PROXY EVIDENCE FOR EASTERLY WINDS IN GLACIAL LAKE ALGONQUIN, FROM THE BLACK RIVER DELTA IN NORTHERN LOWER MICHIGAN

Melissa J. Vader, Bailey K. Zeman, Randall J. Schaetzl,[1] *Kristina L. Anderson, Ryan W. Walquist, Katharina M. Freiberger,* and *Jacob A. Emmendorfer*
Department of Geography
Michigan State University
East Lansing, Michigan 48824

Hong Wang
Illinois State Geological Survey
615 East Peabody
Champaign, IL 61820

Abstract: We examined a large, Late Pleistocene delta in northern Lower Michigan, formed by the Black River in Glacial Lake Algonquin. Today, this sandy, arcuate, wave-influenced delta stands several meters above the lake floor. The Black River transported mainly well-sorted, medium, and fine sands to the delta—at remarkably rapid rates. Our subsurface data, taken at 153 sites across the delta, show subtle and consistent trends in sediment texture across the delta surface. Although found in low amounts, gravel and very coarse sands are concentrated near the shoreline, presumably eroded by waves from the till and bedrock that crop out there. Sediments of very fine sand size (and finer) exist in higher concentrations near the eastern shore, sourced from eroded tills and also carried there on longshore currents. A clear sediment plume of medium and finer sands also traverses the delta SE to NW, which we interpret as evidence of sand transport by longshore currents flowing east to west, driven by easterly winds. High, perched spits on the head of the delta also suggest westerly longshore drift. These paleoclimate proxy data support previous interpretations of strong easterly winds here during the Late Pleistocene, probably in association with a glacial anticyclone. [Key words: GIS, soils, paleoclimate, paleolakes, glacial anticyclone, Glacial Lake Algonquin.]

INTRODUCTION

Deltas develop where rivers deposit more sediment into a body of water than can be carried away by waves, currents, and tides (e.g., Wright and Coleman, 1973). Deltas can assume many different forms, depending on the geographical processes dominating the area, particularly the balance between wave energy/regime of the water body, and sediment input rates from the river (Wright and Coleman, 1972; Galloway, 1975). As a result, delta forms can provide important information about paleoconditions of wave energy, wind direction, and river discharge.

[1]Corresponding author; email: soils@msu.edu

Physical Geography, 2012, **33**, 3, pp. 252–268. http://dx.doi.org/10.2747/0272-3646.33.3.252

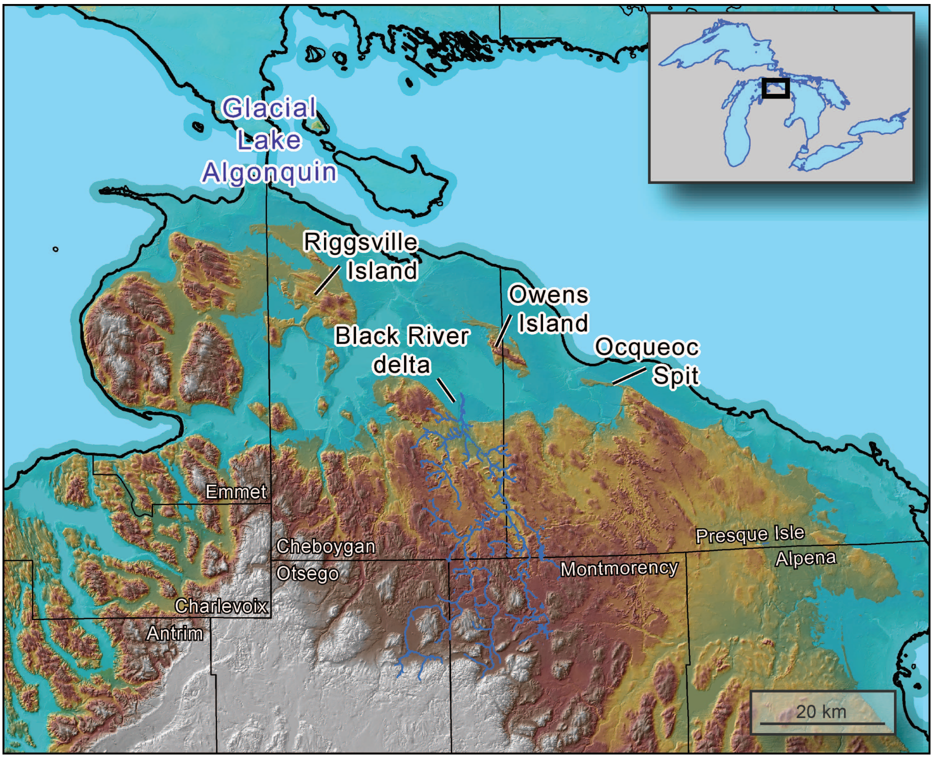

Fig. 1. Extent of Glacial Lake Algonquin in northern lower Michigan, shown in medium blue and based on Drzyzga et al. (2012). Prominent physical features of the region, and the location of the Black River delta, are also shown. The Black River and its tributaries are shown in dark blue; current Lakes Michigan and Huron are shown in light blue.

During the waning phases of the Late Wisconsin glaciation, several conditions led to the formation of numerous Pleistocene deltas throughout the Great Lakes region: (1) abundant runoff, sometimes promoted by permafrost within drainage basins; (2) minimally vegetated and hence, erodible, landscapes; and (3) many large, expansive, and long-lasting proglacial lakes. Most of these deltas are now stranded, high and dry, above former lake levels. Of particular importance to our study was the largest of these proglacial lakes: Glacial Lake Algonquin (Karrow and Calkin, 1985; Larsen, 1987; Farrand, 1995; Schaetzl et al., 2002; Drzyzga et al., 2012). During Glacial Lake Algonquin's existence, many rivers in northern Lower Michigan drained the sandy High Plains area, forming large deltas in the bordering lake, e.g., the Pigeon, Sturgeon, Boardman and Black rivers. Our study focuses on the Black River delta in Cheboygan County, Michigan (Fig. 1). This sandy, arcuate delta is a conspicuous landform on the post-glacial landscape (Fig. 2). Surprisingly, none of these deltas has yet been the focus of a geologic or geomorphic study. We believe

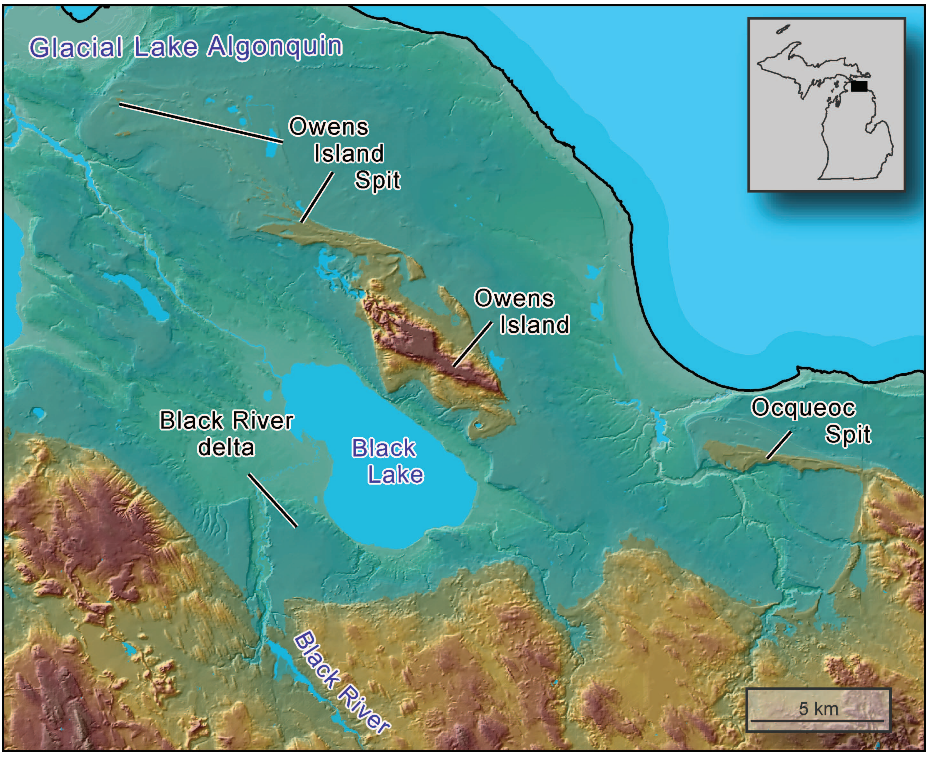

Fig. 2. Extent of Glacial Lake Algonquin in northeastern lower Michigan, showing the prominent physical features of the region, and the location of the Black River delta.

that these deltas can provide important information about Glacial Lake Algonquin, including its paleoclimate, waves and longshore currents, as well as the relative dominance of river versus wave energy in the lake.

To that end, the purpose of this study was to describe, map, and interpret the physical characteristics of the Black River delta, and to use these data to better understand the paleoenvironmental conditions, particularly with regard to coastal and eolian systems, at the time of its formation. To accomplish this, we collected and analyzed samples from soils on different features—i.e., topset beds, dunes, and spits—to glean insight into the paleoclimate of the region during the existence of Glacial Lake Algonquin and into the timing of the river's incision into the delta. Krist and Schaetzl (2001) reported evidence for strong easterly winds during this time period. Our work provides additional paleoclimatic proxy evidence from the Black River delta, which we use to sharpen our understanding of the paleoclimate near the ice margin during the Late Pleistocene. Luminescence dates on some sand dunes are also used to provide data on wind direction at the time of their formation, i.e., subsequent to the period of delta formation.

STUDY AREA

The Black River delta, located in eastern Cheboygan County, in northeastern Lower Michigan, formed as the junction of the northward-flowing Black River and Lake Algonquin, a late Pleistocene proglacial lake (Fig. 1). The 899 km^2 Black River basin is long and narrow, with a length of 43 km and a typical width of 17–19 km. The basin heads in the sandy, dry, High Plains province of northern Lower Michigan (Schaetzl and Weisenborn, 2004; Schaetzl et al., under review), falling from ca. 420 m in elevation to ca. 197 m at its outlet on the delta. After the demise and draining of Glacial Lake Algonquin, the Black River incised into the delta, forming a 20 m deep valley with inset terraces (Fig. 2). The arcuate-shaped Black River delta spans approximately 34 km^2. From the head of the delta to its apex—a distance of roughly 5.3 km—the delta maintains an extremely low gradient: 0.15%. At its toe, the edge of the delta drops steeply, 9–15 m, to the flat, sandy lake floor (Fig. 2).

The delta today contains a mix of xeric, low-density forests in various stages of regeneration. Although it is mostly forested today, and was as at the time of settlement, clear-cutting of forest patches on the delta is routine; most forest management is done to sustain jack pine regeneration. Some red pine plantations are also present.

Sandy sediments and dry, well-drained soils dominate the delta. Most soils are weakly developed Spodosols or sandy Entisols. In the Black River valley and within some of the smaller, inset valleys, wet sandy soils and Histosols are found.

Several groups of small sand dunes occur on the delta, and are named informally here for the first time. The Black River Terrace Dunes include several dunes scattered along the western edge of the Black River valley. These dunes range from 3–10 m in height and 20–110 m in length. Most of these dunes lack a specific orientation. The second group of dunes, the Black River Eastern Cut Bank Dunes, includes several dunes located immediately east of the incised Black River valley. These dunes are smaller, ranging from 1–6 m in height and 20–60 m in length. Most are irregularly shaped and have no specific orientation. A third group of dunes, over 50 in all, occurs on the eastern delta. The Eastern Delta Dunes range in height from 1–7 m and in length from 20–180 m; they also lack orientation. Finally, the Southeastern Delta Dunes consist of 14 dunes on the far southeastern part of the delta. These dunes range from 3–8 m in height and 40–180 m in length, with no preferred orientation.

Two small spits are located in the southeastern part of the delta, near the Black River (Fig. 3). The first spit is ca. 1 km in length and approximatelyl 5–6 m in height, whereas a second spit is about 500 m in length and ca. 4–5 m in height. In addition, several channels, some dry and some containing small amounts of running water, are located at the margins of the delta. These channels are not relict distributaries, as they clearly postdate the formation of the delta.

METHODS

Field and Lab Methods

Soil samples were collected from 153 sites, located uniformly across the delta. We chose places within the delta that were not on or near the shoreline of Glacial

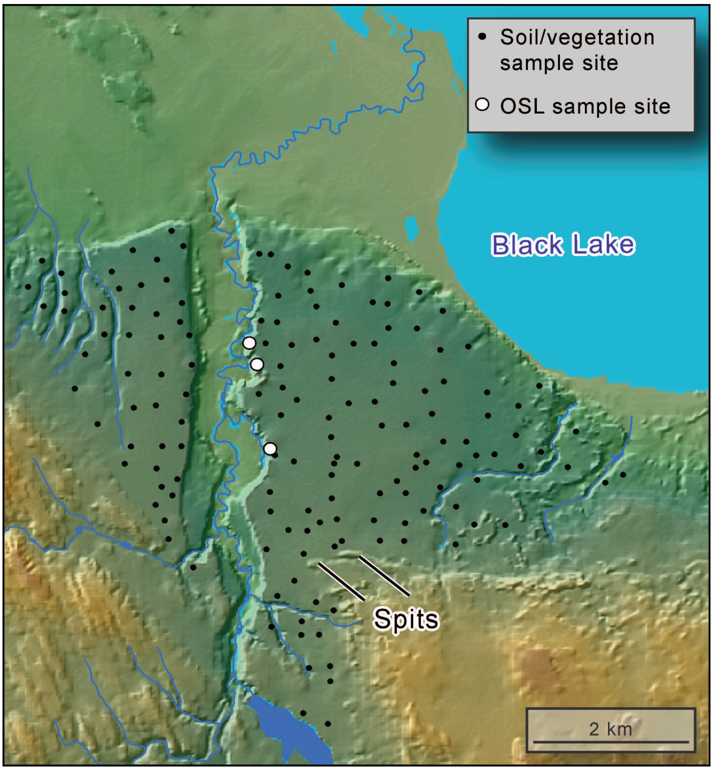

Fig. 3. Sample site locations and spits on the Black River delta.

Lake Algonquin, as soils in those areas may have been more indicative of shorezone than deltaic depositional conditions. All samples were taken at flat sites, at least 25 m away from any existing dunes or channels, to better reflect the deltaic depositional system.

At each location, we used a bucket auger to retrieve samples of ca. 400–500 g, from between 75 and 150 cm depth—i.e., the C horizon. In the field, the location of each sample was documented in ArcMap 10 GIS software, running on a laptop computer. The computer had a built-in GPS that allowed us to place each sample point on a base map. At each sample location we entered the name of the soil series, as determined in the field, as well as notes on soil texture or horizonation, into the GIS attribute table.

Samples were air-dried and passed through a 2 mm sieve, allowing for the determination of gravel (>2 mm) content. The remaining fine earth was sent through a 1 mm sieve to determine very coarse sand (1–2 mm diameter) content. Lastly, the fully homogenized 0–1 mm diameter fraction was prepared for detailed particle size analysis by adding 1–2 g of soil to a vial containing a water-based solution, using $(NaPO_3)_{13} \cdot Na_2O$ as the dispersant (Scull and Schaetzl, 2011) and agitated slowly for two hours to disperse the sample. The dispersed soil was analyzed on a

Malvern Mastersizer 2000 laser particle size analyzer (Malvern Instruments Ltd., Worcestershire, UK).

Three sand dunes were sampled for optically stimulated luminescence (OSL) dating. We chose dunes within the Black River Eastern Cut Bank Dunes, near the eastern bluff of the Black River, where it had deeply incised into the delta. We assumed that the dunes formed shortly after the fluvial incision event, with the sand source being the exposed cutbanks. We obtained the OSL samples from the C horizons of soils exposed in pits, dug at the crest of each of the dunes. Samples were retrieved from between 155 and 170 cm, using two-inch (5 cm), black PVC tubing, and processed at the Illinois State Geological Survey, Urbana, IL. About 500 g of soil, from an area within 25 cm of the tube sample, were recovered for dose rate analysis. OSL analyses were run on the 250 μm fraction.

Lastly, we took samples of shallowly buried clasts, to characterize two ridges thought to be spits. We assumed that clasts moved by waves and currents would become increasingly spherical and rounded with distance, particularly because most of the clasts here have soft, carbonate lithologies. We sampled clasts from 15 sites at sites recently disturbed by logging equipment or by gravel excavations, exposing numerous clasts in the upper 25 to 50 cm. Other locations, i.e., undisturbed sites, were not sampled. At each site, several dozen clasts were passed through a stack of two sieves, with openings of 37.5 and 25 mm. Clasts between 25 and 37.5 mm in diameter were retained; final sample sizes ranged from 63 to 86 clasts. The sphericity and roundness of the clast samples were determined by one person, using a double-blind method to minimize interpreter bias. Clasts were compared to standard sphericity and roundness charts, as found in Schoeneberger et al. (2002), and the data entered into an Excel spreadsheet for linear regression analysis and graphing.

GIS, Data Analysis, and Soils Mapping

Features associated with the physical geography of the delta and the Black River drainage basin were mapped in a GIS. Dedicated shapefiles were created for rivers, sand dunes, lakes, and dry channels by digitizing layers (DRG and a hillshade) in ArcGIS 10 and entering data (points or polylines) directly over the georectified maps. Rivers were differentiated from dry channels based on symbology as shown on topographic maps. These data enabled us to determine the extent of the Black River drainage basin, which was later verified using a flow accumulation routine in ArcGIS.

Our soil map of the delta began with the published NRCS county soil survey data (Tardy, 1991). We imported the GIS data from the NRCS's Soil Data Mart web site (http://soildatamart.nrcs.usda.gov/) and clipped the map to the extent of the delta. Because our soil map was to be published at a smaller scale than was the original NRCS map, we simplified the latter by dissolving small map units into similar, surrounding ones, where appropriate. We also created map unit complexes in some areas where the NRCS had mapped consociations, again because of scale issues but also based on field observations of soil complexity in those areas. Lastly, we adjusted some of the NRCS map unit boundaries based on data observed in the field.

Particle size data were exported from the laser particle size analyzer and summed into logical size groupings—e.g., fine sand, coarse silt, medium silt through medium sand—based largely on the USDA naming scheme (Soil Survey Division Staff, 1993). Grouped particle size data were joined to the existing shapefile of soil sample points, to facilitate mapping of particle size variability across the delta. These data were kriged, with various amounts of smoothing, to create isoline maps of particle size fractions across the delta.

RESULTS AND DISCUSSION

Delta Formation and Incision

Glacial Lake Algonquin maintained high levels between approximately 13.1 and 12.5 ka cal yr BP (Harrison, 1972; Karrow, 2004). It drained, perhaps catastrophically, to very low levels when an outlet opened near North Bay, Ontario (Harrison, 1972; Finamore, 1985). Presumably as a result of this drop in base level, the Black River began to incise into its delta, eventually forming a 20 m deep valley with at least two sets of terraces—one at roughly 198 m and another at ca. 210 m elevation. We assumed that the dunes that line the eastern margin of the valley formed as the river exposed sandy sediment in its cut banks, allowing it to be deflated and transported to the lip, i.e., onto the delta surface proper. Therefore, ages obtained from these dunes should provide minimum limiting dates for the demise of Glacial Lake Algonquin and the subsequent incision of the Black River.

The three dunes we dated by OSL yielded ages between 8.31 and 9.33 ka (Table 1). These ages confirm that the river had begun incising its valley shortly after the demise and fall of Glacial Lake Algonquin, and that the dunes had formed and became stabilized within 4000 years of that time. Because the dates came from samples near the dune crests, i.e., the last parts of the dunes to stabilize, it is likely that river incision and dune formation began considerably earlier than 9 ka. The dates confirm that dune formation had ended by ca. 8.3 ka.

More importantly, their locations on the eastern edge of the river bluff indicate that the dunes were formed by westerly winds. No dunes of comparable size exist on the western bluff. Together, the OSL ages on the dunes, as well as their locations, suggest that, by ca. 9.3 ka, the dominant winds were westerly at this location and latitude.

Delta Soils and Sediments

The soil map created for this project shows that the vast majority of the delta surface is composed of dry, sandy soils (Fig. 4, Table 2). Inset valleys contain somewhat poorly and poorly drained soil series, but also within sandy families. The majority of the Black River valley, exclusive of terraces, is dominated by Histosols.

Soil data, derived entirely from our sample data set, illustrate that the delta soils are extremely sandy, averaging 99.2% sand, with medium and fine sand fractions dominating (Fig. 5C). The mean weighted particle size for all 153 samples is 342 $\pm$ 72 μm, centrally placed within the medium sand fraction. Most samples have less

Table 1. Optically Stimulated Luminescence Dates on Sand Dunes near the Black River Valley

	Sample		
	BRD-1	BRD-2	BRD-3
Depth, cm	165	155	170
Aliquots	27	24	24
Equivalent dose, Gy	13.91 ± 0.71	12.73 ± 0.65	14.91 ± 0.45
U, Bq/kg	4.49 ± 0.33	4.53 ± 0.33	4.38 ± 0.29
Th, Bq/kg	5.18 ± 0.34	4.67 ± 0.32	4.72 ± 0.28
K, Bq/kg	384.16 ± 38.75	397.02 ± 40.02	438.74 ± 44.07
Water content, %	18.39	21.01	26.56
Cosmic dose, Gy/ka	0.177	0.179	0.176
Dose rate, Gy/ka	1.313	1.352	1.477
Age, Kyr	9.33 ± 0.86	8.31 ± 0.77	9.03 ± 0.76

than 3.0% very fine sand and less than 6% very coarse sand. These data illustrate the high degree of sorting shown in the delta sediments and suggest that the Black River was mainly transporting and depositing well-sorted and washed, sandy bedload.

We estimated the volume of the delta (>0.606 km^3) by conservatively measuring its extent and thickness, using its height above the lake floor, and assuming that the lake floor continues beneath the delta without significant amounts of pre-existing hummocky topography. Then, by assuming a 1700-year (maximum) period of existence for Glacial Lake Algonquin, we determined that the Black River transported, on average, 356,800 m^3 of sediment to the delta, per year. Using a density of 1.5 g/cm^3 for dry sand, these data correspond to ca. 53,500 metric tons of sand transported to the delta annually, or 147 tons/day. If we account for a four-month freeze-over period, during which little or no sediment would have been transported, the data are even more impressive: an average of 220 tons of sediment transported to the delta, daily, during the warm seasons. These data illustrate the great rapidity with which the delta was constructed and suggest that runoff and sediment transport rates on the early Holocene landscapes of northern Lower Michigan were as much as two, to perhaps even four, orders of magnitude greater than today.

On the delta, gravel (>2 mm) is uncommon, comprising on average only 0.3% of delta sediments. Samples with gravel contents >1% tend to occur near the Lake Algonquin shoreline, and at the head of the delta (Fig. 5B). This pattern is as expected; in wave-dominated deltas, coarse sediment tends to remain close to shorezone areas (Ashton and Giosan, 2011). The silt content of the delta is also very low, averaging only about 0.6% of delta sediment. Silt contents are also maximal near the shorelines, particularly along the eastern margins of the delta, where they approach 8% (Fig. 5H). We believe that the gravel- and silt-rich areas developed as waves eroded gravelly, loamy tills at the shorelines, releasing a variety of sediment

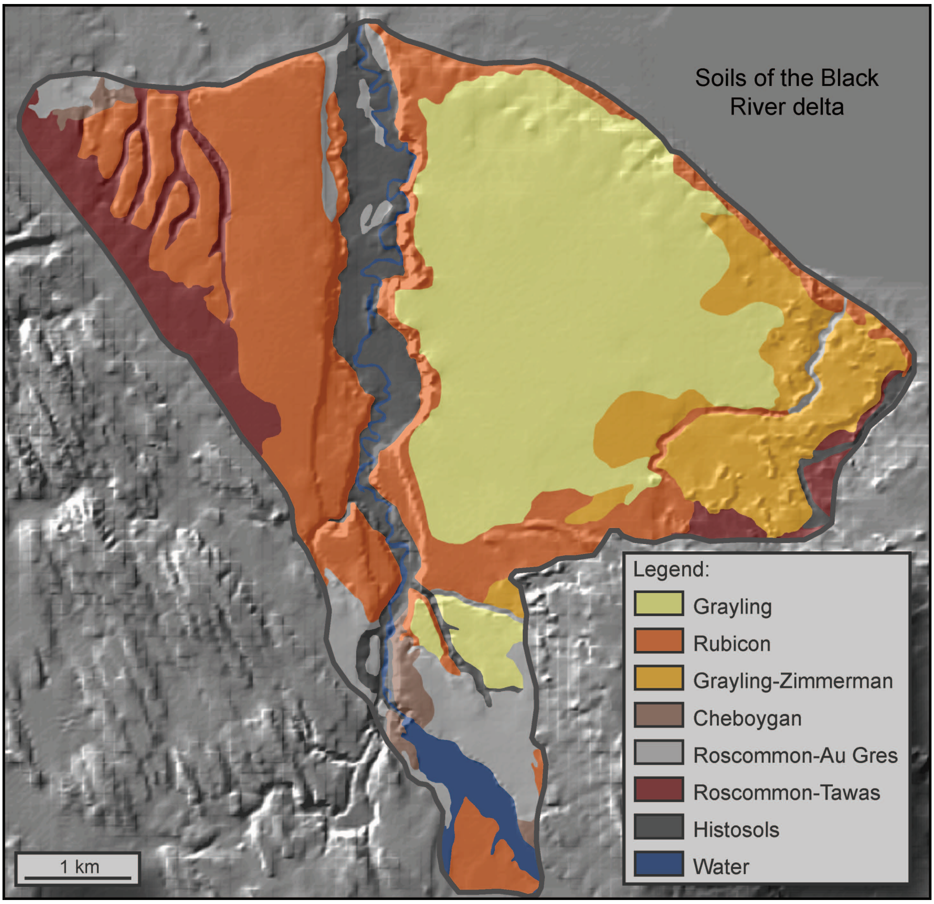

Fig. 4. Soil map of the delta created for this project, showing the distribution of the major soil series (and soil series complexes) across the delta (see Table 2). The map represents a merged product using NRCS data (Tardy 1991), slightly generalized because of scale differences, and our field data.

into the nearshore environment. Much of the coarser sediment, however, remained in the vicinity, becoming particularly concentrated in the eastern margins of the delta, while many of the finer sands were transported away by waves and currents. Silts and clays entered into suspension in the lake and, as a result, were generally dispersed widely across the delta, nonetheless maintaining slightly higher concentrations near the source (Fig. 5H). These trends are well illustrated in the map of mean weighted particle size data (Fig. 5A).

Although the topset delta sediments appear at first to be monotonously uniform—dry and sandy—notable variations do occur. Indeed, isoline maps of various sediment contents (Fig. 5) revealed many important, consistent, and explainable textural patterns across the delta. Mapped data show that sediment sizes are finest near the eastern margin of the delta and get progressively coarser toward the delta's center (Fig. 5). A key aspect of these maps is the unmistakable pattern whereby the area of

Table 2. Major Soils of the Black River Delta

Soil series	Subgroup classification	Drainage class
Grayling	Mixed, frigid, Typic Udipsamments	Excessively drained
Rubicon	Sandy, mixed, frigid Entic Haplorthods	Somewhat excessively drained
Zimmerman	Mixed, frigid Lamellic Udipsamments	Somewhat excessively drained
Cheboygan	Coarse-loamy, mixed, active, frigid Alfic Haplorthods	Well or moderately well drained
Au Gres	Sandy, mixed, frigid Typic Endoaquods	Somewhat poorly drained
Roscommon	Mixed, frigid Mollic Psammaquents	Poorly and very poorly drained
Tawas	Sandy or sandy-skeletal, mixed, euic, frigid Terric Haplosaprists	Very poorly drained

Source: Tardy, 1991.

finest sediment continues into the mid-delta region as a distinct "plume," trending to the northwest. Coarse sediment areas occur on either side, i.e., southwest and north, of this plume. For example, note the area of very coarse sand that occurs west of the river, in the southwestern corner of the delta (Fig. 5D). Comparable plumes exist for most sediment fractions that span the 50–1000 μm range (Figs. 5E–5G).

We believe that the patterns shown in Figure 5 are explained by interplay between the two main forces that typically interact on deltas: (1) waves and longshore currents versus (2) fluvial transport and deposition (Wright and Coleman, 1973; Galloway, 1975). Medium-sand-dominated bedload was being transported northward, onto the delta, by the Black River and its distributaries. The high rate of delta progradation is evident from our estimates. For this reason, the delta is dominated by well-sorted, medium sands across most of its extent (Fig. 5C). Because the river was transporting sediment at such a rapid rate, the delta built out, into Glacial Lake Algonquin, without any significant asymmetry (Li et al., 2011). Coarser and finer materials were then added to the mix, having been eroded from shoreline areas and variously transported onto the delta. Coarse sediment, i.e., gravels and very coarse sands, remained in coastal areas and near the head of the delta, where much of it had been initially deposited by the river (Figs. 5B and 5D). Sediment smaller than roughly 60 μm was spread out, onto the delta, in a more dispersed manner, probably in suspension (Fig. 5H).

Key to this pattern, however, are the finer sands, i.e., the fractions between 50 and ca. 900 μm. We believe that these sands were being eroded to (and from) the southeastern delta area by westwardly flowing littoral drift in the Lake Algonquin shorezone. Note that the eastern edge of the delta is located at the far western end of a long, relatively straight shoreline (Fig. 2), that has only one small embayment in it. Longshore currents could easily have set up along this east-west–trending coastline, transporting the finer sands of coastal origin onto the delta, after which they veered northward into the central delta, where northwardly flowing currents, set up within distributaries, would have been more dominant. The resultant flow direction is shown in northwesterly trending sediment plumes in Figures 5E, 5F, and 5G. The

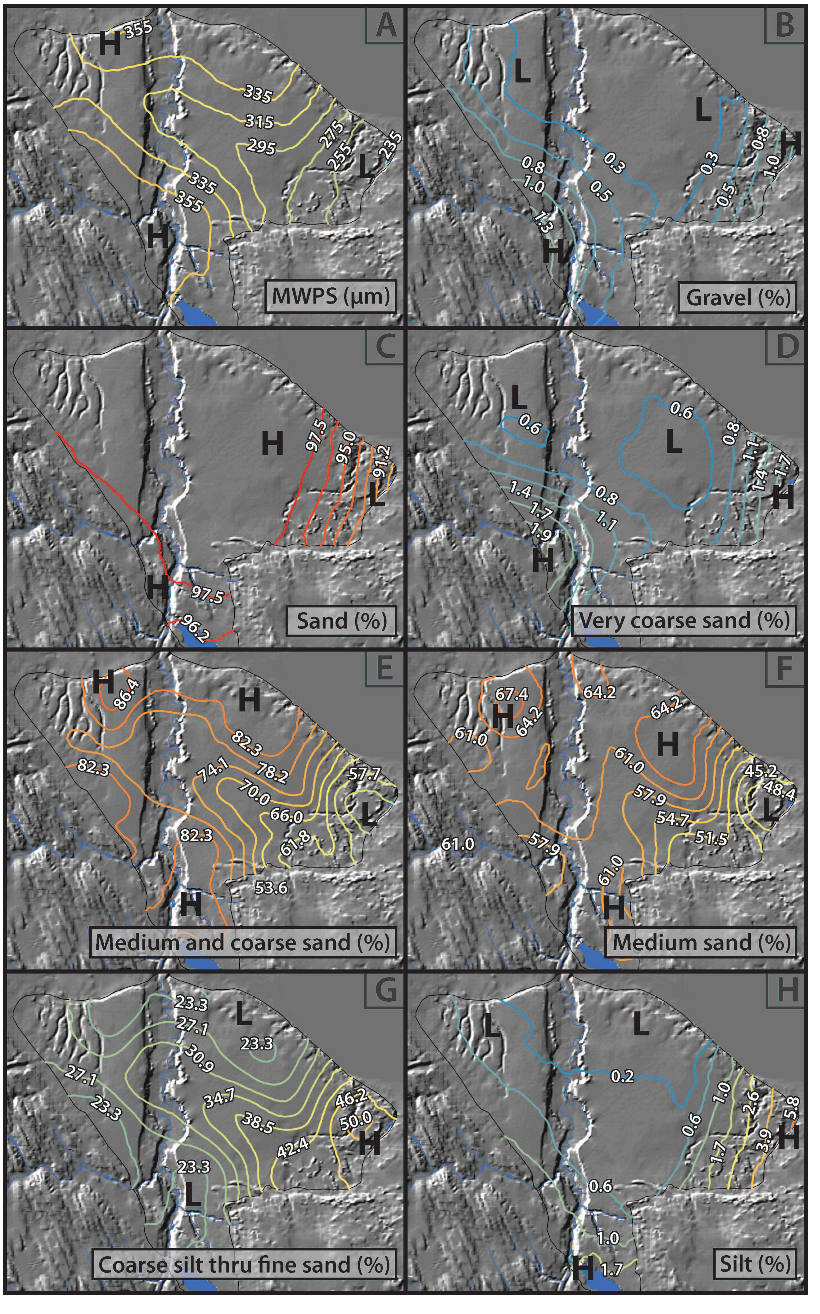

Fig. 5. Isoline maps of various sediment concentrations on the Black River delta. The maps were created using the standard kriging routine in ArcGIS. A. Mean weighted particle size value (of the 0–1000 μm fraction), in μm. B. Gravel (>2 mm diameter) content, in %. C. Sand (50–2000 μm) content, in %. D. Very coarse sand (1000–2000 μm) content, in %. E. Medium and coarse sand (250–1000 μm) content, in %. F. Medium sand (250–500 μm) content, in %. G. Coarse silt and fine sand (40–125 μm), in %. H. Silt (2–50 μm) content, in %.

widespread occurrence of Zimmerman soils (Table 1, Fig. 4) in the southeastern parts of the delta provide field evidence for the fine-sediment additions to the deltaic system, presumably from shorezone areas. Zimmerman soils are similar to the sandier Grayling and Rubicon soils, but have silty and clayey bands (lamellae) at depth, and generally have more fine sands than do Grayling soils.

We reiterate that the general symmetry of the delta and its uniformly sandy textures suggest that fluvial contributions outpaced additions from longshore drift. Nonetheless, subtle patterns, clearly evident in Figures 5A and 5E–5G, point to persistent, east-to-west longshore drift within the delta depositional system. Unfortunately, we do not have core or facies data that could have more convincingly ascertained the importance of longshore drift to the delta (e.g., Evans and Clark, 2011).

The data in Figure 5 show that longshore transport on the delta was dominantly westward; these currents must have been driven by easterly winds. These may be the first proxy paleoclimate data of their kind for this region. A wider view of the region's paleogeography (Figs. 1 and 2) indicates that the delta lies in a somewhat protected area along the Lake Algonquin shore. As a result, wave energy may not have been as strong here as on the islands and headlands studied by Krist and Schaetzl (2001) because of shorter fetches and the protection afforded the delta by the Ocqueoc spit, its headland, and Owens Island. Thus, (1) gravels and very coarse sand were not transported in the delta center, and (2) the delta does not show pronounced asymmetry. In sum, longshore drift may not have been intense, but was, rather, continuous and steady within the study area.

Although the best expressed sediment plumes are within grain-size ranges that are often transported by wind, we are confident that the sediment we sampled is deltaic. First, areas near obvious dunes on the delta were avoided while sampling. Second, we observed no evidence of eolian ripples, sand sheets, or other eolian forms on the delta surface; it is monotonously flat, especially in the center, where the plume is most pronounced.

Delta Landforms

The gross morphology and composition of the Black River delta suggest that it fits within Galloway's (1975) wave-dominated category. The smooth outline of the delta, coupled with a general lack of paleodistributary channels, suggest that the margin of the delta was under attack by waves during at least the latter stages of its formation (Jerolmack and Swenson, 2007). Additionally, the steep subaqueous slope at the toe of the delta suggests that wave energy could have been strong against its outer margins (Wright and Coleman, 1972). In sum, the delta formed under conditions of strong sediment supply, as well as intense wave action at its outer margins. Strong littoral currents are likely to have existed under such a scenario.

Spit orientation has long been used as a proxy for the direction of winds along coasts (Krist and Schaetzl, 2001; Jewell, 2007). The two small spits that exist near the head of the delta extend from a small headland, westward into the delta. Their orientation supports our hypothesis that easterly winds were driving westwardly flowing longshore currents (e.g., Bakker and Edelman, 1965; Schofield et al., 2004). Because of their elevation, several meters above the delta, these spits probably formed early, when the lake was at a higher level, or are barrier spits from a single storm event, and breached later. Clasts in the spits were probably eroded from the limestone-cored headland that exists just to the east. Data on clast roundness and sphericity show almost no change along the spits (Fig. 6), which we interpret as evidence that they formed quickly, perhaps in association with one, or only a few, storm events.

Paleoclimate Implications of the Black River Delta

The Late Pleistocene circulation patterns of North America are still being debated. As more research is published on landforms and sediment that formed under specific wind regimes—e.g., dunes, loess, spits, and other proxies—our knowledge of atmospheric circulation patterns near the retreating ice margin is becoming clearer, although some evidence is contradictory. For example, early work suggested that strong northwesterly winds were "skirting the southern perimeter of the Laurentide ice sheet" (Wells 1983, p. 324). Alternatively, the notion of a glacial anticyclone, first introduced by Hobbs (1943) and supported by the work of David (1981), began to be debated. Climate model simulations supported the early work by Hobbs (1943) and reinforced the concept of a glacial anticyclone driving easterly winds near the ice margin (COHMAP Members, 1988). The COHMAP model suggested that the anticyclone existed until at least 9 ka in the Midwestern U.S.; this work has been further supported by other model refinements (Bartlein et al., 1998; Kutzbach et al., 1998). Questions still exist, however, about the strength of these anticyclonic winds, as well as their seasonality and geographic extent (Muhs and Bettis; 2000, Jewell, 2010).

In part, the COHMAP model spurred others to search for supporting or refuting evidence—largely in proxy form—of the glacial anticyclone, and more details about its extent and strength. Based on geochemical data from loess deposits, Muhs and Bettis (2000) showed that Late Glacial paleowinds were westerly in and around the latitude of Iowa. Although they recognized the presence of a glacial anticyclone, Muhs and Bettis (2000) reasoned that loess deposition patterns there may have developed because of infrequent but strong northwesterly winds generated by passing storm systems, unrelated to the perhaps more prevalent easterly winds generated by the anticyclone. They dismissed the notion that anticyclonic winds could have existed, but in a relatively narrow band next to the ice. Nonetheless, it is worth noting that their study sites were hundreds of kilometers south of the ice margin, allowing for the possibility that easterly winds could have existed at this time, constrained to areas nearer the ice margin. Again based on data from eolian systems, Sweeney et al. (2004) found the evidence for anticyclonic circulation, or at least a weakening of the westerlies, from 35 to 15 ka in Washington state. Earlier, the work of Krist and Schaetzl (2001) had reported on Late Glacial–age landforms that formed due to easterly winds and which existed <100 km from the ice margin. They suggested that the many large, long spits that trail to the northwest, off of headlands and islands in Glacial Lake Algonquin in northern Lower Michigan, formed due to high waves driven by strong, easterly winds (Figs. 1 and 2). Many of the Lake Algonquin islands also show evidence of pronounced erosion on their eastern sides

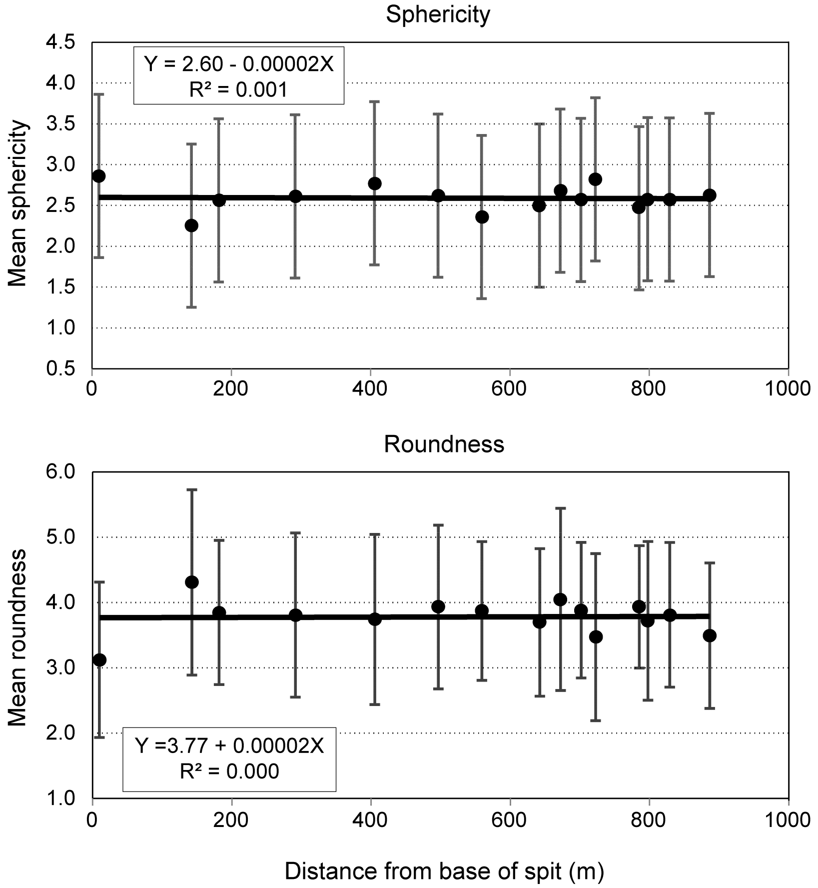

Fig. 6. Scatterplots of sphericity and roundness of clast samples recovered from two spits on the Black River delta. Bars represent one standard deviation from the mean.

(Fig. 2), supporting this interpretation. These sites, like the Black River delta, would have existed less than 150 km from the ice margin.

Our work supports that of Krist and Schaetzl (2011) for this region; sediment distribution patterns on the Black River delta strongly suggest that longshore currents and transport were driven westward by easterly winds (Fig. 5). Although the plan view of the delta is not asymmetrical, which would have unequivocally suggested oblique wave approach angles during its formation (Ashton and Giosan, 2011), sediment redistribution within the delta clearly points to wave approach angles from the east, coupled with longshore currents transporting medium and finer sands to the west-northwest (Bhattacharya and Giosan 2003).

In deltas where wave energy is high, cuspate forms can develop, especially if fluvial inputs are minimal (Komar, 1973). However, given the large rate of bedload transport likely to have been occurring here, and the somewhat sheltered location of the delta (Fig. 1), it seems likely that fluvial (sediment supply) processes were able to keep pace, or outpace, erosion by waves and littoral currents. Thus, the delta developed its arcuate shape by balancing rapid fluvial sediment inputs with wave-driven erosion, and developed its sediment patterns via longshore transport of medium and finer sands across a rapidly growing, sandy, deltaic plain.

CONCLUSIONS

Sediment patterns on the Black River delta reflect, first, northward fluvial transport of large amounts of medium-fine sand bedload, onto the delta. Most of these sediments were widely distributed across the delta, although the delta front developed a steep but smooth margin, presumably due to erosive wave action. Areas of erosion along shorelines also contributed gravel, fine sand, and silt to the deltaic system. Gravels and very coarse sands remained preferentially concentrated in these shorezone areas, while the finer sands were transported westwardly and northerly, in longshore currents, out onto the delta. We suggest that this pattern developed because of easterly winds, driving westwardly flowing littoral currents. This research, using paloeclimate proxy data from the Black River delta, supports the notion of a easterly winds coming from a glacial anticyclone during the Late Pleistocene, in this area. OSL ages on sand dunes that formed shortly after the delta had become subaerial indicate that, by ca. 9.3 ka, the dominant winds here had become westerly.

Acknowledgements: This project was supported by a grant from the Michigan State University Honors College, and the work was largely performed as part of a Freshman Honors seminar at MSU. We thank Sarah Acmoody for GIS support and Mike Luehmann for graphics work. Ryan Haag and Emily Pasek assisted with the project in the field and lab, as part of their Professorial Assistantships at MSU. We also thank Lance Lindell of the United Auto Workers and the Walter and Mae Ruether Family Education Center for kindly granting us access to the UAW property for sampling.

REFERENCES

Ashton, A. D. and Giosan, L. (2011) Wave-angle control of delta evolution. *Geophysical Research Letters*, Vol. 38 [doi: 10.1029/2011GL047630].

Bakker, W. and Edelman, T. (1965) The coastline of river deltas. In *Proceedings of the 10th Coastal Engineering Conference*. New York, NY: American Society of Civil Engineers, 199–218.

Bartlein, P. J., Anderson, K. H., Anderson, P. M., Edwards, M. E., Mock, C. J., Thompson, R. S., Webb, R. S., Webb, T., III, and Whitlock, C. (1998) Paleoclimate simulations for North America over the past 21,000 years: Features of the simulated climate and comparisons with paleoenvironmental data. *Quaternary Science Reviews*, Vol. 17, 494–585.

Bhattacharya, J. P. and Giosan, L. (2003) Wave-influenced deltas: Geomorphological implications for facies reconstruction. *Sedimentology*, Vol. 50, 187–210.

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

David, P. P. (1981) Stabilized dune ridges in Northern Saskatchewan. *Canadian Journal of Earth Sciences*, Vol. 18, 286–310.

Drzyzga, S. A., Shortridge, A. M., and Schaetzl, R.J. (2012) Mapping the stages of Glacial Lake Algonquin in Northern Michigan, USA, and nearby Ontario, Canada, using an isostatic rebound model. *Journal of Paleolimnology*, Vol. 46, in press.

Evans, J. E., and Clark, A. (2011) Re-interpreting Great Lakes shorelines as components of wave-influenced deltas: An example from the Portage River delta (Lake Erie). *Journal of Great Lakes Research*, Vol. 37, 64–77.

Farrand, W. R. (1995) The Pleistocene glacial record in the area of Alpena, Montmorency, and Presque Isle counties, Michigan. In T. J. Black, ed., *Karst Geology of the Northeast Lower Peninsula, Michigan*. East Lansing MI: Michigan Basin Geological Society, Department of Geological Science, Michigan State University, 35–41.

Finamore, P. F. (1985) Glacial Lake Algonquin and the Fenelon Falls outlet. In P. F. Karrow and P. E. Calkin, eds., *Quaternary Evolution of the Great Lakes*. Toronto, Canada: Geological Society of Canada Special Paper, Vol. 30, 127–132.

Galloway, W. E. (1975) Process framework for describing the morphologic and stratigraphic evolution of deltaic depositional systems. In M. L. Broussard, ed., *Deltas: Models for Exploration*. Houston, TX: Houston Geological Society, 87–98.

Harrison, J. E. (1972) *Quaternary Geology of the North Bay–Mattawa Region*. Toronto, Canada: Geological Survey of Canada Paper, 71–26.

Hobbs, W. H. (1943) The glacial anticyclone and the continental glaciers of North America. *Proceedings of the American Philosophical Society*, Vol. 86, 368–402.

Jerolmack, D. J. and Swenson, J. B. (2007) Scaling relationships and evolution of distributary networks on wave-influenced deltas. *Geophysical Research Letters*, Vol. 34, L23402 [doi: 10.1029/2007GL031823].

Jewell, P. W. (2007) Morphology and paleoclimatic significance of Pleistocene Lake Bonneville spits. *Quaternary Research*, Vol. 68, 421–430.

Jewell, P. W. (2010) River incision, circulation, and wind regime of Pleistocene Lake Bonneville, USA. *Palaeogeography, Palaeoclimatology, Palaeoecology*, Vol. 293, 41–50.

Karrow, P. F. (2004) Algonquin-Nipissing Shorelines, North Bay, Ontario. *Géographie Physique et Quaternaire*, Vol. 58, 297–304.

Karrow, P. and Calkin, P. (1985) *Quaternary Evolution of the Great Lakes*. Toronto, Canada: Geological Association of Canada Special Paper, Vol. 30.

Komar, P. D. (1973) Computer models of delta growth due to sediment input from rivers and longshore transport. *Geological Society of America Bulletin*, Vol. 84, 2217–2226.

Krist, F. and Schaetzl, R. J. (2001) Paleowind (11,000 BP) directions derived from lake spits in northern Michigan. *Geomorphology*, Vol. 38, 1–18.

Kutzbach, J. E., Gallimore, R., Harrison, S. P., Behling, P., Selin, R., and Laarif, F. (1998) Climate and biome simulations for the past 21,000 years. *Quaternary Science Reviews*, Vol. 17, 473–506.

Larsen, C. E. (1987) *Geological History of Glacial Lake Algonquin and the Upper Great Lakes*. Washington, DC: United States Geological Survey Bulletin 1801.

Li, W. G., Bhattacharya, J. P., and Wang, Y.M. (2011) Delta asymmetry: Concepts, characteristics, and depositional models. *Petroleum Science*, Vol. 8, 278–289.

Muhs, D. R. and Bettis, E. A., III. (2000) Geochemical variations in Peoria loess of western Iowa indicate paleowinds of midcontinental North America during last glaciation. *Quaternary Research*, Vol. 53, 49–61.

Schaetzl, R. J., Drzyzga, S. A., Weisenborn, B. N., Kincare, K. A., Lepczyk, X. C., Shein, K. A., Dowd, C. M., and Linker, J. (2002) Measurement, correlation, and mapping of Glacial Lake Algonquin shorelines in northern Michigan. *Annals of the Association of American Geographers*, Vol. 92, 399–415.

Schaetzl, R. J., Enander, H., Luehmann, M. D., Lusch, D. P., Fish, C., Bigsby, M., Steigmeyer, M., Powers, J., Forgacs, C., and Pollyea, A. (under review) Mapping the physiography of Michigan using GIS. Manuscript submitted to *Physical Geography* (April 2012).

Schaetzl, R. J. and Weisenborn, B.N. (2004) The Grayling Fingers geomorphic region of Michigan: Soils, sedimentology, stratigraphy, and geomorphic development. *Geomorphology*, Vol. 61, 251–274.

Schoeneberger, P. J., Wysocki, D. A., Benham, E. C., and Broderson, W. D., eds. (2002) *Field Book for Describing and Sampling Soils*, version 2.0. Lincoln, NE: Natural Resources Conservation Service, National Soil Survey Center.

Schofield, I., Jewell, P., Chan, M., Currey, D., and Gregory, M. (2004) Shoreline development, longshore transport, and surface wave dynamics, Pleistocene Lake Bonneville, Utah. *Earth Surface Processes and Landforms*, Vol. 29, 1675–1690.

Scull, P. and Schaetzl, R. J. (2011) Using PCA to characterize and differentiate the character of loess deposits in Wisconsin and Upper Michigan, USA. *Geomorphology*, Vol. 127, 143–155.

Soil Survey Division Staff (1993) *Soil Survey Manual*. Washington, DC: U.S. Government Printing Office, USDA Handbook No. 18.

Sweeney, M. R., Busacca, A. J., Richardson, C. A., Blinnikov, M., and McDonald, E. V. (2004) Glacial anticyclone recorded in Palouse loess of northwestern United States. *Geology*, Vol. 32, 705–708.

Tardy, S. W. (1991) *Soil Survey of Cheboygan County, Michigan*. Washington, DC: US Government Printing Office, USDA Soil Conservation Service.

Wells, G. L. (1983) Late-glacial circulation over central North America revealed by aeolian features. In A. Street-Perrott, M. Beran, and R. Ratcliffe, eds., *Variations in the Global Water Budget*. Boston, MA: D. Reidel, 317–330.

Wright, L. D. and Coleman, J. M. (1972) River delta morphology: Wave climate and role of subaqueous profile. *Science*, Vol. 176, 282–284.

Wright, L. D. and Coleman, J. M. (1973) Variations in morphology of major river deltas as functions of ocean wave and river discharge regimes. *American Association of Petroleum Geologists Bulletin*, Vol. 57, 370–398.