

## Kame deltas provide evidence for a new glacial lake and suggest early glacial retreat from central Lower Michigan, USA



Randall J. Schaetzl<sup>a,\*</sup>, Kenneth Lepper<sup>b</sup>, Sarah E. Thomas<sup>a</sup>, Leslie Grove<sup>a</sup>, Emma Treiber<sup>a</sup>, Alison Farmer<sup>a</sup>, Austin Fillmore<sup>a</sup>, Jordan Lee<sup>a</sup>, Bethany Dickerson<sup>a</sup>, Kayleigh Alme<sup>b</sup>

<sup>a</sup> Department of Geography, Environment, and Spatial Sciences, 673 Auditorium Rd, Michigan State University, East Lansing, MI 48823, United States

<sup>b</sup> Optical Dating and Dosimetry Lab, Geosciences Department, North Dakota State University, P.O. Box 6050, Dept. #2745, Fargo, ND 58108-6050, United States

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### ABSTRACT

In association with an undergraduate Honors Seminar at Michigan State University, we studied two small kame deltas in north-central Lower Michigan. These recently identified deltas provide clear evidence for a previously unknown proglacial lake (Glacial Lake Roscommon) in this large basin located in an interlobate upland. Our first goal was to document and characterize the geomorphology of these deltas. Because both deltas are tied to ice-contact ridges that mark the former position of the retreating ice margin within the lake, our second goal was to establish the age of one of the deltas, thereby constraining the timing of ice retreat in this part of Michigan, for which little information currently exists. Both deltas are composed of well-sorted fine and medium sands with little gravel, and have broad, nearly flat surfaces and comparatively steep fronts. Samples taken from the upper 1.5 m of the deltas show little spatial variation in texture, aside from a general fining toward their outer margins. Gullies on the outer margins of both deltas probably postdate the formation of the deltas proper; we suggest that they formed by runoff during a permafrost period, subsequent to lake drawdown. We named the ice lobe that once covered this area the Mackinac Lobe, because it had likely advanced into the region across the Mackinac Straits area. Five of six optically stimulated luminescence (OSL) ages from one of the deltas had minimal scatter and were within  $\pm 1000$  years of one another, with a mean age of  $23.1 \pm 0.4$  ka. These ages suggest that the Mackinac Lobe had started to retreat from the region considerably earlier than previously thought, even while ice was near its maximum extent in Illinois and Indiana, and the remainder of Michigan was ice-covered. This early retreat, which appears to coincide with a short-lived warm period indicated from the Greenland ice core, formed an “opening” that was at least occasionally flooded. Thick and deep, fine-textured deposits, which underlie much of the region, probably date to this time. Our work provides the first evidence of this extremely early ice retreat from central Lower Michigan, occurring almost 4000 years before the southern margin of the ice (Saginaw Lobe) had started its retreat from the state.

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### 1. Introduction

Deltas can form where rivers deposit more sediment into a standing body of water than can be carried away by the erosive forces of currents, waves, and tides. These forces act on the deltaic sediment, eventually determining the form, shape, extent, and sedimentology of the delta. As a result, information about conditions at the time of delta formation can often be determined from various physical characteristics of the delta (Wright and Coleman, 1972, 1973; Galloway, 1975; Bhattacharya and Giosan, 2003; Howard, 2010; Ashton and Giosan, 2011; Vader et al., 2012; Anthony, 2015). Key to our study is the dating of sandy, fluvio-deltaic sediment by luminescence techniques (Roberts et al.,

2009; Wallinga and Bos, 2010; Schirmer et al., 2011; Shen and Mauz, 2011; Tamura et al., 2012), thereby constraining the period of delta formation.

Using GIS techniques, Luehmann (2015) developed an inventory of the Pleistocene deltas of southern Michigan but did not study any of them in detail. In our study, we focused on two small kame deltas in north-central Lower Michigan, USA, first identified by Luehmann. Both deltas formed in close association with large, sandy, ice-contact ridges that mark a stationary position of the Laurentide Ice Sheet as it retreated from the uplands of central Lower Michigan during Marine Isotope Stage (MIS) 2. Together, the two deltas also provide clear evidence for a previously unknown, high-elevation, proglacial lake, which we here informally name *Glacial Lake Roscommon*. Therefore, this study not only is the first to confirm the existence of this lake, but also constrains its age by reporting optically stimulated luminescence (OSL) ages from

\* Corresponding author.

E-mail address: [soils@msu.edu](mailto:soils@msu.edu) (R.J. Schaetzl).

one of the deltas associated with the lake. These deltas formed as the ice margin was subaqueously grounded, and are associated with ice-contact ridges.

To that end, the purpose of this study is to examine the physical characteristics of two kame deltas on the high, sandy plains of north-central Lower Michigan. OSL data from one of the deltas were used to constrain the age of both the delta and its associated ice margin. Additionally, physical characteristics of the deltas were used to provide insight into the paleoclimate and sedimentological processes at work during their formation. This study represents the first significant research on the glacial geomorphology of this key interlobate area between the Saginaw and Lake Michigan Lobes.

## 2. Study area

The deltas are part of a large, sandy upland known locally as Michigan's "High Plains" (Davis, 1935; Fig. 1). The High Plains is a large interlobate area of the Laurentide Ice Sheet (Rieck and Winters, 1993), bounded in part by the Cadillac Morainic Uplands associated with the Lake Michigan Lobe to the west, and the West Branch moraine of the Saginaw Lobe to the southeast (Fig. 1; Leverett and Taylor, 1915; Mickelson et al., 1983; Blewett et al., 2009). Burgis (1977) and Schaetzl (2001) suggested that the ice that entered this region moved as a discrete lobe, rather than as part of the Saginaw Lobe to the south. Both authors argued that this ice entered the region generally from the northeast. Burgis (1977) referred to this ice as the "northwestern sublobe". For reasons that we will elaborate on later, we are naming the ice that advanced into the study area from the north and northeast during MIS 2 the *Mackinac Lobe*.

Rieck and Winters (1993), who called the High Plains region the "North-Central Interlobate," reported on the extreme thickness of the glacial deposits in this part of Lower Michigan. Glacial deposits exceed 200 m in thickness across the High Plains, and are commonly well in excess of 250 m thick (Schaetzl and Weisenborn, 2004; Schaetzl et al., 2013). Soil and sediment textures across the High Plains are almost uniformly sandy, but with Histosols in the many swamps (Schaetzl, 2002). Much of the coarse-textured, stratified sediment is not directly glacial, but is more commonly associated with glaciofluvial and, as

we suggest below, glaciolacustrine processes (Blewett and Winters, 1995; Schaetzl et al., 2006).

Much of the High Plains north of the Au Sable and Manistee Rivers are large, broad outwash plains (sandur) of the Port Huron readvance (Leverett and Taylor, 1915; Blewett, 1991, 1995; Blewett and Winters, 1995; Schaetzl et al., 2006; Fig. 2), which reached its maximum extent between 12.7 and 13.5  $^{14}\text{C}$  yrs. BP (Blewett et al., 1993). The Port Huron advance ended with widespread stagnation, forming large heads of outwash that transition into flat outwash plains or sandurs. The Port Huron's head of outwash has a conspicuous ice-contact face/escarpment, forming most of the northern margins of the High Plains; its broad sandur extends far into the Plains proper (Fig. 2). Set within the northern-middle section of the High Plains are the Grayling Fingers (Schaetzl and Weisenborn, 2004). They are the highest part of this northern Michigan landscape, and serve as the drainage divide for the lower peninsula. Two of the larger rivers in Michigan - the Au Sable and Manistee - head here, where elevations are highest, and flow within large valleys through the High Plains, eventually draining into modern-day Lakes Huron and Michigan, respectively (Fig. 1).

The High Plains area has a significant amount of relief; local relief often exceeds 50–80 m. Much of the relief derives from the deeply incised river valleys and from the large morainic systems that ring the southern and western margins of the Plains (Fig. 1). Notable, however, is the large, broad basin that occupies the south-central part of the High Plains (Figs. 2, 3), which is today drained primarily by the Muskegon River (Figs. 1, 2). We name this basin the Houghton Lake basin, for modern-day Houghton Lake, which occupies its central section (Figs. 2, 3). Houghton Lake, which forms the headwaters of the Muskegon River, is not a kettle, but instead is a shallow lake that essentially fills the lowermost part of the Houghton Lake basin. The lake - the largest in Michigan - has an average depth of  $\approx 2.3$  m, with only a few small areas deeper than 5 m.

As the ice was retreating from the Houghton Lake basin, we believe that the area was variously inundated by proglacial waters, and large areas of it became infilled with sandy and clayey sediment. Burgis (1977) referred to the large areas of flat, sandy topography that lie between the ridges as the St. Helen Plain (Fig. 3). The St. Helen Plain is likely a combination of flat, sandy, glaciolacustrine plains, along with

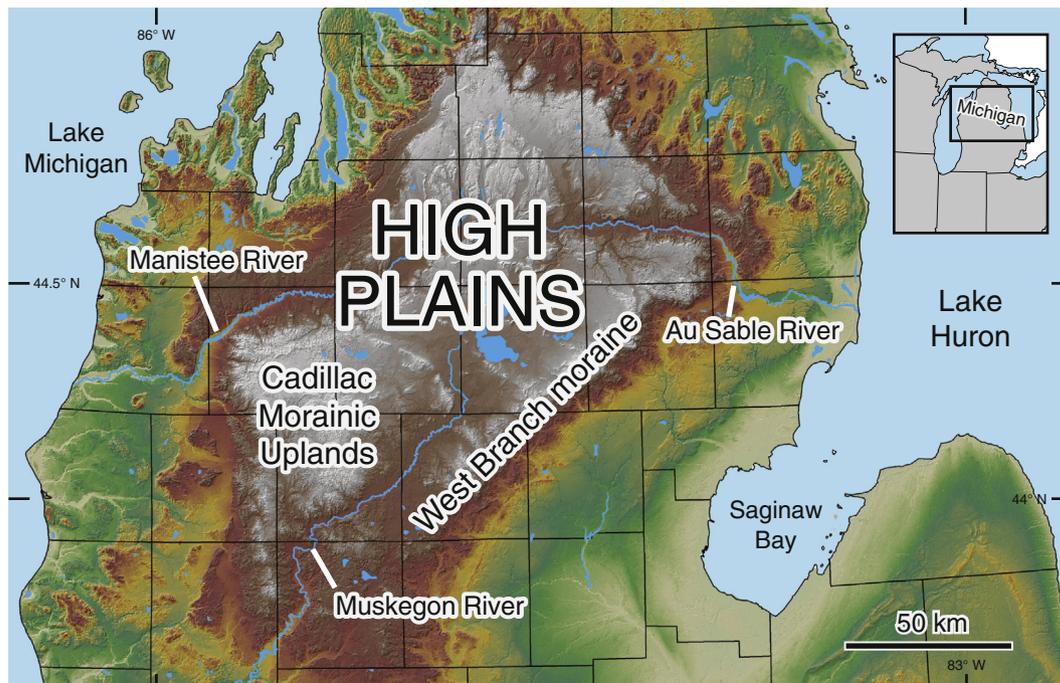
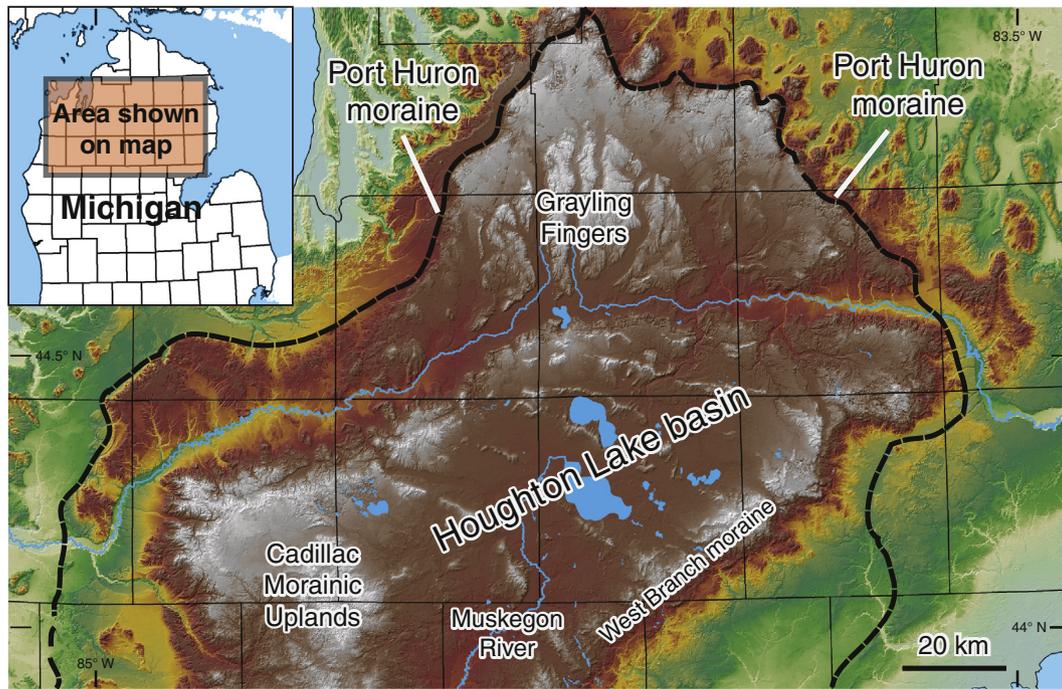


Fig. 1. Topography of central Lower Michigan on a color elevation base, showing the area known as the High Plains, and other important physical features.



**Fig. 2.** Topography of the study area, broadly defined, on a color elevation base. In the northwestern part of the map, the dashed line shows the inferred extent of the Outer Port Huron advance.

outwash surfaces that accordantly grade into them. Although surface textures across the St. Helen Plain are predominantly sandy, thick sequences of clayey and silty sediment occur commonly at depth, based on water well log data. Early glacial mapping also noted the clays at depth (Leverett and Taylor, 1915). The numerous swamps and wetlands in the basin – an otherwise high, sandy region – also point to the widespread occurrence of slowly permeable clays and silts at depth.

Several high, often sharp-crested ridges, composed of coarse-textured, stratified sediment, break up the Houghton Lake basin (Fig. 2). Together, they form a subparallel series of ice-contact ridges. Gravel pits in each of these ridges attest to the sandy, generally stratified, ice-contact nature of the deposits there. Burgis (1977) referred to these uplands as kamic ridges, and named several of them (Fig. 3). The ridges are distinctly arcuate and convex inward, suggestive of a subaqueously grounded ice margin retreating to the northeast, leading to accelerated melting and calving within the middle part of the submerged ice front. Gaps in the ridges are common. The presence of some cross-cutting ridges in the basin points to a complex history of ice advance and retreat. It is not our purpose to explore the nature of ice retreat from the basin; rather, we used the ages from one of the kame deltas associated with the North Higgins Lake Ridge to provide a key temporal anchor for ice retreat from the central part of the basin.

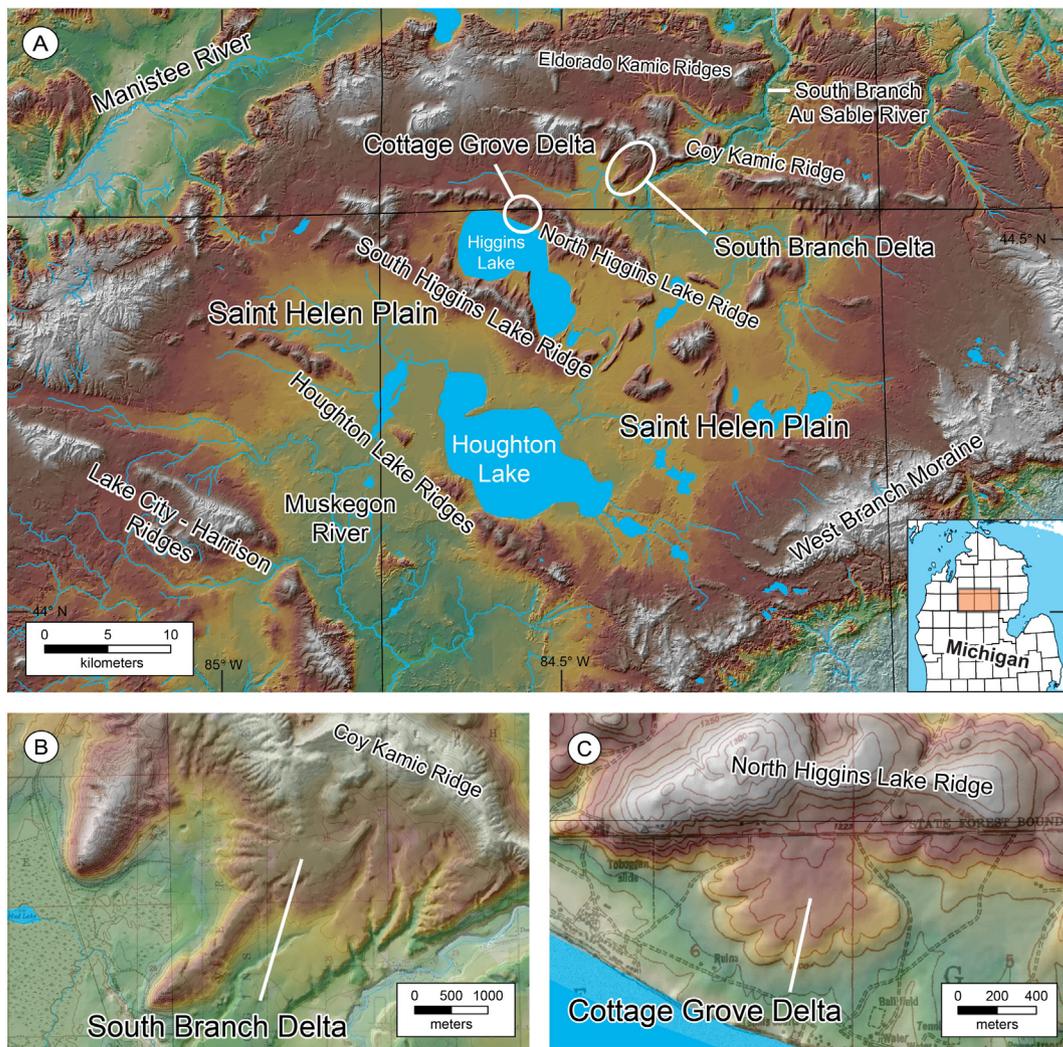
Luehmann (2015) first identified the two small deltas that we elected to study. Both were identified as deltas based on their geomorphology and association with presumed ice-contact ridges. Both occur on the southern sides of their respective ridges, implying that ice retreat within the Houghton Lake basin was from southwest-to-northeast. We named the deltas as follows: the South Branch (SB) Delta is the easternmost feature, named for its location within South Branch Township, Crawford County (Fig. 3C). This delta is associated with a large, ice-contact ridge named the Coy Kamic Ridge by Burgis (1977). The second delta we studied – the Cottage Grove (CG) Delta – is farther west and south. It is associated with the North Higgins Lake Ridge, as named by Burgis (1977) (Fig. 3B). We named it the Cottage Grove delta after the land association that currently owns it – the Cottage Grove Association. Today, both deltas are forested upland landscapes composed of excessively drained, sandy soils.

### 3. Methods

Field and lab work for this project were coordinated through an undergraduate Honors Seminar at Michigan State University, led by Schaetzl. This type of team-oriented, class-based research has become a successful model within the Geography, Environment, and Spatial Sciences Department at Michigan State University, e.g., Arbogast et al. (1997), Hupy et al. (2005), Lusch et al. (2009).

The first goal of this project was to characterize the sediments associated with the deltas. After introductory lectures and discussions, the 12 students were divided into two groups of six, one group per delta. An initial grid of potential sample (target) locations for each delta team was entered into a shapefile in ArcMap, running on a field laptop computer. The approach was to obtain a suite of samples that were generally uniformly distributed (as constrained by topography) across each delta, at  $\approx 60$ –110 m spacings, and on level sites. If the initial site was not level or could have been eroded, students navigated to a nearby area that was more suitable and geomorphically stable. Samples were recovered from the upper 30–155 cm of the sediment, using an 8.3-cm dia. bucket auger. Sediment was retrieved incrementally while augering, in order to obtain a representative sample of the entire sediment column. Final sample locations were recorded in a new shapefile. In all, 72 samples were recovered from the South Branch delta and 48 from the Cottage Grove delta.

All samples were air-dried and passed through a 2-mm sieve, isolating the coarse fraction, which was discarded. The remaining fine-earth fraction was then passed through a 1-mm sieve to determine the content of very coarse sand (1–2 mm dia.). The remaining (0–1 mm dia.) fraction was prepared for particle size analysis by dispersing it in a weak solution of  $(\text{NaPO}_3)_{13}\text{Na}_2\text{O}$ , diluted with  $\approx 10$  ml of distilled water. After shaking for 10–15 min, the samples were run on a Malvern Mastersizer 2000E laser particle size analyzer. Data exported from the Mastersizer were examined in Microsoft Excel and then imported into a GIS project as shapefiles, with each suite of data associated with a sample point. In order to examine spatial trends, the data were portrayed in ArcMap both as graduated symbols and as isolines developed using simple kriging.



**Fig. 3.** Topography of the Houghton Lake basin, showing names for the important physical features. Parts B and C provide larger scale maps of the two deltas studied here. Note the differing scales for the maps in B and C.

Our second goal was to determine the age of one of the deltas, using luminescence techniques (Fuchs and Owen, 2008). To this end, six samples were recovered from the Cottage Grove delta for OSL dating. Of these, two were taken from areas of low slope gradient on the relatively coarser-textured center of the delta; we assume these samples represent topset beds. Additionally, two samples were taken from the sloping outer margins of the delta, on presumed foreset beds where surface slope gradients ranged between 5 and 10%. OSL ages on these four samples were assumed to represent the latter stages of the delta's formative period, and might best represent minimum-limiting ages for delta formation and for the period when the ice margin began to recede from the North Higgins Lake Ridge. Lastly, two samples were retrieved from the bottoms of the wide, deep gullies that occur on the delta periphery. These two sites are situated  $\approx 4\text{--}5$  m below the top of the delta proper. Ages from these samples represent deltaic deposition during the middle phase of delta formation, when the ice was situated at the ridge.

The OSL samples were taken from between  $\approx 115$  and 150 cm depth, in sediment freshly exposed in 2 m deep pits. We extracted the samples using metal cylinders of approximately 8 cm dia., which were closed on one end. The sediment in the pits showed little or no stratification, but was instead composed of uniform, well-sorted, fine and medium sands that lacked distinct bedding structures. In two pits, we observed a thin, gravelly layer at depth, and took samples from below this layer.

OSL analyses were performed in the Optical Dating and Dosimetry Lab at North Dakota State University. The ages were determined from

clean quartz sand extracts in the grain size range 150–250  $\mu\text{m}$  using single aliquot regenerative dose (SAR) procedures (Murray and Wintle, 2000; Wintle and Murray, 2006). Sample preparation, data collection and data analysis methodology are described in the supplement to Lepper et al. (2007). Dose rates were calculated following the methods presented in Aitken (1985, 1998) and Prescott and Hutton (1988, 1994).

## 4. Results and discussion

### 4.1. Delta morphologies

Each of the two deltas has a broad, nearly flat, central core that breaks fairly abruptly to a steep delta front, which in turn descends to the flat, sandy lake floor. Both deltas also have wide, broad gullies on their outer margins. The gullies do not connect to any type of relict distributary channels, suggesting that they were cut subaerially by runoff after the lake drained. This period of runoff and erosion was likely associated with an interval of permafrost that occurred after the deltas had become subaerial (Schaetzl, 2008). The Cottage Grove delta has accumulated  $\approx 7\text{--}10$  m of sandy sediment above the former lake floor; the South Branch delta is considerably thicker, measuring 22 to 27 m thick. Although we lack deep subsurface data that would have revealed their internal stratigraphies, we expect that both of the deltas are sandy throughout, have Gilbert-type sedimentologies, and formed under the influence of strong waves within lakes with fairly constant water levels

(Galloway, 1975). Thus, it follows that most of our auger samples represent the topset beds of the deltas.

The main body of the South Branch delta is  $\approx 1.75$  km in width and  $\approx 1.5$  km in length. However, the delta continues as a long, narrow, arm-like ridge (Fig. 3B), extending from the southwestern edge of the delta. The ridge is about  $\approx 2$  km long and averages  $\approx 500$  m in width. Interestingly, the ridge, which is nearly 50 m above the lake floor, is 1–3 m lower than the delta proper, perhaps due to wave planning. We can offer no explanation for the origin of this feature, except to suggest that it may be an ice-contact landform, formed between masses of stagnant ice grounded within the lake.

The Cottage Grove delta is fan-shaped and considerably smaller, being only  $\approx 1$  km wide. It has the appearance of a Gilbert-type delta (Fig. 3C). Where the Cottage Grove delta adjoins its ice-contact ridge, it lacks a conspicuous valley or spillway. The implications of this morphology are unclear, but it may suggest that most of the meltwater was debouching onto the delta from the ice itself, rather than flowing across the ridge proper and cutting a channel. Conversely, meltwater flowing off the Coy Kamic Ridge and onto the South Branch delta appears to have deposited sediment, forming a large, long ridge, in places over 10 m in height, that extends from the delta, back and onto the ridge proper. This morphology is suggestive of a walled-in feeder channel, experiencing aggradation during delta formation. It is likely that stagnant ice was present on either side of this ridge, forming a sluiceway for water flowing from the main ice sheet, onto the delta proper. Fieldwork indicated that soils within this ridge were more gravelly than on the delta proper, as would be expected for a constrained channel. Neither delta shows signs of erosion or incision by meltwater, suggesting that meltwater here was sediment-rich.

In plan view, the Cottage Grove delta's almost symmetrical morphology is suggestive of multi-directional, wave-driven erosion along the delta front (Vader et al., 2012). The steep outer margins of both deltas are typical of wave-influenced deltas, with strong wave energies (Vader et al., 2012). Taken together, the morphologies of the deltas suggest that the basin was replete with isolated ice blocks and stagnant, subaqueously grounded ice margins during deglaciation.

#### 4.2. Delta textures

Sediment texture data for the two deltas are so similar as to justify discussing them together. Surficial, i.e., the upper 1.5 m, sediments in both deltas are extremely sandy (Table 1). "Sand" is by far the most common textural class. The excellent sorting of the delta sediment is evident by their low silt and clay contents. Sediment for both deltas has a mean weighted particle size value in the medium sand fraction (Table 1). Although we did not quantitatively determine the gravel contents because of our small sample sizes, we nonetheless noted in the lab

that gravel contents were seldom greater than  $\approx 7\%$ , and usually near zero. In sum, the surficial sediments of both deltas are sandy and remarkably well sorted, with silt + clay contents rarely  $>4\%$ .

We found no evidence to suggest that the deltas are not also sandy at depth. Indeed, most of the deltas associated with proglacial lakes in northern Michigan are composed of thick and extensive sandy deposits, and often have this type of morphology (Vader et al., 2012; Schaetzl et al., 2013; Blewett et al., 2014; Luehmann, 2015). Sandy textures are also associated with the ice-contact ridges that are linked to the deltas, and the lowlands between them (Schaetzl et al., 2013).

Our data provide spatial information about the sand textures that dominate the topset beds of both deltas (Fig. 4). Both deltas are coarsest in the central sections, and get progressively finer toward the outer edges. The latter areas represent, at least in some locations, foreset beds. In sum, textural data support the traditional model of Gilbert-type deltas, which here are composed of wave-worked, well-sorted, sandy sediment.

#### 4.3. Glacial Lake Roscommon

The presence of deltas in the basin supports the hypothesis that a high-elevation, periodically stable paleolake did exist here. Although broader issues related to Glacial Lake Roscommon are not the focus of this paper, some mention of its possible extent, elevations, and characteristics seems appropriate. Luehmann (2015) identified six deltas in the Houghton Lake basin, pointing to a wide and varied sequence of paleolakes. Other morphological features associated with semi-permanent glacial lakes – wave-cut benches or bluffs, constructional coastal features such as spits, and outlets at elevations consistent with all of the former – are also present within the basin. At various locations within the basin, we have discovered thick sequences of fine-textured sediment that are presumably glaciolacustrine clays and silts, immediately below sandy surficial sediment. These clays were even mentioned by the earliest glacial mappers (Leverett and Taylor, 1915). It is important to note that a lake could have existed only if ice had started to retreat from the area, while the modern (and lowest) outlet to the basin, at the Muskegon River, remained blocked by the Lake Michigan Lobe, the Saginaw Lobe, or their deposits (Figs. 2, 3).

Preliminary research points to at least four, possibly five, distinct lake stages within the basin, each associated with a clear, overfit and overwidened/overdeepened outlet in the uplands that surround it, as well as various types of coastal features. Based on preliminary research on outlet and beach ridge elevations, we have identified lake stages at  $\approx 372$  m,  $\approx 365.5$  m,  $\approx 355$  m, and  $\approx 346$  m. We recognize that any outlet could have undergone erosion or aggradation after its abandonment, implying that these elevations are, at best, rough estimates of prior lake plains. Nonetheless, the Cottage Grove delta appears to correlate well to the 372 m lake stage, whose outlet at approximately the same elevation is located ca. 8 km NW of the city of West Branch (Fig. 5). The elevation of the South Branch delta is considerably (10–11 m) higher than even the 372 m lake stage, pointing to either (1) a still higher-elevation lake stage within the basin, or (2) the delta's possible origin within a smaller, ice-walled lake, perched above the main lake. The former scenario may also suggest that another outlet exists – one that either we don't know about, which was bounded by ice, or which has been deeply downcut since the lake drained. Although much work remains to be done on Glacial Lake Roscommon and its geomorphic evolution, our research clearly indicates that such a proglacial lake did exist in the Houghton Lake basin during the MIS 2 retreat.

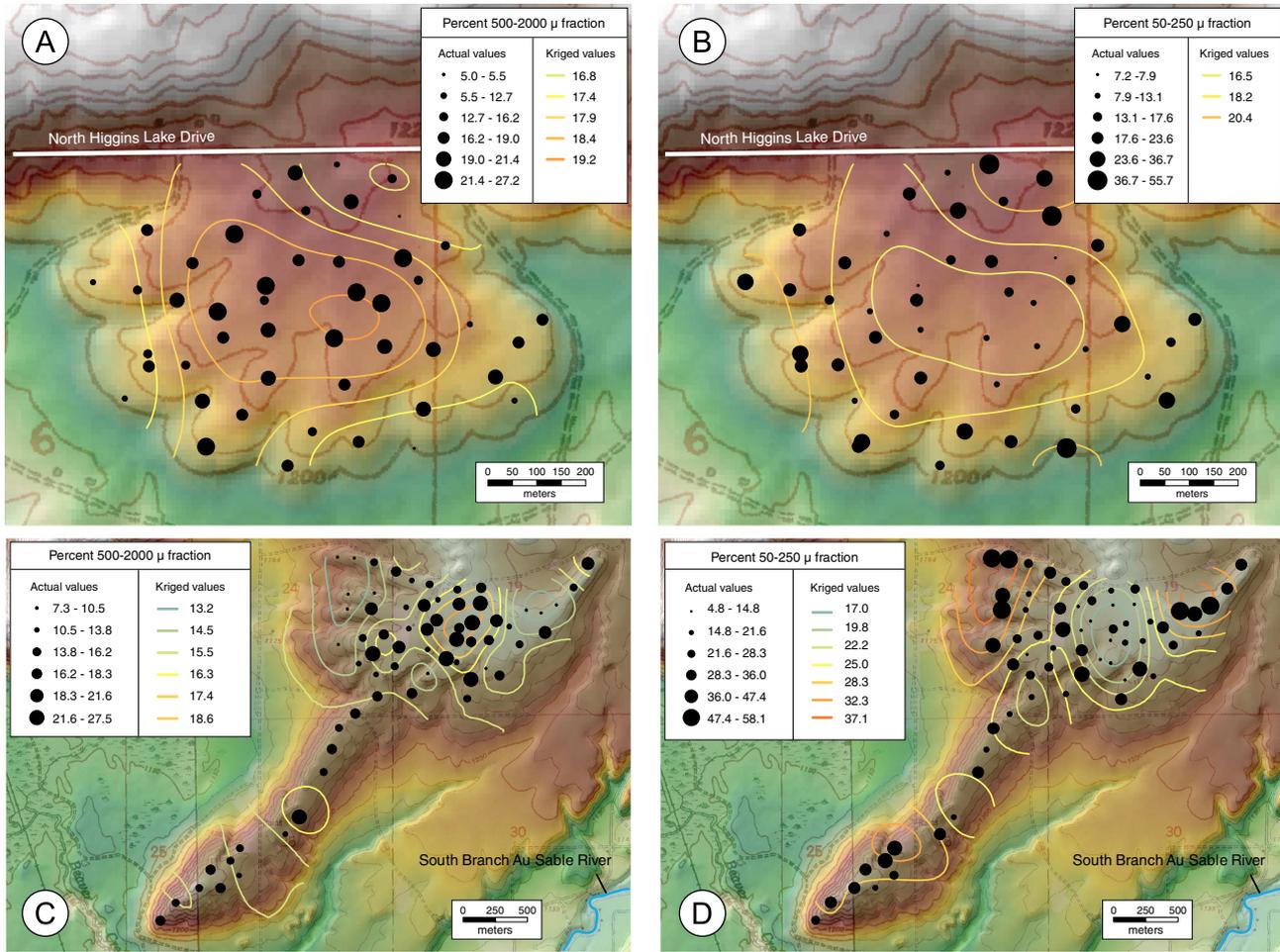
#### 4.4. Age of the Cottage Grove delta

OSL ages and supporting data derived from sands of the Cottage Grove delta are presented in Figs. 6 and 7 and in Tables 2 and 3. The ages were obtained from data collected from between 93 and 96 individual aliquots per sample. Equivalent dose distributions from all

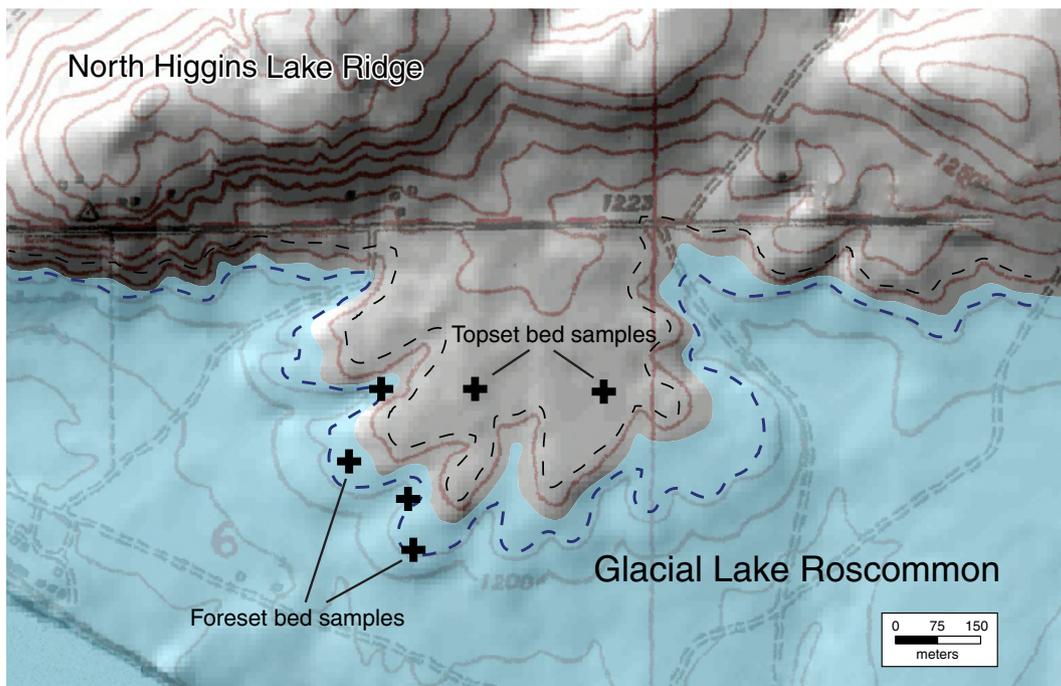
**Table 1**  
Textural data for the Cottage Grove and South Branch deltas<sup>a</sup>.

Variable	Cottage Grove delta	South Branch delta
	Mean particle size contents (%)	
Numbers of samples	48 (plus data from six OSL sample sites)	72
Sand (50–2000 $\mu$ )	97.4	97.1
Silt (2–50 $\mu$ )	2.1	2.2
Clay (<2 $\mu$ )	0.5	0.7
Very coarse sand (1–2 mm)	1.4	1.6
Coarse sand (0.5–1.0 mm)	15.1	12.4
Medium sand (250–500 $\mu$ )	61.8	59.9
Fine sand (125–250 $\mu$ )	17.3	21.1
Very fine sand (50–125 $\mu$ )	1.8	2.2
Mean weighted particle size ( $\mu$ )	442.3	418.7
Most common USDA texture class	Sand	Sand

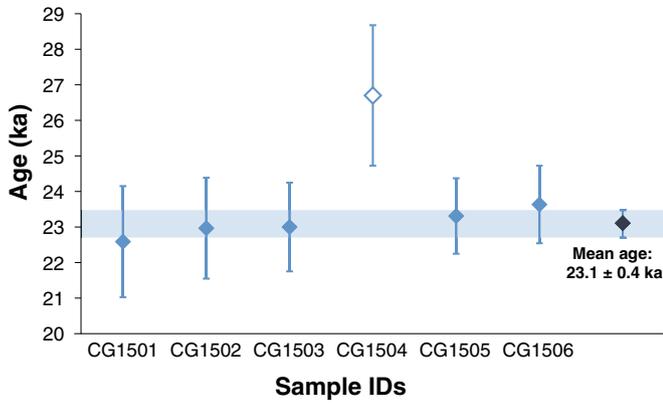
<sup>a</sup> Based on samples from the upper 30–150 cm of the deltas.



**Fig. 4.** Textural data for the Cottage Grove (A and B) and South Branch ((C and D)) deltas, using both graduated symbols and kriged isolines derived in ArcGIS. Data derive from auger samples recovered from the upper 1.5 m. Note the differing scales for the two sets of maps.



**Fig. 5.** Map of the Cottage Grove delta, flooded to 372 m. Dotted lines show an error envelope of  $\pm \approx 1$  m. Also shown are the locations of the OSL samples and their possible interpretations.



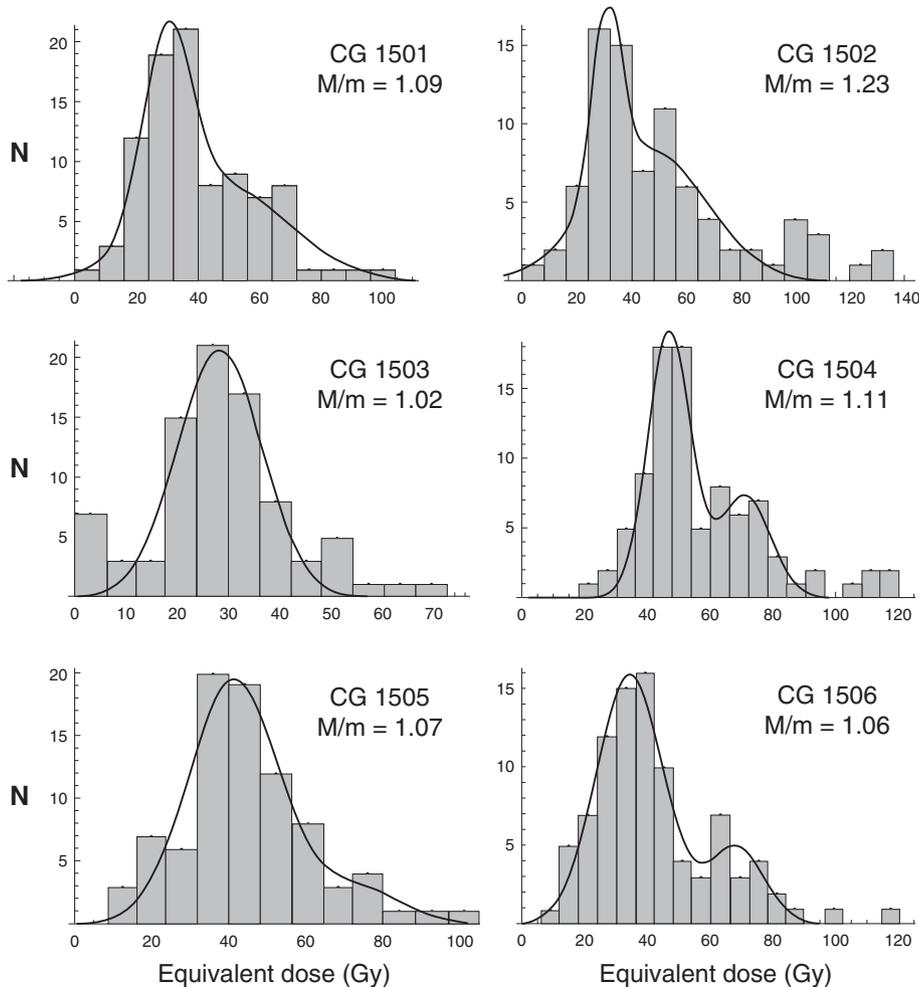
**Fig. 6.** Visual summary of OSL dating results. The filled black diamond represents the mean of the five age determinations (exclusive of sample CG1504).

samples, except one, were asymmetric ( $M/m > 1.05$ , column 3 of Table 2; Fig. 7), suggesting incomplete OSL signal resetting, i.e., partial bleaching, of the samples. This characteristic would be expected in this type of depositional setting, where rapid sedimentation occurs on the same delta. In these cases, OSL ages based on simple measures of central tendency, e.g., the mean, commonly result in over-estimates (Lepper et al., 2000; Lepper and McKeever, 2002). Therefore, we chose an alternate approach to determine the age-representative doses reported in Table 2. We used the “leading edge” approach for five of the six samples (supplement to Lepper et al., 2007). Because sample

CG1503 had a symmetric dose distribution ( $M/m = 1.02$ , column 3 of Table 2; Fig. 7), we interpreted it as having been more completely solar reset, perhaps because it was from sediment that was deposited during a period of (at least temporarily) diminished sediment flux into the lake. The mean and standard error of the equivalent dose distribution were then used to make the age calculation for this symmetric sample (Lepper et al., 2011). Importantly, the age correspondence between CG1503 and the remaining samples (other than one outlier, discussed below) bolsters the age determinations made from the asymmetric (partially bleached) data sets. Ages for five of the six samples cluster tightly around a mean value of  $23.1 \pm 0.4$  ka, which is our best estimate of the “age of the delta,” if a single age is desired.

We consider one of the six samples, CG1504, to be an outlier. It was taken from a foreset bed location and had an anomalously old age ( $26.7 \pm 2.0$  ka). Sample CG1504 had the second highest asymmetry value, but oddly had the lowest data dispersion (columns 3 and 4, Table 2). The combination of high asymmetry and low dispersion is unusual and could be a factor leading to under-correction for data distribution asymmetry, thereby resulting in the anomalously old age. Regardless of the cause of the over-estimate, we have excluded sample CG1504 from the data set, as an outlier.

The five remaining samples were recovered from topset (CG1501 and 1502) and foreset (CG1506) beds, and from the incised gullies (CG1503 and 1505). Samples from the topset and forebeds should capture the very end of the delta’s formative interval; they have a mean age of  $22.8 \pm 1.5$  ka. The gully samples were recovered from sediment that is 3.0–3.5 m below the delta’s top surface, and thus, may represent the middle of the delta sedimentation interval; they have a slightly older



**Fig. 7.** OSL equivalent dose distributions for all reported samples in this study.  $M/m$  is the mean/median ratio – a measure of distribution symmetry/asymmetry.

**Table 2**  
OSL ages of samples recovered from the Cottage Grove delta.

Sample ID	N <sup>a</sup>	M/m <sup>b</sup>	$\chi^2$ (%)	Age-representative dose (Gy)	Dose rate (Gy/ka)	Age <sup>d</sup> (ka)	Uncertainty <sup>e</sup> (ka)
CG1501	94/96	1.09	50.2	22.073 ± 1.527	0.978 ± 0.086	22.6 ± 1.6	2.5
CG1502	84/93	1.23	57.7	25.467 ± 1.564	1.109 ± 0.100	23.0 ± 1.4	2.5
CG1503	87/93	1.02	50.9	27.610 ± 1.506	1.201 ± 0.108	23.0 ± 1.3	2.4
CG1504	90/94	1.11	36.0	39.884 ± 2.962	1.494 ± 0.137	26.7 ± 2.0	3.2
CG1505	86/94	1.07	38.8	29.438 ± 1.344	1.264 ± 0.112	23.3 ± 1.1	2.3
CG1506	92/96	1.06	44.6	23.581 ± 1.090	0.998 ± 0.090	23.6 ± 1.1	2.4

<sup>a</sup> Dose distribution data dispersion (std. dev./mean).

<sup>b</sup> Age and data-derived age error (std. err.; Lepper et al., 2011).

<sup>c</sup> Number of aliquots used for OSL De calculation/number of aliquots from which OSL data was collected (filtering criteria given in Lepper et al., 2003).

<sup>d</sup> Mean/median ratio: a measure of dose distribution symmetry/asymmetry (see supplement to Lepper et al., 2007).

<sup>e</sup> Age uncertainty as propagated error (Aitken, 1985, 1998).

mean age: 23.2 ± 1.2 ka. The ages suggest that the delta may have formed over a span of 400 to potentially 1000 years (Table 2), but a significantly shorter formation interval is also possible (Fig. 6), as would be expected for kame deltas.

#### 4.5. Glacial landform assemblages in northern Michigan

Two well-dated, deglacial-readvance-deglacial morphosequences occur in northern Lower Michigan, i.e., the Port Huron and Greatlakean advances (Blewett, 1991, 1995; Blewett et al., 1993; Larson et al., 1994). Both of these advances *post-date* the retreat of the ice from the Houghton Lake basin (Schaetzl, 2001; Blewett et al., 2009; Kincare and Larson, 2009). They, like the subsequent Marquette readvance in the Upper Peninsula (Lowell et al., 1999; Blewett et al., 2014), were associated with widespread, stagnant margins, forming long ice-contact ridges and/or associated broad sandurs. That is, the deglaciation of northern Lower Michigan and the Upper Peninsula was dominated by stagnant ice margins, forming heads of outwash or sharp-crested ice-contact ridges that grade into distal outwash plains. Each ice margin is, therefore, associated with a coarse-textured morphosequence. This sequence of deglacial landforms is equally well-expressed in the Houghton Lake basin, where ice-contact ridges grade into sandy lowlands. However, unlike the areas mentioned above, in the Houghton Lake basin the ice margin was subaqueously grounded in Glacial Lake Roscommon.

#### 4.6. Glacial geomorphology in northern Lower Michigan

Like the current research, almost all of the glacial geomorphology research in the Midwest has, necessarily, been focused on landforms, sediments and chronology associated with the most recent period (MIS 2) of ice *retreat*. Little is known about the *advance* of the MIS 2 ice, mainly because sediments and landforms from the advancing ice are buried, destroyed, or mixed during retreat. Schaetzl and Forman (2008) compiled the published <sup>14</sup>C ages on wood and charcoal from sites where buried, organic-rich materials in southern Michigan are overlain by MIS 2 sediment, in order to better constrain the advance of the ice onto Michigan's Lower Peninsula. Four such sites occur in the northwestern Lower Peninsula; they provide maximum-limiting ages for the advance of the ice, out of the Lake Michigan basin (Stuiver et al., 1978; Winters et al., 1986; Rieck et al., 1991). All of these ages exceed

39 ka, indicating that ice had not yet advanced very far into the northwestern part of the Lower Peninsula by 39 ka.

Other information about the MIS 2 ice advance in the upper Great Lakes region comes from luminescence ages on outwash sands. For example, OSL ages from outwash within the Grayling Fingers, north of the study area (Fig. 2), indicate that the ice margin was stable and situated at the northern edge of the Fingers by ca. 29 ka (Schaetzl and Forman, 2008; Fig. 8). These data come from two samples recovered from a gravel pit, deep in the outwash column. The ice front must then have remained stable, forming the large, thick sequence of outwash that comprises the core of the Fingers. Eight additional OSL ages from near the top of the outwash stratigraphic column yielded a mean age of ca. 27 ka. Schaetzl and Forman (2008) interpreted these data to mean that ice crossed over the Grayling Fingers at or shortly after ca. 27 ka, burying its own outwash. In essence, the advancing ice margin stalled for 1000–2000 years at the northern margin of the Fingers (Fig. 8).

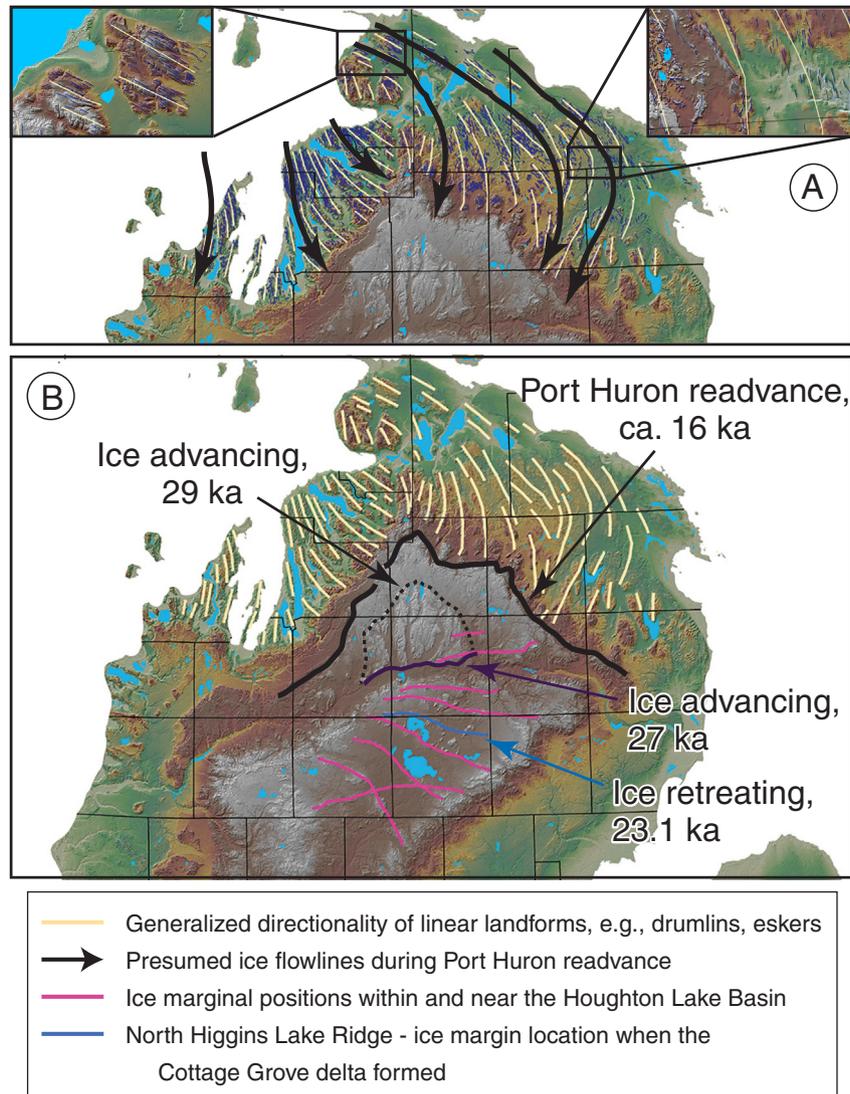
Using till fabrics from the till that overlies this outwash, Schaetzl and Weisenborn (2004) concluded that the MIS 2 ice sheet advanced across the Fingers along a north-to-south trajectory. Nothing is known about the eventual pathway or extent of this ice advance, after it crossed the Fingers. Nonetheless, our study provides an opportunity to learn more about the flowlines and pathways of MIS 2 ice in northern Lower Michigan (Fig. 8). We start by assuming that the pathway of the *retreating* ice is generally similar to the pathway taken by the ice during its advance. Streamlined features, whether constructional or erosional, have long been used to determine the flowlines of ice sheets, and we will do that here as well. Past work of this kind was performed by Schaetzl (2001), who mapped linear constructional landforms such as drumlins and eskers. This work demonstrated that, during the Port Huron readvance, ice advanced into northern Lower Michigan from the northwest, turning south after it entered the Lower Peninsula (Fig. 8). Ice flowing to the southeast, across the tip of the Lower Peninsula, has been postulated by others as well (Dworkin et al., 1985).

The outer Port Huron readvance reached its maximum extent between 12.7 and 13.5 <sup>14</sup>C yrs. BP (Blewett et al., 1993), which calibrates to between 15,100 and 16,470 cal yrs. ago, based on the online CalPal calibration curve (<http://www.calpal-online.de>). Schaetzl (2001) was able to demonstrate that the Greatlakean readvance (ca. 11,500 cal yrs. ago; Larson et al., 1994), which occurred *after* the Port Huron, probably flowed along a similar pathway. Thus, it seems reasonable to assume that ice advancing into the northern Lower Peninsula

**Table 3**  
Concentrations of dosimetrically relevant elements from instrumental neutron activation analysis (INAA)<sup>a</sup>, and supporting data for dose rate calculations.

Sample ID	Landscape position	Depth (cm)	H <sub>2</sub> O content (%)	K conc. (ppm)	Rb conc. (ppm)	Th conc. (ppm)	U conc. (ppm)
CG1501	Topset beds	165	10 ± 3	7415 ± 655	21.05 ± 2.71	1.347 ± 0.139	0.493 ± 0.051
CG1502	Topset beds	116	10 ± 3	9164 ± 805	23.14 ± 2.58	1.239 ± 0.128	0.402 ± 0.046
CG1503	Gully	145	12 ± 3	10,496 ± 919	34.16 ± 3.52	1.193 ± 0.124	0.462 ± 0.049
CG1504	Foreset beds	135	10 ± 3	13,703 ± 1203	36.70 ± 4.05	1.079 ± 0.119	0.474 ± 0.053
CG1505	Gully	153	12 ± 3	10,856 ± 956	29.98 ± 3.42	1.510 ± 0.157	0.537 ± 0.060
CG1506	Foreset beds	130	10 ± 3	7854 ± 696	24.31 ± 2.78	1.141 ± 0.118	0.438 ± 0.043

<sup>a</sup> Irradiations for INAA were performed at the Ohio State University Research reactor. INAA data reduction was carried out by Scientific Consulting Services, Dublin, OH.



**Fig. 8.** Theoretical MIS 2 flowlines in northern Lower Michigan. Ages of known and inferred ice marginal positions at key locations within the northern lower Peninsula are shown in part B. See text for details.

before the Port Huron would also have taken a similar pathway. Because this ice lobe has not before been mentioned or studied, we hereby define it as the *Mackinac Lobe*. The Mackinac Lobe probably originated in the eastern Upper Peninsula and crossed the Straits of Mackinac, flowing to the southeast (Schaetzl, 2001). This lobe advanced into the region at ca. 35–30 ka, would likely have taken a path similar to that of the Port Huron and Greatlakean advances, and as indicated by the work of Schaetzl and Weisenborn (2004) in the Grayling Fingers, eventually flowed south and into the Houghton Lake basin. It is important to recognize that any ice crossing the Mackinac Straits, and flowing to the southeast, would have eventually encountered the Saginaw Lobe, forcing a turn to the south and eventually, southwest. This interpretation helps explain why ice appears to have advanced into the Houghton Lake basin from the northeast, retreating in the same direction (Fig. 8).

Exactly how far the MIS 2 ice margin advanced into the Houghton Lake basin is unknown, although while retreating it did stabilize at six or more different positions, each one associated with an ice-contact ridge (Figs. 3A, 8). Based on the morphology and location of the two deltas studied here, as well that of as several others in the basin first identified by Luehmann (2015) and which are tied to ice-contact ridges, the ice margin retreated from the Houghton Lake basin from southwest to northeast (Figs. 3A, 8). That is, all known deltas in the basin are on the south or southwest sides of the ice-contact ridges. The presence of

deltas in the basin also confirms that the retreating ice margin was, at least in places, subaqueously grounded.

The ages from the Cottage Grove delta constrain this ice margin at the North Higgins Lake Ridge at ca. 23.1 ka, as the ice was intermittently retreating to the northeast (Figs. 6, 7). Using the elevation of the Cottage Grove delta as a proxy for water plane elevation, we estimate that this stage of Glacial Lake Roscommon was at  $\approx 372$ – $374$  m asl. A likely outlet for this lake exists in the West Branch moraine (Fig. 3A), south and east of the delta, near the city of West Branch. Here, a large, flat-floored, wide channel at  $\approx 373$ – $375$  m has been cut through the moraine. The gradient of this channel and the orientation of its tributary valleys, some barbed and some not, indicate that water flowed south, through this channel. Most of the channel is comprised of sandy soils with minimal gravel content. At the end of the channel, within the city of West Branch, the channel widens and several large features, probably mid-channel bars, and aligned parallel to the paleoflow direction, occur. Most of these bars are mapped in the East Lake, Epoufette, and Wheatley soil series, all of which are sandy in their upper profiles but which have gravelly sand C horizons. As the channel widens to the south, these bars and channels take on the form of a weakly defined delta. This delta is mainly sandy, but with some of the same “gravelly” bars mentioned above, as well as some distributary-like channels. The geomorphology here suggests that, while the ice margin was at the North Higgins Lake Ridge, it

was grounded in Glacial Lake Roscommon, which drained through the channel at West Branch, forming a small delta. We have no information on the extent of this lake, but its presence suggests that, ca.  $23.1 \pm 0.4$  ka ago, the Saginaw Lobe was not at the West Branch moraine, but instead, was pulled back from it, with ponded water between the moraine and the ice margin.

#### 4.7. Implications for glacial chronology

The  $23.1 \pm 0.4$  ka age of the Cottage Grove delta has regionally significant implications for MIS 2 ice dynamics across the Midwestern US, if not globally. The early 20,000 s have long been viewed as a time of maximal cold - when ice sheets were near their maximal extents and volume (Fig. 9). This period in time is commonly referred to as the Last Glacial Maximum (LGM) (Clark et al., 2009). Globally, most ice sheets were at their LGM positions sometime between 26.5 and 19–20 ka (Clark et al., 2009). In their summary of the Michigan Subepisode in the Lake Michigan Lobe, Johnson et al. (1997) put the ice sheets in the upper Midwest at their farthest southern extent at ca. 21.6 ka (radiocarbon calibrations based on CalPal). Recent data add considerable precision to the overall estimates of the age of the MIS 2 maximum in the upper Midwest, and appear to somewhat push back this earlier estimate for the LGM. For example, Caron and Curry (2016) reported that the Lake Michigan Lobe in south-central Illinois was at its maximum extent (Shebly Phase) between 24.5 and 24.2 ka ago. Unpublished radiocarbon ages on organics within a shallow lake beneath MIS 2 till from southern Indiana, near the glacial terminus, point to the LGM here at between 23.8 and 24.0 ka ago (H. Loope, pers. comm., 2016).

Given this background, few would have thought that the interlobate region between the Lake Michigan and Saginaw Lobes in north-central Lower Michigan would have become at least partially ice-free by 23 ka ago, i.e., several thousands of years before early retreat of the Saginaw

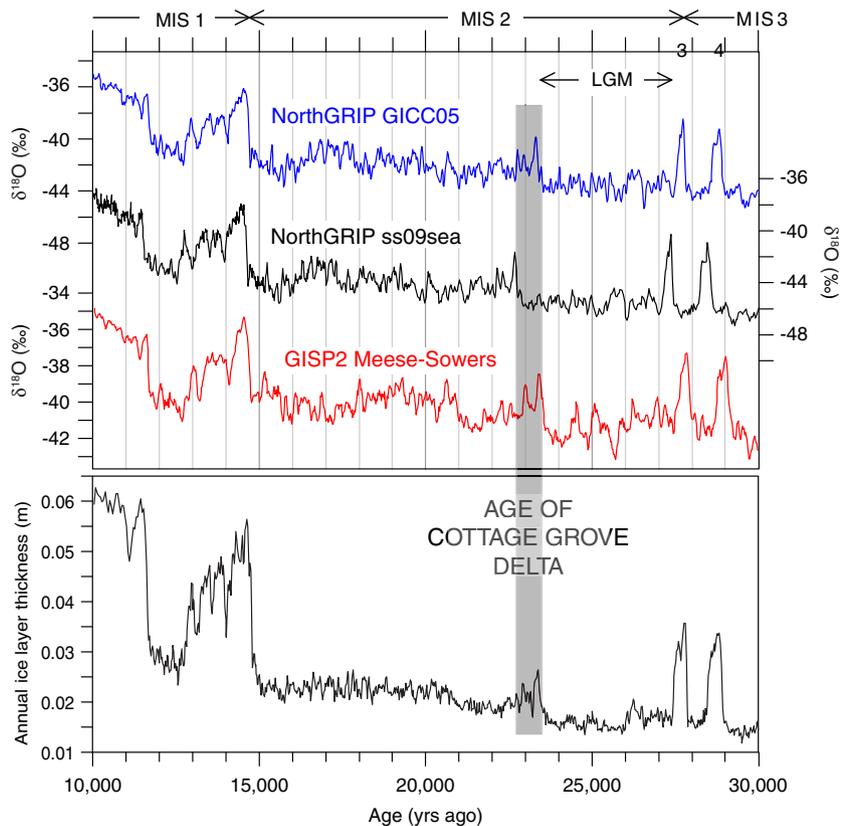
Lobe would have uncovered parts of what is today extreme southern Michigan. We suggest that the Mackinac Lobe in this area started its extremely early retreat because of its precipitous location atop a regional topographic and bedrock high, surrounded as it was by deep lake basins. Enhancing the early and likely rapid retreat may have been the subaqueous nature of the ice margin.

As Dyke (2004) stated, “Improved age control and more detailed mapping of deglacial patterns have had the net result of bringing the North American deglaciation sequence into more evident correlation with the major climatic events recognised in the North Atlantic region and in the Greenland ice cores.” Indeed, ice core data from Greenland point to a short-lived warm event in the Late Pleistocene between ca. 22.5 and 23.5 ka ago (Svensson et al., 2006), possibly coinciding with retreat of the Mackinac Lobe and the development of Glacial Lake Roscommon (Fig. 9). Our data may indicate that such a climatic event initiated locally important ice retreat in the upper Midwest.

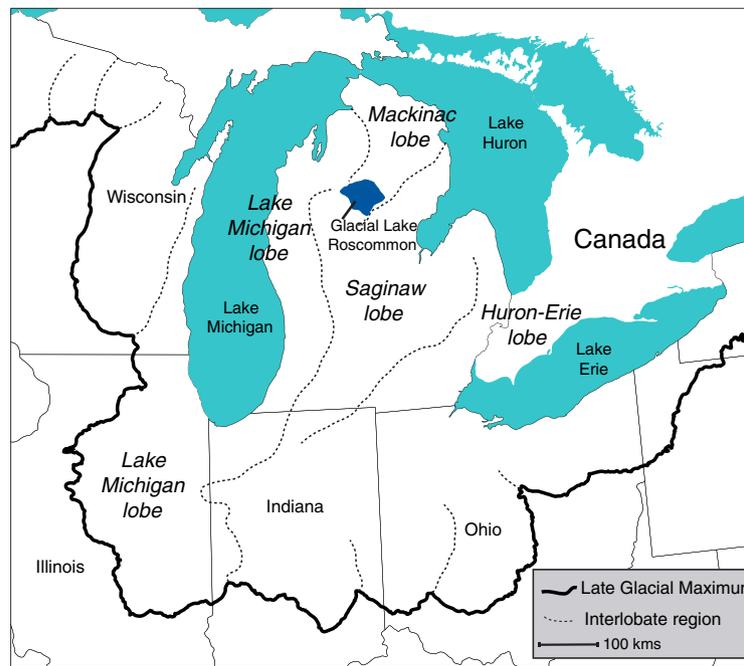
Additionally, this retreat, located hundreds of kms north of the glacial terminus, formed a “hole-in-the-doughnut” in the Laurentide Ice Sheet (Fig. 10). Future work on this lake and its associated landforms may be able to refine our understanding of this previously unknown period of early ice retreat, and help model ice sheet retreat in high, interlobate areas.

#### 5. Conclusions and implications

Our data on two small kame deltas in north-central Lower Michigan confirm the presence of a previously unknown, high-elevation glacial lake, which we name Glacial Lake Roscommon. The lake variously spanned a broad upland known as the Houghton Lake basin, which is surrounded by higher uplands. Hence, provided that its (low) modern outlet was blocked, Glacial Lake Roscommon was able to flood the basin to the elevations of several different outlets as ice margin



**Fig. 9.** Comparison of climate-related records from various Greenland ice cores. (A)  $\delta^{18}\text{O}$  values, with the timescale used for correlation listed after the name of the core. (B) NorthGRIP annual layer thicknesses, using the GICC05 time scale. The Marine Isotopic Stages (MIS) and the generally interpreted Last Glacial Maximum (LGM) are shown for reference. The age of the Cottage Grove delta, as indicated by our OSL data, is shown in gray. See Svensson et al. (2006) for original references.



**Fig. 10.** Map showing the maximum extent of the Laurentide ice sheet in the Great Lakes region, locations of the major interlobate regions, and one possible permutation/stade of Glacial Lake Roscommon, while the Mackinac lobe ice margin was at the North Higgins Lake Ridge. LGM lines after Flint et al. (1959).

retreated through it. As a result, the basin contains landforms normally associated with proglacial lakes – deltas, overwidened outlets, wave-cut bluffs and beach ridges, and spits. Set within this lake are a series of ice-contact ridges that appear to represent episodic stillstands of the retreating ice margin. We name the lobe associated with the retreating ice the Mackinac Lobe. Configuration of ice-contact ridges within the basin show that the Mackinac Lobe retreated to the northeast, ponding water and leading to the formation of several kame deltas. OSL ages from one of these deltas clustered around a mean age of  $23.1 \pm 0.4$  ka, suggesting that ice had started its retreat from the basin <1000 years after the LGM in Indiana and Illinois, and several thousand years before any other part of southern Michigan became ice-free. Thus, our study provides new evidence for a period of early retreat in north-central Lower Michigan, which may have occurred here because (1) the region is a topographic high surrounded by deep lake basins, (2) the ice margin was subaqueously grounded, and (2) this period may have been a short, climatically warm period, as inferred from Greenland ice core data. Future work on the landforms of this region should add detail and precision to the deglaciation sequence and landforms of this unique area, and better determine its regional and perhaps global paleoclimatic implications.

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