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Paleowind (11,000 BP) directions derived from lake spits in Northern Michigan

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Abstract

We report on the characteristics of several, previously unstudied, late Pleistocene spits in northern lower Michigan. Each spit developed as strong waves eroded a headland or island within the Main and/or later stages of glacial Lake Algonquin. Most have ESE to WNW orientations with prominent recurved hooks at their ends. Some are as long as 20 km. Sedimentologically, the spits contain thick (several meters or more) sequences of sand and well-rounded gravel. We suggest that summertime winds during the spits' formation (11,800 to ≈ 10,500 BP) were both very strong and dominantly from the E and SE, based on the following data: (1) their ESE (source, or head, of the spit) to WNW orientation, (2) the presence of steep, wave-cut bluffs on the east sides of the islands and headlands, and (3) spit locations (on the *northeastern* shore of Michigan's lower peninsula, coupled with their absence on the *northwestern* shore, just 100 km away). Wind direction data provided by these spits agree with paleoclimatic models that suggest that the Laurentide Ice Sheet had developed a strong anticyclonic circulation. The near lack of archeological sites from this time period in the northern lower peninsula, which was surrounded by Lake Algonquin at that time, supports the notion that the climate of northern lower Michigan was inhospitably cold and very windy in the late Pleistocene. © 2001 Elsevier Science B.V. All rights reserved.

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1. Introduction

Geomorphic and sedimentologic indicators are often useful in providing vector information about paleoenvironments, particularly regarding winds and currents. Streamlined landforms can provide directional/vector data on the processes that formed them, such as drumlins or crevasse fillings that indicate the flow direction of glacial ice (Borowiecka and Erickson, 1985). Likewise, dunes are often used to indicate the predominance of regional-scale winds (Carver and Brook, 1989; Galloway and Carter, 1993; Arbogast et al., 1997; Zeeberg, 1998). Ventifacts, fluted bedrock, faceted stones and wind-polished rock can provide information about local-scale winds (Hartshorn, 1962; Schlyter, 1995; Christiansen and

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Svensson, 1998). Also, certain subaqueous landforms and their sediments, such as spits and imbricated gravel in beaches, can be used to infer wave, current, and wind direction (e.g., Colton, 1962; Tanner, 1996).

In a similar vein, this paper provides information on paleowind directions based on spits in northern lower Michigan, USA. Here, high lake levels were commonplace in the late Pleistocene; many of these lakes were ice-marginal, with the Laurentide Ice Sheet covering low outlets or damming the lakes on their northern shores. This study focuses on one of these proglacial lakes, glacial Lake Algonquin, which existed in various forms from about 12,500 to 10,400 BP (Futyma, 1981; Larsen, 1987). Many landscapes in the Great Lakes region contain landforms that, in part, formed subaqueously prior to 10,500 years BP, but which are now subaerially exposed. Such landforms include offshore bars, submerged channels, wave beveled till plains, drumlin fields infilled with lacustrine clays, and lastly, spits. Spits are the focus of this study, for they can be used to indicate dominant wind, wave, and longshore current directions during their formation (Evans, 1942).

The potential import of this type of information is four-fold: (i) it can validate or refute paleoclimatic models that have been used to infer wind directions within a few hundred kilometers of the Laurentide ice margin, (ii) data on paleowinds can clear up misconceptions regarding wind directions and climate characteristics in this region during the late Pleistocene, (iii) the spits are important economically

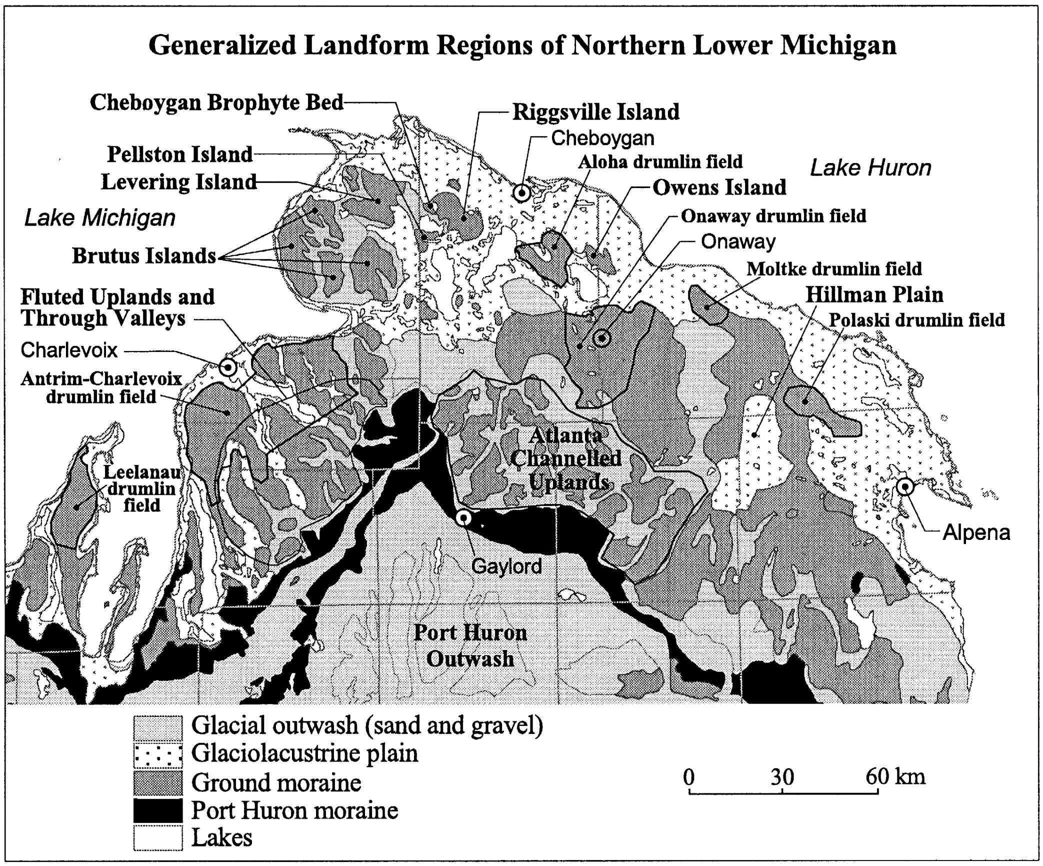

Fig. 1. Map of some of the more prominent glacial landforms on northern lower Michigan. After Burgis (1977), Farrand and Bell (1982), and Schaetzl et al. (2000).

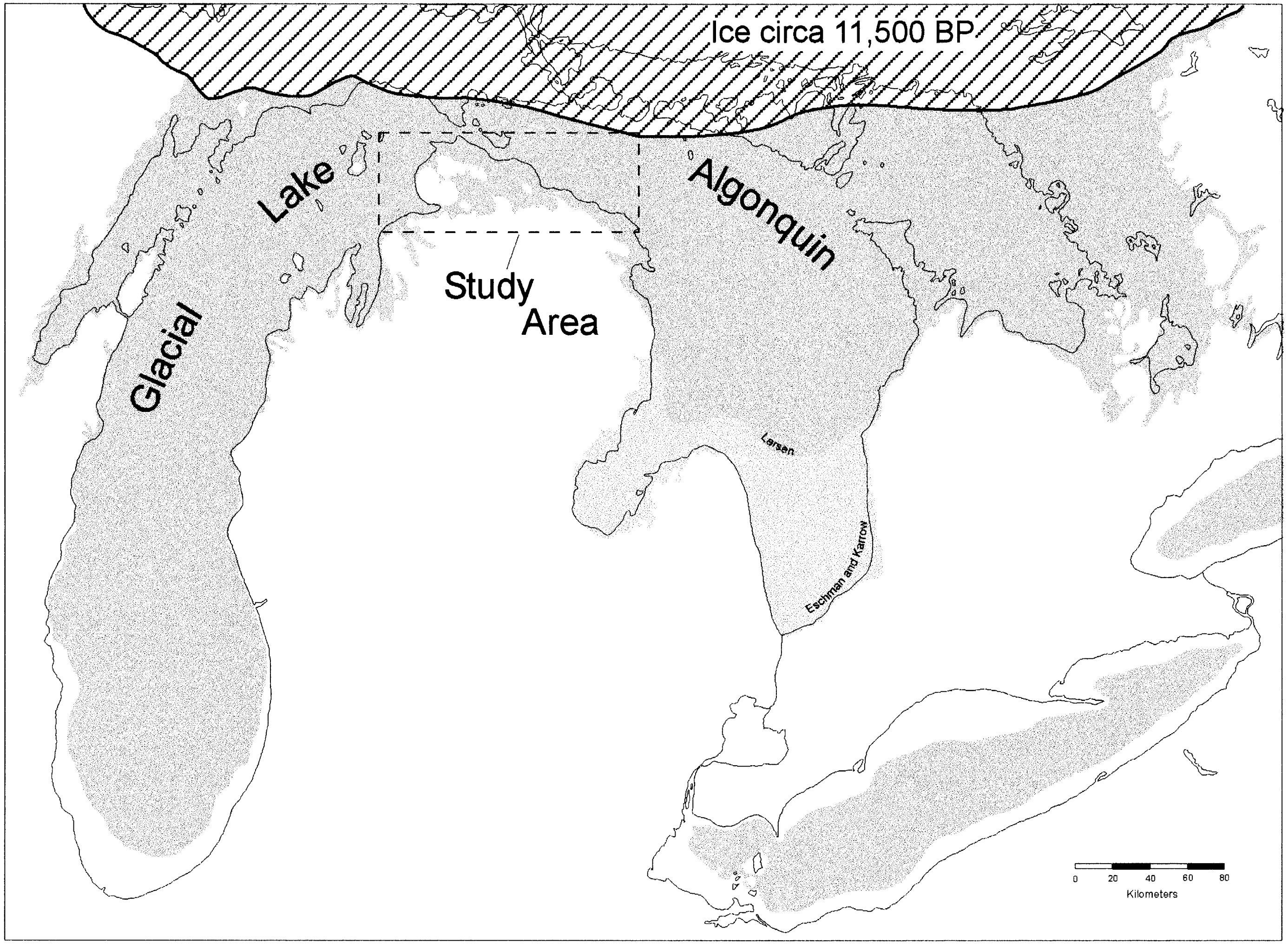

Fig. 2. Map showing the possible extent of Main Lake Algonquin in the Great Lakes region. After Eschman and Karrow (1985), Larsen (1987), and this study.

(a)

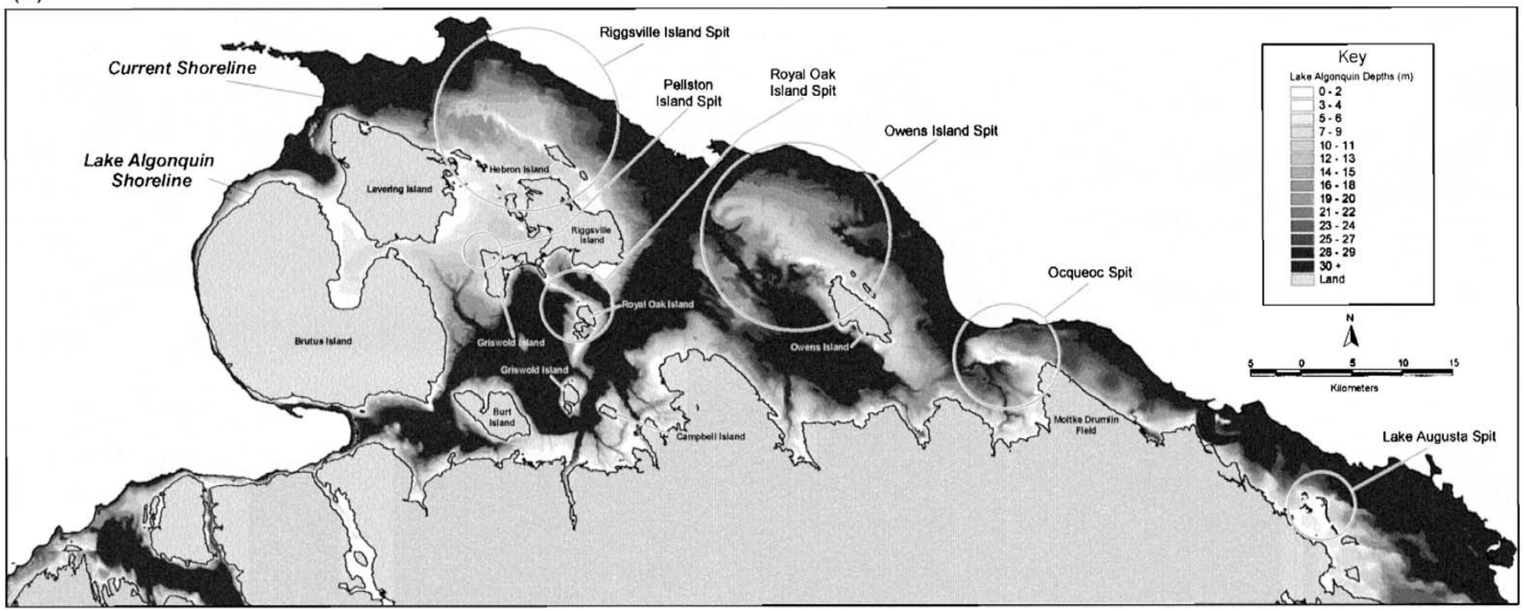

Fig. 3. (a) DEM of northern lower Michigan, showing the main Algonquin spits identified in this study. The rebound-adjusted elevation of the Main Algonquin shoreline is 184 m. (b) Close up of the Owens Island spit. Same shading scale as in (a). (c) Close up of the Ocqueoc spit. Same shading scale as in (a).

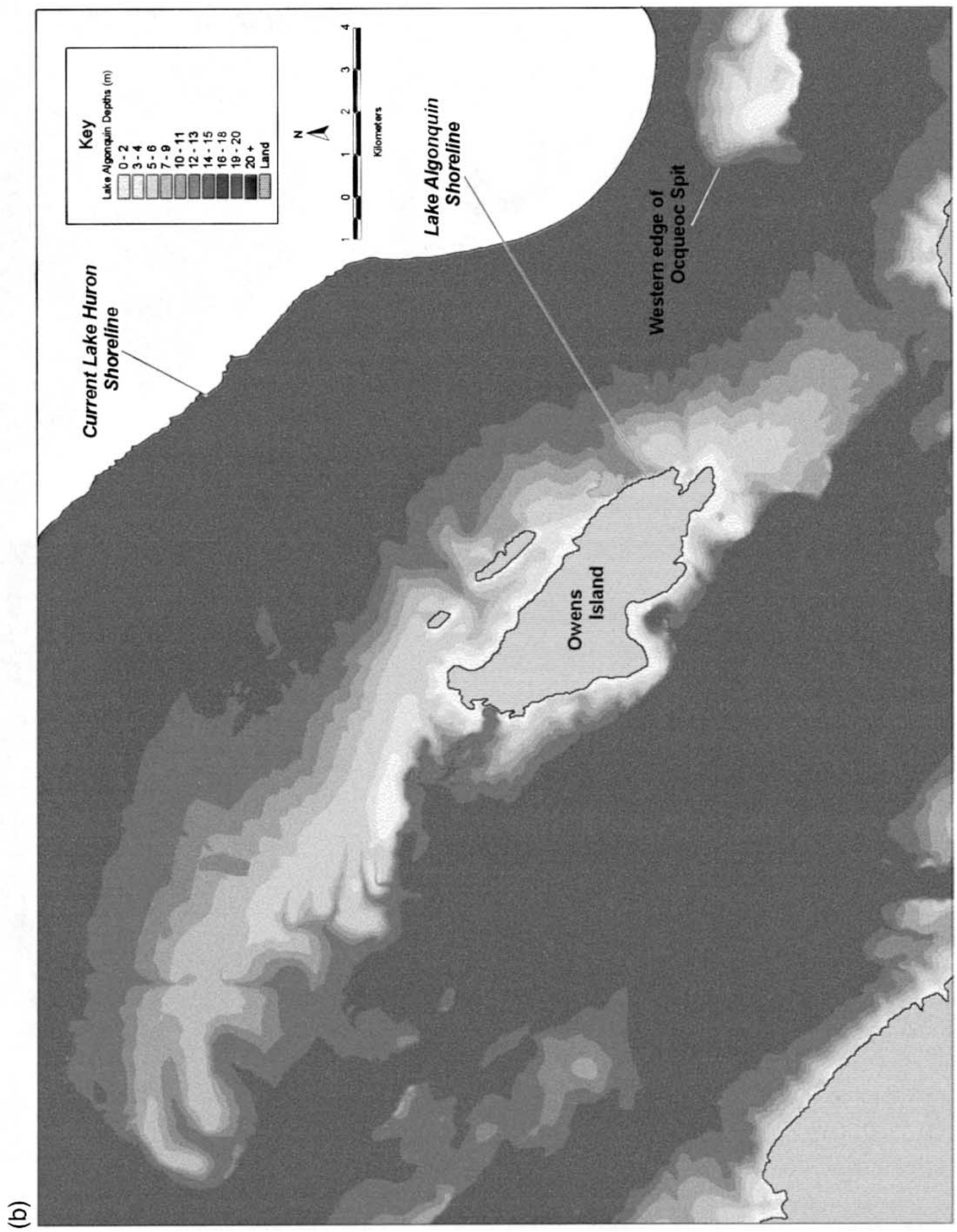

Fig. 3 (*continued*).

(c)

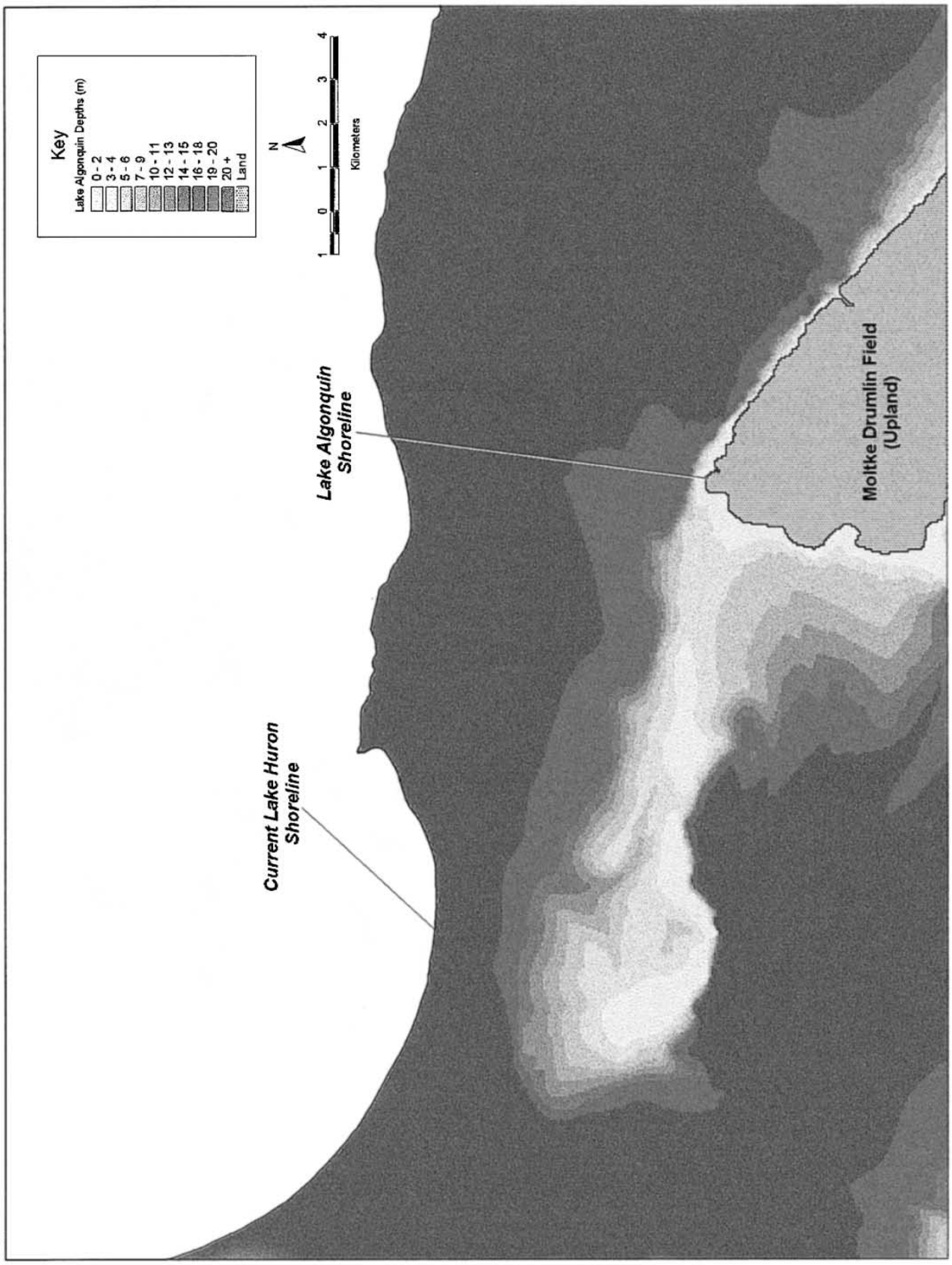

Fig. 3 (*continued*).

because they provide important local sources of construction aggregate, and (iv) it has implications for archeological research, since we will argue that strong easterly winds at this time dramatically affected human habitation patterns in the region. With this background in mind, the purpose of this study is to identify and characterize several spits from northern lower Michigan and to use their size and orientation to determine dominant wind directions from the late Pleistocene in the Great Lakes region.

2. Geologic background and the study area

The terrain of extreme NE lower Michigan, the focus of this study, owes most of its characteristics to glacigenic and lacustrine processes operative since about 13,000 BP. At about that time, the Port Huron readvance of the Laurentide Ice Sheet moved into northern lower Michigan, stopping at the Port Huron moraine (Blewett and Winters, 1995; Fig. 1). Following the recession of the Port Huron ice, a second (smaller) readvance occurred, initially known as Valderan (a.k.a. Greatlakean, but now referred to as the Two Rivers Phase (Black, 1970; Evenson et al., 1976; Johnson et al., 1997). The rapid and vigorous, yet short-lived, Greatlakean readvance extended some distance into the northern half of the Lake Michigan basin, spilling up onto eastern Wisconsin (Fig. 1).

The discussion that follows is not intended to be complete and exhaustive but rather to highlight the lakes that may have impacted the study area. Following the recession of the Greatlakean ice, a series of proglacial lakes came into existence within the Huron–Michigan basin. The lakes in these basins occupied high-water planes due to the ice covering some low-lying outlets and because the landmass was isostatically depressed (Clark et al., 1994). An early phase of Lake Algonquin (early Lake Algonquin) may have developed initially (between 11,800 and 11,500 BP) (Fig. 2; Karrow et al., 1975; Larsen, 1987). Little is known about this lake because it was very short lived; and evidence for it, either as shoreline features or as sediments, is scant.

"Main Lake Algonquin" was initially identified from shoreline evidence by Spencer (1889) and Leverett and Taylor (1915). Because the ice margin had, by this time, retreated into the upper peninsula of Michigan, Main Lake Algonquin was confluent between the Michigan, Huron, and Superior basins, and also covered large parts of the (then isostatically depressed) upper peninsula (Fig. 2; Cowan, 1985). Although the exact dates of the emergence of this lake are questionable, due to lack of radiocarbon age control, the Main Algonquin level was clearly established by 11,500 BP. As the ice margin receded across the isostatically depressed landscape, successively lower outlets were uncovered over the next few centuries, forming a series of post-Algonquin lakes (Eschman and Karrow, 1985; Hansel et al., 1985). At about 10,300 BP, the retreating ice margin exposed some very low outlets near North Bay, Ontario, which opened into the St. Lawrence Valley (Hough, 1955; Harrison, 1972; Colman et al., 1994). Consequently, Lake Algonquin drained rapidly to more than 120 m below its Main level.

In NE lower Michigan, the shoreline of Main Lake Algonquin is a nearly continuous and highly conspicuous feature — the "Algonquin bluff" (Fig. 3a; Melhorn, 1954). In places, this bluff has a relief of 35 m. In SE Presque Isle County, the base of this bluff is at about 220 m, while in NW Cheboygan County, it is at 225 m due to differential isostatic rebound (Clark et al., 1994). North and east of this wave-cut bluff are wave-beveled lake plains of Main Lake Algonquin and its lower successors. Most of the Algonquin surface is veneered in sand of varying thickness, with organic soils (mucks) accumulating on the wet sand (Tardy, 1991; Knapp, 1993). The sand probably reflects gradual shoaling during coastal emergence as lake levels fell.

3. Methods

The Algonquin spits were first studied by inspection of 1:24,000 topographic maps. Field research consisted of examining gravel and borrow pits in each spit, and in some cases, we hand-augered into the spits. In the laboratory, a digital elevation model (DEM) of the study area was generated from USGS 7.5 min, 30 m DEM data. In small areas that lacked USGS DEM data, the TOPOGRID command in the ArcInfo GIS package was used to produce a DEM from existing contour and hydrology data. Details of this modelling procedure are presented in Schaetzl et

Table 1
Locations and characteristics of the major Algonquin spits in northern lower Michigan

Spit name[a]	Eastern or SE end	Western or NW end	Total length[b] (km)	Other characteristics
Lake Augusta	Sec. 28, T34N, R7E	Sec. 23, T34N, R6E	7.5	Lies on bedrock for some of its extent, gravel within is poorly rounded
Ocqueoc	Sec. 31, T36N, R4E	Sec. 29, T36N, R3E	8.8	Extremely well-rounded and sorted gravel
Owens Island	Sec. 31, T37N, R2E	Sec. 10, T37N, R1W	16.5	Low, sandy
Riggsville Island	Sec. 8, T37N, R2W	Sec. 11, T38N, R4W	19.7	Dominated by sand in its NW reaches
Royal Oak Island	Sec. 18, T36N, R2W	Sec. 3, T36N, R3W	4.9	Connected to islands on each end; may simply be the expression of an ice-contact ridge between two kettles
Pellston Island	Sec. 25, T37N, R4W	Sec. 25, T37N, R4W	0.9	Sandy, little gravel present

[a] If a spit is not named for the island it extends from, it is safe to assume that it extends from a headland on the Algonquin "mainland".
[b] Length along the major axis of the spit: not straight-line distance. Length includes islands "intercepted" by the spit.

al. (2000). However, the procedure centered on creating a DEM of the late Pleistocene landscape, prior to isostatic rebound-referred to as an "isostatic rebound DEM". To do this, "rebound contours" were generated by digitizing lines between known points of uplift located along the Main Lake Algonquin beach ridge (Leverett and Taylor, 1915; Larsen, 1987). The rebound DEM, generated using the TOPOGRID command with the drainage enforcement routine turned off, produced a wedge-shaped DEM without stream valleys, representing the amount that the landscape has risen during the last 11,200 radiocarbon years. The rebound DEM was then subtracted from the "modern" DEM, lowering the elevations of the latter and creating an isostatic rebound DEM — closely resembling the terrain ca 11,200 BP, when the ice is assumed to have last exited the study area.

4. Results and discussion

4.1. General characteristics

Spits are common features of many coasts that have active littoral transport of sand, including the coasts of the Great Lakes. Willman (1971) mapped several major spits near Chicago, which formed when Lake Michigan was at a higher level during the late Pleistocene. Chrzastowski and Thompson (1994) discussed in some detail several spits in the Chicago region, including the Wilmette, Rose Hill, Toleston, and Graceland spits. Sharpe and Edwards (1979) reported on a large spit in Ontario that formed within glacial Lake Algonquin.

Several large spits were identified in NE lower Michigan from DEM (topographic) data (Fig. 3a). The spits are up to 19 km long and 3 km wide (Table 1). The spits mostly lie below the level of Main Lake Algonquin, suggesting that some of their accretion occurred during the later (lower) stages of the lake. Local relief on the largest spits approaches 20 m, although 3 to 8 m is more common. The spits all contain abundant, lineated depressions and ridges ("fingers"), which parallel the long axis of the spit. Both of these features are characteristic of spits and illustrate the direction of longshore drift along the spit axis. Chrzastowski and Thompson (1994) used detailed elevation data on the "fingers" of the Glenwood and Griffith spits to support the case for slowly falling lake levels during their formation. As is the case for spits near Chicago (Chrzastowski and Thompson, 1994), the Algonquin spits are all anchored either on an island or a headland.

The spits are composed of sand and gravel[1] deposits, often with a thin "cap" (<2 m) of gravel-poor sand with interbedded silty zones, like those

[1] In this paper we use grain-size terminology of the USDA-Natural Resources Conservation Service, wherein the "sand" size fraction ranges from 0.05 to 2.0 mm in diameter, and "gravel" fragments range from 2 to 76 mm in diameter (Schoeneberger et al., 1998).

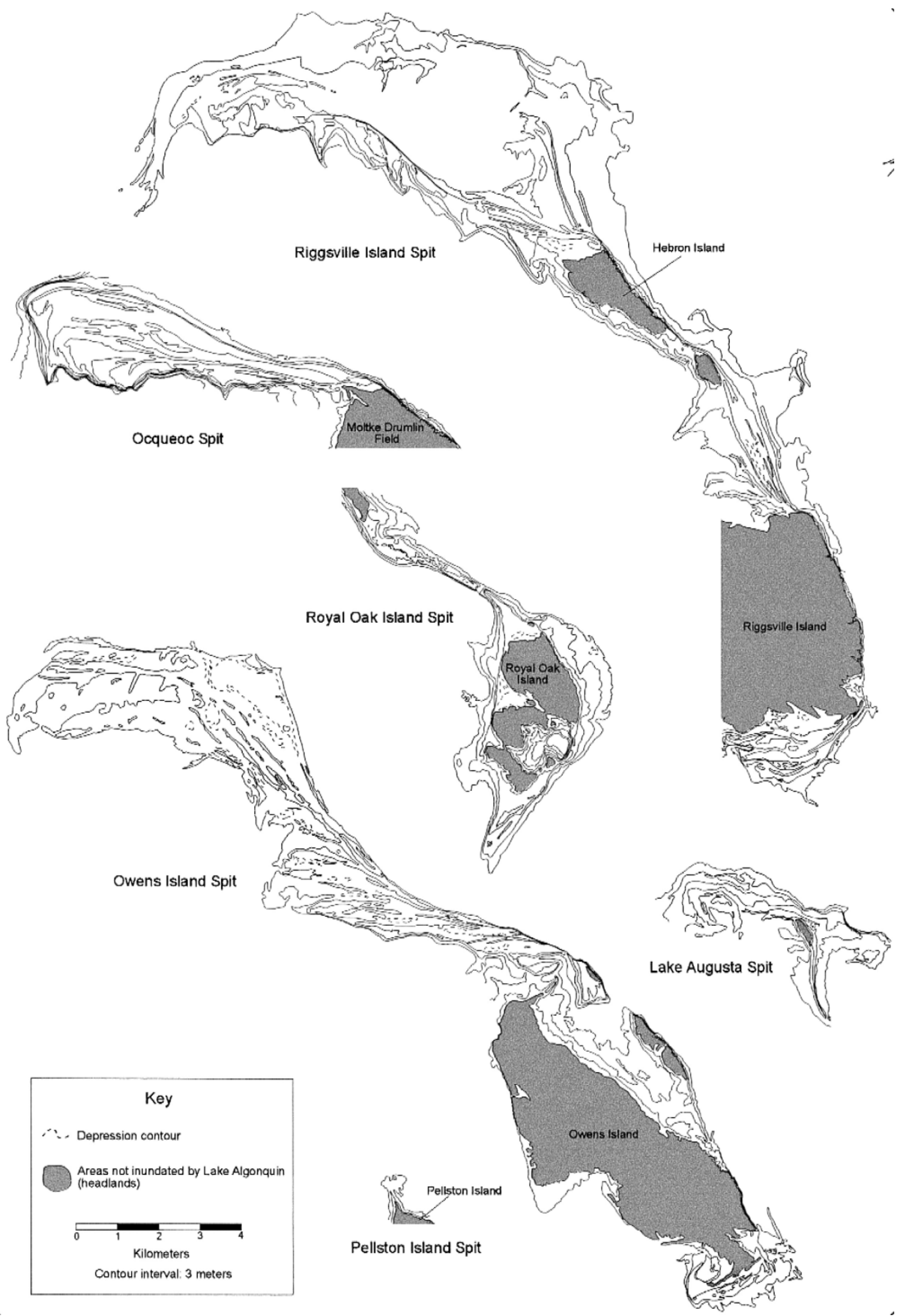

Fig. 4. Contour maps of four of the Lake Algonquin spits examined in this study.

reported by Nolin and Gwyn (1997). They have abundant gravel and sand pits scattered across their surfaces. The large sizes and highly rounded nature of the cobbles and gravel within suggest that very strong, even hurricane-force, winds were commonplace near the ice margin. On their E or SE ends, each spit is anchored on a till- or bedrock-defended upland. The till in this area is a gravelly sandy loam, with 10–40% gravel by volume (Schaetzl, 1998). Most spits trend off to the NW, at approximately 320° to 280° azimuth, with hooks on the end that curl around to the W and SW. These orientations, and the absence of similar features on the northwestern side of the peninsula, are suggestive of wind directions from the E and SE during the time of formation.

4.2. Individual spits

4.2.1. Ocqueoc spit

The Ocqueoc spit is named for the town of Ocqueoc, which lies about 8 km SW of the spit (Figs. 3a,c, 4). This spit is anchored on its SE side by the Moltke drumlin field. This field is composed of NW–SE trending drumlins formed in gravelly sandy loam drift (Burgis, 1977; Schaetzl et al., 2000). At their highest points, the drumlins stand over 65 m above the Algonquin floor. On its eastern edge, the drumlin field has an abrupt bluff that descends more than 25 m to the Algonquin lacustrine plain. The smooth, almost linear outline of the eastern face of the Moltke field (Fig. 1) strongly suggests that it is an eroded headland, having been planed by waves approaching from the E and SE.

The Ocqueoc spit trails off from the Moltke field to the WNW for about 9 km, and in most places rises nearly 15 m above the surrounding lake floor (Table 1). Between the spit and the uplands to the south an Algonquin bay once existed; this bay today serves as a source of fine sand. Leverett and Taylor (1915, p. 422) make reference to this bay as lying south of "a great high bar or spit of rather sandy gravel", and later (p. 422) refer to it as the "great spit". Three

Fig. 5. Sediments within the Ocqueoc spit, NE 1/4, NW 1/4 Sec. 28, T36N, R3E, Presque Isle County, MI.

large gravel pits within the head of the spit reveal extremely well rounded, stratified gravel mixed with sand (Fig. 5) similar to a Lake Algonquin spit in Ontario described by Nolin and Gwyn (1997). Gravel size is routinely less than 10 cm in diameter, with 5 cm being the estimated median size. Thin stringers of reddish, clayey sediment are interbedded with gravel. The pits lie more than 7 km from the headland (the Moltke field) — the presumed source — suggestive of long-distance transport. The sheltered "bay" that lies between the spit and the uplands to its south contains abundant evidence of low-energy coastal deposition. Sand pits with low amounts of small gravel (mostly less than 3 cm in diameter) dot this landscape; the stratified sands here exceed 18 m in thickness.

4.2.2. Owens Island spit

Owens Island was named by Burgis (1977) for an island in glacial Lake Algonquin that lies on the border of Cheboygan and Presque Isle Counties. It is a kame that goes by the local name of "Black Mountain". Two smaller, unnamed islands lie within a kilometer to the NE of Owens Island. Black Mountain rises more than 60 m above the Algonquin floor. Local soils data show it to be covered with till- and outwash-derived soils similar to those on the Moltke drumlin field (Tardy, 1991). Owens Island has two spits. The main spit trails off to the NW and was first noted by Leverett and Taylor (1915, p. 423). It is nearly 12 km long (Table 1); along this length, it rarely rises more than 10 to 12 m above the lake floor (Figs. 3a,b, 4). Along most of its extent, it is composed of gravelly sand. Another, smaller, secondary spit occurs on the southern side of the island, trailing off to the W and SW (Fig. 3).

4.2.3. Riggsville Island spit

Riggsville Island is a large, drumlinized upland that rises over 40 m above the Algonquin floor (Spurr and Zumberge, 1956; Burgis, 1977; Fig. 1). To its NE and SE are several, smaller islands (Fig. 4). The eastern side of the island contains a conspicuous bluff 15 to 18 m in height. As the eastern side of the Moltke upland, the bluff line here is nearly linear due to prolonged erosion, is oriented in a SSE–NNW direction, and is very abrupt. To the immediate SE of this bluff, on what would have been the windward side of the island (assuming strong SE or E winds), are two to three linear bars, each paralleling the bluff line. Gravel pits in these bars (SW 1/4, Sec. 33, T37N, R2W) reveal that they are composed of highly rounded boulders and cobbles set amidst a sand and gravel matrix. Many are 15 to 50 cm in diameter, with an estimated median diameter of the larger ones being 25 cm. According to the owner, the depth of these gravelly and bouldery deposits is 3 to 5 m; and they are underlain by sand. We suggest that only large waves, repeatedly pounding the E and SE side of the island, driven by strong (hurricane-force) winds, could have produced such extreme rounding of these large clasts. The boulders are much too rounded to represent simply a lag deposit winnowed from local till by wave action.

Riggsville Island has two spits. The main spit trails off to the NW. It is about 8 to 12 m in height and almost 20 km in length. It is the longest of the Algonquin spits, and perhaps the narrowest (in places, only 300 to 400 m in width; Table 1; Figs. 3a, 4). Although Riggsville spit begins on Riggsville Island, it intercepts two smaller islands along its length, one in Sec. 25, T38N, R3W, and the other in Sec. 31, T38N, R2W. Leverett and Taylor (1915, p. 423) noted the presence of a spit that "runs northwest about 2 miles" from the north end of one of these smaller islands. Secondary, recurved hooks are observed at several places along the entire south side of the spit and on its distal end (e.g., Sec. 15, T38N, R3W; Figs. 3a, 4). These hooks, indicative of spits and common to all the Algonquin spits in this region, negate the possibility that these features are simply beach ridges or strandlines (Chrzastowski and Thompson, 1994). Similarly, the recurved hooks serve to refute Spurr and Zumberge's (1956, p. 101) assertion that the feature is built largely of outwash sands and was later planed by Lake Algonquin "to create a shallow lake bottom dotted with small residual islands". Interstate highway 75 runs along the spit for nearly 8 km, for on either side of the spit are the swamps and flat lowlands of the Algonquin lake floor.

A second, much smaller and less-developed spit occurs on the SE corner of Riggsville Island on the opposite end of the erosional bluff that serves as the source of the sediments. The major spit begins at the northern end of this erosional bluff and trails off to the NW, whereas the smaller spit trails off to the SW, from the southern end of the same bluff. The small spit parallels the gravel bars mentioned above. As at Owens Island, the smaller spit probably formed when longshore current split into two cells along the eastern face of the island; the majority of the current and sediment were swept to the NW (implying a southeasterly component to the wind), whereas a small segment of the sediment traversed the southern edge of the island, forming the spit and the gravel bars.

4.2.4. Royal Oak Island spit

To the south of the main Riggsville Island is the small Royal Oak Island (Burgis, 1977). Royal Oak Island (Secs. 18 and 19, T36N, R2W) contains a scenic lookout for the I-75 interstate highway that runs along its western margin. The island has a small spit that trails off to the northwest (Fig. 3a). This spit is about 4.5 km long, and 12 to 15 m in height (Table 1). On its extreme northwestern end it abuts another Algonquin Island: Pellston Island (Spurr and Zumberge, 1956; Burgis, 1977). No pits exist in the Royal Oak spit. It is possible that Royal Oak Island spit is not a spit at all but a crevasse filling between two large kettles, each of which exists astride the spit.

4.2.5. Pellston Island spit

As with the other islands and uplands in northern lower Michigan, Pellston Island also has a spit on its NW side, although it does not show on local-scale geomorphic maps (Pearsall et al., 1995). The spit, located in the Sec. 25, T37N, R4W, is about 1 km W of the SW corner of Douglas Lake. Perhaps because of its small size, this spit was not noted by earlier researchers. The spit is quite small and low (≈ 2 m), probably because it was sheltered by the large Pellston and Riggsville Islands several kilometers to the E and N, around Douglas Lake (Table 1). Pellston spit trails off to the NNW; it is about a kilometer in length. Fieldwork and hand augering on this spit revealed that the sediments within are estimated to be $\approx 90\%$ sand, with some gravel. A small borrow pit is located on the spit, and it appears that it was used in the past as a gravel source.

4.2.6. Lake Augusta spit

In SE Presque Isle County, the Lake Augusta spit lies immediately N and E of Lake Augusta (Figs. 3a, 4; Table 1). Leverett and Taylor (1915, p. 421) made reference to this spit as a "great gravel bar on a low, broad ridge". They go on to point out that "spits and bars of such proportions (are) seldom seen" (p. 422) as in the Lake Augusta area. The Lake Augusta spit is marked by several small gravel pits, most of which were excavated to bedrock and are now abandoned. At its northwestern end, the spit contains about 2 to 3 m of rounded and subrounded gravel (little of which is as rounded as that in the Ocqueoc spit) and thin, flat fragments of limestone on top of a scoured, smooth bedrock surface. It is likely that much of the gravel in the Lake Augusta spit was derived from erosion of bedrock (which is within a few meters of the surface) rather than from erosion of gravelly till. If true, the gravel would not have been transported as far as the gravel from other spits, which may explain why the Lake Augusta spit gravel is not as well rounded as are spit gravel elsewhere.

4.3. Spit formation

Spits tend to form on irregular coasts where sand and possibly gravel are dragged downdrift by longshore drift from a protruding headland (King, 1959). Many spits are complex, recurved features caused by wave refraction at their ends (Evans, 1942; Ollerhead and Davidson-Arnott, 1995). They are often driven by intense wave erosion of a headland or island, littoral transport of sediments down beach, and concomitant deposition of the sediments as a spit in the leeward wind shadow (Chrzastowski and Thompson, 1994). Thorson and Schile (1995) examined spits formed downwind from drumlin "islands" in paleo-Lake Hitchcock (New England, USA). Like the Algonquin spits, they had simple morphologies (i.e., no secondary spits) and extended primarily in one direction (downwind) from the islands. Thorson and Schile used these spatio-geomorphic data to make inferences about paleo-currents and the dominantly northeasterly winds that drove them. Because the Algonquin spits all developed to the WNW, and lack compound or complex morphologies, we assume that winds were dominantly from the same quadrant (E, ESE, or SE) during the period of their formation.

4.4. Implications for paleoclimate

Currently, winds in the region are predominantly from the west, with a strong southwesterly component being dominant in summer; northwesterly winds can be quite strong in winter (Eichenlaub et al., 1990). Wind directions at Sault Ste. Marie, Michigan, about 100 km to the north of the major Algonquin spits, show a bimodal annual distribution, with WNW and ESE components being dominant. Farther south, within the central lower peninsula, wind bimodality does not occur. Rather, westerly and southwesterly winds are common and strong. If modern dunes were to form in this area, they would show a strong resultant drift direction to the ENE (Arbogast et al., 1997).

The Algonquin spits provide excellent data about direction of longshore transport, which in turn was dependent upon dominant wind direction (Sterr et al., 1998). In this respect, the spits integrate wind directionality over long periods of time. Dunes, however, can form quickly, even during one storm event with winds from a direction that is vastly different from the regional mean. Spit formation in NE lower Michigan would have required great energy for coastal erosion and transport, which was probably facilitated by (i) an environment of strong winds out of the E or SE quadrant with (ii) a long fetch (Fig. 2). Presumably, Lake Algonquin was frozen in winter and spring and thus, the spits provide information only on summertime winds. The streamlined nature and the orientation of headlands in the study area, and the intense erosion some of them were subjected to on their SE sides, also point to exceedingly strong waves and currents driven by E or SE winds.

More detailed geomorphic data from, for example, Riggsville Island (Fig. 3a) can also be used in support of the easterly wind hypothesis. Riggsville Island has a steep, wave-cut bluff on its east side. The bluff, in places nearly 20 m in height, is quite linear in extent and is strongest where it is aligned at azimuths between 335° and 360°, suggestive of strong waves approaching the island (perpendicularly) from 65° to 90° (ENE). The main axis of its spit connects with two small islands to the NW of Riggsville Island, and then trails off at approximately 310°. The spit has several prominent recurves at its distal end. Evans (1942) noted that recurves develop best when the wind that forms them approaches the shore at an angle of 30° to 45°. Such an angle (to the spit axis) would suggest winds dominantly from azimuths of 85° to 100°, or ESE. Both lines of evidence point to winds dominantly from the eastern sector.

Finally, more supporting evidence comes from a sand/gravel spit in the upper peninsula of Michigan, some 50 km due north of the westernmost end of the Riggsville Island spit (Futyma, 1981). This spit trails off to the WNW from the dolomite-cored, Algonquin Island named Maple Hill.

Although our conclusion of strong E and SE winds during Lake Algonquin time seems intuitive after examining our geomorphic (spit) data, it is not widely known and does conflict with data from other parts of the lake. For example, Storck (1984, p. 287) felt that “geological studies of beach development and orientation and current directions in Lake Algonquin indicate that, as today, the prevailing winds were from the north and west”. Spurr and Zumberge (1956) describe SE-facing shores of Lake Algonquin in northern lower Michigan as having been “sheltered” from the wind. Deane (1950) suggested that storm winds at this time were predominantly from the north, and yet he cites geomorphic evidence that would seem to contradict that: strong, SE-facing bluffs on islands, coupled with spits extending northward from other Algonquin Islands in Ontario. At another site in Ontario, Nolin and Gwyn (1997) report on a small Lake Algonquin spit and offshore bar that may have formed from currents moving dominantly to the E–SE, driven by westerly winds. Such a finding may appear to contradict ours, but when the fact that their site is in a sheltered, bay-like area on the eastern shore of Lake Algonquin is also considered, their finding seems reasonable and not contradictory. Currents in a protected lacustrine environment like theirs are likely to swirl, refract, and reflect based on shoreline configurations and underwater promontories, and thus, may not accurately reflect regional wind vectors, as would more “open” sites like ours. In addition, geomorphic data from slightly later in time but in close proximity to the Algonquin spits (Arbogast et al., 1997) suggest that strong westerly and northwesterly winds existed shortly after Lake Algonquin drained. Parabolic dunes believed to be early Holocene in age in the Saginaw lowlands (150–250 km to the south) have limbs that extend to the ESE or SE, suggestive of strong WNW or NW winds during their early Holocene development (Arbogast et al., 1997).

Thus, data from our study may help clear uncertainties about, and rapid changes that may have taken place within, regional circulations ca 11,000 BP. Such data should assist in future geomorphic and paleoclimatic interpretations.

Paleoclimate data from some general circulation models (GCMs; COHMAP Members, 1988) suggest that winds over the Laurentide Ice Sheet circulated beneath a large, cold, dry, glacial anticyclone (Manabe and Broccoli, 1985; Kutzbach et al., 1993). The COHMAP model, which shows the presence of a glacially forced anticyclone, goes on to suggest that winds from 18,000 to 9000 BP had a greater easterly component in the Great Lakes region than they do today, since this region would have been at the southern margins of the anticyclone (Kutzbach et al., 1993). Other models (e.g., Rind, 1987) are less conclusive regarding surface winds in the Great Lakes region when compared to winds at present, or suggest that wind shifts varied markedly, depending on season. The coarse resolution and large scale of all such models, when taken in conjunction with subtle disagreements regarding late Pleistocene surface wind directions in the Great Lakes region, point to the need for studies such as ours, in which dominant wind directions at a specific time and place can be used as a form of ground truth.

Strong winds during the time of Lake Algonquin were probably created as cold, stable, dry air formed on the ice sheet and descended anticyclonically at the margins of the glacier (Kutzbach and Wright, 1985). Most models agree that in conjunction with glacially derived anticyclonic flow, a westerly flowing, polar jet stream paralleled the ice margin and was as strong or stronger than today (COHMAP Members, 1988). Thus, sharp temperature and pressure gradients within this jet stream/storm track area (between the core of the ice sheet [in Labrador] and the then-deglaciated Ohio Valley) would have led to frequent and intense cyclonic storms and their associated wind fields.

The easterly winds of the glacial anticyclone, which was particularly evident in July, were probably quite strong; the eroded SE coasts of Riggsville Island and the Moltke drumlin field attest to that.

With the long fetch afforded by Lake Algonquin, even moderate winds from the E, many of which would have been in association with strong cyclonic storms passing to the south, could have led to large wave heights and transported much sand and gravel to the WNW along the coast. Thus, we suggest that our spit data do corroborate the COHMAP model (1988) and its glacial anticyclone.

Related geomorphic studies provide additional "ground truth" that is also in support of the glacial anticyclone model. Data on ventifacts and spits in New England have been used to support the presence of a strong anticyclonic circulation immediately after the early recession of the Laurentide Ice Sheet (Thorson and Schile, 1995). Similarly, evidence from the Longmeadow dune (Connecticut) suggests that gusty anticyclonic winds existed out to 150 km from the ice margin. These winds were unimodally from the NE. Stabilized parabolic dunes in the St. Lawrence lowland were used by Filion (1987) to suggest that NE winds were strong in that area at about 10,000 BP. Filion suggested that these winds were part of the glacial anticyclone. David (1981) reported on eolian depositional and erosional features in Saskatchewan that had formed from uniformly SE paleowinds. These features formed between 10,000 and 8800 BP, when the ice margin was nearby, possibly acting as a forcing agent for strong SE winds descending off the ice sheet; modern winds are dominantly from the NW. Near Edinburg, North Dakota, a spit approximately 10 km in length extends NNW from a moraine that was a nearshore island within glacial Lake Aggasiz. This spit lies less than 2 km to the east of the Herman Beach on the west side of Lake Aggasiz. Its presence strongly suggests that longshore drift in NE North Dakota at about 11,000 BP was south to north. The North Dakota data corroborate the implied paleowind data from David (1981) in Saskatchewan. In New England, Thorson and Schile (1995) believed that spits developed on proglacial Lake Hitchcock, where they extend to the SW from drumlin islands, provide good evidence for wind-driven littoral currents in the lake during ice-free conditions. Directional data from

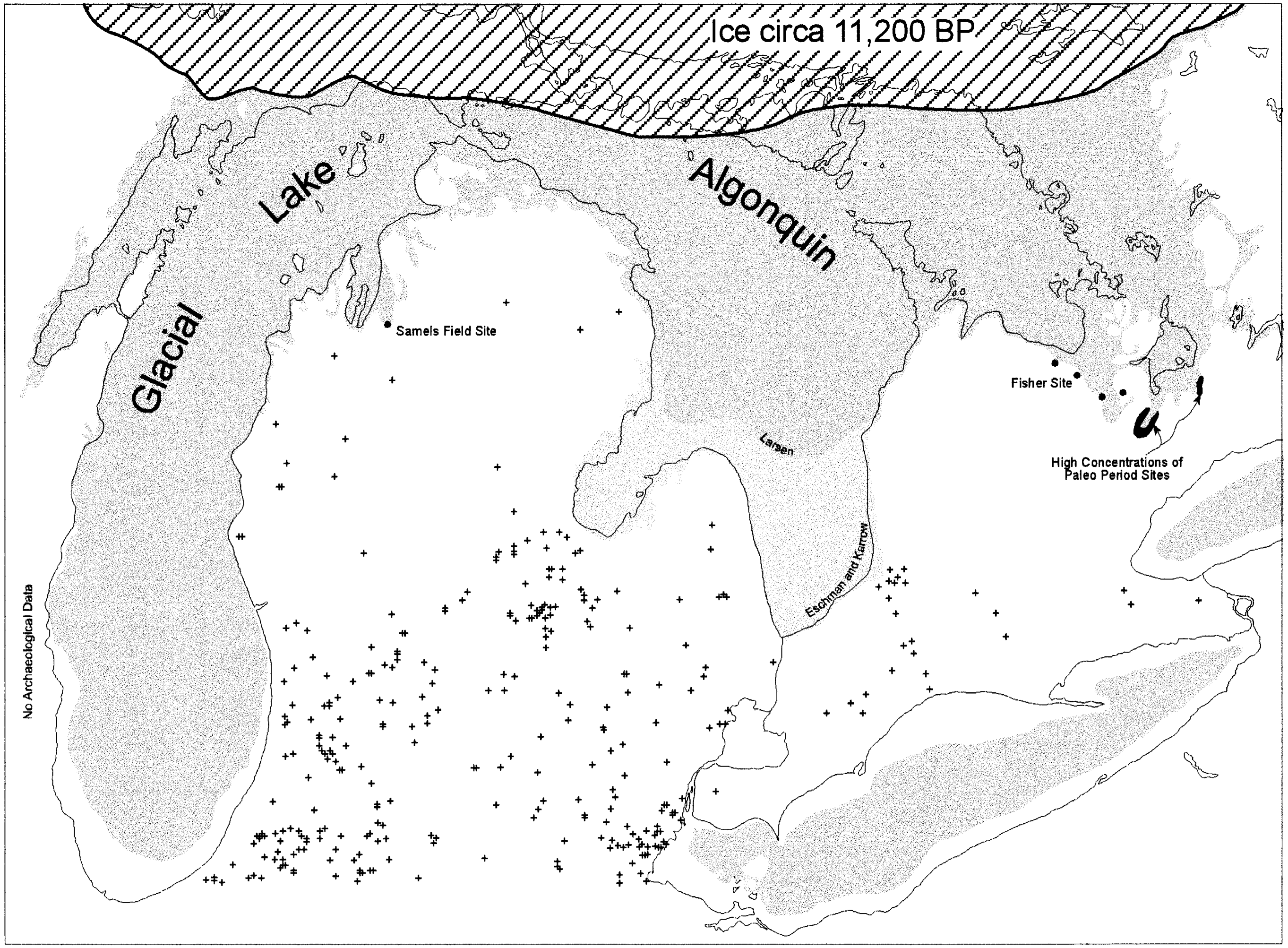

Fig. 6. Distribution of known Paleo-Indian archeological sites on uplands and nearshore sites during the time of Main Lake Algonquin for Michigan and Ontario. Data are based on a survey of the literature and knowledge of unpublished archeological surveys. Due to our ability to directly access the Michigan Bureau of History files on Paleo period archeological sites in Michigan, sites in Michigan are more numerous than are sites in Ontario.

these spits were used to support the theory that "strong summer winds driven by the glacial anticyclone were responsible for creating the spits" (p. 755).

By 9000 BP, the anticyclone was quite weak (COHMAP Members, 1988) and present only over eastern North America, suggesting that westerly winds may have begun to increasingly dominate the regional circulation. However, by this time, glacial Lake Algonquin had drained to a much lower phase, and its spits were subaerially exposed. Data from dunes in central lower Michigan support the interpretation that early Holocene winds were predominantly from the west (Arbogast et al., 1977).

4.5. Archeological data and paleoclimate

Archeological reconnaissance surveys undertaken along the Lake Algonquin shoreline in Ontario have uncovered numerous Paleo-Indian period sites (Stewart, 1984; Storck, 1984; Fig. 6). Some of these sites are probably the result of seasonal band aggregations from which communal hunting activities were undertaken (Deller and Ellis, 1988). As Algonquin waters receded, former coastal zones still played a vital role in Paleo-Indian settlement systems by allowing access to newly exposed lake beds which would have contained a variety of plant communities and possibly large numbers of deer, moose, and elk (Storck, 1984). Paleo-Indian sites associated with Lake Algonquin in central Ontario are usually adjacent to lagoons, bays, and small inlets (Deller, 1979; Storck, 1982; Deller and Ellis, 1988; Fig. 6). These physiographic features provided access to a wide range of resources, while enabling hunter/gatherers to intercept herbivores such as caribou. Barren ground caribou (*Rangifer tarandus*), probably a significant food source of northern Paleo-Indian groups, may have actually preferred to migrate along shorelines in large herds (Storck, 1984).

Evidence in support of strong winds amidst a harsh climate at 11,000–10,000 BP comes from the *virtual lack* of Paleo-Indian period (11,200 BP) archeological sites associated with glacial Lake Algonquin shoreline in northern lower Michigan (Fig. 6). Despite the important role Lake Algonquin must have played in the seasonal movements of many late Pleistocene hunter/gatherer groups, archeological reconnaissance surveys undertaken on similar physiographic features in eastern and northeastern lower Michigan have failed to yield a single site conclusively belonging to the Paleo-Indian period (Lovis, 1976; Smith, 1985; Fig. 6). The only Paleo-Indian period site in southern Michigan along an Algonquin strandline, Samels Field, is in the northwestern lower peninsula (Fig. 6). Hunter/gatherers residing at the Samels Field site would have been less impacted by cold, strong easterly winds and heavy lake-effect snows (which would have accumulated on the eastern side of the peninsula) than would their counterparts nearer the NE shore. Whereas early humans would normally have sought to occupy coastal zones (e.g., Schwartz and Grabert, 1973), these locational data suggest that intense winds, large waves, and heavy lake-enhanced snows, aided by a fetch of nearly 400 km, would have generated nearly intolerable conditions along many of the bays and inlets of late Pleistocene NE lower Michigan. Conversely, along the *eastern* (windward) *shores* of Lake Algonquin, in Ontario, where archeological sites are numerous (Fig. 6), climatically ameliorated conditions may have facilitated late Pleistocene hunter/gatherer settlement systems.

5. Conclusions

Large spits, found primarily on the NE side of the southern peninsula of Michigan, were formed within glacial Lake Algonquin and apparently partially grew during its later (falling) stages. They provide important "ground truth" in support of paleoclimatic models. These models suggest that the Laurentide Ice Sheet developed a strong glacial anticyclone during its retreat. The spits contain large, rounded gravel, usually derived from erosion of gravelly drift uplands that served as both sediment sources and headland "anchors". Archeological evidence also supports the hypothesis that winds were strong and conditions severe during the late Pleistocene in this ice-marginal setting, since few Paleo-Indian age sites have been found on the lee (western) side of Lake Algonquin in northern Michigan.

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