incision, differential isostatic adjustments, and postglacial relative sea-level rise. Gaps in strandline preservation reflect times of rapid water-level decline associated with breakout floods and abrupt shifts in drainage to new outlets. Water levels returned to slower, steady decline and renewed beach sedimentation during the later stages of a breakout as water levels in the source and receiving waterbodies equilibrated. Our conclusions contrast with previous models that infer discrete lake stages were controlled by stable outlets then fell abruptly as lower outlets were exhumed from beneath the Laurentide Ice Sheet during deglaciation. We present a new deglacial chronology and lake nomenclature that reflects this paradigm and redefines the spatial and temporal distributions of proglacial lake and marine water in the region.

Keywords: Pleistocene; North America; Paleogeography; Glacial geomorphology; Proglacial lakes; Champlain Estuary; Hochelagan Estuary; Beach ridges; Lake Abenaki; Lake Akwesasne

Introduction

Warren Upham recognized the significance of the proglacial lake and marine waterbodies in the Champlain and Hudson lowlands when he wrote;

"The Hudson—Champlain area, made classic in glacial geology by the works of C.H. Hitchcock, Baldwin, Baron de Geer, Gilbert, Merrill, Peet, Woodworth, and others, which through the writings of Hitchcock and Dana gave the name Champlain to the closing epoch of the Ice Age, deserves yet further work of detailed surveys, with exact leveling for determination of the relations of all its lacustrine and marine shore lines. No other area of our continent promises more important information concerning the Glacial and Recent periods" (Upham, 1905)

One hundred and twenty years later, high-resolution LiDAR elevation models provide an important new tool to conduct the kind of detailed analysis Upham envisioned. This study reevaluates the deglacial lake and marine chronology of the eastern Ontario, western St. Lawrence, and Champlain Lowlands (Fig. 1) in the context of newly interpreted strandline data, principally beach ridges, compiled from LIDAR-derived digital elevation models (DEMs).

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The deglacial chronology of this region has important implications for ice recessional history, meltwater routing to the North Atlantic, and global climate (Teller, 1988; Broecker et al., 1989; Rahmstorf, 1995; Donnelly et al., 2005; Tarasov and Peltier, 2005; Broecker, 2006). Proglacial lakes and marine estuaries, described later, also overlapped with Paleoindian occupation of New York and could have factored into the migration, regional subsistence, and land-use practices of the earliest people in Hudson and St. Lawrence Valleys (Lothrop and Bradley, 2012).

Many proglacial lake phases in the published literature were defined from small sample populations of comparatively low-resolution data that included unreliable strandline proxies, inaccurate elevation estimates, or a limited understanding of the direction and magnitude of regional isostatic rebound and, in most cases, were presumed to have stable outlet thresholds. Furthermore, shorelines of large proglacial lakes are diachronous, so elevation data used for shoreline reconstruction may not be the same age everywhere in the basin (Lewis et al., 2022). These limitations contributed to the proliferation of names given to presumed proglacial lake stages in different areas. Published references to proglacial lake names have become a matter of individual discretion, leading to the development of an overlapping and complex nomenclature for different parts of the region (Table 1). From our spatial analysis of strandline deposits and landforms, principally beach ridges, we revise and redefine proglacial lake and marine

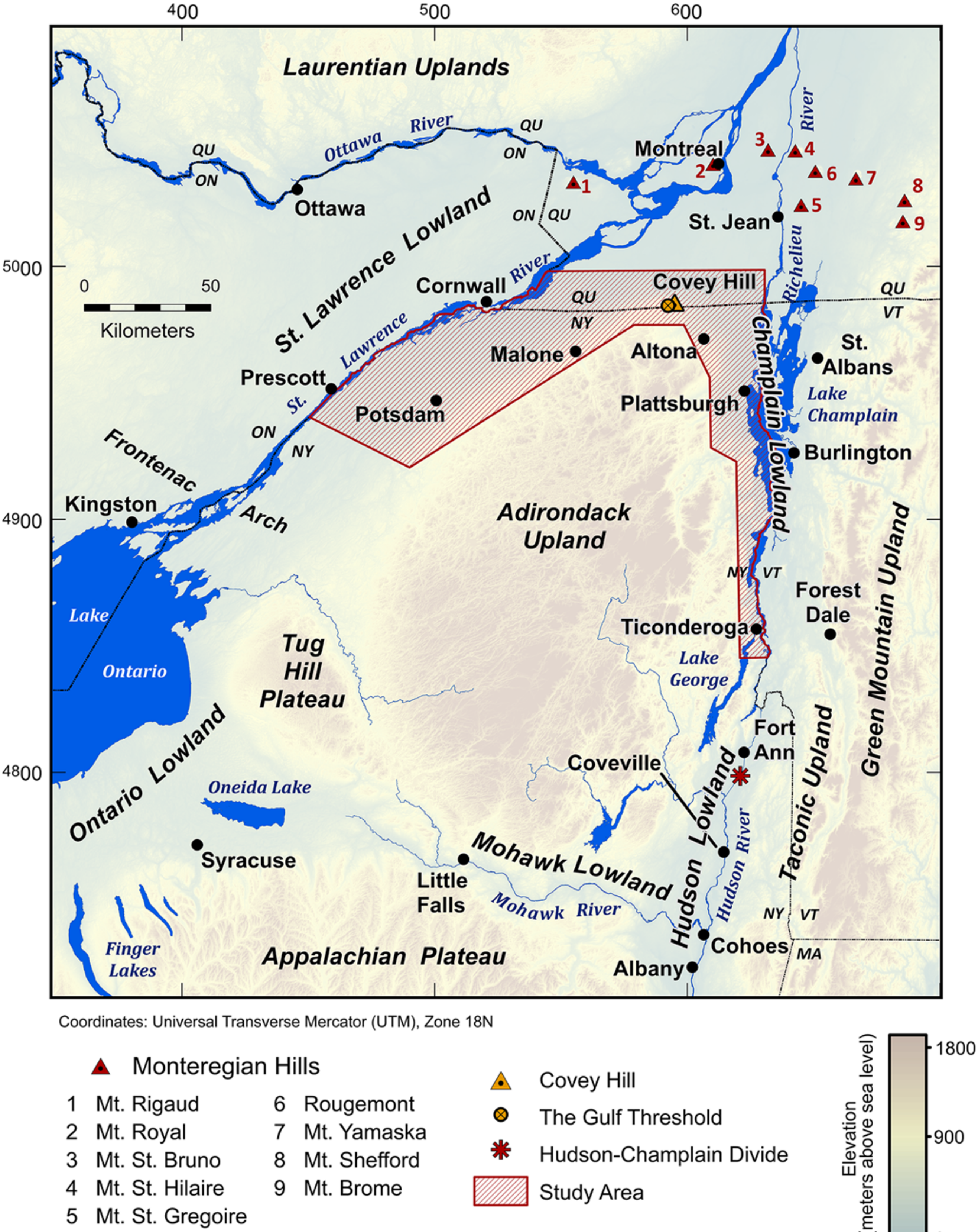

Figure 1. Shaded relief map of the Ontario, St. Lawrence, and Champlain Lowlands. The study area is indicated by the red shading adjacent to the northern and eastern Adirondack Upland.

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Table 1. Nomenclature for proglacial lake and marine waterbodies in the Hudson–Champlain, eastern Ontario, and western St. Lawrence Lowlands.[a]

Eastern Ontario Basin–Western St. Lawrence Lowlands

MacClintock & Stewart 1965	Muller & Prest 1985	Parent & Occhietti 1988, 1999	Pair & Rodrigues 1993	Lewis and Todd 2019		This Study	
		Lake Lampsilis Estuarine Ph.		Lake Ontario lowstand	Champ-plain Sea	Endo-rheic Lake Ontario	Hoche-lagan Estuary
Champlain Sea	Early Lake Ontario/ Champlain Sea	Champlain Sea: Phase III Phase II	Early Lake Ontario/ Champlain Sea	Early Lake Ontario/ Champlain Sea		Champlain Estuary	
Vermont (Ft. Ann)	Trenton Belleville Sidney	Candona Vermont (Ft. Ann)	St. Lawrence	St. Lawrence		Akwesasne	
Iroquois	Frontenac	Memphremagog (No. Appalachian Mtns.)	Frontenac	Iroquois		Iroquois	
	Iroquois		Iroquois: Main Phase Watertown Phase				
	Vanuxeum Newberry Ithaca/Watkins Primitive Lakes (Appalachian Plateau)						

Hudson–Champlain Lowlands

Woodworth 1905a Chapman 1937 Denny 1974	Wagner 1972	Wall & Lafleur 1995 DeSimone et al. 2008	Stanford 2009, 2010	Franzi et al. 2007 Cronin et al. 2008 Rayburn et al. 2011	This Study
Champlain Sea	Champlain Sea: Greens Corners Fort Ann Marine Phase			Champlain Sea: Marine Phase II	Hochelagan Estuary
				Transitional Ph. Freshwater Ph. Marine Phase I	Champlain Estuary
Vermont: Fort Ann	Fort Ann	Fort Ann III Fort Ann II Fort Ann I	Vermont (Fort Ann)	Vermont: Fort Ann	Akwesasne
Vermont: Coveville	Coveville	Coveville	↑ Albany (Unstable) ↓	Vermont: Coveville	Abenaki
Quaker Springs	Quaker Springs	Quaker Springs			↑ Albany (Unstable) ↓
Albany		Albany II			
		Albany	Albany (Hell Gate)		
			Bayonne		

[a]Principal sources: Woodworth, 1905a; Chapman, 1937; MacClintock and Stewart, 1965; Wagner, 1972; Denny, 1974; Muller and Prest, 1985; Parent and Occhietti, 1988, 1999; Pair and Rodrigues, 1993; Wall and Lafleur, 1995; Franzi et al., 2007; Cronin et al., 2008; DeSimone et al., 2008; Stanford, 2009; Rayburn et al., 2011; Lewis and Todd, 2019; the present study.

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phases in a way that reflects the interaction between ice recession and changes in outlet elevation or location, glacial isostatic adjustment, and relative sea-level change.

Proglacial lake and marine nomenclature

The sequence of proglacial lakes and marine waterbodies in the Ontario, St. Lawrence, and Champlain Lowlands has been studied for more than a century (Table 1). Thoughtful summaries of early work can be found in MacClintock and Stewart (1965), Muller and Prest (1985), Rodrigues (1992), Lewis and Todd (2019), and Lewis et al. (2022) for the Ontario and western St. Lawrence Lowlands, and in Chapman (1937), Connally and Sirkin (1973), Muller et al. (1986), Wall and Lafleur (1995), Rayburn et al. (2005, 2018), and DeSimone et al. (2008) for the Hudson–Mohawk and Champlain Lowlands. Deglacial thinning of the LIS over upland regions (Franzi et al., 2016; Barth et al., 2019) and drawdown of ice lobes into peripheral lowlands impounded extensive proglacial lakes along the receding margin of the LIS (Fig. 2). These lakes expanded northward with ice recession and evolved through a series of falling lake phases in response to differential glacial isostatic uplift, relative sea-level change, outlet incision, and shifting positions of their drainage outlets. We assign the names Lake Abenaki, Lake Akwesasne, endorheic Lake Ontario, Champlain Estuary, and Hochelagan Estuary in the following summary (Table 1). These names are explained in the "Discussion."

Lake Iroquois formed in the Ontario basin following ice recession from the northern flank of the Appalachian Plateau ~14.0 cal ka BP (Fairchild, 1909; Coleman, 1937; Muller and Calkin, 1993; Lewis and Todd, 2019; Fig. 2A). Early high-level lake phases remained confined to the southern and eastern portions of the Ontario Lowland and drained eastward across a threshold near Little Falls, New York (Pair and Rodrigues, 1993; Bird and Kozlowski, 2016; Porreca et al., 2018; Fig. 1), through the Mohawk Valley as the Glaciomohawk River (Fairchild, 1912) into Lake Albany in the upper Hudson Lowland (Figs. 1 and 2A). Lake Iroquois expanded northward with ice recession and became connected to lake outflow from proglacial lakes in the upper Great Lakes basin (Fig. 2B, Table 1). Flow through the Mohawk Lowland continued as the larger Iromohawk River (Fairchild, 1912). Falling water level and northward expansion of Lake Albany accompanied recession of the ice margin in the upper Hudson and Champlain Lowlands (DeSimone et al., 2008; Stanford, 2009). As Lake Albany water level fell, a low point on the Hudson–Champlain drainage divide emerged about 6 km south of Fort Ann, New York, separating Lake Abenaki in the Champlain Lowland from Lake Albany in the upper Hudson Lowland (Fig. 2B, Table 1).

Outflow from Lake Iroquois shifted northward to the Champlain Lowland about 13 cal ka BP (Lewis and Todd, 2019; Lewis and Anderson, 2020; Lewis et al., 2022; Fig. 2B) as lower outlets emerged on the St. Lawrence–Champlain drainage divide near The Gulf Unique Area (The Gulf) in Clinton County, New York, about 2.5 km southwest of Covey Hill, Quebec (Woodworth, 1905a; Fairchild, 1912, 1919; Denny, 1974; Pair et al., 1988; Pair and Rodrigues, 1993; Franzi et al., 2002, 2007, 2016; Rayburn et al., 2005; Fig. 1). The sudden outflow scoured the surficial cover material to form bedrock pavements, or Flat Rocks, in the northwestern Champlain Lowland (Woodworth, 1905a, 1905b; Denny, 1974; Franzi et al., 2002, 2007, 2016; Rayburn et al., 2005) and flow through the Mohawk Lowland as the Iromohawk River ended.

Lake Iroquois briefly stabilized at The Gulf bedrock threshold (elevation 305 m) near Covey Hill (Franzi et al., 2007, 2016; Rayburn et al., 2005, 2011). The stable interval correlates with the Lake Frontenac phase of Pair and Rodrigues (1993) and may have lasted ~50 yr based upon stratigraphic evidence in varve records from the Champlain Lowland (Franzi et al., 2007; Rayburn et al., 2011). Final drainage of Lake Iroquois occurred as ice receded and floodwater discharged eastward along the northern flank of Covey Hill. Lake Iroquois fell until proglacial lakes in the Ontario, St. Lawrence, and Champlain Lowlands merged to form Lake Akwesasne (Pair and Rodrigues, 1993; Rayburn, 2004; Rayburn et al., 2005; Franzi et al., 2007; Fig. 2C, Table 1).

Post-Iroquois proglacial lakes drained ~12.8 cal ka BP (Lewis et al., 2022) when ice recession in the Lake Chaudière–Etchemin area, Quebec, opened a connection to the Goldthwait Sea at the mouth of the St. Lawrence River and marine water inundated the isostatically depressed St. Lawrence and Champlain Lowlands, creating the Champlain Sea (Occhietti et al., 2011). Freshwater outflow across the Frontenac Arch, a broad structural high in eastern Ontario and northern New York, restricted circulation between the Champlain Sea and coeval Early Lake Ontario (ELO) (Pair and Rodrigues, 1993; Lewis and Todd, 2019; Lewis and Anderson, 2020; Lewis et al., 2022; Fig. 2D, Table 1). We refer to these contiguous waterbodies as the Champlain Estuary (Fig. 2D).

Falling water level, controlled by differential isostatic uplift and associated shift in lake outlet, relative sea-level change, and warming late Pleistocene climate, isolated water in the Ontario Basin from the upper glacial Great Lakes and the Champlain Estuary (Lewis, 2016; Lewis and Todd, 2019; Table 1). Endorheic (internally drained or closed basin) Lake Ontario occupied the lowest portion of the Ontario Basin and was separated from the Hochelagan Estuary by the Frontenac Arch (Lewis, 2016; Lewis and Todd, 2019; Fig. 2E, Table 1).

Shoaling, eastward regression of the Champlain Estuary in the western St. Lawrence Lowland, and freshwater inflow from adjacent uplands freshened water in the Hochelagan Estuary (Lake Lampsilis of Elson and Elson [1959], Elson [1962, 1988], Richard [1978], and Parent and Occhietti [1988]; Fig. 2E, Table 1). The Hochelagan Estuary occupied the lowland until ~8.3 cal ka BP, when Lake Ontario reestablished connection to the western St. Lawrence Lowland and the Great Lakes to create the modern Lake Ontario–St. Lawrence River drainage system (Lewis, 2016; Lewis and Todd, 2019).

Strandline data

Strandline deposits and landforms such as deltas, shorezone platforms, and beach ridges mark the shores of proglacial lake and marine waterbodies in the study area. Many strandline features are diachronous or yield ambiguous water level estimates, especially on regressive shorelines. Elevations of deltaic topset–foreset contacts are commonly used proxies for paleo-water levels in northern New York and New England (Pair et al., 1988; Koteff and Larsen, 1989; Pair and Rodrigues, 1993; Rayburn et al., 2005; Hooke and Ridge, 2016), but their use requires identification of internal stratigraphy. Delta surfaces slope basinward on regressive shorelines and topset bed thickness is often unknown, leading to uncertainty regarding paleo-water level. Erosional shorezone platforms are horizontal to subhorizontal bedrock surfaces that form between the highest elevation of spring tide or storm surge erosion and the breaking depth of incoming waves (Kennedy, 2015; Rovere et al., 2016). The platform–sea cliff junction at the inner edge of a platform develops

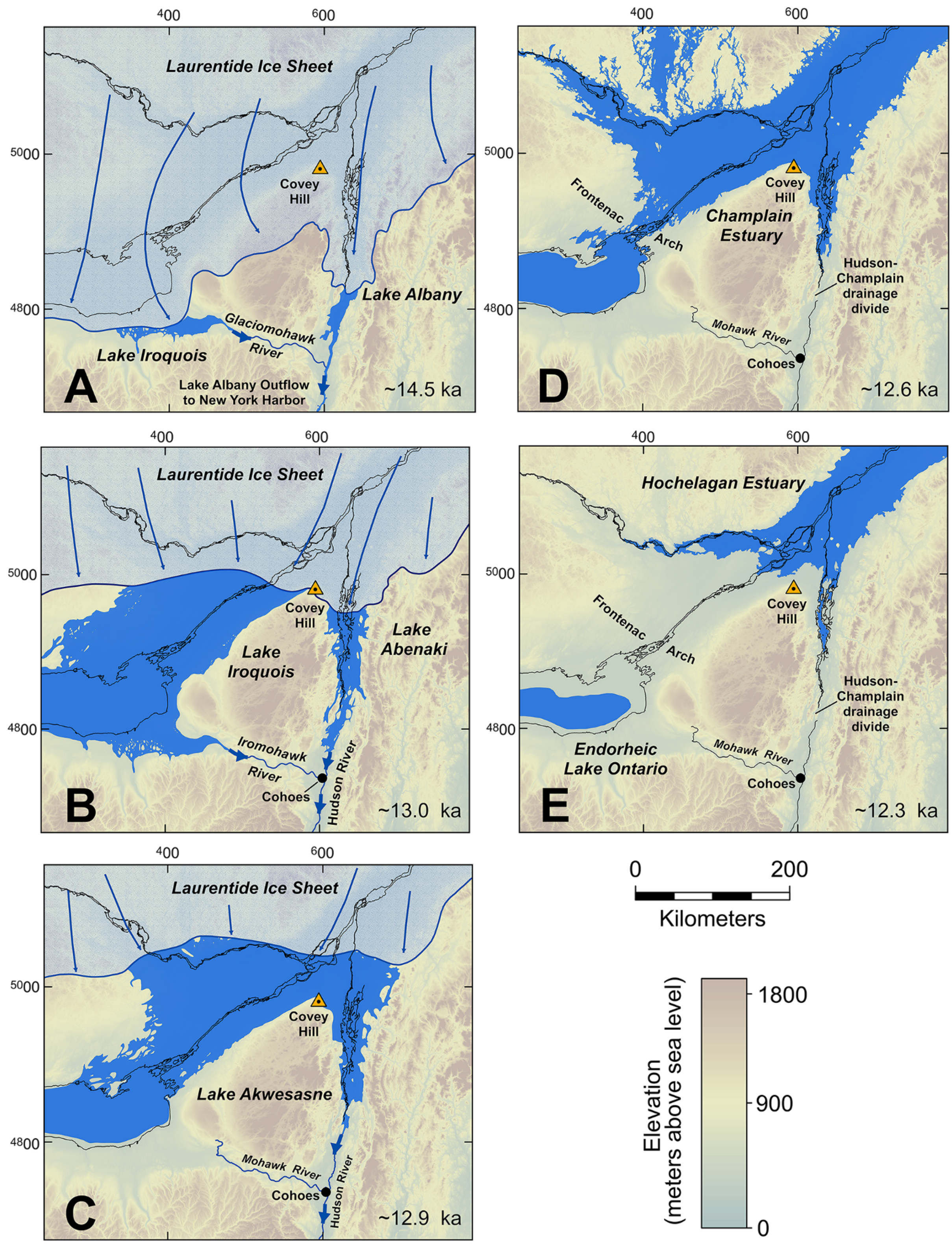

Figure 2. Proglacial lake succession in the western Ontario, western St. Lawrence, and Hudson–Champlain Lowlands. Details given in the text. Arrows indicate outflow routes from glacial lakes. Principal sources: Muller and Prest (1985); Parent and Occhietti (1988); Pair and Rodrigues (1993); Lewis and Todd (2019), Lewis et al. (2022), and Franzi et al. (2016). Modified from figures in Franzi et al. (2016) and prepared in collaboration with the *Adirondack Journal of Environmental Studies*. The names Lake Abenaki, Lake Akwesasne, Endorheic Lake Ontario, Champlain Estuary, and Hochelagan Estuary (Table 1) are explained in the "Discussion." (**A**) Early Lake Iroquois with outflow via the Glaciomohawk River to Lake Albany; (**B**) Lake Iroquois with outflow via the Iromohawk River to Lake Abenaki. The lakes are depicted near their maximum extents immediately before the Lake Iroquois breakout at The Gulf near Covey Hill; (**C**) Lake Akwesasne with outflow across the bedrock threshold at Fort Ann; (**D**) the Champlain Estuary at the upper marine limit; (**E**) Endorheic Lake Ontario and the Hochelagan Estuary.

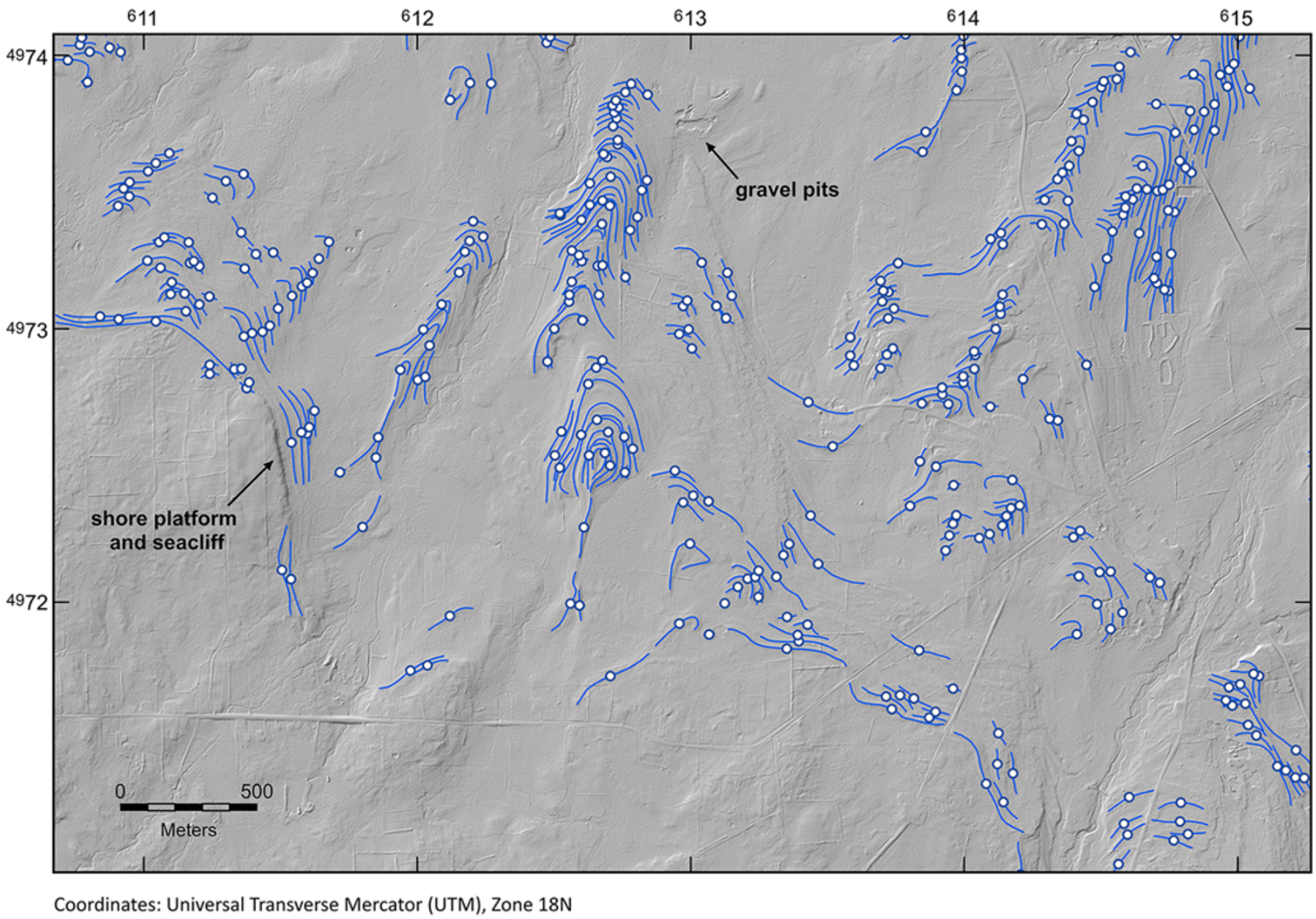

Figure 3. Examples of Champlain Estuary beach ridges illustrating ridge-crest segments and midpoint location in the Champlain Lowland near Altona, New York.

within a narrower range of elevation (∼1–4 m) between mean water level and the upper limit of spring tide or storm surge erosion (Kelsey, 2015; Rovere et al., 2016). Shore platform morphology in the northwestern Champlain Lowland and on the northern flank of Covey Hill may be confused with the eroded edges of gently dipping lower Paleozoic sedimentary strata, especially where beach deposits lap onto horizontal or gently dipping bedrock exposures, making them less accurate as water-level indicators.

The term "beach ridge" applies to relict, shore-parallel, wave- or swash-built, gravel and sand ridges, or erosional shoreface scarps (Otvos, 2000). Beach ridges commonly occur as clusters of low-relief, multiple, subparallel ridges in basin-sloping, progradational strandplains (Otvos, 2000; Tamura, 2012; Lindhorst and Schutter, 2014; Kelsey, 2015; Rovere et al., 2016). Lindhorst and Schutter (2014) found that most beach ridges on King George Island, Antarctica, formed by storm waves, but strandline progradation primarily occurred by swash deposition during calmer intervals. Individual ridges form between mean water level and the highest storm-surge or spring-tide levels (Kelsey, 2015). Successive offlapping sequences of ridges form as basinward regression disconnects earlier-formed beach deposits from active beach processes. Principal controls on shoreline regression in the study area include outlet incision, glacial isostatic adjustments, and relative sea-level change. Beach ridges are the principal focus of our investigation, because they are the most conspicuous, widespread, and traceable strandline features on surface elevation models in the study area (Fig. 3).

Materials and methods

DEM data

We downloaded bare-earth DEM data for New York, Vermont, Ontario, and Quebec from publicly available data resources (Table 2) with spatial (x,y) resolution of 2 m or less and vertical accuracy of <0.2 m. DEM data were merged into a single mosaic image and resampled at 1 m resolution using ArcMap 10.8.2 (Release 10, Environmental Systems Research Institute, Redlands, CA). The resampling did not improve the resolution of the 2 m data but provided a seamless base upon which to map. Derivative surface models such as hill shade, slope, and contour lines were generated using 3D Analyst raster tools in the ArcMap 10.8.2 ArcToolbox.

DEM resolution varied throughout the study area, so data were merged with 0.75 arcsec Canadian digital elevation models and 1 m DEM data from northwestern Massachusetts and resampled at 10 m spatial resolution to produce a seamless elevation model for the purpose of plotting summary maps of beach ridge interpretation. All DEM models use Universal Transverse Mercator (UTM) Zone 18N spatial coordinates and North American Datum 1983 (NAD83) vertical datum.

Individual ridges are subtle features that may be difficult to observe in the field due to dense vegetation and low relief, but they are easily identified on DEM images. We hand-digitized beach ridge crests as polyline features at a scale of 1:1000 or larger across >7800 km^2 within the study area. Beach ridge examples are shown

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Table 2. Sources of digital elevation model (DEM) data.[a]

Agency	Geographical Area	Resolution	Obtained From
Federal Emergency Management Agency (FEMA)	New York	1m, 2m	NYS GIS Clearinghouse
US Department of Agriculture (USDA)	Vermont	2m	Vermont Geodata Portal
US Geological Survey (USGS)	New York	1m	NYS GIS Clearinghouse
Ontario Ministry of Nat. Res. and Forests (OMNRF)	Ontario	0.5m, 2m	OMNRF
Dept. of Agriculture, Energy and Nat. Resources	Quebec	1m, 2m	DAENR
Dept. of Agriculture, Energy and Nat. Resources	Quebec	0.75 sec	Natural Resources
Massachusetts Bureau of Geographic Data	Massachusetts	1m	Get MassGIS Data

Notes: [a]USGS – United States Geological Survey; FEMA – Federal Emergency Management Agency; NYS – New York State; OMNRF – Ontario Ministry of Natural Resources and Forests; DAENR – Department of Agriculture, Energy and Natural Resources.

in Figure 3 for an area near Altona, New York. We also mapped beaches on the flanks of the Monteregian Hills in southern Quebec and in the eastern Champlain Lowland of Vermont, but mapping in these areas was limited to beaches near the upper marine limit (UML) of the Champlain Estuary.

Spatial coordinates and elevations were extracted from the endpoints and midpoint of each polyline segment using the ArcMap Data Management tools Add Surface Information and Add Geometry Attributes (Fig. 4). Ridge crest segments with >3 m relief along their length or >1 km in length were checked individually for continuity and accuracy. A subset of ridges, mostly in northeastern New York, was field verified.

Only beach ridges mapped on DEM images within the study area (Fig. 1) were used in statistical analyses. Beach ridges mapped outside the study area as well as strandline data from Rayburn (2004) and Lewis et al. (2022) are presented for comparative purposes. Rayburn (2004) compiled strandline data from beaches and other features such as deltas, bars, terraces, and outlet elevations, for proglacial Lakes Iroquois, Coveville, and Fort Ann and the Champlain Sea in the Champlain and western St. Lawrence Lowlands (Table 1). Lewis et al. (2022) compiled spatial data for proglacial Lake Iroquois and the Champlain Sea. These authors selected data from previous investigations, including Rayburn (2004), collected by traditional surveying or differential global positioning methods to avoid elevation inaccuracies inherent with less-reliable aneroid barometer measurements and estimates made from topographic maps. Geographic coordinates of latitude and longitude reported by Lewis et al. (2022) were converted to UTM Zone 18N coordinates using the online National Geodetic Survey Coordinate Conversion and Transformation Tool (www.ngs.noaa.gov/NCAT/).

Lake Iroquois and Lake Abenaki are unique to the St. Lawrence and Champlain Lowlands, respectively, so beach ridge data, including previously published strandline data, were divided into St. Lawrence and Champlain subsets east and west of a north–south line that passes through Covey Hill at Easting 594790m (Fig. 4). The midpoint of each beach ridge segment was projected onto graphs of UTM Northing (abscissa) versus elevation (ordinate) along N–S elevation profiles: in the western St. Lawrence Lowland along Easting 522320m through Cornwall, Ontario, and another in the Champlain Lowland along Easting 626108m through Plattsburgh, New York (Fig. 4). The profile lines approximately bisect the St. Lawrence and Champlain datasets.

Previously reported isobase azimuths for proglacial lakes in the western St. Lawrence and Champlain Lowlands trend 90°–112° (Parent and Occhietti, 1999; Rayburn, 2004; Rayburn et al., 2005; Lewis et al., 2022), roughly perpendicular to the N–S elevation profiles. The vertical distribution of beaches facilitates correlation to known lake or marine phases (Fig. 4). All graphics and regression analyses for the profiles were performed using Microsoft Excel.

Isobase trend surfaces

A trend surface is a three-dimensional polynomial surface produced by least-squares regression that predicts the value of an observation, in this case beach ridge elevation, as a function of geographic coordinates (Davis, 2002). We used beach data within ∼2 m of well-defined water planes from the N-S profiles. First- and second-order trend surfaces were fit to beach ridge data to assess the magnitude and direction of postglacial uplift. The analyses were conducted using trend surface tools in R Studio v. 4.2.2.

Results

Beach ridge morphology and distribution

The morphology and distribution of beach ridges are complex functions of atmospheric variables (wind speed, wind direction, and fetch); shoreline physiography (slope, aspect, and paleobathymetry); thickness, texture, and composition of surface materials; sediment supply; and rate of shoreline regression. Beach ridges in the study area occur individually or as offlapping groups of closely spaced, subparallel, curvilinear ridges. More than 19,500 beach ridge segments were identified in the study area, across the St. Lawrence and Champlain Lowlands in northeastern New York and adjacent Quebec south of the St. Lawrence River and UTM 18N Northing 5000000 m (Fig. 4, Supplementary Data). The region north of this latitude lies below the UML where, except for the flanks of the Monteregian Hills, the St. Lawrence Lowland is covered by marine or lacustrine mud or younger eolian dune sand.

Beach ridge segments range in length from a few tens of meters to ∼1 km (average ∼250 m) and in width from a few meters to ∼20 m. Relief along individual ridge crests averages about 1.5 m. Published field descriptions report that most ridges are composed of pebble to cobble gravel, sandy gravel, and gravelly sand (Woodworth, 1905a, 1905b; Fairchild, 1919; Denny, 1967, 1970; LaSalle, 1985). Occasionally, beach deposits occur as thin <1-m-thick boulder to cobble lag underlain by till (Pair et al., 1988).

In map view, beach ridges occur in distinct bands separated by areas with few strandline features along the southern flank of the St. Lawrence Lowland and the western flank of the Champlain Lowland in New York (Fig. 4). A similar distribution is evident in N–S elevation profiles, which show beaches distributed in three groups of closely spaced points separated by vertical gaps with few points (Figs. 5 and 6). Beach ridge groups correlate with known elevations of proglacial lake and marine waterbodies in the published literature (Woodworth, 1905a, 1905b; Fairchild, 1919; Chapman,

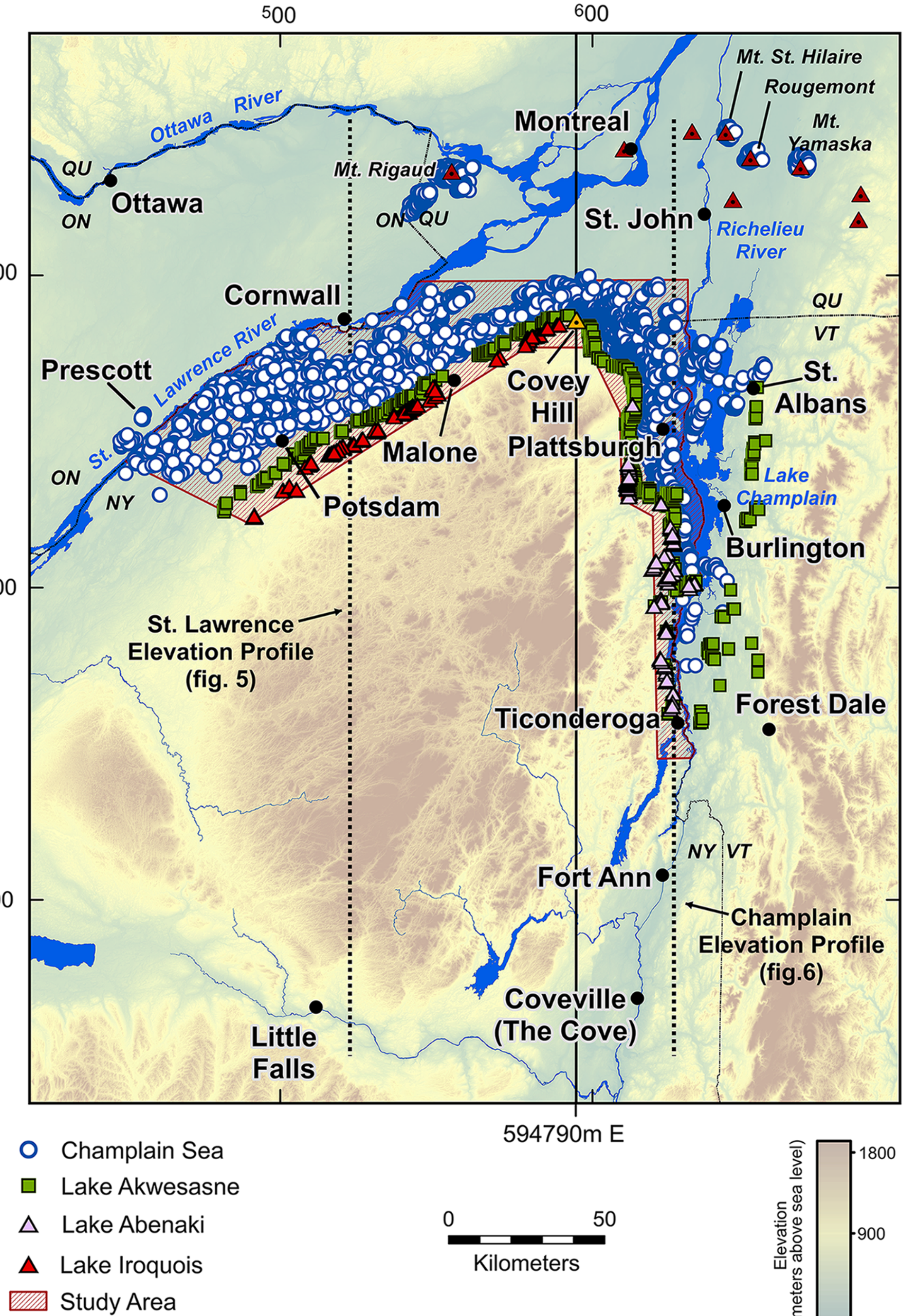

Figure 4. Locations of beach ridges mapped in this study. Also shown is the line used to divide the data into St. Lawrence (western) and Champlain (eastern) subsets (UTM 594790 m E) and the lines of cross section for Figs. 4 and 5. Most beaches formed in the Champlain Sea (88.5%), followed by Lake Fort Ann (10.1%), Lake Iroquois (1.3%), and Lake Coveville (0.1%).

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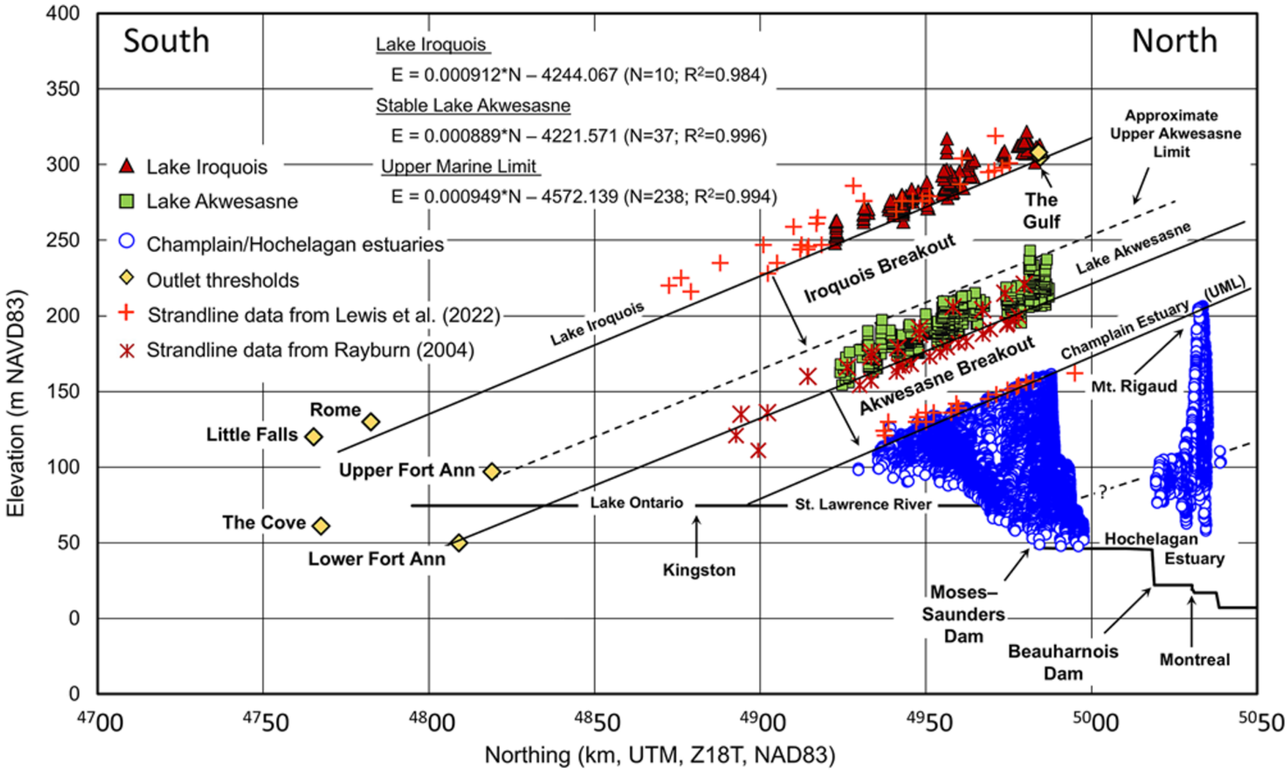

Figure 5. Plot of beach ridge midpoint elevations vs. UTM Northing for beach deposits and landforms in the St. Lawrence Valley. Beaches delineated in this study are represented by circles, triangles represent strandline data from Lewis et al. (2022) for the upper marine limit of the Champlain Estuary and Lake Iroquois, and squares represent upper and lower Lake Fort Ann (Akwesasne) strandlines from Rayburn (2004). Elevations of presumed outlet thresholds include Rome (Kozlowski, A., and Backhaus, K., personal communication, 2023), Little Falls (Bird and Kozlowski, 2016; Porecca et al., 2018), The Gulf near Covey Hill (this study, from digital elevation model [DEM]), upper Lake Fort Ann (Rayburn, 2004), lower Fort Ann (Rayburn, 2004), and the Cove at Coveville (this study, from DEM).

1937; MacClintock and Stewart, 1965; Wagner, 1972; Clark and Karrow, 1984; Muller and Prest, 1985; LaSalle, 1985; Parent and Occhietti, 1988, 1999; Pair et al., 1988; Pair and Rodrigues, 1993; Rayburn, 2004; Rayburn et al., 2011; Stanford, 2009; Bird and Kozlowski, 2016; Lewis et al., 2022).

The highest beach ridges in the St. Lawrence Lowland, depicted by red triangles in Figures 4 and 5, correlate with proglacial Lakes Iroquois and Frontenac (Table 1). The distribution of beach ridge elevations within this group does not provide evidence for differentiation into separate lake phases (Fig. 5). The well-defined lower boundary slopes southward at 0.91 m/km and projects northward to the elevation of The Gulf bedrock threshold southwest of Covey Hill (Fig. 5). The highest beaches in the Champlain Lowland, depicted by purple triangles in Figures 4 and 6, correlate with Lake Abenaki (Lake Coveville of Chapman [1937], Denny [1967, 1970, 1974], Rayburn [2004], Rayburn et al. [2005], and Franzi et al. [2007], and the unstable phase of Lake Albany of Stanford [2009]; Table 1). Lakes Iroquois and Abenaki were separated by the LIS where it straddled the St. Lawrence–Champlain drainage divide and blocked The Gulf outlet threshold (Franzi et al., 2016). The scarcity of beaches in Lakes Iroquois and Abenaki may reflect proximity to the ice sheet, which limited fetch, and the short time interval before ice recession exhumed The Gulf threshold and water levels in both lowlands dropped to the Lake Akwesasne level (Table 1).

The intermediate group of beach ridges, depicted by green squares in Figures 4–6, represents Lake Akwesasne, a lake phase that flooded the Ontario, St. Lawrence, and Champlain Lowlands. These beaches correlate with proglacial lakes variously named Vermont (Fort Ann Phase), Fort Ann, Candona, St. Lawrence, Sidney, Belleville, and Trenton from the published literature (Table 1). Water level fell rapidly, >70 m, during the Iroquois breakout to the Champlain Lowland, as evidenced by a lack of preserved beaches between the lowest Lake Iroquois and uppermost Lake Akwesasne beaches (Fig. 5). In the Champlain Lowland, beaches span the transition between Lake Abenaki and Lake Akwesasne (Fig. 6, Table 1), indicating a continuous, steady water-level decline unaffected by inflow of water from Lake Iroquois.

Gradual incision through newly emergent glacial and lacustrine deposits or bedrock on the Hudson–Champlain drainage divide south of Fort Ann, New York, and differential isostatic rebound may account for the steady water-level decline for both Lakes Abenaki and Akwesasne in the Champlain Lowland (Fig. 1, Table 1). The lower boundary of Lake Akwesasne projects southward between 0.89 and 0.92 m/km to the village of Fort Ann in both the St. Lawrence and Champlain Lowland profiles (Figs. 1, 5, and 6). This boundary corresponds to a relatively stable phase of Lake Akwesasne (Lake Fort Ann of Stanford [2009] and Rayburn et al. [2011]), when outlet incision slowed where it exhumed a bedrock threshold at Fort Ann (Fig. 1, Table 1).

The lowest set of beaches, depicted by blue circles in Figures 4–6, correlates with the Champlain Estuary in the St. Lawrence and Champlain Lowlands. The well-defined UML slopes southward between 0.89 and 0.95 m/km in the St. Lawrence and Champlain Lowlands (Figs. 5 and 6, Table 1). Water level fell rapidly, ~45 m, when Lake Akwesasne drained to the UML, as evidenced by

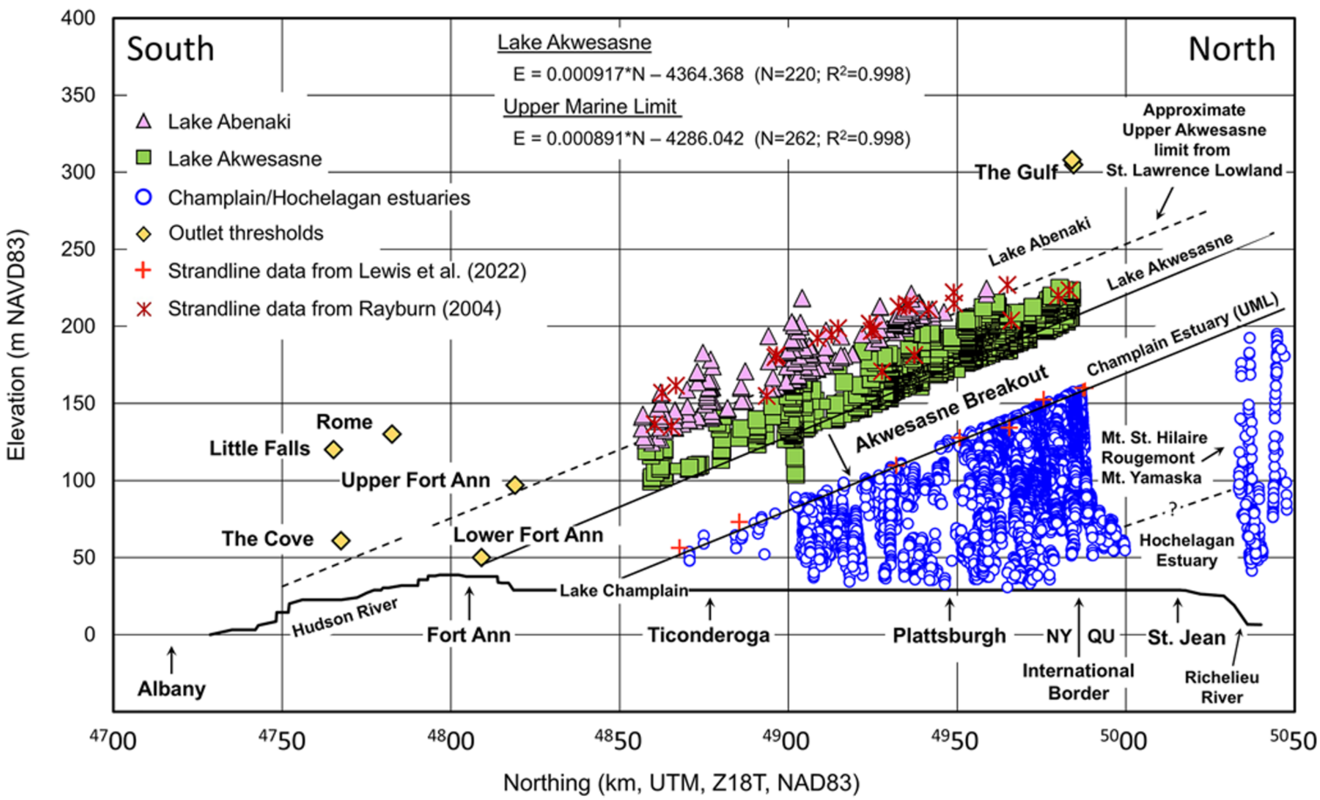

Figure 6. Plot of beach ridge midpoint elevations vs. UTM Northing for beach deposits and landforms in the Champlain Lowland in New York. Beaches delineated in this study are represented by circles, triangles represent strandline data from Lewis et al. (2022) for the upper marine limit, and squares represent Lake Coveville and upper and lower Lake Fort Ann strandlines from Rayburn (2004). Elevations of presumed outlet thresholds are the same as (Fig. 5).

the gap in beach preservation (Figs. 1, 5, and 6) between the lowest Akwesasne beaches and the UML. The UML projects northward in the St. Lawrence Lowland to the highest beaches on Mt. Rigaud in Quebec (Figs. 1 and 5) and projects above the highest beaches on Mt. St. Hilaire, Mount Yamaska, and Rougemont in the Monteregian Hills north of the Champlain Lowland (Figs. 1 and 6).

The abundance and close spacing of beaches below the UML (Figs. 5 and 6) record the forced regression of marine water in the St. Lawrence Lowland caused by the net effects of differential postglacial isostatic uplift and relative sea-level change. The Frontenac Arch (Figs. 1 and 2) emerged above sea level ~12.6 cal ka BP, and endorheic Lake Ontario became isolated in the Ontario Lowland (Lewis, 2016; Lewis and Todd, 2019) from the Hochelagan Estuary in the St. Lawrence Lowland (Parent and Occhietti, 1988; Lewis and Todd, 2019; Fig. 2E).

Regional isobases and glacial isostatic uplift

First- and second-order trend surfaces were fit to three water levels in N–S plots of beach midpoint elevations (Fig. 7). These levels represent Lake Iroquois, when outflow stabilized across The Gulf bedrock threshold near Covey Hill; the lowest phase of Lake Akwesasne, when the bedrock threshold near Fort Ann controlled outflow; and the UML of the Champlain Estuary. First-order trend surfaces adequately define the trends as indicated by their adjusted r^2 and the low values of the second-order regression coefficients (Table 3). Second-order trend surfaces nearly matched first-order trends and are not further described.

Isobases derived from the first-order trend surface for Lake Iroquois strike ESE (~119°) with 0.70 m/km gradient to the SSW (Fig. 7A). This trend differs >25° clockwise from Lake Akwesasne and UML isobases and may reflect regional or temporal patterns of postglacial rebound or limitations associated with a small sample size (n = 10) and limited spatial distribution of Lake Iroquois beaches. The Lake Iroquois isobase gradient is also lower than the gradient estimated from the N–S elevation profile for the western St. Lawrence Lowland (0.91 m/km; Fig. 5).

Isobases derived from the first-order trend surfaces for Lake Akwesasne (LA) and UML water levels are nearly identical in strike azimuth (LA = 90.0°; UML = 88.0°), with a gradient of ~0.92 m/km to the south (Fig. 7B and C, Table 3). These surfaces fit the observed data well (Table 3), reflecting large sample populations (LA = 196; UML n = 348) and widespread spatial distribution of beaches. The results compare well with previous studies of isostatic uplift in the region (Koteff and Larsen, 1989; Parent and Occhietti, 1999; Rayburn, 2004; Rayburn et al., 2011; Bird and Kozlowski, 2016; Hooke and Ridge, 2016; Lewis et al., 2022). The similarity of isobase azimuth and slope for the Akwesasne and UML surfaces probably reflects a short duration for drainage to occur and serves as a quality indicator for the beach ridge datasets.

Discussion

Beach ridges in the study area are most abundant in the northwestern Champlain Lowland and the southern flank of the St. Lawrence Lowland near Covey Hill (Fig. 4). These areas would have been exposed to the greatest fetch from prevailing northeasterly winds across the lake and marine water surfaces, generating high wave energy consistent with anticyclonic atmospheric conditions in the

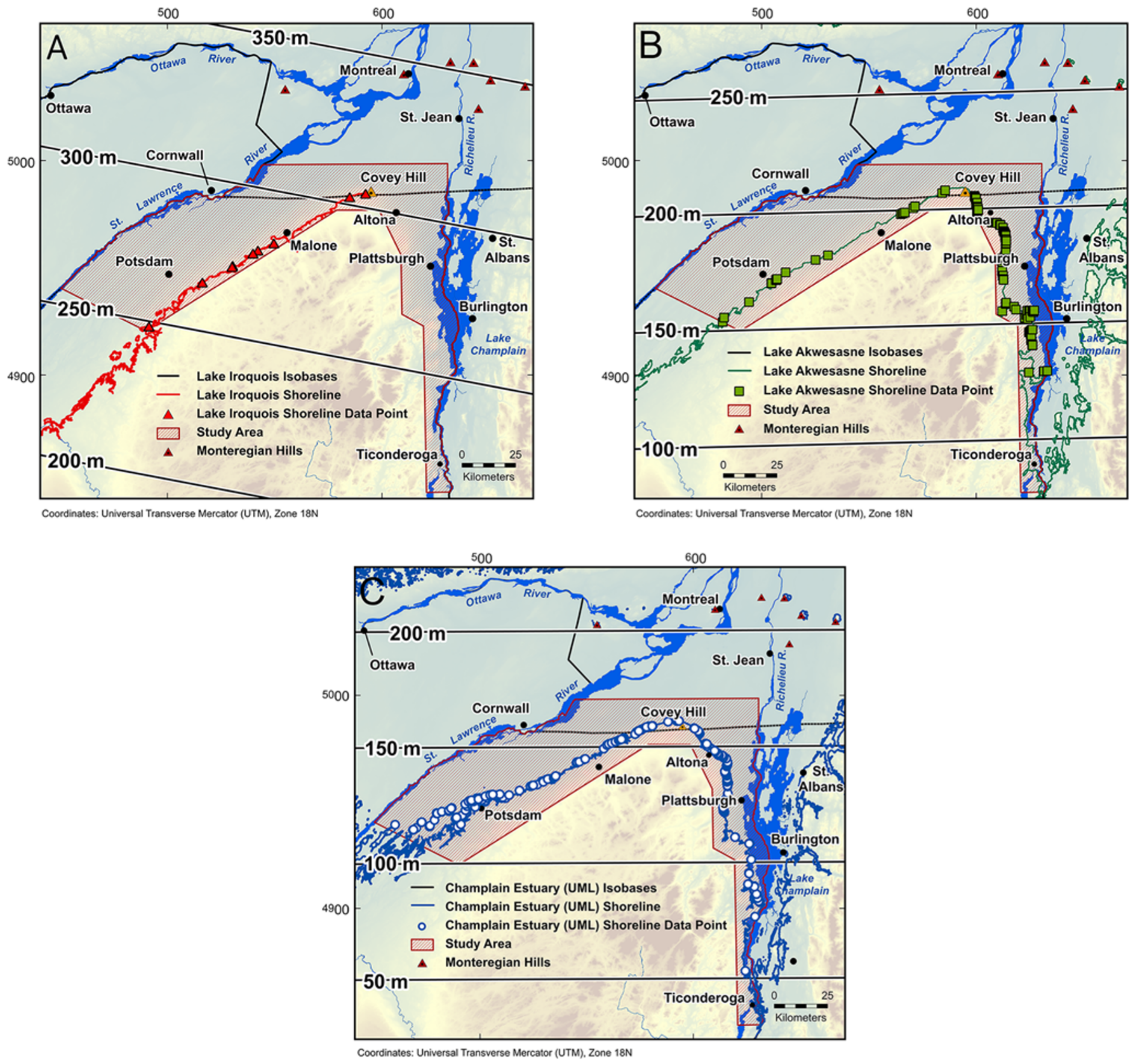

Figure 7. Isobases derived from first-order trend surfaces of beaches on (**A**) Lake Iroquois (The Gulf threshold), (**B**) Akwesasne (Fort Ann threshold), and (**C**) the upper marine limit of the Champlain Estuary in the St. Lawrence and Champlain Valleys.

late Pleistocene and Early Holocene. Similar conditions existed on the flanks of the Monteregian Hills. Postglacial dunes found in the St. Lawrence Lowland northeast of Montreal, Quebec (Filion, 1987; David, 1988) and northern New York (MacClintock and Stewart, 1965; Cadwell and Pair, 1991; Carlisle et al., 2015) probably formed under similar wind conditions soon after the Hochelagan Estuary regressed (Filion, 1987; David, 1988; Borracci et al., 2023; Carl et al., 2023; Table 1). The lack of widespread beaches in Vermont and the southern Champlain Valley reflects the wind shadow created by the high relief of the Green Mountain Upland to the east and narrowing of the Champlain Lowland to the south.

Beach ridges in the St. Lawrence and Champlain Lowlands occur in distinct groups separated spatially and vertically by areas with few strandline features (Figs. 4–6). Closely spaced points within a group represent times of steady, gradual net shoreline regression. Preservation of offlapping sequences of beach deposits occurred when shoreline regression disconnected older beach deposits from the upper limit of active shoreline processes. Abandonment at any given location probably occurred over a period of decades, given the short time frame for deglaciation in the region (Rayburn et al., 2011). Gaps between groups represent times of rapid water-level fall during breakout floods when there was insufficient time for beach ridges to form. The rate of water-level decline decelerated during the waning stages of a breakout as water levels in the source and receiving reservoirs equilibrated, allowing sufficient time for beach ridges to form.

No evidence for shoreline transgression, as might occur if ice readvanced over a lake outlet or sea-level rose, was found. Strandline deposits probably formed and reformed repeatedly along the shore during periods of steady water-level decline,

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Table 3. Regression coefficients and goodness-of-fit statistics for trend surfaces on stable Lake Iroquois (The Gulf threshold near Covey Hill), lower Lake Akwesasne (Fort Ann threshold), and Champlain Sea (upper marine limit), in the Ontario, western St. Lawrence, and Champlain Lowlands.

Lake Iroquois			
First-Order Trend Surface		Second-Order Trend Surface	
$b_0 =$	−3233.380	$b_0 =$	1.108E+07
$b_1 =$	0.000132	$b_1 =$	2.880
$b_2 =$	0.000694	$b_2 =$	−4.788
		$b_3 =$	1.854E−07
		$b_4 =$	−6.216E−07
		$b_5 =$	5.171E−07
Adjusted $R^2 =$	0.993	Adjusted $R^2 =$	0.990
	Sample Size (N):	10	
	Isobase Azimuth:	118.75°	
	Isobase Slope:	0.694 m/km Southwest	
Lake Akwesasne – Stable Phase			
First-Order Trend Surface		Second-Order Trend Surface	
$b_0 =$	−4383.653	$b_0 =$	−9595.6942
$b_1 =$	−2.256E−05	$b_1 =$	−0.0005782
$b_2 =$	0.000924	$b_2 =$	0.003109
		$b_3 =$	−1.913E−10
		$b_4 =$	1.561E−10
		$b_5 =$	−2.313E−10
Adjusted $R^2 =$	0.998	Adjusted $R^2 =$	0.998
	Sample Size (N):	196	
	Isobase Azimuth:	88.60°	
	Isobase Slope:	0.923 m/km South	
Champlain Sea – Upper Marine Limit			
First-Order Trend Surface		Second-Order Trend Surface	
$b_0 =$	−4417.874	$b_0 =$	−11934
$b_1 =$	−4.457E−06	$b_1 =$	0.003326
$b_2 =$	0.0009236	$b_2 =$	0.003567
		$b_3 =$	−1.896E−10
		$b_4 =$	−6.304E−10
		$b_5 =$	−2.306E−10
Adjusted $R^2 =$	0.997	Adjusted $R^2 =$	0.998
	Sample Size (N):	348	
	Isobase Azimuth:	89.97°	
	Isobase Slope:	0.924 m/km South	

preserving only regressive deposits as isostatic-rebound raised beaches above the level of active shorezone processes.

Proposed proglacial lake and marine nomenclature

Beach ridges record steady, gradual shoreline regression controlled by outlet incision and the net effects of differential isostatic uplift and postglacial relative sea-level change. Spatial analyses of beach deposits and landforms interpreted from DEM data demonstrate continuous progression of steadily falling water levels was interrupted by rapid water-level drops caused by breakout floods from Lake Iroquois, across the St. Lawrence–Champlain divide in northeastern New York (Figs. 8 and 9), and Lake Akwesasne in the Lake Chaudière–Etchemin area, Quebec (Occhietti et al., 2011). The revised nomenclature for the proglacial lake sequences presented here reflects new data and interpretations of strandline data (Fig. 10).

Lake Albany

We retain the name Lake Albany to include the stable and unstable lake phases largely confined to the Hudson Lowland (Stanford, 2009). The extent to which Lake Albany may have expanded into the Champlain Lowland remains uncertain. Fairchild (1919) considered the shoreline features presently assigned to Lakes Abenaki and Akwesasne to be part of an estuarine system open to the Atlantic Ocean in the lower Hudson Lowland. Stanford (2009) suggested that Lake Albany expanded northward to Altona, New York (Fig. 1) in the Champlain Lowland. However, Wall (2008) determined that Lake Albany drained to near the present grade of the Hudson River at the time the Iromohawk River began to cut the gorge below Cohoes Falls (Figs. 1 and 2). Proglacial lakes confined to the Champlain Lowland and controlled by outflow across the Hudson–Champlain divide must predate the Iroquois breakout by at least the time required to cut the Cohoes gorge. DeSimone and LaFleur (2008) and DeSimone et al. (2008) indicated that the ice margin may have stood at the Forest Dale delta in Vermont when Lake Albany fell sufficiently to expose older glacial and lacustrine deposits, or bedrock on the Hudson–Champlain divide near Fort Ann (Fig. 1), separating lakes in the upper Hudson and Champlain Lowlands. We consider it unlikely that Lake Albany expanded northward beyond the southern Champlain Lowland.

Lake Iroquois

Lake Iroquois drained through the Mohawk Lowland via the Iromohawk River (Fig. 2B) until ∼13 cal ka BP (Lewis and Todd, 2019; Lewis and Anderson, 2020; Lewis et al., 2022), when lower outlets emerged on the St. Lawrence–Champlain drainage divide near The Gulf, about 2.5 km southwest of Covey Hill, Quebec (Figs. 8 and 9). The highest bedrock channels on the northeastern flank of the Champlain Lowland (Fairchild, 1919; Denny, 1974) may have served as ephemeral outlets during the initial stages (Fig. 8). Outflow discharged southeastward along the ice margin to Lake Abenaki in the Champlain Lowland across deglaciated upland slopes southeast of Altona. Rapid discharge scoured surficial cover and created the Altona Flat Rock (AFR in Fig. 8) sandstone pavement (Woodworth, 1905a, 1905b; Denny, 1974; Rayburn et al., 2005; Franzi et al., 2007).

Beach ridge formation kept pace with water-level declines in the Champlain Lowland (Fig. 6), despite widespread geomorphic and sedimentological evidence for a high volume of water discharge during initial outflow of Lake Iroquois to the Champlain Lowland (Woodworth, 1905a, 1905b; Chapman, 1937; Denny, 1974; Franzi et al., 2002, 2007, 2016; Rayburn, 2004; Rayburn et al., 2005, 2011). Sandstone pavements between Covey Hill and Altona were mostly ice-covered during the initial flooding (Denny, 1974). Lake Iroquois beaches in the western St. Lawrence Lowland provide evidence for steady water-level decline during the initial event, with no distinction between a Lake Iroquois "Main Phase" and "Frontenac Phase" proposed by Pair and Rodrigues (1993; Fig. 5,

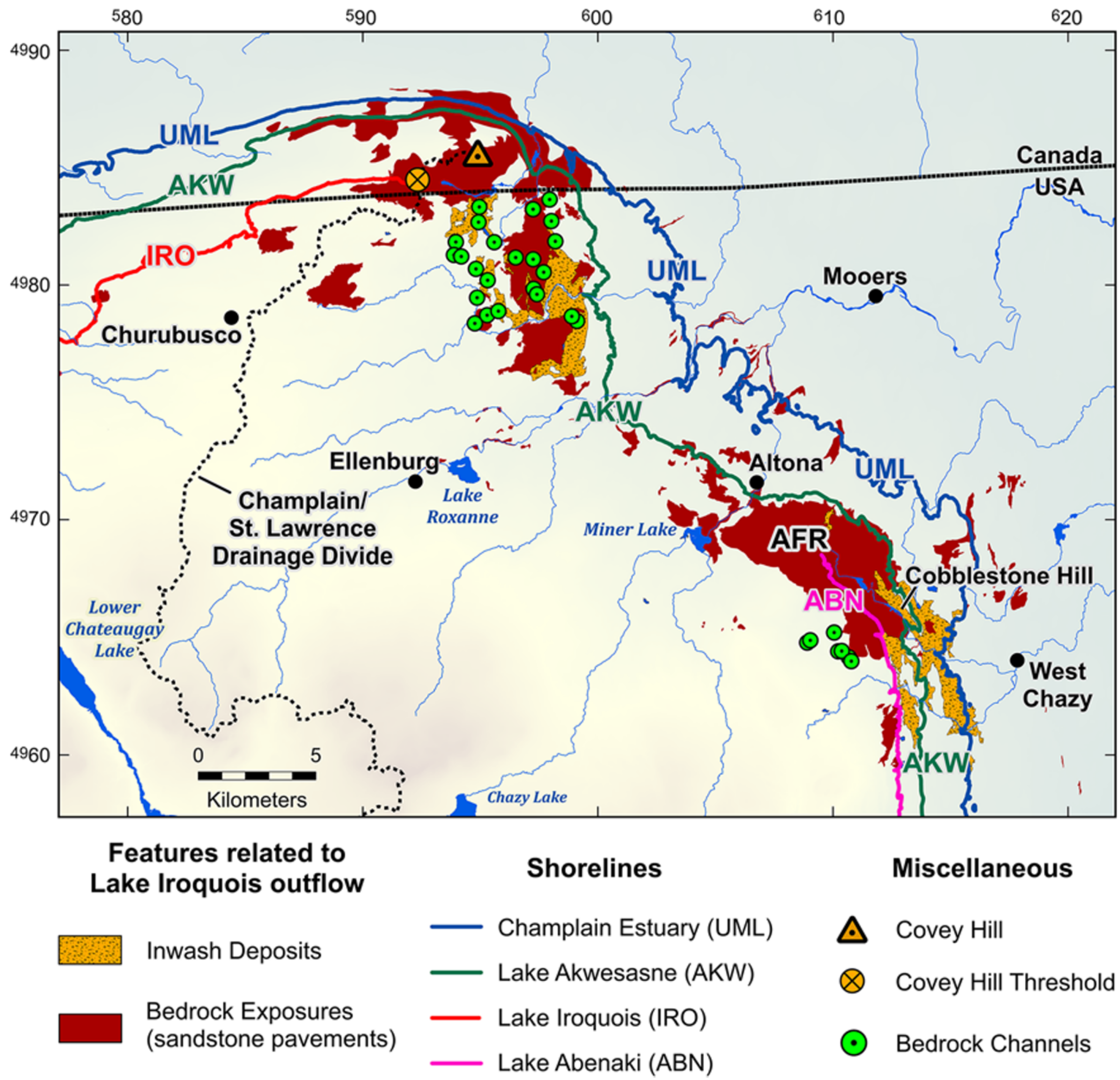

Figure 8. Surficial features of the Covey Hill area related to Lake Iroquois outflow in the Champlain Lowland and the shorelines of lakes Abenaki, Iroquois, and Akwesasne and the upper marine limit of the Champlain Estuary. The map is adapted from LaSalle (1985), Denny (1970, 1974), and Trevail (2006). The Altona Flat Rock sandstone pavement is labeled AFR.

Table 1). Steady water-level decline further indicates that the transition from the southern outlets of Lake Iroquois in the western Mohawk Lowland to northern outlets near Covey Hill did not involve an abrupt change in water level in the St. Lawrence Lowland as previously proposed (Rayburn et al., 2005; Franzi et al., 2007).

Lake Iroquois stabilized for several decades (Franzi et al., 2007; Rayburn et al., 2011) at The Gulf bedrock threshold until further ice recession on the north slope of Covey Hill caused catastrophic breakout of the remaining impounded water to the Champlain Lowland. Outflow around the northern flank of Covey Hill created large sandstone pavements across nearly flat-lying sedimentary rocks north and southeast of Covey Hill (Denny, 1974; Rayburn et al., 2005; Franzi et al., 2007; Fig. 8). Proglacial lake level fell >70 m during the event (Figs. 5 and 9). The absence of beaches between the lowest Lake Iroquois and highest Lake Akwesasne level in the western St. Lawrence Lowland (Fig. 5) indicates a rapid drop in water level. As water levels equilibrated, beaches began forming along the shore of Lake Akwesasne, a lake that spanned the Ontario, western St. Lawrence, and Champlain Lowlands.

Lake Abenaki

Proglacial Lake Abenaki (Abenaki: "dawn-land people"; Snow, 2012) formed in the Champlain Lowland after the Hudson–Champlain divide emerged near Coveville, New York (Figs. 1, 2B, and 10). The lake is named for the indigenous Algonquin-speaking people who lived in southern Quebec and northern New England. The name Abenaki replaces the names Lake Vermont (Coveville Stage), Lake Coveville, and the northern portion of the unstable phase of Lake Albany (ULA) (Stanford, 2009; Table 1) in the Champlain Lowlands. Lake Abenaki differs from Lake Vermont (Woodworth, 1905a; Chapman, 1937) in that the lake was confined to the Champlain Lowland for its entire existence and does not include the Fort Ann Stage of Woodworth (1905a) and Chapman (1937), which extended into the western St. Lawrence Lowland, nor does it include unstable Lake Albany phases that may have straddled the Hudson–Champlain divide in the southern Champlain Lowland (Stanford, 2009). Beaches formed on the shore of Lake Abenaki in the Champlain Lowland were previously attributed to Lake Coveville (Woodworth, 1905a,

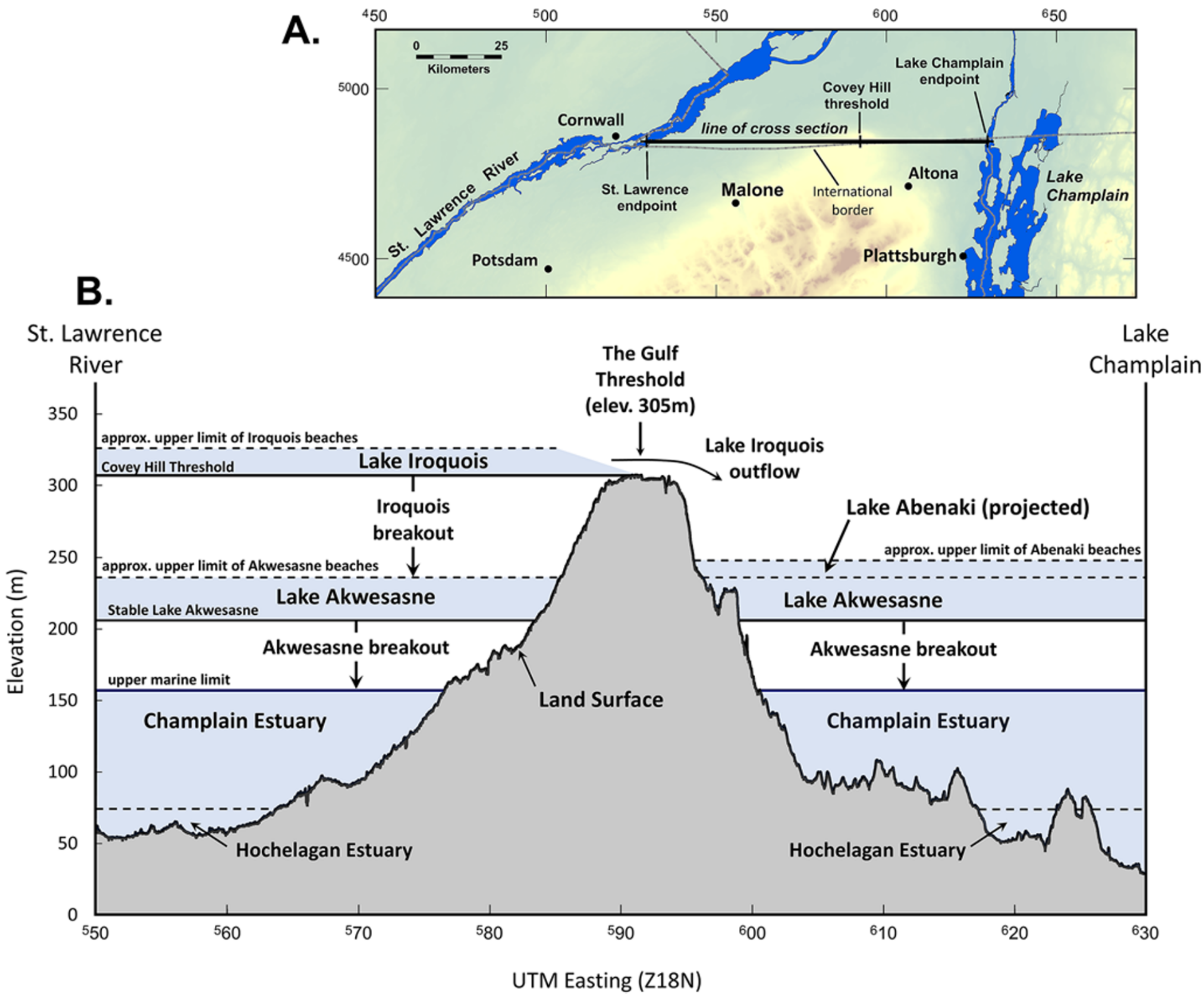

Figure 9. East–west topographic profile between the St. Lawrence River and Lake Champlain through The Gulf threshold near Covey Hill showing late Pleistocene proglacial lake and marine water levels. The transect follows UTM Northing 4984486 m N (UTM Z18N). Vertical exaggeration ~110×.

1905b; Chapman, 1937; Denny, 1967, 1970, 1974; Franzi et al., 2002, 2007; Rayburn, 2004; Rayburn et al., 2005).

Lake Abenaki drained southward across emergent glacial and lacustrine deposits or bedrock on the Hudson–Champlain divide. The close spacing of Abenaki beaches (Fig. 6) indicates shorelines adjusted continuously in response to outlet incision and differential isostatic rebound. The lake expanded northward ~105 km to the latitude of Altona, New York (Figs. 1 and 8), at which point the lake received discharge from Lake Iroquois. Bouldery inwash deposits on Cobblestone Hill, located at the SE margin of Altona Flat Rock, accumulated where the Iroquois floodwater entered Lake Abenaki (Franzi et al., 2002, 2007; Rayburn, 2004; Rayburn et al., 2005; Fig. 8). The inwash deposits range in present-day elevation between 230 and 205 m, indicating that Lake Abenaki water level fell to near the level of Lake Akwesasne while the ice margin stood at Cobblestone Hill. Lake Abenaki ended when ice receded from the northern flank of Covey Hill and water in the Ontario, western St. Lawrence, and Champlain Lowlands merged to form Lake Akwesasne (Figs. 2C and 8–10).

Franzi et al. (2007) reported ice recession rates in the northern Champlain Lowland range between 0.19 and 0.44 km/yr (mean = 0.32 km/yr). Connally and Sirkin (1973), Ridge et al. (2012), and Wright et al. (2024) similarly report recession rates of ~0.3 km/yr in the northern Champlain Lowland, Lake Hitchcock in the Connecticut Valley, and Lake Winooski in western Vermont, respectively. We infer that Lake Abenaki existed in the Champlain Lowland for ~340 yr, assuming ice recession of 105 km at an average rate of 0.31 km/yr.

Lake Akwesasne

Proglacial Lake Akwesasne ("land where the grouse drum"; Klemp, 2022) occupied the Ontario, western St. Lawrence, and Champlain Lowlands following the Lake Iroquois breakout. The lake is named after the St. Regis Mohawk tribal land in northern New York, southeastern Ontario, and southwestern Quebec that straddles the U.S.–Canada international border. Lake Akwesasne replaces Lake St. Lawrence, Lake Candona, the Frontenac, Sydney,

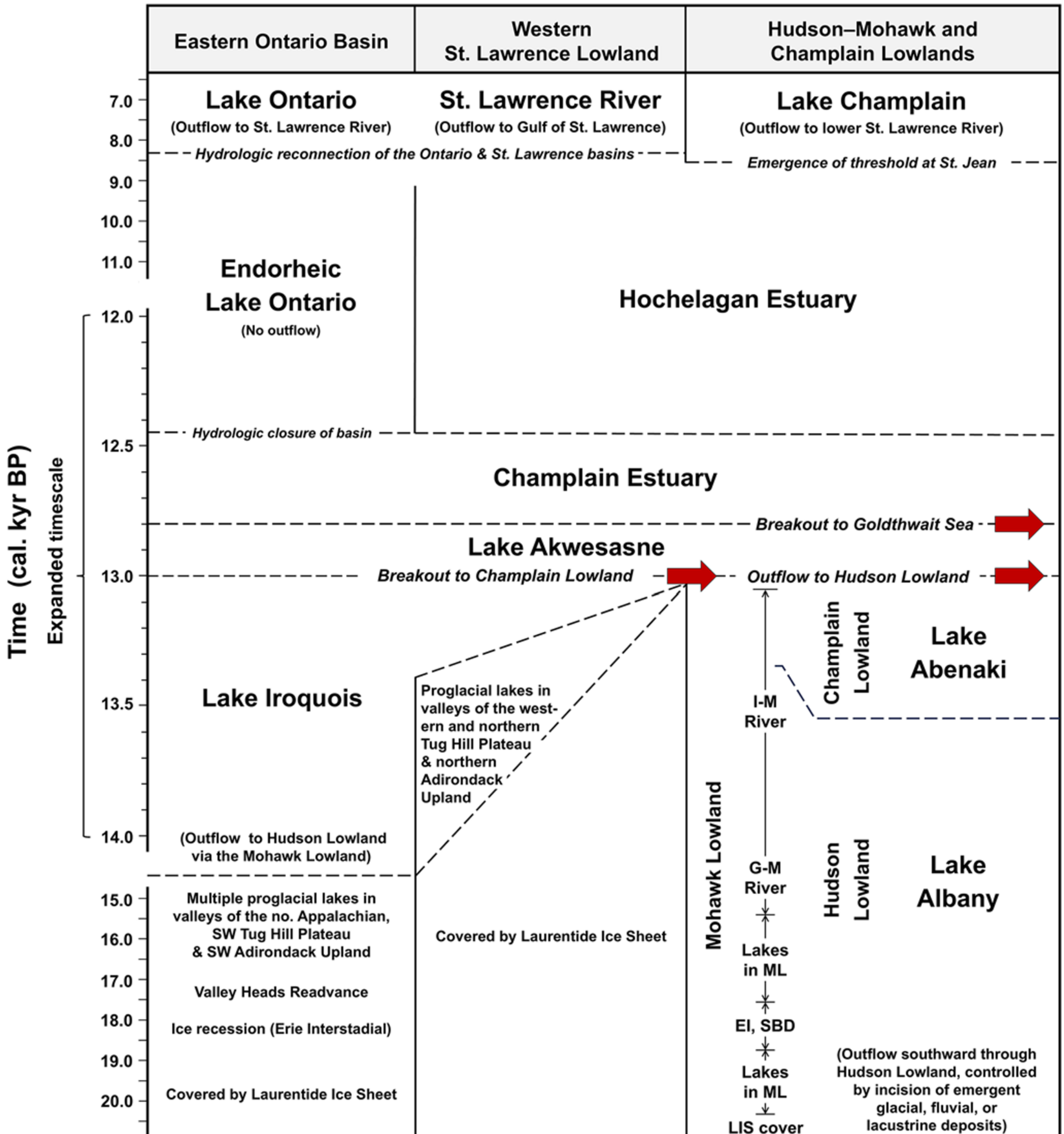

Figure 10. New proglacial lake nomenclature for the eastern Ontario, western St. Lawrence, and Hudson–Mohawk–Champlain Lowlands. Abbreviations: ML, Mohawk Lowland; EI, Erie Interstade; SBD, Shed Brook Discontinuity; G–M, Glaciomohawk; I–M Iromohawk River. Principal sources: Muller and Prest (1985), Muller and Calkin (1993), Parent and Occhietti (1988), Occhietti et al. (2011), Ridge et al. (1991, 2012), Ridge (1997, 2003, 2004), Ridge and Franzi (1992), Pair and Rodrigues (1993), Stanford (2009), Franzi et al. (2016), Lewis (2016), Lewis and Todd (2019), and Lewis et al. (2022).

Belleville, and Trenton phases of Lake Iroquois, and Lake Fort Ann (Fig. 10, Table 1).

Lake Akwesasne drained southward across emergent glacial and lacustrine deposits, and bedrock near the present Hudson–Champlain drainage divide near Fort Ann, New York. Lake Akwesasne water level fell gradually ~21–24 m before stabilizing briefly when the bedrock threshold near Fort Ann was exhumed. The lake existed for at least 216 yr (Rayburn et al., 2011), at which point ice recession in the Lake Chaudière–Etchemin area, Quebec (Occhietti et al., 2011) opened a connection to the Goldthwait Sea in the Gulf of St. Lawrence and the level of Lake Akwesasne dropped abruptly ~45 m to the UML of the Champlain Estuary (Figs. 5, 6, 9, and 10).

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Champlain and Hochelagan Estuaries

The Champlain Estuary inundated the Ontario, western St. Lawrence, and Champlain Lowlands and opened northeastward to the Atlantic Ocean via the Goldthwait Sea (Chapman, 1937; MacClintock and Stewart, 1965; Muller and Prest 1985; Occhietti et al., 2011; Figs. 2D, 9, and 10, Table 1). The highest beaches formed at the UML during the latter stages of the Akwesasne breakout. Widespread beach development in the western St. Lawrence and Champlain Lowlands below the UML records the forced regression of marine water. The Champlain Estuary phase ended when shoaling from isostatic rebound and relative sea-level change raised the Frontenac Arch and separated endorheic Lake Ontario (an internally drained lake phase) from the Hochelagan Estuary (Figs. 2E and 10).

Continued shoaling from isostatic rebound and freshwater inflow progressively decreased salinity in Hochelagan Estuary, freshening the western portion, previously known as Lake Lampsilis (Elson and Elson, 1959; Elson, 1962, 1988; Richard, 1978; Parent and Occhietti, 1988; Table 1). Lake Lampsilis was named for a genus of freshwater mussels found in sediments overlying marine deposits in the western St. Lawrence Lowland.

The Hochelagan Estuary is named for the Iroquois village Hochelaga, visited by Samuel de Champlain in 1535, at the confluence of the Ottawa and St. Lawrence Rivers near Montreal. The name is derived from the Iroquoian terms "beaver path" or "big rapids" (Gagné, 2013). Use of the name dates to Woodworth (1905a, p. 220), who proposed the name "Hochelagan formation" for the deposits of the marine incursion and the subepoch or stage during which they were deposited. Its use here is restricted to the estuarine conditions that were confined to the St. Lawrence and Champlain Lowlands following the separation of endorheic Lake Ontario and led to deposition of freshwater sediments in the Montreal area (Fig. 2E). The Hochelagan Estuary phase ended ~8.3 cal ka BP (Lewis and Todd, 2019) with the emergence of the western St. Lawrence Lowland and hydrologic reconnection to the Ontario Basin, establishing the modern drainage system (Fig. 10). Present-day Lake Champlain formed as postglacial isostatic rebound raised ground above sea level near St. Jean, forming a threshold that separated Lake Champlain from the Hochelagan Estuary.

Conclusion

The deglacial paradigm presented here underpins a new nomenclature for proglacial lake and marine succession in the Ontario, St. Lawrence, and Champlain Lowlands (Fig. 10). The new chronology and nomenclature clarify the spatial and temporal extents of deglacial waterbodies in the region. Shoreline regression in late Pleistocene to Early Holocene proglacial lakes and the Champlain and Hochelagan estuaries in Ontario, St. Lawrence, and Champlain Lowlands created offlapping strandline deposits and landforms. Beach ridges record steady, gradual shoreline regression interrupted by breakout floods from lakes Iroquois and Akwesasne. The names for proglacial lakes Iroquois and Albany are retained but redefined to conform to new data presented in this study. The names Lake Abenaki and Lake Akwesasne replace multiple names given to proglacial lakes in the Ontario, St. Lawrence, and Champlain Lowlands (Table 1). Contiguous Early Lake Ontario and Champlain Sea and later contiguous Lake Lampsilis and Champlain Sea are assigned the names Champlain Estuary and Hochelagan Estuary. The Lake Ontario Lowstand (Lewis and Todd, 2019) is renamed as endorheic Lake Ontario to reflect the internally drained basin the lake occupied (Fig. 10). The new proglacial lake designations provide a simplified, uniform nomenclature that considers abundant new beach ridge data, eliminates multiple and overlapping names by removing local naming conventions, and recognizes the indigenous peoples whose ancestral lands once lay beneath these glacial waters.

Supplementary material. The supplementary material for this article can be found at https://doi.org/10.1017/10.1017/qua.2025.15.

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Data availability statement. The beach data are available in the Supplementary Data File. GIS shapefiles are available upon request from the corresponding author.

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Competing interests statement. The authors declare that they have no known competing financial interests or personal relationships that influenced the research presented here.

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