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ORIGINAL PAPER

Spits formed in Glacial Lake Algonquin indicate strong easterly winds over the Laurentian Great Lakes during late Pleistocene

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Abstract We report on a unique, new dataset: 49 spits that formed in the various phases of Glacial Lake Algonquin in the northern Great Lakes region, between approximately 13,200 and 11,500 years BP. The spits, which are now subaerially exposed well above the level of the current Great Lakes, trail off from former Lake Algonquin islands and headlands. Several exceed 10 km in length. Steep, eroded headlands coupled with their coarse-textured sediments, suggest that spit development was driven by large waves and strong longshore currents. The lake's islands and exposed headlands are usually strongly eroded on their eastern margins. Additionally, spits within ≈150–200 km of the former ice margin, and especially the very large spits in northern Michigan, trail to the west, particularly the WNW and SW. Some small spits that lie farther south trail to the east, and others, within confined bays, better reflect the localized littoral circulation systems. Together, these features provide on-the-ground evidence for persistent, easterly, summertime winds in the late Pleistocene in the northern Great Lakes region, supporting paleoclimate models that show southeasterly to easterly air flows, originating from a glacial anticyclone above the Laurentide Ice Sheet. Our research suggests that strong, anticyclonically driven, easterly winds were a key part of the regional circulation within ≈150–200 km of the southern ice margin, while acknowledging that winds may have been more dominantly westerly at locations farther south. The latter conclusion reconciles with the record of loess transport and dune formation on westerly winds during this (and earlier) time periods in the south-central Great Lakes region and the Great Plains of North America.

Keywords Glacial Lake Algonquin · Relict spits · Glacial anticyclone · Paleoclimate · Erosional headlands · Isthmi, Isostatic rebound

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Introduction

Despite the general agreement among models of paleoclimate data (COHMAP 1988; Bartlein et al. 1998; Kutzbach et al. 1998), global and hemispheric circulation patterns during the late Pleistocene and early Holocene continue to be debated. The debate may be the result of the coarse spatial resolution of these models, or the general lack of ground truth data with which these models could be verified, modified, or refuted. Fortunately, some landforms and sediments, e.g., dunes and their bedforms, spatial patterns of loess deposits, spit orientations, ventifacts, and delta sedimentology, can provide important proxy data for paleoclimate, and especially paleowinds. Using these data, paleoclimate models can be evaluated more precisely.

Our goal is to map and provide morphologic data on spits formed in Glacial Lake Algonquin (GLA), and to use these data to inform paleoclimate models. GLA mostly maintained high levels in the Lake Michigan-Huron basin of the Great Lakes during its Kirkfield Algonquin to Main Algonquin phases between about 13,200 and 12,500 years BP (Eschman and Karrow 1985; Hansel et al. 1985). Some spits were likely also formed in the Post Algonquin lake phases between about 12,500 and 11,500 years BP.

Note that, in this paper, ages are reported in calibrated, calendar years before present (AD 1950) (BP); original radiocarbon dates are reported as ^{14}C BP. Radiocarbon calibrations follow Stuiver and Reimer (1993) and Reimer et al. (2013).

General background on Glacial Lake Algonquin

GLA formed as the ice margin of the Laurentide Ice Sheet withdrew northward, exposing the northern basins of the Laurentian Great Lakes (Karrow et al. 1975; Eschman and Karrow 1985). Records of high stages of GLA are well preserved as relict coastal features, mainly wave-cut bluffs.

Lake levels in GLA (Kirkfield Algonquin phase) were controlled initially by eastward drainage at a mid-lake position over sills of the Kirkfield–Fenelon Falls outlet (Fig. 1). During the next, or Main, Algonquin phase, ongoing isostatic uplift and basin tilt had eventually shifted lake drainage to southern outlets at Port Huron, Michigan, and possibly Chicago, Illinois. Soon thereafter, between approximately 12,500 and 11,500 years BP, lower shorelines of the Post Algonquin phases were formed as the lake level dropped. This drainage occurred in a stepwise manner, as a series of lower outlets became exposed in the northeastern part of the lake (Harrison 1972; Eschman and Karrow 1985; Larson and Schaetzl 2001; Schaetzl et al. 2002; Karrow 2004; Heath and Karrow 2007). Later, high lake stands associated with the early Holocene Mattawa phases (Lewis and Anderson 2012) and the mid-Holocene Nipissing Great Lakes were unable to inundate any of the GLA spits studied here, partly due to isostatic rebound of the land surface (Larsen 1985; Lewis and Anderson 2012), allowing them to persist as subaerial features.

Most early work on this lake focused on shorelines and bluffs, rather than spits, because the main research thrust was on identifying lake levels and outlets (Goldthwait 1910; Stanley 1936; 1937; Deane 1950; Cronin 1984); few interpretations of directions of longshore drift or paleoclimate were offered in these publications. Contemporary, detailed, data on topography and bathymetry, coupled with GIS software, have allowed researchers to more easily identify landforms such as spits and other coastal features, and to also quantify their extents and dimensions. Spits provide excellent proxy information for paleowinds and longshore drift because they form slowly and integrate wind-driven waves and sediment transport over long periods of time (Krist and Schaetzl 2001; Jewell 2007). In this paper, we map 49 spits in GLA and evaluate the morphologic data they present, to shed light on modeled paleoclimate data for the late Pleistocene wind regimes of the Great Lakes region.

Background on paleoclimate

The concept of a glacial anticyclone with its clockwise atmospheric rotation was introduced by Hobbs (1943) and made more widely known by Bryson and Wendland (1967). Based on dune orientations in Saskatchewan, Canada, the anticyclone model found on-the-ground, geomorphic support (David 1981). Subsequent simulations from atmospheric general circulation models corroborated and clarified the concept, making it a viable source of potentially strong, easterly winds near the ice sheet's southern margin that may have persisted until as late as 9000 years BP in the Midwest United States (COHMAP 1988). Bromwich et al. (2004) described well-defined anticyclonic, ice sheet drainage (katabatic) winds, and the anticyclone as being well established over the Laurentide Ice Sheet during January, with mean near-surface wind speeds >14 m s^{-1} (>50 km h^{-1}) along the ice sheet margin.

Questions remain about the strength, persistence, seasonality and geographic extent of the winds near and beyond the retreating ice margin, especially in summer when seasonal ice cover would have been

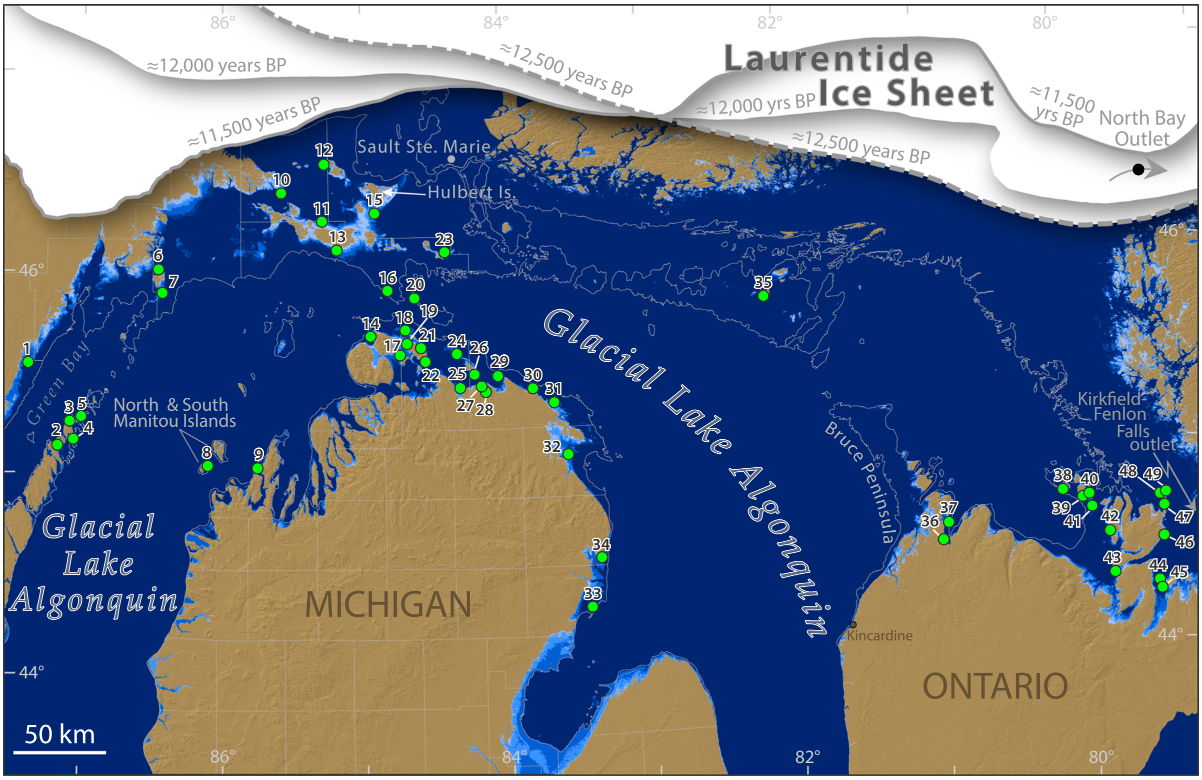

Fig. 1 Map of Glacial Lake Algonquin north of 43.5° latitude. Different water planes, associated with lower lake stages, are shown in progressively *darker shades of blue*. *Brown areas* were dry land at even the highest lake stage. Current topography shows through as a hillshade. The Kirkfield to Main Algonquin phases drained eastward from about 13,200 to 12,500 years BP by the Kirkfield–Fenelon Falls outlet shown at the eastern *edge* of the *map*. The isobase through this outlet trended west-northwest (290°). Lake waters transgressed their shorelines south of this isobase as regional glacioisostatic uplift tilted the lake basin southward, while north of the isobase uplift tilted the basin upward and the lake regressed from the landscape where it had been uncovered by ice. Later phases of the Post Algonquin series of lakes drained by a set a progressively lower outlets in the North Bay region between about 12,500 and 11,500 years BP. The southerly position of the ice margin for 11,500 years BP in the west reflects the post-Main Algonquin Marquette readvance of ice in the Lake Superior basin. (Color figure online)

minimal. At 12,000 years BP, the general circulation model of Bartlein et al. (1998) suggested a glacial anticyclone mainly in July, but Bromwich et al. (2004) argued that the anticyclone south of Hudson Bay in July at the Laurentide Glacial Maximum was "poorly defined." Indeed, most models have the glacial anticyclone as stronger in winter. Atmospheric general circulation models also vary in their predictions of persistent easterly flow versus a less pronounced and more seasonally variable easterly flow, with westerly flow returning in the winter. Mason et al. (2011) contended that the modeled anticyclonic winds occurred mainly over the ice sheet, with northeasterly to northerly winds at its southern margin.

Although geomorphic data have the potential to resolve these questions, they have at times been somewhat contradictory (Voelker et al. 2015). For example, evidence from Midwestern US loess and dune deposits point to westerly and northwesterly winds at the time of GLA or slightly before (Muhs and Bettis 2000; Mason et al. 2011; Schaetzl et al. 2014; Arbogast et al. 2015), making it difficult to reconcile the modeled glacial anticyclone, which Muhs and Bettis (2000) agree was a robust feature of the paleoclimate at full-glacial time, with the geomorphic record. Muhs and Bettis (2000) pointed to loess thicknesses that decrease over short distances to the west of the major Midwestern rivers as evidence for only infrequent and weak easterly winds at these latitudes. They reconciled the anticyclone with the loess record by suggesting loess transport on infrequent but strong winds from the NW, intermixed with weaker winds from the NE, possibly derived from the glacial anticyclone. Importantly, they rejected the notion that the easterly winds from the anticyclone were restricted to a narrow band near the ice margin, with westerly winds farther out. It is worth noting that most of the loess data come from sites that are hundreds of km south of the ice margin at the time of deposition, allowing for the possibility that easterly winds could have dominated, or at least been more prevalent, nearer the ice (Krist and Schaetzl 2001; Luehmann et al. 2013; Schaetzl and Attig 2013).

Work on sand dune orientations in the central Great Lakes region for the period 14,000–10,000 years BP provide additional data for westerly winds at a distance from the ice margin, during the latest Pleistocene. Dunes in central Lower Michigan—only about 200–250 km south of the ice margin—suggest that westerly and northwesterly winds were dominant here between 13,000 and 10,000 years BP (Arbogast et al. 2015). Dunes in central Wisconsin, slightly farther from the ice margin, were also formed on westerly winds. These dunes formed between 14,000 and 10,000 years BP (Rawling et al. 2008).

Alternatively, a considerable body of geomorphic data appears to support the existence of easterly winds in areas near the ice margin, probably driven by an anticyclonic circulation pattern that developed on it. In general, these winds usually are associated with, or strengthened by, katabatic processes. For example, dunes in western Canada, within about 200 km of the former ice margin, formed on southeasterly winds, while farther away from the ice northwesterly winds were dominant (Fisher 1996; Wolfe et al. 2004). Dunes on the Algonquin plain in Ontario appear to have formed on northeasterly winds, although the exact age of these dunes is unclear (To et al. 2015). Nonetheless, dunes on younger surfaces in the same region are oriented such that they likely formed on northwesterly winds. Dune orientations in other locations in eastern Canada indicate that anticyclonic winds near the ice margin were replaced by winds from the NW as the margin retreated (Filion 1987; David 1988). On the Columbia Plateau from 35,000 to 15,000 years BP, Sweeney et al. (2004) concluded that the modeled easterly wind anomaly did exist there as well, but mainly as weakened westerlies. Thorson and Schile (1995) reported that ventifact-bearing cover sands, lacustrine spits, and fluted bedrock outcrops formed in southern New England, prior to 12,400 years BP, were due to a strong, summertime, anticyclonic circulation, strengthened by katabatic outflow. They argued that these winds were in existence for up to 150 km from the ice margin. Other work on soils and landforms within 200–300 km of the former ice margin in New Jersey supports strong, cold, easterly and northeasterly winds in the immediate postglacial period (French and Demitroff 2001). Together, these studies suggest that easterly winds during at least the early stages of GLA were a major part of the paleocirculation, but may have been restricted to a narrow (<200 km wide) band near the ice margin.

Finally, we report on two, more localized, precursors to this study. Krist and Schaetzl (2001) studied six Algonquin-aged spits in northern Lower Michigan, all within $\approx$175 km of the former ice margin. These spits trail to the NW, from headlands and islands in the lake, suggesting that they formed due to high waves and currents driven by strong, easterly winds in summer coming from the anticyclone. Steep bluffs on the eastern and southeastern margins of the headlands and islands indicate pronounced erosion. In the vicinity of these spits, the northerly flowing Black River drained nearby uplands and debauched into GLA, forming a large, sandy delta. Sediment patterns within the delta, and a small spit near its head, both indicate strong waves and currents, driven by easterly winds (Vader et al. 2012).

The geomorphic data appear to be convincing—a glacial anticyclone did exist and where it did, it was strong enough to form large spits and dunes, and to erode whole flanks of islands. Key to this argument—most of these landforms were formed in only a few centuries, as explained in following sections. This point speaks to the potential strength of the winds during the late Pleistocene in the study area, especially given that most of these lacustrine features could only have formed in the summer when the lake and subaerial surfaces were unfrozen.

There is much that we still do not know about the glacial anticyclone. Did strong easterly winds derive from it, or was the easterly wind anomaly depicted in atmospheric general circulation models simply a weakening of the westerlies? What was the extent of its influence beyond the ice margin? In answer to these questions, we observe that data remain absent from key areas along the former ice margin, particularly east and west of the northern Lower Michigan spits. In our study, we expand upon the Krist and Schaetzl (2001) data set and in so doing, address these scientific deficiencies.

Study area, including a history of Glacial Lake Algonquin

Our study area spans northern Lower Michigan, the eastern Upper Peninsula of Michigan, and parts of southern and western Ontario (Fig. 1), where, between 13,200 and 11,500 years BP all three phases of Glacial Lake Algonquin inundated parts of what are now the Lake Michigan, Lake Huron including Georgian Bay, and southeastern Lake Superior basins. Due to isostatic depression, the lake spilled considerable distances onto the surrounding uplands. During the Post Algonquin phase, as lower outlets were successively uncovered during ice recession, lake levels dropped in discrete stages, until a very low outlet was uncovered near North Bay, Ontario (Harrison 1972; Karrow 2004; Drzyzga et al. 2012; Fig. 1). Thus, spits that formed in the lake, and wave-cut bluffs that developed on its margins, often have stepped or terraced edges, reflecting the incremental drops in lake level (Schaetzl et al. 2002). Opening of the North Bay outlet and the presumed dry climate at this time allowed the water plane to drop between 109 and 188 m (depending on the basin) to extremely low levels, even forming isolated basins of interior drainage (Edwards et al. 1996; Rea et al. 1994a, b; Lewis et al. 2005, 2008a, b). Subsequent isostatic rebound of the outlets did not raise the water levels to the previous levels of Main Lake Algonquin or the higher levels of the Post Algonquin phase studied here (Larson and Schaetzl 2001). Thus, the coastal Algonquin landforms in our study remain today as excellent geomorphic indicators of the littoral system during this time.

Glacial Lake Algonquin is not well dated, although the ages of several of its phases are well established in a relative sense. The earliest (Kirkfield) Algonquin phase in the Lake Michigan and Lake Huron-Georgian Bay basins came into existence about 11,300 ^{14}C BP (13,200 years BP), when the retreating ice opened straits between these basins and exposed the Kirkfield–Fenelon Falls outlet to the east, into the Trent River valley and then on to the Ontario basin (Eschman and Karrow 1985; Karrow et al. 1995). Discharge continued via this route until drainage was (possibly) shared with southern outlets at Port Huron, Michigan, and Chicago, Illinois. These southern outlets came into play because of differential uplift of the Kirkfield–Fenelon Falls outlet, during the Main Lake Algonquin phase, which occurred at about 10,500 ^{14}C BP (12,500 years BP) (Karrow et al. 1975; Karrow 1986; Anderson 1979). After this time, outlets opened in the North Bay region of Ontario, initiating the Post Algonquin series of lake phases (Eschman and Karrow 1985). Studies of small, isolated basins, associated with Main Algonquin coastal features farther north in the Lake Algonquin region, have generally confirmed the Main Algonquin age determinations (Futyma and Miller 1986; Futyma pers. comm. 1988).

Except where it bordered the retreating ice sheet, the maximum geographic extent of GLA is well constrained because the Main Algonquin shoreline is a clearly expressed coastal feature. It was first named by Spencer (1889) and extensively surveyed by Goldthwait (1907, 1910) and others to the north (Taylor 1895; Leverett and Taylor 1915; Cowan 1985; Karrow 1987; Schaetzl et al. 2002; Drzyzga 2007; Drzyzga et al. 2012; Blewett et al. 2014). Owing to glacial isostatic adjustment, the Main Algonquin shoreline now rises from 184 m above sea level in the southern Huron basin to about 310 m at Sault Ste. Marie, Ontario, and on the northeastern sector of Manitoulin Island, Ontario (Cowan 1985; Heath and Karrow 2007).

As the ice margin continued to retreat, a series of outlets opened in the North Bay, Ontario area, between northern Georgian Bay and the Ottawa River valley (Chapman 1954; Harrison 1972; Ford and Geddes 1986). Flow through these outlets dropped lake waters step-wise, as recorded in nine, progressively lower, Post-Algonquin phases, formally recognized by Stanley (1936), Deane (1950), and Hough (1958). This stepwise drop ended around 10,000 ^{14}C BP (11,500 years BP), when the lake drained through the North Bay outlet (Karrow et al. 1975). Some of the Post-Algonquin shorelines occur as far north as the Sudbury (Ontario) Basin, about 75 km north of Georgian Bay (Heath and Karrow 2007) and in the North Bay area (Karrow 2004). Thus, the entire series of lake levels from Main Algonquin (ca. 12,500 years BP) to the lowest of the Post-Algonquin lakes (approximately 11,500 years BP) was formed and abandoned in about 1000 years, and the average existence of any one phase of the nine recognized GLA levels was on the order of a century. At present, however, no precise dates or durations have been reported for any of the individual, post-Algonquin lake phases.

Materials and methods

Spits were first mapped and visualized in ArcGIS 10.1 (ESRI, Redlands, CA) and later corroborated in the field, following the methods of Jewell (2007). In the GIS, we overlaid flooded, partially transparent, water surfaces, representing the various stages of Lake Algonquin, onto a hillshaded, digital elevation model (DEM) that had been adjusted for post-Algonquin isostatic rebound. Contemporary DEM data were obtained from the 30-m resolution National Elevation Dataset (Gesch et al. 2009) and the 1:50,000-scale Canadian Digital Elevation Data (CDED 2010). CDED data were resampled to a 30-m resolution because the original resolution varies from 0.75 to 3 arcsec.

We created a DEM depicting the late Pleistocene landscape by subtracting an isostatic response surface from the DEM of the modern landscape. The response surface was constructed by using a digital version of the rebound isolines depicted in Lewis et al. (2005). Using positional and elevation data collected along the Lake Algonquin shoreline (Drzyzga et al. 2012; Finamore 1985; Kaszycki 1985), we adjusted and added supplemental isolines to the original data provided by Lewis et al. (2005). We then linearly interpolated a 30-m surface from the isolines using the Contour Gridder extension for ESRI's ArcView 3.x (Stuckens 2004), thereby ensuring that the final surface is smooth and not stepped. This surface was taken to represent the amount of isostatic rebound that has occurred since the demise of Main Lake Algonquin at about 12,500 years BP. Elevations on the rebound-adjusted DEM were also broken into classes to mimic the upper levels of the Post Algonquin phase below Main Algonquin, which also facilitated the identification of spits (Fig. 1).

Although the location of the ice margin at the time of GLA is only generally known, we assumed that a relatively early stage of GLA coincided with the formation of the Munising moraine in the eastern Upper Peninsula of Michigan before the ice retreated (Blewett et al. 2014; Fig. 1). Thus, when we mapped the extent of the lake, we allowed it to expand into the eastern and southern Lake Superior basin at the Main Lake Algonquin phase (Dyke et al. 2003).

Morphologic, sedimentologic, and textural data were used to identify potential spits in the field. Morphologic data included hooks on the distal ends of spits (Ollerhead and Davidson-Arnott 1995), stepped and terraced edges, and evidence of erosion on the headland, opposite the spit. Where possible, we also examined spit stratigraphy, to check for imbrication, stratification, and on the ends of the spits, foreset bedding (Fig. 2). Likely spits were checked for soil and sediment texture using the GIS database, or in the field, to insure that they were composed of sorted sands and gravels, or in the case of some of the Ontario spits, shingle gravels, following Jewell (2007). Our approach was conservative; spits that were not obvious were excluded from further consideration, including two small spits from the original work of Krist and Schaetzl (2001), which at the time were viewed as questionable.

All spits that were visible from the GIS data and were confirmed in the field were then mapped, and their major morphological characteristics tabulated.

Results

Figure 1 shows most of the extent of Main Glacial Lake Algonquin and its associated lake stages. Our lake stage DEMs and levels nearly match those of Drzyzga et al. (2012), but with a wider extent. This figure also provides our best approximations of three ice marginal retreat locations that were present during GLA, using information from Dyke et al. (2003). These margin locations support the conclusion that the ice margin was at the Munising Moraine in Michigan's eastern Upper Peninsula during the early high lake stages, before receding farther north into the southeastern Lake Superior basin and then advancing late in the Post Algonquin period (Marquette advance) (Fig. 1; Farrand and Drexler 1985; Blewett and Rieck 1987; Dyke et al. 2003; Blewett et al. 2014). Farrand and Drexler (1985) placed the ice margin during Main Lake Algonquin about 80 km north of Sault Ste. Marie, Ontario. However, precise ice marginal locations east of the Munising Moraine are unclear, because the ice margin was probably subaqueous.

We identified 49 prominent spits that formed in various phases of GLA (Figs. 1, 3, 4; Table 1), all of which presumably formed in less than 1000 years. We believe that, with improved elevation data in the future, e.g., LiDAR surfaces, considerably more spits could be documented.

Fig. 2 Photos of spit sediments and sedimentology. See Table 1 and Fig. 1 for locations. **a** Looking to the south at foreset beds near the end of the large Ardtrea Island South spit, Ontario. **b**, **c** Looking to the north at weakly sorted sediment within the Auchinean spit on the Bruce Peninsula, Ontario, but showing rounded and imbricated limestone clasts. **d** Looking to the south at well-sorted and rounded sands and gravels in the Ocqueoc spit, northern Lower Michigan. This site is 7.4 km from the nearest headland, pointing to the strength of the currents that must have formed this feature. *Tape scale* in cms

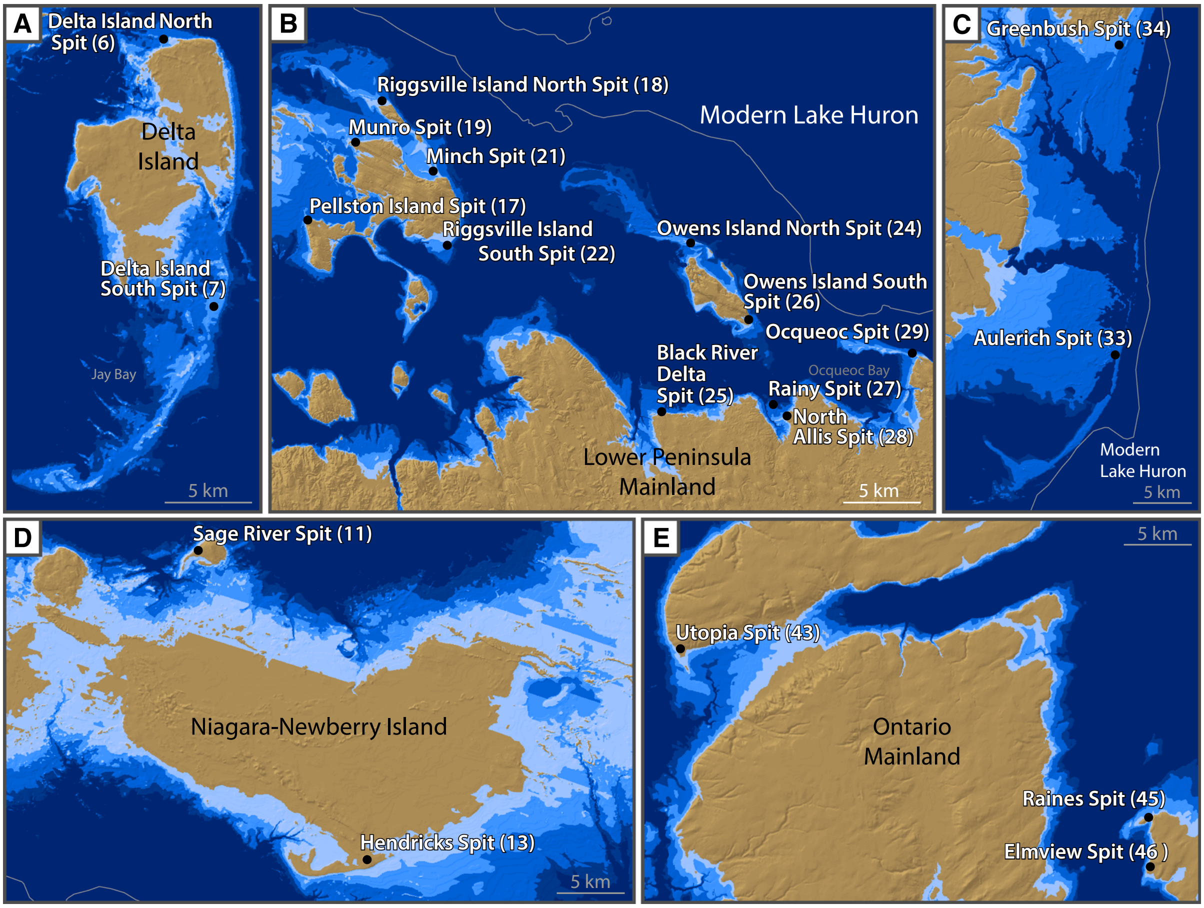

Fig. 3 Maps of five representative areas where spits are particularly well formed. As in Fig. 1, the different water planes, associated with lower lake stages, are shown in progressively *darker shades of blue*. *Brown areas* were dry land at even the highest lake stage. Note that several of these spits have hooks that trail to the west. (Color figure online)

Discussion

Paleoclimate data for this region and time period, which roughly coincides with the cold Younger Dryas period (12,900–11,700 years BP), generally indicate near glacial conditions. Both terrestrial and aquatic molluscan fauna from, or related to, Algonquin-age sediments indicate low summer air temperatures, and that lake surface waters were <3.6 °C. These cold conditions are generally attributed to the proglacial nature of Lake Algonquin (Miller et al. 1985).

Much of what is known is based on extrapolations of bioclimate relationships from sites considerably farther south or southeast of our study area, and much farther from the ice margin (Shane and Anderson 1993; Gonzales et al. 2009; Voelker et al. 2015). However, interpretation of two sites within the study area can help understand the study area's paleoclimate. First, Karrow et al. (1995) used a site near Clarksburg, Ontario, southwest of Georgian Bay, about mid-way between sites 35 and 42 (Fig. 1), to provide paleoclimate data for this period. They excavated a gravel beach bar of GLA to expose a lens of buried plant debris. This site is the northernmost and most deeply buried Lake Algonquin fossil site in Ontario. Plant macrofossil, pollen, mollusc, and ostracode data from this site served as bioclimatic indicators for the beginning period of Glacial Lake Algonquin, and indicated that the climate was colder than present by several degrees. A second site exists in northern Lower Michigan, <2 km south of the Main Algonquin shoreline (Schaetzl et al. 2013b). Here, pollen recovered from organic materials that were buried by sandy alluvium between 10,900 and

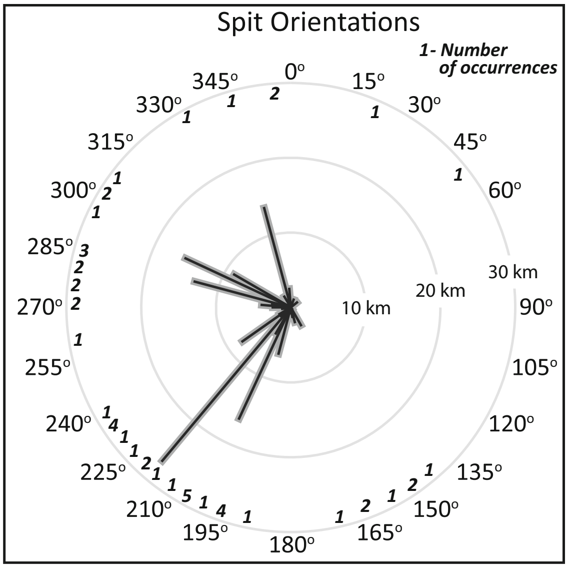

Fig. 4 Rose showing comparative spit lengths (n = 49), split into groups of 5° of compass orientation. *Line lengths* represent cumulative spit lengths where the "number of occurrences" is >1. Spit lengths were measured as the *straight line* distance from the head to the end of the spit, even if it had a curved end

10,300 years BP provide paleobotanical data for the millennium of post-GLA time. Pollen and plant macrofossil analyses suggested that, by this time, a tundra–boreal parkland had been established at the site. Earlier in time, when GLA was present in this area and when the spits were forming, the climate was almost certainly colder.

Thus, there is every reason to believe that the GLA region generally remained under a cold, glacial climate during its existence, as also shown in a climate reconstruction for southern Ontario using geochemical isotopic data (Edwards et al. 1996), rather than having warmed to interglacial conditions (Voelker et al. 2015). We therefore believe that GLA was likely frozen, at least partially, for much of the year.

Spit ages, or timespans of formation

Determining the precise ages of the spits was not the purpose of this study. Most spits are dateable by luminescence techniques (Ollerhead and Davidson-Arnott 1995), but these methods might only be able to provide a broad timespan for formation. We can, nonetheless, infer approximate chronological information by using constraints provided by the few radiocarbon dates available, viewed in conjunction with known information about glacial rebound. Relative lake level on the rebound isobase trending 290° through the Kirkfield–Fenelon Falls outlet (Fig. 1) would have been stable with respect to the surrounding land surface throughout the span of the Kirkfield Algonquin to Main Algonquin lake phases. Thus, coastal or other features that may have formed near the outlet isobase in association with the lake likely developed during the full span of this period, i.e., between 13,200 and 12,500 years BP, or over an approximate 700 year timespan. Sites offset from the outlet isobase would have experienced vertical water level movement relative to the local land surfaces, which would have shortened this time window. Lake levels would have transgressed the land surface southwest of the outlet isobase, and regressed from the land surface northeast of the isobase.

Paleocoastal features associated with Glacial Lake Algonquin are commonly found 2 m above or below the known and inferred Algonquin water planes (Stanley 1936; Deane 1950), suggesting that they formed during a specific lake phase or were formed during timespans when the relative water level changes were ±2 m. By dating estuarine and lagoon sediment sequences, Karrow et al. (1975) and Eschman and Karrow (1985) found that a 10 m rise of lake level 115 km southwest of the outlet isobase near Kincardine Ontario (Fig. 1) had resulted from uplift of the Kirkfield–Fenelon Falls outlet over its 700 year lifespan. Applying this 10 m rise at a distance of 115 km from the outlet isobase implies that a 4 m rise would have occurred within about $115 \times 4/10 = 46$ km of the outlet isobase. Thus, any coastal features within a few tens of kms of the isobase would likely have developed over a maximum timespan of approximately 700 years. At Kincardine, Ontario, 115 km from the outlet isobase (Fig. 1), the last 4 m rise in which Main Algonquin coastal features might have formed would have occurred in $700 \times 4/10 = 280$ years. Proportionally greater rises of lake level would have occurred at more distant sites from the outlet isobase. For example, relative lake level at sites 180 km south-southeast of the outlet isobase would have risen approximately $10 \times 180/115 = 15.7$ m in 700 years, and the last 4 m of lake rise during which the Main Algonquin shore features might have developed would have occurred in about $700 \times 4/15.7 = 178$ years. Thus, spits or other

Table 1 Some of the major characteristics of the Glacial Lake Algonquin spits

Number (see Fig. 1)	Name	Approximate orientation (head to end)	Length (km)	Lat (N)	Long (W)
1	Cedarville	SW	4.0	45°32′	87°22′
2	Ephraim	SSE	0.3	45°8′	87°10′
3	Ellison Bay	SSE	0.3	45°15′	87°4′
4	Kinsey	SSW	0.4	45°10′	87°3′
5	Hedgehog	SSW	0.4	45°17′	87°1′
6	Delta Island N.	W	2.4	46°0′	86°27′
7	Delta Island S.	SW	22.9	45°53′	86°25′
8	S. Manitou Island	SW	0.7	45°2′	86°6′
9	Leland	SE	1.3	45°1′	85°45′
10	Camp Six	SW	6.3	46°23′	85°34′
11	Sage River	SSW	2.1	46°14′	85°17′
12	Big Spring	S	2.9	46°31′	85°16′
13	Hendricks	SW	14.0	46°6′	85°10′
14	Wycamp	SW	1.2	45°40′	84°56′
15	Betchler	SSW	8.5	46°17′	84°54′
16	Moran	NW	0.4	45°53′	84°49′
17	Pellston Island	N	1.0	45°34′	84°44′
18	Riggsville Island N.	NW	20.5	45°41′	84°41′
19	Munro	SW	0.7	45°37′	84°41′
20	Mackinac Island	SW	0.9	45°51′	84°37′
21	Minch	W	1.7	45°36′	84°35′
22	Riggsville Island S.	WSW	4.3	45°33′	84°34′
23	Rockview	NNE	3.5	46°5′	84°24′
24	Owens Island N.	NW	22.8	45°34′	84°20′
25	Black River Delta	WNW	1.2	45°24′	84°19′
26	Owens Island S.	SW	2.4	45°28′	84°13′
27	Rainy	NW	0.7	45°25′	84°10′
28	North Allis	WSW	1.3	45°23′	84°9′
29	Ocqueoc	WNW	8.8	45°27′	84°2′
30	Rogers City	N	1.3	45°23′	83°48′
31	Lake Augusta	WNW	2.8	45°19′	83°39′
32	Kerston	NNW	14.2	45°3′	83°34′
33	Aulerich	SW	26.1	44°18′	83°25′
34	Greenbush	SSW	11.3	44°32′	83°21′
35	West Bay	SSW	0.5	45°48′	82°8′
36	Pottawatomi	NNE	0.3	44°33′	80°57′
37	Auchinean	SSW	2.9	44°37′	80°57′
38	Cedar Point	SSW	1.6	44°46′	80°7′
39	Copeland	SSE	2.0	44°44′	79°59′
40	Penetanguishene	NE	2.0	44°45′	79°56′
41	Wyevale	SE	4.2	44°40′	79°55′
42	Phelpston	SE	0.4	44°32′	79°48′
43	Utopia	SSE	1.7	44°20′	79°47′
44	Raines	SW	1.3	44°16′	79°30′

Table 1 continued

Number (see Fig. 1)	Name	Approximate orientation (head to end)	Length (km)	Lat (N)	Long (W)
45	Elmview	SW	1.1	44°14′	79°29′
46	Maplewood	SSW	3.5	44°30′	79°26′
47	Ardtrea Island S.	S	0.6	44°39′	79°26′
48	Ardtrea Island N.	NW	1.5	44°42′	79°25′
49	Ardtrea Island NW	N	1.6	44°42′	79°24′

Spits are numbered, starting with the spits farthest west, progressing to those farthest east

coastal features associated with Main Lake Algonquin in this study can be assumed to have formed over timespans of roughly 200–700 years, depending on their proximity to the outlet isobase. This difference in duration is a function of glacial isostatic adjustment and may have been altered by other factors, such as variation in water and sediment supply, or by ice movements. As derived earlier in the 'Background' section, the inferred mean duration for any Post Algonquin lake was about 100 years.

Spits as indicators of paleoclimate

Spit orientations are usually assumed to be excellent proxies for the direction of littoral currents, wave action, and hence, maximum wind energy (Jewell 2007). Most spits (indeed, all spits less than ≈150–200 km of the presumed ice margin) generally trail off to the W, indicative of formation by easterly winds that generated west-flowing longshore drift (Krist and Schaetzl 2001; Vader et al. 2012; Fig. 4). Spits, including many of the longest ones, are generally oriented to the WNW, W, WSW or SW (Fig. 4). Sediment availability and shoreline orientation may have also contributed to the apparent modality (grouping) of spit orientations in Fig. 4. Only a few spits trail to the eastern sections of the quadrant, and the ones that do are quite short. No spits trail due east, or even close to due east (Fig. 4).

Several isthmi that occur in the eastern Upper Peninsula of Michigan, as narrow connections between islands, generally have SE-to-NW orientations (Fig. 4). Spits on N-S oriented coastlines, e.g., along the eastern coast of Michigan's Lower Peninsula, in the Upper Peninsula near present-day Green Bay, and on Delta Island and other N-S oriented islands in the Upper Peninsula, trail to the south but they, too, eventually hook to the west (Figs. 3, 5).

Of the 49 spits, only two small ones, distant from the outlet isobase with minimal exposure to Lake Algonquin wave action, trail to the east: one (South Manitou Island spit) on South Manitou Island in present-day Lake Michigan, and one (Leland spit) just to its east, on the Leelanau Peninsula, on the west coast of the Lower Peninsula (Fig. 1; Table 1). The Leland spit trails off an island that lies just west of the large, N-S oriented peninsula. Both of these spits are ≈150 km from the nearest presumed ice margin. Although small, they may indicate a weakened influence of easterly winds in the lee of the landmass of the Lower Peninsula. Weakened easterly flow would be consistent with data from loess deposits and sand dune orientations in the midcontinent and middle-southern Great Lakes region (Arbogast et al. 2015).

Together, these data support the conclusion that most of the longshore drift in GLA was flowing westerly, and that this drift was driven by generally easterly winds.

Theoretically, spits can form from sediment derived from (1) erosion of nearby headlands, (2) rivers that discharge into the water body, and/or (3) landward movement of inner shelf deposits. We discounted fluvial systems as major sediment sources for the spits, because most of the GLA spits are not found in association with river mouths. And although we cannot discount shelf deposits as a source for some of the spit sediment, we argue that the majority of the spit sediment was derived by erosion of headlands or islands, and then transported generally to the west or northwest on longshore drift. Supporting this conclusion is the observation that almost all of the GLA spits occur in association with islands or headlands. And in most cases, these islands and headlands have steep bluffs on their eastern sides, but lack steep bluffs elsewhere (Fig. 5). This finding suggests that the

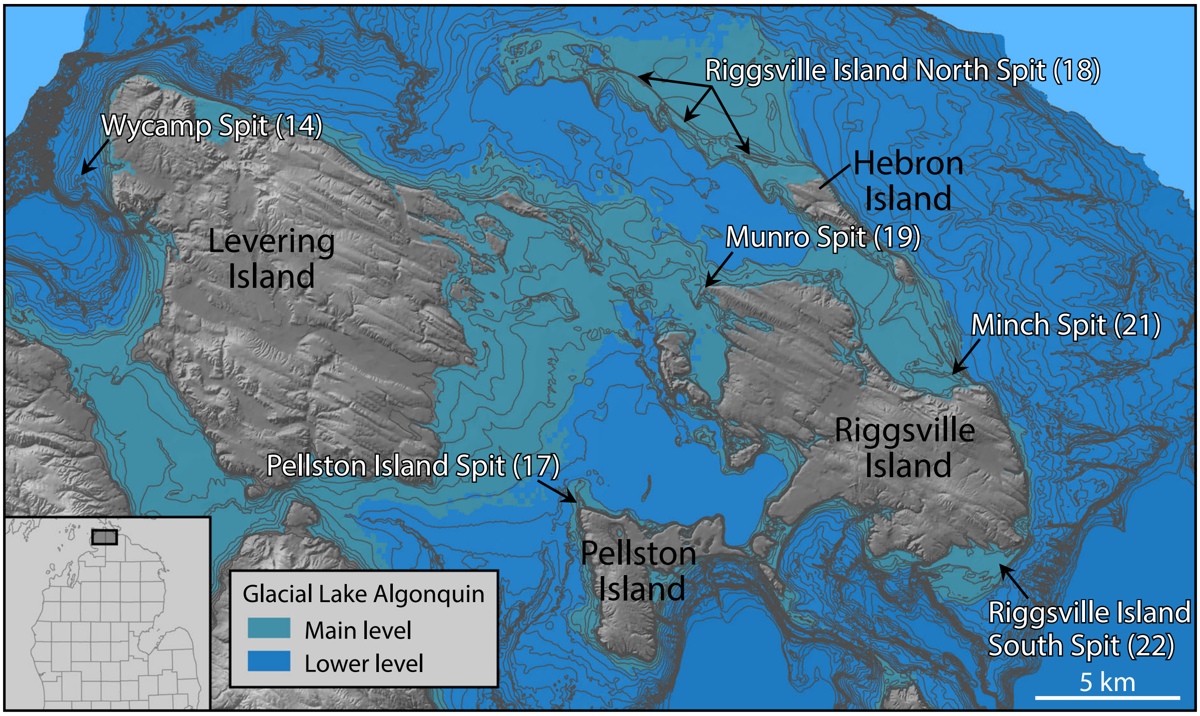

Fig. 5 Large scale map of some of the large spits in northern Lower Michigan. The map is flooded both to the Main level of Lake Algonquin, as well as to a lower stage. Modern *contour lines* are shown in order to help visualize spit morphologies. Contrast the steep, nearly straight, (presumably severely) eroded, eastern margins of Riggsville and Hebron Islands with the jagged, minimally eroded, eastern margin of Levering Island and the western margin of Riggsvile Island. Note the SE–NW isthmus between Riggsville and Hebron Islands, and the prominent, westward hooking end to the Riggsville Island North Spit, as mentioned in the text

bluffs have been eroded, probably by strong wave action, and that the erosive action has mainly been concentrated on the eastern margins of landmasses that projected out, into the lake. Also, this finding is consistent with the paraglacial coast model for glaciated coasts (Forbes 2005) which suggests rapid reworking of easily remobilized sediment after deglaciation in a cold climate when stabilization of backshore bluffs by vegetation would have been minimal, and that slopes intersected by the water plane would have been readily eroded. Islands that would have been protected from such easterly winds and waves, such as the one connected to the Leland spit, just off the NW coast of the northern Lower Peninsula of Michigan, show little evidence of erosion on their eastern margins.

Many of the sediments in northern Michigan and southern Ontario are sandy and gravelly (Schaetzl et al. 2013a) and hence, more easily erodible and suitable for spit formation than many bedrock areas or deposits of clayey lacustrine sediment would have been. The coarse textured sediment rendered many islands and headlands susceptible to erosion, facilitating sediment production for the littoral system. A key factor in spit growth, in general, is the ample supply of sediment, coupled with a shallow platform within which the spit can grow; both these conditions were met for most of the GLA spits in northern Michigan. Thus, the GLA spits developed and elongated rapidly as sands and gravels were eroded from headlands and deposited by longshore drift in (oftentimes) shallow, down-drift, protected areas (Fig. 5). In Ontario, more headlands are formed on bedrock, which limited the potential for erosion and hence, spit formation. Thus, spits here are considerably smaller and fewer in number (Table 1). Even here, however, the spits trail mainly to the west.

The GLA spits are especially long, prominent and well formed in the northern Lower Peninsula of Michigan, presumably because of (1) erodible sandy sediment, (2) persistent easterly winds across (in places) very long fetches, resulting in strong and reliable longshore drift across (3) fairly shallow nearshore platforms (Krist and Schaetzl 2001).

Other smaller, but still westerly-trailing spits occur in areas that may have been sheltered from the strongest easterly winds: (1) areas adjoining the mainland of the northern Lower Peninsula, where islands and protruding headlands created lower-energy lagoons (Vader et al. 2012; Figs. 3, 5), (2) on the western (lee) sides of islands throughout the lake, especially in Michigan's Upper Peninsula, and (3) on the south sides of islands that have larger spits trailing off to the NW, e.g., Owens Island and Delta Island (Figs. 1, 3). The latter situation suggests that, assuming offshore platforms are shallow and conducive to spit formation—winds from the E and SE were more common, and stronger, than winds from the N and NE. Shorelines in Ontario, on the far eastern margin of GLA, as well as on the western side of the Lower Peninsula of Michigan, are nearly devoid of spits, again suggesting a wind regime dominated by easterly flow; these coastlines would have been areas of mainly offshore winds, which would have minimized coastal erosion and thus, starved the littoral system of sediment.

As first reported by Krist and Schaetzl (2001) and as documented in Table 1, the immense size of some of these spits is noteworthy and relevant to the paleoclimate of the late Pleistocene in this region. In the northern Lower Peninsula, the Riggsville Island and Owens Island spits are nearly 21 and 22 km long, respectively (Figs. 1, 3, 5; Table 1). The nearby Ocqueoc spit is almost 9 km long, and the spit that trails southwesterly from Delta Island exceeds 22 km in length (Figs. 1, 3; Table 1). Betchler Spit on the eastern flank of Hulbert Island (Fig. 1) is 8.5 km long. In the far eastern Upper Peninsula is a 3-km long, SE–NW trending isthmus, connecting two bedrock-cored islands, the easternmost island is the headland of the Rockview Spit (Figs. 1, 3; Table 1).

Equally impressive is the internal sedimentology of the spits, often with classic-type foreset beds and coarse, rounded, imbricated flagstone fragments common to many spits, where exposed (Fig. 2). Many of the large spits also contain abundant (sometimes large) gravels, which would have required high energy and persistent longshore drift to transport great distances (Krist and Schaetzl 2001; Jewell 2007). Most of the spits in northern Lower Michigan are, in many places, quite gravelly (Krist and Schaetzl 2001). In both Ontario and Michigan, several large gravel pit operations are mining former spit sediment, attesting to their gravelly sedimentology and resource value as aggregate. In at least one location on the Bruce Peninsula, the shingle-gravel sedimentology resembles storm beds (Fig. 2) and appears to suggest "frequent, more intense summer storms …, stoked by strong katabatic winds blowing down the terminus of the Laurentide Ice Sheet" as suggested on page 543 in Pascucci et al. (2008). Further work on these spits may help identify new and important sources of construction aggregate. The data presented in Fig. 1 and Table 1 provide an excellent starting point for entrepreneurs in the aggregate industry to begin exploratory work.

Together, the spits point to paleoenvironmental conditions of high wave energy and strong longshore drift, which could have only resulted from strong and persistent easterly winds. Observations of modern (Fig. 6) systems confirm that littoral zone current and waves can transport sand and gravel considerable distances; what delays or confounds spit growth are short pulses of waves from other directions. Thus, the spits here argue for persistent easterly winds, especially when the nearshore water was ice-free, i.e., mostly in summer. Therefore, the spits are mainly a proxy for summertime circulation patterns, although there is little reason to believe that any anticyclonic winds in the region would have been weaker in the winter.

We suggest that the strong winds over the lake were derived from the glacial anticyclone, as likely assisted by katabatic forcings (Schaetzl and Attig 2013). The presence of so many spits along GLA coasts also indicates that climatic conditions had ameliorated sufficiently by this time to allow for ice-free conditions on the lake, for at least several months annually. Because all of the spits reported here formed within a timespan of less than 1000 years, the rate of formation was impressively rapid, sometimes exceeding one to two km of spit length accretion per century (Table 1).

As Bartlein et al. (1998) explained, strong temperature gradients that would have existed at the southern margin of the ice sheet may have helped spawn deep cyclonic storms passing over the lake. Such storms are well-known generators of strong westerly winds in their wake. Indeed, such winds would have been espoused as key transport vectors for loess in the

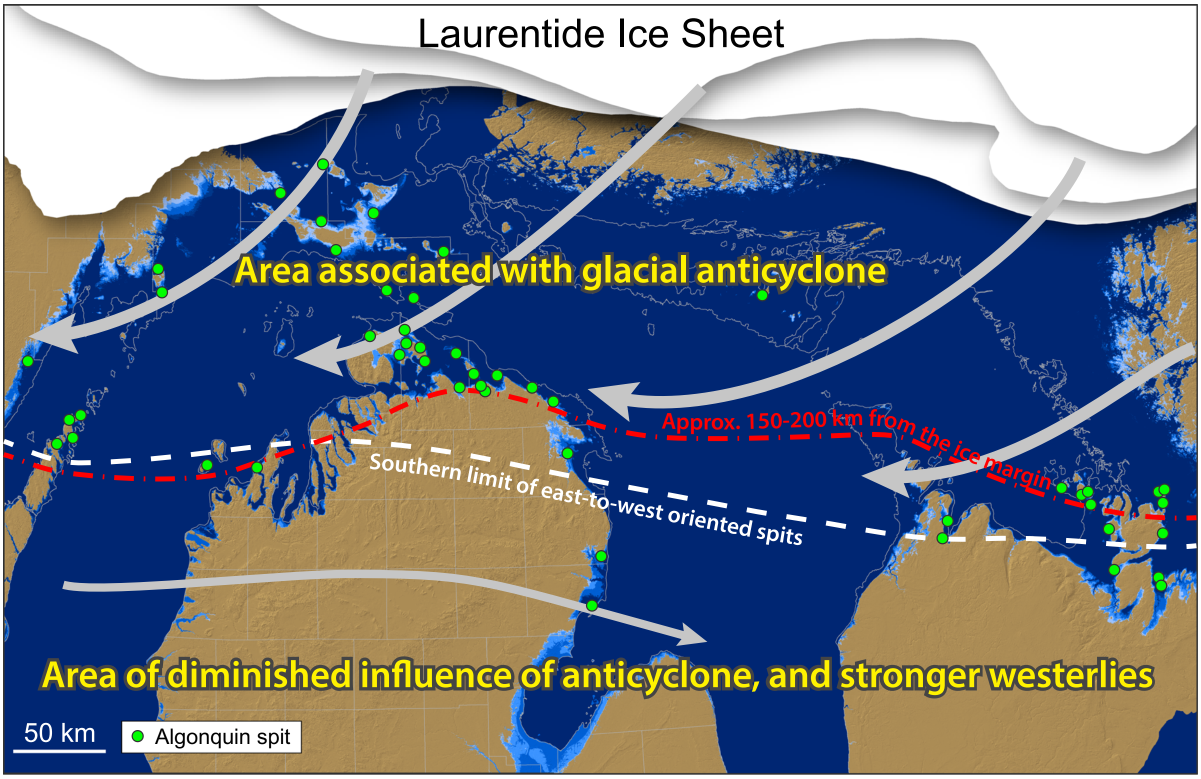

Fig. 6 A summary model of the possible paleoclimate conditions associated with Glacial Lake Algonquin, showing spit and ice margin locations

Midwestern United States (Muhs and Bettis 2000) and as the formative mechanism for spits in Paleolake Bonneville in Utah (Jewell 2007). However, westerly winds following even storms such as these, passing through the northern reaches of GLA, were apparently unable to transport as much sediment as the strong and presumably dominant easterly flows coming off the anticyclone.

Conclusions

We report on 49 spits, many of which are very large and most of which are tied to severely eroded headlands, in Glacial Lake Algonquin. Many of the largest spits formed near the outlet isobase in the Kirkfield to Main Algonquin phase, which existed for about 700 years, from 13,200 to 12,500 years BP. Other spits with lifespans of only one or a few centuries formed at sites distant from the outlet isobase, or in the Post Algonquin lake phases between about 12,500 and 11,500 years BP.

These landforms point to strong, persistent (and likely, seasonal) longshore currents and waves in the lake. The paleoclimate proxy data provided by the spits point to frequent easterly winds and even stormy conditions during the late Pleistocene summers. Such winds may have persisted throughout the year, although the lake would have been frozen in winter and thus, the spits reflect mainly summertime wind flow.

These winds probably continued into the earliest Holocene. The longest spits are oriented to the W and NW, indicating that the strongest and most persistent winds were from the E and SE. The growth of the long spits that formed to the NW of islands and headlands in present-day Michigan was assisted by erodible, sandy bluff sediment, susceptible to summertime wave erosion, and littoral transport across shallow platforms, all aided by long fetches of easterly winds. Alternatively, bedrock islands in Ontario have no, or only small, spits, lacking such favorable conditions for spit formation.

Our work confirms that the easterly wind anomaly at the southern margins of ice sheets in paleoclimate models is not simply a weakening of the westerlies, but represents strong, likely persistent easterly winds, almost certainly derived from a glacial anticyclone centered above the Laurentide Ice Sheet. Farther south, other paleoclimate proxy data, e.g., sand dune orientations, point to the weakening of these easterlies and the increasing dominance of westerly flow (Fig. 6), which is consistent with data from loess deposits of the midcontinent.

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References

Anderson TW (1979) Stratigraphy, age and environment of a Lake Algonquin embayment site at Kincardine, Ontario, vol 79-1B. Geological Survey of Canada, Ottawa, Current Research pp 147–152

Arbogast AF, Luehmann MD, Miller BA, Wernette PA, Adams KM, Waha JD, O'Neil GA, Tang Y, Boothroyd JJ, Babcock CR, Hanson PR, Young AR (2015) Late-Pleistocene paleowinds and aeolian sand mobilization in north-central Lower Michigan. Aeolian Res 16:109–116

Bartlein PJ, Anderson KH, Anderson PM, Edwards ME, Mock CJ, Thompson RS, Webb RS, Webb T III, Whitlock C (1998) Paleoclimate simulations for North America over the past 21,000 years: features of the simulated climate and comparisons with paleoenvironmental data. Quat Sci Rev 17:549–585

Blewett WL, Rieck RL (1987) Reinterpretation of a portion of the Munising moraine in northern Michigan. Geol Soc Am Bull 98:169–175

Blewett WL, Drzyzga SA, Sherrod L, Wang H (2014) Geomorphic relations among glacial Lake Algonquin and the Munising and Grand Marais moraines in eastern Upper Michigan, USA. Geomorphology 219:270–284

Bromwich DH, Toracinta ER, Wei H, Oglesby RJ, Fastook JL, Hughes TJ (2004) Polar MM5 simulations of the winter climate of the Laurentide Ice Sheet at the LGM. J Clim 17:3415–3433

Bryson RA, Wendland WM (1967) Tentative climatic patterns for some late glacial and post-glacial episodes in central North America. In: Mayer-Oakes WJ (ed) Life, land and water. Proceedings of the 1966 conference on environmental studies of the Glacial Lake Agassiz Region. Occasional paper 1. Univerity of Manitoba Press, pp 271–298

CDED (2010) Ottawa, ON: Natural Resources Canada, 2000–2010. Ottawa, ON: Ministry of Natural Resources. Online at: ftp://ftp2.cits.rncan.gc.ca/pub/geobase/official/cded/

Chapman LJ (1954) An outlet of Lake Algonquin at Fossmill, Ontario. In: Proceedings of the Geological Association of Canada 6 part, vol 2, pp 61–68

COHMAP Members (1988) Climatic changes of the last 18,000 years: observations and model simulations. Science 241:1043–1052

Cowan WR (1985) Deglacial Great Lakes shorelines at Sault Ste. Marie, Ontario. In: Karrow PF, Calkin PE (eds) Quaternary evolution of the Great Lakes: Geological Association of Canada, St. John's Newfoundland, Special Paper, vol 30, pp 33–37

Cronin TJ (1984) The raised shorelines of the northern Penetanguishene Peninsula. M.S. thesis, Department of Geography, University of Western Ontario, London

David PP (1981) Stabilized dune ridges in Northern Saskatchewan. Can J Earth Sci 18:286–310

David PP (1988) The coeval eolian environment of the Champlain Sea episode. In: Gadd NR (ed) The late Quaternary development of the Champlain Sea Basin. Geological Association of Canada Specialist Paper 35. St. John's NL, pp 291–305

Deane RE (1950) Pleistocene geology of the Lake Simcoe district, Ontario. Geological Survey Canada Memoir 256. 108 pp

Drzyzga SA (2007) Relict shoreline features at Cockburn Island, Ontario. J Paleolimnol 37:411–417

Drzyzga SA, Shortridge AM, Schaetzl RJ (2012) Mapping the stages of Glacial Lake Algonquin in Northern Michigan, USA, and nearby Ontario, Canada, using an isostatic rebound model. J Paleolimnol 47:357–371

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

Edwards TWD, Wolfe BB, MacDonald GM (1996) Influence of changing atmospheric circulation on precipitation δ^{18}O—temperature relations in Canada during the Holocene. Quat Res 46:211–218

Eschman DF, Karrow PF (1985) Huron basin glacial lakes: a review. In: Karrow PF, Calkin PE (eds) Quaternary evolution of the Great Lakes, St. John's, Newfoundland. Geological Association of Canada Specialist Paper 30, pp 79–93

Farrand WR, Drexler CW (1985) Late Wisconsinan and Holocene history of the Lake Superior basin. In: Karrow PF, Calkin PE (eds) Quaternary evolution of the Great Lakes. St. John's, Newfoundland: Geological Association of Canada Specialist Paper 30, pp 17–32

Filion L (1987) Holocene development of parabolic dunes in the Central St. Lawrence Lowland, Quebec. Quat Res 28:196–209

Finamore PF (1985) Glacial Lake Algonquin and the Fenelon Falls outlet. In: Karrow PF, Calkin PE (eds) Quaternary evolution of the Great Lakes: St. John's, Newfoundland. Geological Society of Canada Specialist Paper 30, pp 127–132

Fisher TG (1996) Sand-wedge and ventifact palaeoenvironmental indicators in northwest Saskatchewan, Canada, 11 ka to 9.9 ka BP. Permafr Periglac Proc 7:391–408

Forbes DL (2005) Paraglacial coasts. In: Schwartz ML (ed) Encyclopedia of coastal science. Springer, Dordrecht, pp 760–762

Ford MJ, Geddes RS (1986) Quaternary geology of the Algonquin Park area. Ontario Geological Survey Open File report 5600, 87 pp

French HM, Demitroff M (2001) Cold-climate origin of the enclosed depressions and wetlands ('spungs') of the Pine Barrens, Southern New Jersey, USA. Permafr Periglac Proc 12:337–350

Futyma RP, Miller NG (1986) Stratigraphy and genesis of the Lake Sixteen peatland, northern Michigan. Can J Bot 64:3008–3019

Gesch DB, Evans GA, Mauck J, Hutchinson JA, Carswell WJ, Jr (2009) The national map-elevation: U.S. Geological Survey fact sheet, 2009–3053, 4 pp. Online at: http://pubs.usgs.gov/fs/2009/3053/pdf/fs2009_3053.pdf

Goldthwait JW (1907) The abandoned shorelines of eastern Wisconsin. Wisconsin Geological and Natural History Survey Bulletin 17, 134 pp

Goldthwait JW (1910) An instrumental survey of the shore-lines of the extinct Lakes Algonquin and Nipissing in southwestern Ontario. Geological Survey Canada, Branch Memoir 10, pp 1–57

Gonzales LM, Williams JW, Grimm EC (2009) Expanded response-surfaces: a new method to reconstruct paleoclimates from fossil pollen assemblages that lack modern analogues. Quat Sci Rev 28:3315–3332

Hansel AK, Mickelson DM, Schneider AF, Larsen CE (1985) Late Wisconsinan and Early Holocene history of the Lake Michigan Basin. In: Karrow PF, Calkins P (eds) Quaternary evolution of the Great Lakes. Geol. Assoc. Canada Spec. Paper 30. pp. 39-53

Harrison JE (1972) Quaternary Geology of the North Bay-Mattawa Region. Geological Survey of Canada Paper 71-26. 36 pp

Heath AJ, Karrow PF (2007) Northernmost(?) glacial Lake Algonquin series shorelines, Sudbury Basin, Ontario. J Great Lakes Res 33:264–278

Hobbs WH (1943) The glacial anticyclone and the continental glaciers of North America. Proc Am Philos Soc 86:368–402

Hough JL (1958) Geology of the Great Lakes. University of Illinois Press, Urbana **313 p**

Jewell PW (2007) Morphology and paleoclimatic significance of Pleistocene Lake Bonneville spits. Quat Res 68:421–430

Karrow PF (1986) Valley terraces and Huron basin water levels, southwestern Ontario. Geol Soc Am Bull 97:1089–1097

Karrow PF (1987) Glacial and glaciolacustrine events in northwestern Lake Huron, Michigan and Ontario. Geol Soc Am Bull 98:113–120

Karrow PF (2004) Algonquin-Nipissing Shorelines, North Bay, Ontario. Géog physique Quat 58:297–304

Karrow PF, Anderson TW, Clarke AH, Delorme LD, Sreenivasa MR (1975) Stratigraphy, paleontology, and age of Lake Algonquin sediments in southwestern Ontario, Canada. Quat Res 5:49–87

Karrow PF, Anderson TW, Delorme LD, Miller BB, Chapman LJ (1995) Late-glacial paleoenvironment of Lake Algonquin sediments near Clarksburg, Ontario. J Paleolimnol 14:297–309

Kaszycki CA (1985) History of glacial Lake Algonquin in the Haliburton region, south central, Ontario. In: Karrow PF, Calkin PE (eds) Quaternary evolution of the Great Lakes: St. John's, Newfoundland. Geological Association of Canada Specialist 30, pp 109–123

Krist F, Schaetzl RJ (2001) Paleowind (11,000 BP) directions derived from lake spits in northern Michigan. Geomorphology 38:1–18

Kutzbach JE, Gallimore R, Harrison SP, Behling P, Selin R, Laarif F (1998) Climate and biome simulations for the past 21,000 years. Quat Sci Rev 17:473–506

Larsen CE (1985) Lake level, uplift, and outlet incision, the Nipissing and Algoma Great Lakes. In: Karrow PF, Calkin PE (eds) Quaternary evolution of the Great Lakes: St. John's, Newfoundland: Geological Association of Canada Specialist Paper 30, pp 63–77

Larson GJ, Schaetzl RJ (2001) Origin and evolution of the Great Lakes. J Great Lakes Res 27:518–546

Leverett F, Taylor FB (1915) The Pleistocene of Indiana and Michigan and the history of the Great Lakes. U.S. Geol Surv Mon 53. 529 pp

Lewis CFM, Anderson TW (2012) The sedimentary and palynological records of Serpent River Bog, and revised early Holocene lake-level changes in the Lake Huron and Georgian Bay region. J Paleolimnol 47:391–410

Lewis CFM, Blasco SM, Gareau PL (2005) Glacial isostatic adjustment of the Laurentian Great Lakes Basin: using the empirical record of strandline deformation for reconstruction of Early Holocene paleo-lakes and discovery of a hydrologically closed phase. Géog physique Quat 59:187–210

Lewis CFM, Karrow PF, Blasco SM, McCarthy FMG, King JW, Moore TC, Rea DK (2008a) Evolution of lakes in the Huron basin: deglaciation to present. Aquat Ecosyst Health Manag 11:127–136

Lewis CFM, King JW, Blasco SM, Brooks GR, Coakley JP, Croley TE II, Dettman DL, Edwards TWD, Heil CW Jr, Hubeny JB, Laird KR, McAndrews JH, McCarthy FMG, Medioli BE, Moore TC Jr, Rea DK, Smith AJ (2008b) Dry climate disconnected the Laurentian Great Lakes. EOS Trans Am Geophys Union 89:541–542

Luehmann MD, Schaetzl RJ, Miller BA, Bigsby M (2013) Thin, pedoturbated and locally sourced loess in the western Upper Peninsula of Michigan. Aeolian Res 8:85–100

Mason JA, Swinehart JB, Hanson PR, Loope DB, Goble RJ, Miao X, Schmeisser RL (2011) Late Pleistocene dune activity in the central Great Plains, USA. Quat Sci Rev 30:3858–3870

Miller BB, Karrow PF, Mackie GL (1985) Late Quaternary molluscan faunal changes in the Huron basin. In Karrow PF, Calkin PE (eds) Quaternary evolution of the Great Lakes, St. John's, Newfoundland. Geological Association of Canada Specialist Paper 30, pp 95–107

Muhs DR, Bettis EA III (2000) Geochemical variations in Peoria loess of western Iowa indicate paleowinds of midcontinental North America during last glaciations. Quat Res 53:49–61

Ollerhead J, Davidson-Arnott RGD (1995) The evolution of Buctouche Spit, New Brunswick, Canada. Mar Geol 124:215–236

Pascucci V, Martini IP, Endres AL (2008) Facies and ground-penetrating radar characteristics of coarse-grained beach

deposits of the uppermost Pleistocene glacial Lake Algonquin, Ontario, Canada. Sedimentology 56:529–545
Rawling JE III, Hanson PR, Young AR, Attig JW (2008) Late Pleistocene dune construction in the central sand plain of Wisconsin, USA. Geomorphology 100:494–505
Rea DK, Moore TC Jr, Anderson TW, Lewis CFM, Dobson DM, Dettman DL, Smith AJ, Mayer LA (1994a) Great Lakes paleohydrology: complex interplay of glacial meltwater, lake levels, and sill depths. Geology 22:1059–1062
Rea DK, Moore TC Jr, Lewis CFM, Mayer LA, Dettman DL, Smith AJ, Dobson DM (1994b) Stratigraphy and paleolimnologic record of lower Holocene sediments in northern Lake Huron and Georgian Bay. Can J Earth Sci 31:1586–1605
Reimer PJ, Bard E, Bayliss A, Beck JW, Blackwell PG, Ramsey CB, Buck CE, Cheng H, Edwards RL, Friedrich M, Grootes PM, Guilderson TP, Haflidason H, Hajdas I, Hatté C, Heaton TJ, Hoffmann DL, Hogg AG, Hughen KA, Kaiser KF, Kromer B, Manning SW, Niu M, Reimer RW, Richards DA, Scott EM, Southon JR, Staff RA, Turney CSM, van der Plicht J (2013) IntCal13 and Marine13 radiocarbon age calibration curves 0–50,000 years cal BP. Radiocarbon 55:1869–1887
Schaetzl RJ, Attig JW (2013) The loess cover of northeastern Wisconsin. Quat Res 79:199–214
Schaetzl RJ, Drzyzga SA, Weisenborn BN, Kincare KA, Lepczyk XC, Shein KA, Dowd CM, Linker J (2002) Measurement, correlation, and mapping of Glacial Lake Algonquin shorelines in northern Michigan. Ann Assoc Am Geogr 92:399–415
Schaetzl RJ, Enander H, Luehmann MD, Lusch DP, Fish C, Bigsby M, Steigmeyer M, Guasco J, Forgacs C, Pollyea A (2013a) Mapping the physiography of Michigan using GIS. Phys Geogr 34:1–38
Schaetzl RJ, Yansa CH, Luehmann MD (2013b) Paleobotanical and environmental implications of a buried forest bed in northern Lower Michigan, USA. Can J Earth Sci 50:483–493
Schaetzl RJ, Forman SL, Attig JW (2014) Optical ages on loess derived from outwash surfaces constrain the advance of the Laurentide ice from the Lake Superior Basin, Wisconsin, USA. Quat Res 81:318–329
Shane LCK, Anderson KH (1993) Intensity, gradients and reversals in late glacial environmental change in east-central North America. Quat Sci Rev 12:307–320
Spencer JW (1889) Notes on the origin of the Great Lakes of North America. Proc Am Assoc Adv Sci 37:197–199
Stanley GM (1936) Lower Algonquin beaches of the Penetanguishene peninsula. Geol Soc Am Bull 47:1933–1960
Stanley GM (1937) Lower Algonquin beaches at Cape Rich, Georgian Bay. Geol Soc Am Bull 48:1665–1686
Stuckens J (2004) Contour gridder extension for ESRI ArcView 3.X. Online at: http://arcscripts.esri.com/details.asp?dbid=12531
Stuiver M, Reimer PJ (1993) Extended ^{14}C data base and revised Calib 3.0 ^{14}C age calibration program. Radiocarbon 35:215–230
Sweeney MR, Busacca AJ, Richardson CA, Blinnikov M, McDonald EV (2004) Glacial anticyclone recorded in Palouse loess of northwestern United States. Geology 32:705–708
Taylor FB (1895) The Munuscong Islands. Am Geol 15:24–33
Thorson RM, Schile CA (1995) Deglacial eolian regimes in New England. Geol Soc Am Bull 107:751–761
To KT, Clements KA, DeThomasis SL, Smolarz AG, van Beest CES, Pollock MA, Zuber CR, Francis ND, Mulligan RPM (2015) Delineation of paleowind direction from dunes in Simcoe County, Ontario. Cartographica 50:187–194
Vader MJ, Zeman BK, Schaetzl RJ, Anderson KL, Walquist RW, Freiberger KM, Emmendorfer JA, Wang H (2012) Proxy evidence for easterly winds in Glacial Lake Algonquin, from the Black River Delta in northern Lower Michigan. Phys Geogr 33:252–268
Voelker SL, Stambaugh MC, Guyette RP, Feng X, Grimley DA, Leavitt SW, Panyushkina I, Grimm EC, Marsicek JP, Shuman B, Curry BB (2015) Deglacial hydroclimate of midcontinental North America. Quat Res 83:336–344
Wolfe SA, Huntley DJ, Ollerhead J (2004) Relict Late Wisconsinan dune fields of the northern Great Plains, Canada. Géog physique Quat 58:323–336