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Geomorphology of the Chippewa River delta of Glacial Lake Saginaw, central Lower Michigan, USA

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ABSTRACT

We introduce, characterize, and interpret the geomorphic history of a relict, Pleistocene-aged delta of the Chippewa River in central Lower Michigan. The broad, sandy Chippewa delta developed into various stages of Glacial Lake Saginaw, between ca. ≈ 17 and 15 ka·BP (calibrated ages). Although the delta was first identified in 1955 on a statewide glacial geology map, neither its extent nor its Pleistocene history had been previously determined. The delta is typically forested, owing to its wet, sandy soils, which stand out against the agricultural fields of the surrounding, loamy lake plain sediments. The delta heads near the city of Mt Pleasant and extends eastward onto the Saginaw Lowlands, i.e., the plain of Glacial Lake Saginaw. Data from 3285 water well logs, 180 hand augered sites, and 185 points randomly located in a GIS on two-storied (sand over loam) soils were used to determine the extent, textural properties, and thickness of the delta. The delta is ≈ 18 km wide and ≈ 38 km long and is sandy throughout. Deltaic sediments from neighboring rivers that also drained into Glacial Lake Saginaw merge with the lower Chippewa delta, obscuring its boundary there. The delta is thickest near the delta's head and in the center, but thins to 1–2 m or less on its eastern margins. Mean thicknesses are 2.3–2.9 m, suggestive of a thin sediment body, frequently impacted by the waves and fluctuating waters of the lakes. Although beach ridges are only weakly expressed across the delta because of the sandy sediment, the coarsest parts of the delta are generally coincident with some of these inferred former shorezones and have a broad, incised channel that formed while lake levels were low. The thick upper delta generally lies above the relict shorelines of Glacial Lakes Saginaw and Arkona (≈ 17.1 to ≈ 16 ka·BP), whereas most of the thin, distal delta is associated with Glacial Lake Warren (≈ 15 ka·BP). Together, these data suggest that the Chippewa delta formed and prograded as lake levels in the Saginaw Lowlands alternated and episodically fell. The result is a delta that is comparatively thin, expansive, and sandy. In some places, these sands have subsequently been reworked into fields of small parabolic dunes.

1. Introduction

Sediments (and in the past few decades, soils) have been increasingly utilized to help understand paleodepositional systems of all kinds (Karathanasis and Golrick, 1991; Muhs et al., 1997; Schaetzl, 1998; Krist and Schaetzl, 2001; Silva et al., 2009; Schaetzl and Attig, 2013; Luehmann et al., 2016). In geologically young landscapes, where sediments have not been subjected to intense weathering or erosion, many parent materials, i.e., the stratum below the depth of soil development, remain essentially unaltered. In such cases, these parent materials retain many sedimentary characteristics, e.g., structure, texture, degree of sorting, and stratification, that can help us to understand the processes, timing, and extent of their original depositional system(s) (Miller et al., 2008; Schaetzl and Luehmann, 2013; Schaetzl and Miller, 2016).

Michigan's geologically young landscape is primarily composed of glacial and related sediments (Farrand and Eschman, 1974; Blewett et al., 2009; Schaetzl et al., 2013). In many cases, Natural Resources Conservation Service (NRCS) soils data provide informative descriptions of these sediments in their official soil series descriptions (OSDs). This association enables soil data to serve as potential proxies for surficial geologic data, allowing researchers to examine and map parent materials, observe patterns, and draw inferences about past geomorphic systems (Veatch, 1937; Hunt, 1972; Schaetzl et al., 2000; Schaetzl and Weisenborn, 2004; Hupy et al., 2005; Wysocki et al., 2005; Luehmann et al., 2013; Wald et al., 2013). Examining such data spatially can

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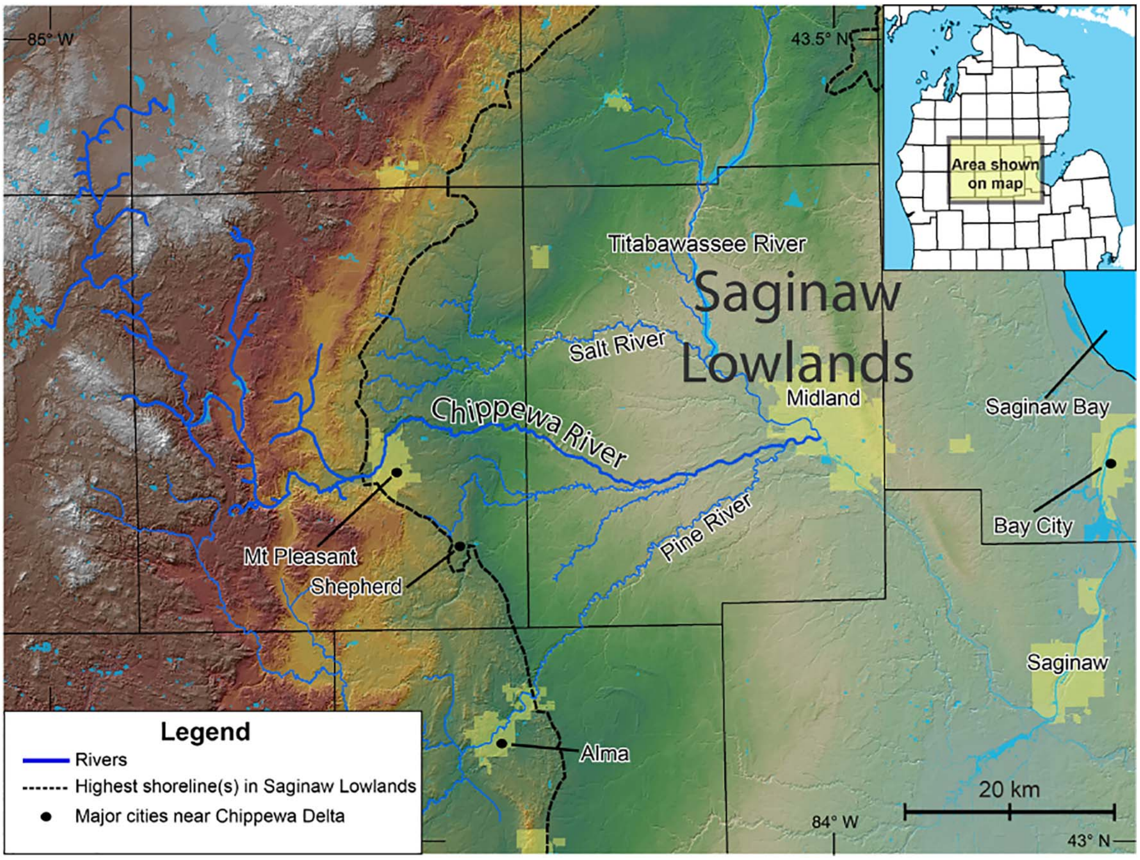

Fig. 1. Topography, rivers, and cities in central Lower Michigan, in and around the Chippewa delta, showing the highest extent of all the lake stages in the Saginaw Lowlands, according to Lusch et al. (2009). Smaller rivers downstream from the confluence of the Chippewa and Titabawassee confluence, which generally mark the margin of the delta, are not shown.

facilitate a better understanding of past systems across the landscape. Typically, this approach is operationalized in a GIS (Schaetzl et al., 2000; Stanley and Schaetzl, 2011; Luehmann et al., 2013). In this paper we employ such a geographical approach, by first using NRCS soils data to identify different parent materials across an area generally known to be associated with the Chippewa River delta, then by using NRCS soils data to delineate the delta's extent, and then using these data to identify areas for sampling.

This research focuses on a sandy, relict delta associated with the Chippewa River. As the Saginaw lobe ice margin was receding between ca. ≈ 17 and 15 ka·YBP, the Chippewa delta developed within a series of proglacial lakes that occupied what is currently known as the Saginaw Lowlands (Fig. 1). Generally grouped under the name Glacial Lake Saginaw, the various lake stages likely associated with the Chippewa delta include Glacial Lakes Early Saginaw, Arkona, Saginaw, and Warren (Leverett and Taylor, 1915; Bretz, 1951; Martin, 1955; Hough, 1966; Kincare and Larson, 2009). The purpose of our study is to document and define the Chippewa delta, characterize its sediments and geomorphology, and explore its geomorphic history. To that end, we used soils data within a GIS to identify sampling locations. We then employed the GIS to analyze the sampling data and to correlate the data with inferred shoreline locations. Our work enabled us to make inferences about the relative timing of delta progradation by spatial association of the delta's sediments with shorezones of the various lake stages. This research also is an example of a geospatial approach for mapping and characterizing landforms in landscapes that recently have been glacially active.

2. Study area

The study area in central Lower Michigan is mainly underlain by glacial and related deposits. Loamy, till-cored morainic uplands in the western part of the region adjoin the comparatively low relief Saginaw lake plain on the east (Fig. 1). The morainic uplands are characterized by N—S trending ridges, mostly formed of till, and associated with the Saginaw lobe, which had advanced out of the lowlands to the east. Deposits of the Saginaw lobe tend to be loamy (Schaetzl et al., 2013), as are large parts of the Saginaw Lowlands.

The Saginaw Lowlands refer to an area that was variously inundated by many lake stages associated with Glacial Lake Saginaw, broadly defined (Fig. 1). Much of this landscape is low relief and the soils within often have high water tables (Veatch, 1930; Schaetzl et al., 2013). The background soils, i.e., those soils whose characteristics are typical of the landscape outside of the delta, are loam textured; many are associated with tills of the Saginaw Lobe (Veatch, 1953; Lusch et al., 2009). In lower parts of the Lowlands, fine-textured sediments, mostly silty clays and silty clay loams, are common; these presumably have glaciolacustrine origins. Broad tracts of the Lowlands are also sandy (Veatch, 1953; Schaetzl et al., 2013), and in many of these areas, fields of sand dunes are commonplace (Arbogast et al., 1997). Until recently, the initial geomorphic origin of these sands has been elusive, although increasing amounts of evidence are now accruing, including this study, that point to their likely fluviodeltaic origins. Most of these sands are so thick that the standard 2-m deep soil profile descriptions do not describe the underlying sediment. Where they are shallow, soil profile descriptions usually indicate that the sands overlie the loamy sediments that are typical of the Lowlands.

The Chippewa River heads in the southern end of a broad basin in central Lower Michigan known as the Houghton Lake Basin (Schaetzl et al., 2013, 2016). The river drains southward through the morainic uplands, eventually turning east and debouching onto the Saginaw Lowlands at the city of Mt. Pleasant, which lies near the highest shoreline of Glacial Lake Saginaw (Fig. 1). Martin (1955) first mapped a small delta in the vicinity of Mt. Pleasant but did not define its

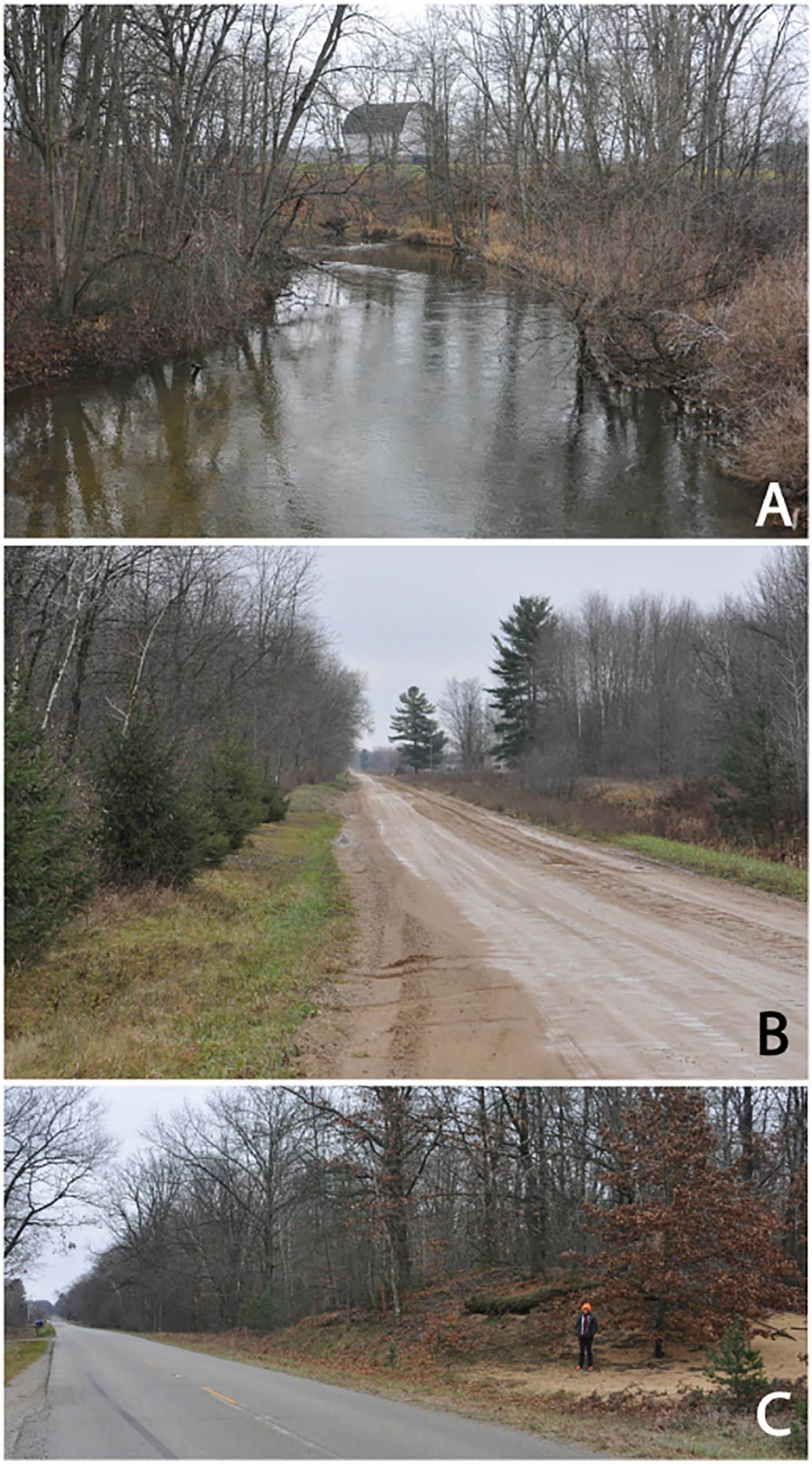

Fig. 2. Photos of modern land use and topography on the Chippewa delta. (A) The incised Chippewa River in November 2016, about 10 km downstream from the City of Mt. Pleasant; (B) Typical topography and land use of the Chippewa delta; and (C) a small sand dune on the delta. Photos by RJS.

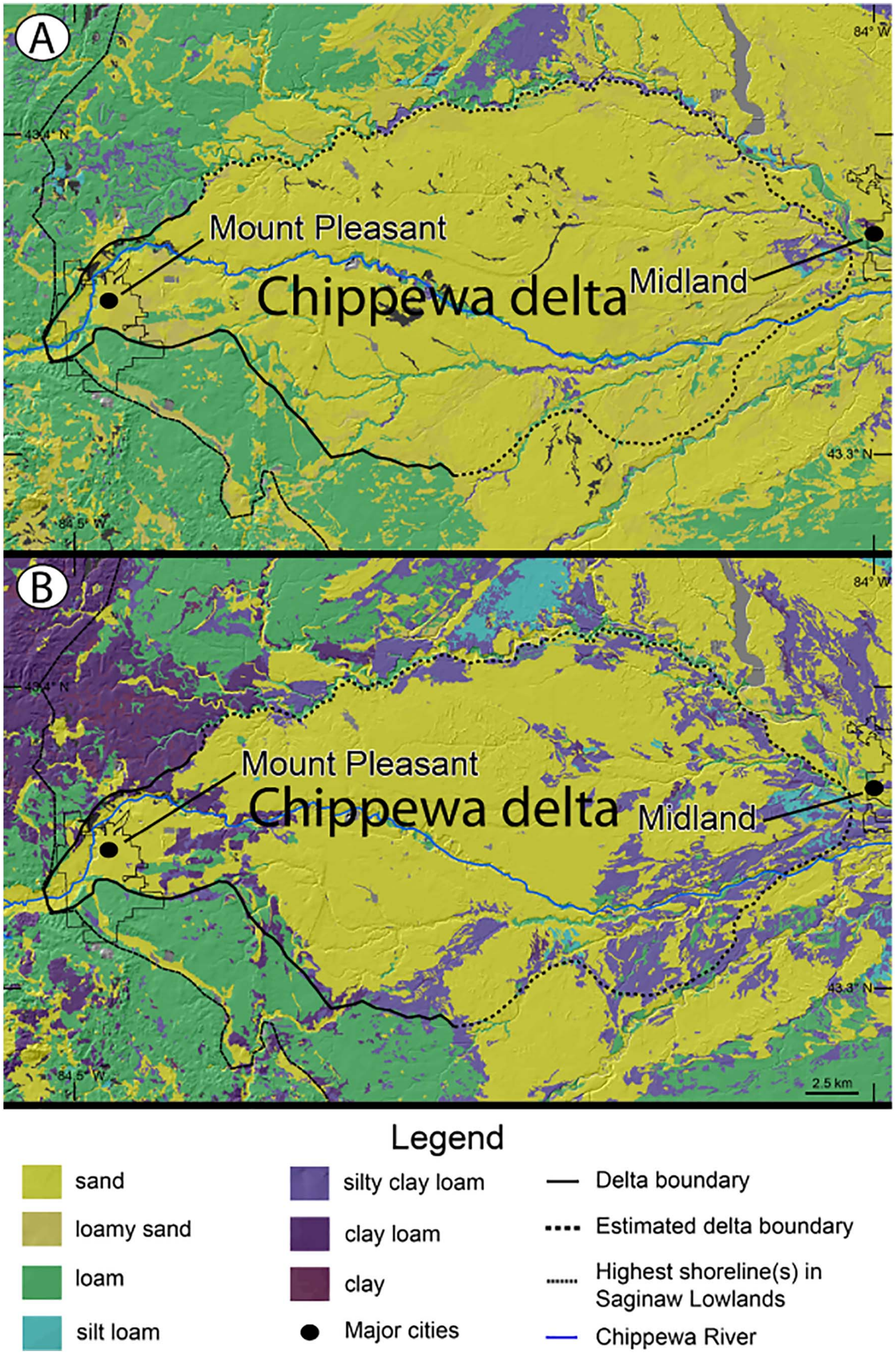

Fig. 3. Textures of the (A) surface (uppermost mineral horizon) and (B) deep subsurface (deepest described mineral horizon) soils on and near the Chippewa delta.

boundary nor characterize its morphology or age. To the east of Mt. Pleasant, the river continues toward Midland, and for several kilometers is incised into a 3–8 m deep valley (Fig. 2A). The Chippewa River flows into the Tittabawassee River near the city of Midland, ≈ 51 km downstream from Mt. Pleasant. We credit Martin (1955) as the first to identify a delta of the Chippewa River; our work informally names the delta and provides information on its morphology, sediments, relative age, and formation. Because we did not collect dateable material in this study, we cannot offer specific age estimates of the delta. Date ranges reported in this paper are aggregated from previous studies within the Saginaw Lowlands and associated basins.

The soils on the delta are mainly sandy and stand in contrast with the loamy soils on the lake plain (Fig. 3). The sandy sediments near the Chippewa River have an elongate, almost lobe-shaped, distribution, suggestive of a delta (Galloway, 1975). This pattern is especially apparent when examining the distribution of soils whose sands exceed 2 m in thickness (Fig. 3B). Most of the soils whose sand thickness is < 2 m occur in areas near the margins of the delta. Here, two-storied soils, which exhibit sandy-over-loamy profile textures, are common. The stacked parent materials of these soils are taken to represent two distinct depositional environments: thin sandy delta sediments over waterlain diamicts or lacustrine sediments. Two-storied soils like these can be potentially useful for the identification of thin sand mantles on the former lake floor. In places where two-storied soils appear outside of the delta proper, they are generally coincident with former shorelines and are therefore also useful in identifying shoreline locations.

2.1. *Proglacial lakes in the Saginaw lowlands*

Much of central Lower Michigan was last glaciated during the late-Wisconsinan by the Saginaw Lobe of the Laurentide Ice Sheet (Leverett and Taylor, 1915; Bretz, 1951; Hough, 1966; Farrand and Eschman, 1974; Kehew, 1993; Larson and Schaetzl, 2001; Kincare and Larson, 2009; Howard, 2010; Kehew et al., 2012; Fisher et al., 2015; Fig. 4). Proglacial lakes occupied the Saginaw Lowlands beginning around 17.1 ka·BP (Leverett and Taylor, 1915; Eschman and Karrow, 1985; Kincare and Larson, 2009). (Radiocarbon dates reported in this paper have been calibrated to calendar years BP using the CalPal website http://www.calpal-online.de/.) Over the next few thousand years, a series of proglacial lakes successively occupied the Lowlands before the region finally drained completely sometime after ≈ 12 ka·BP (Table 1; Hough, 1966; Kincare and Larson, 2009). Most of these lake stages were ponded in front of the retreating ice margin and drained westwardly, through the valley currently occupied by the Maple and Grand Rivers.

Early Lake Saginaw was the first and highest-level proglacial lake to occupy the Saginaw Lowlands during the last glacial retreat, draining westwardly through the Maple-Grand Valley. As the Saginaw Lobe continued its retreat and uncovered the *thumb* of Michigan, Saginaw basin waters merged with waters ponded in the Erie basin around 16.5 ka·BP. This merged lake is called Glacial Lake Arkona, which formed three distinct, successive beach ridges (Leverett and Taylor, 1915; Bretz, 1951; Hough, 1966; Kincare and Larson, 2009).

Near the demise of Lake Arkona, or between Arkona phases, further retreat uncovered a lower drainageway to the east, causing a low lake-stand in the Saginaw Lowlands and elsewhere, called Lake Ypsilanti (also called Intra-Glenwood low phase in the Lake Michigan basin by Monaghan and Hansel, 1990). Although the Ypsilanti low stage is thought to have been short-lived, little detail is known about this phase (Hough, 1966; Kunkle, 1963; Monaghan and Hansel, 1990; Fisher et al., 2015).

By around 15.5 ka·BP, the ice margin had re-advanced into the Saginaw Lowlands, where it formed the Port Huron moraine and closed the drainageway at the tip of Michigan's *thumb*, forming Glacial Lake Saginaw (Bretz, 1951; Monaghan and Hansel, 1990; Blewett, 1991; Kincare and Larson, 2009). Recent work in the Lake Erie basin by Fisher et al. (2015) suggested that the timeline of pre-Saginaw-age lakes may be more constrained than was indicated by previous studies. Glacial Lake Saginaw's water plane was roughly coincident with the lowest level of Glacial Lake Arkona (Bretz, 1951; Monaghan and Hansel, 1990). Shortly thereafter, the tip of the *thumb* once again became ice-free, allowing the merger of the two lakes in the Erie and Saginaw basins, forming Glacial Lake Warren. Glacial Lake Warren had two main stages, separated by about 3–7 m of elevation, but some sources cite three stages (Bretz, 1951; Kunkle, 1963; Eschman and Karrow, 1985; Kincare and Larson, 2009; Fisher et al., 2015).

It is generally accepted — although poorly documented — that further retreat of the ice margin from the Port Huron moraine in the Saginaw Lowlands again opened a drainage way to the east, likely in Ontario or New York, causing a relatively short-lived, low-water stand called Lake Wayne to form in the Erie and Saginaw basins (Bretz, 1951; Larson and Schaetzl, 2001). Most sources place Lake Wayne either after Lake Warren or between the Lake Warren high- and low-stands, but the chronology is uncertain (Hough, 1966; Barnett, 1985). After the eventual draining of Lake Warren, the Saginaw Lowlands were not inundated with lake waters until the late Holocene, when the Nipissing Great Lakes formed. Nonetheless, this lake failed to rise to a level that could have flooded the Chippewa delta, so it will not be discussed further (Butterfield, 1986; Monaghan et al., 1986).

Evidence of the complex history of fluctuating lake levels in the Saginaw Lowlands is preserved as relict shorelines and wave-cut bluffs. Many of these features are spatially discontinuous, whereas others are faint or equivocal, likely because they were either not strongly formed and/or were not well preserved because of their sandy composition. Early work by Leverett and Taylor (1915) and the statewide surficial geology map of Martin (1955), which was largely derived from Leverett and Taylor's work, reported the locations of many relict shorelines within the Saginaw Lowlands. Nonetheless, because these are small-scale maps, details as to their exact locations and elevations of these shorelines are few. More recent mapping efforts (Farrand and Bell, 1982; Lusch et al., 2009) have led to spatially rectified data that can be used to identify shoreline features in the region; but again, they derive from small-scale maps and their spatial accuracy is often questionable. Most commonly, the locations of shorelines and shorezones within the Saginaw Lowlands are best identified by linear strips of sandy sediment set within the loamy lake plain.

In addition to mapping relict shorelines, Leverett and Taylor (1915) also identified a number of relict deltas in Michigan, which were subsequently mapped by Martin (1955). The most strongly expressed of these deltas are in southeastern Michigan and would have prograded into lakes within the Lake Erie basin. These deltas, like the Chippewa delta in the Saginaw Basin, can be observed in the NRCS soil data expressed as a lobate distribution of well-drained coarse and medium sand textured soils, surrounded by the wetter and loamier background soils, which have formed in the typically fine-grained lake plain or till deposits. Leverett and Taylor (1915) described one Arkona delta associated with the Huron River south of Ypsilanti, 'This delta, and in fact all of the Arkona deltas, protrude farther into the lake bed than do the deltas of any other state of the lake waters.' These southeastern deltas sometimes express clearly identifiable delta morphologies, such as a cuspate delta front, or well-defined lobate morphologies. Deltas associated with the Clinton and Raisin Rivers in southeastern Michigan have, like the Chippewa delta, a deeply incised valley through the main body of the delta through which the modern river flows.

3. Methods

Before entering the field, we first examined the soil and sedimentological attributes of the study area, widely defined. We identified potential sample sites using ArcGIS by viewing SSURGO-scale soil data from NRCS county soil surveys, overlain onto a 10-m digital elevation model (DEM) hillshade from the U.S. Geological Survey (USGS). The SSURGO data set was upgraded to include a number of additional

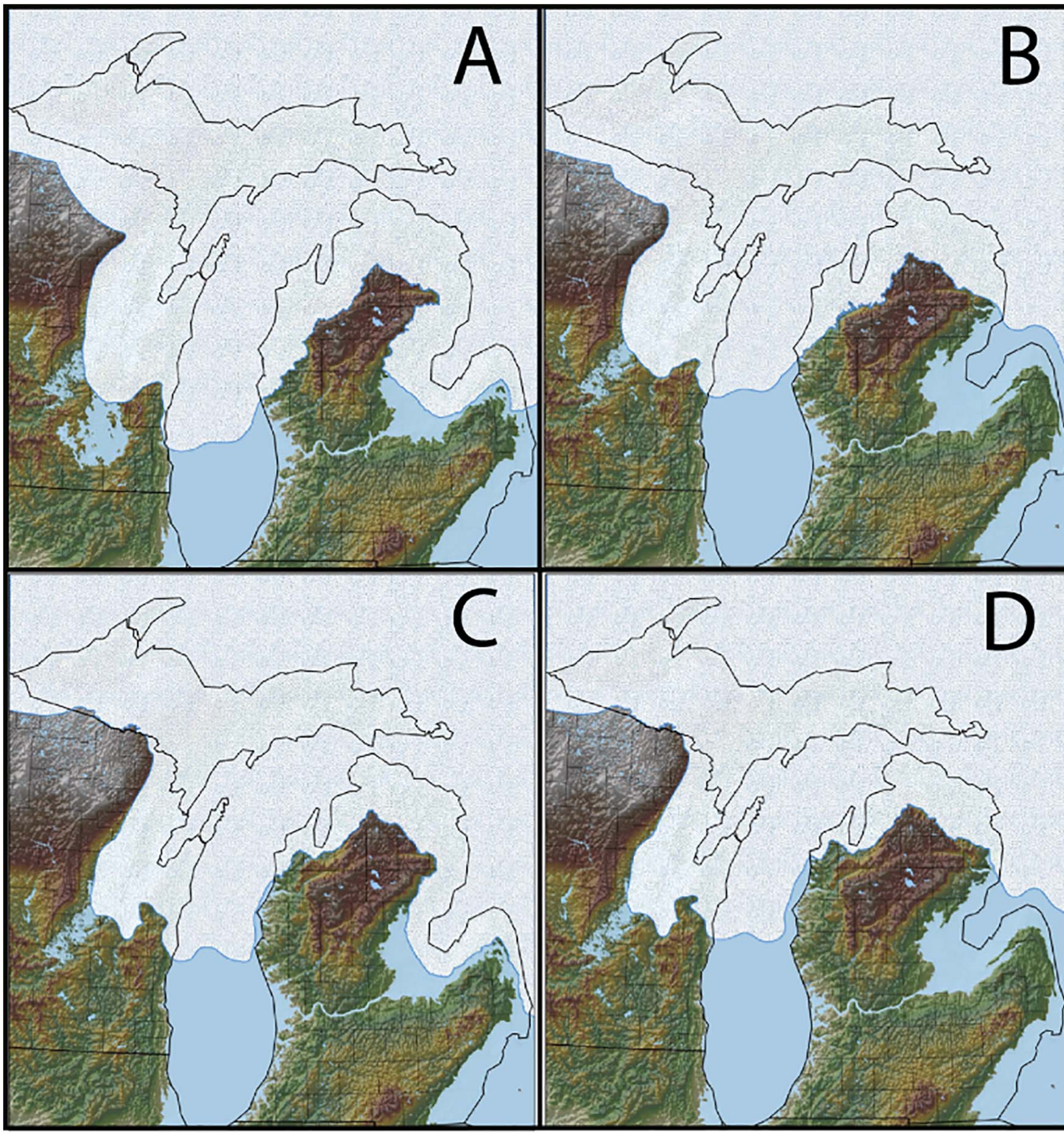

Fig. 4. Representation of the approximate configurations of the glacial margin and proglacial lakes in Lower Michigan and eastern Wisconsin during (A) early Glacial Lake Saginaw, (B) Glacial Lake Arkona, (C) Glacial Lake Saginaw, and (D) Glacial Lake Warren.

variables, including upper (A horizon) and subsoil (lowest described horizon) textures and parent material type as described in the OSDs. We used subsoil (lowest described horizon) textures as proxies for sedimentologic data on which the field sampling strategy (described below) was based.

Using the soils data, we then identified an area of sandy sediments/soils in the area first documented by Martin (1955) as a delta of the Chippewa River. We postulated that this large sandy area could mark the full extent, i.e., wider than that outlined by Martin (1955), of the Chippewa delta. Using that information as a first approximation of the delta, we next set out to sample across it. The sampling campaign was guided by a field laptop, equipped with a GPS, that had a GIS project loaded on it. Potential sample sites, located ≈ 1.5 km apart and uniformly spaced, were added to the project, avoiding sites near areas of human disturbance, erosion, or secondary deposition. Using a standard 8.3-cm-wide diameter and 2-m-long bucket auger, samples of ≈ 900–1200 g were collected from the (presumably) unaltered sand parent materials, typically from depths of 1.0–1.5 m. At sites where the sands were < 2 m thick, their thickness was recorded. The location of each sample site was recorded in a point shapefile. In total, we collected 180 samples of sand-textured C horizon material (Fig. 5).

All samples were dried and lightly ground with a mortar and pestle. Gravels (> 2 mm) were removed from the sample by sieving, weighed, and their mass content determined. Each sample of the remaining fine-earth fraction was then passed through a sample splitter three times to homogenize it before being passed through a 1-mm sieve to determine the very coarse sand (1.0–2.0 mm) fraction. Samples of the < 1.0-mm fraction were prepared for particle size analysis by first homogenizing them using a sample splitter and then dispersing them in a weak solution of $(NaPO_3)_{13}$ Na_2O. All samples were measured using a Mastersizer 2000E laser particle size analyzer (Malvern Instruments Ltd., Worcestershire, UK). The Mastersizer data were uploaded into an Excel spreadsheet and adjusted to include the manually calculated data for very coarse sand. The particle size data were then joined in the GIS project to each sample location.

The thickness of sandy delta sediment was estimated using groundwater well data and soil data acquired randomly in a GIS for two-storied soils mapped on the delta by the NRCS. These data were entered

Table 1
Proglacial lakes within and near the study area, arranged chronologically.

Lake name	Age[a]	Highest elevation (m) within study area	Select ages[a] and sources
Early Glacial Lake Saginaw	≈ 17.1–16.5 ka·BP	239	16.8 ka·BP (Lake Erie Basin; Fisher et al., 2015) ^{14}C 17.4 ± 251 ka·BP (earliest, contemporaneous lake, Lake Erie Basin, Goldthwait, 1958)
Glacial Lake Arkona	≈ 16.5–15.5 ka·BP	230	^{14}C 16.8 ± 398 ka·BP (Saginaw/Arkona transition; Burgis, 1970) ^{14}C 16.4 ± 767 ka·BP (Lake Erie Basin, Arkona; Hough, 1958)
Lake Ypsilanti	Unknown	Not expressed	^{14}C 16.3 ± 428 ka·BP, 16.1 ± 471 ka·BP, and 16.0 ± 407 ka·BP (Arkona/Ypsilanti, Lake Erie Basin, Ontario; Morris et al., 1993) ^{14}C 16.4 ± 438 ka·BP (Lake Michigan Basin, proposed low phase; Monaghan and Hansel, 1990)
Glacial Lake Saginaw	≈ 15.5–15.0 ka·BP	222	^{14}C 15.5 ± 818 ka·BP and 15.4 ± 651 ka·BP (contemporaneous lake, Lake Erie Basin; Goldthwait, 1958)
Glacial Lake Warren	≈ 15.0–14.3 ka·BP	212	14.1 ka (Lake Erie Basin; Fisher et al., 2015) 14.1–13.9 ka·BP (post-Warren, Lake Erie Basin, Calkin and Feenstra, 1985)

^{14}C ages referenced from previous publications were calibrated using CalPal (http://www.calpal-online.de/index.html) to cal yrs BP.
[a] Ages reported in calendar years.

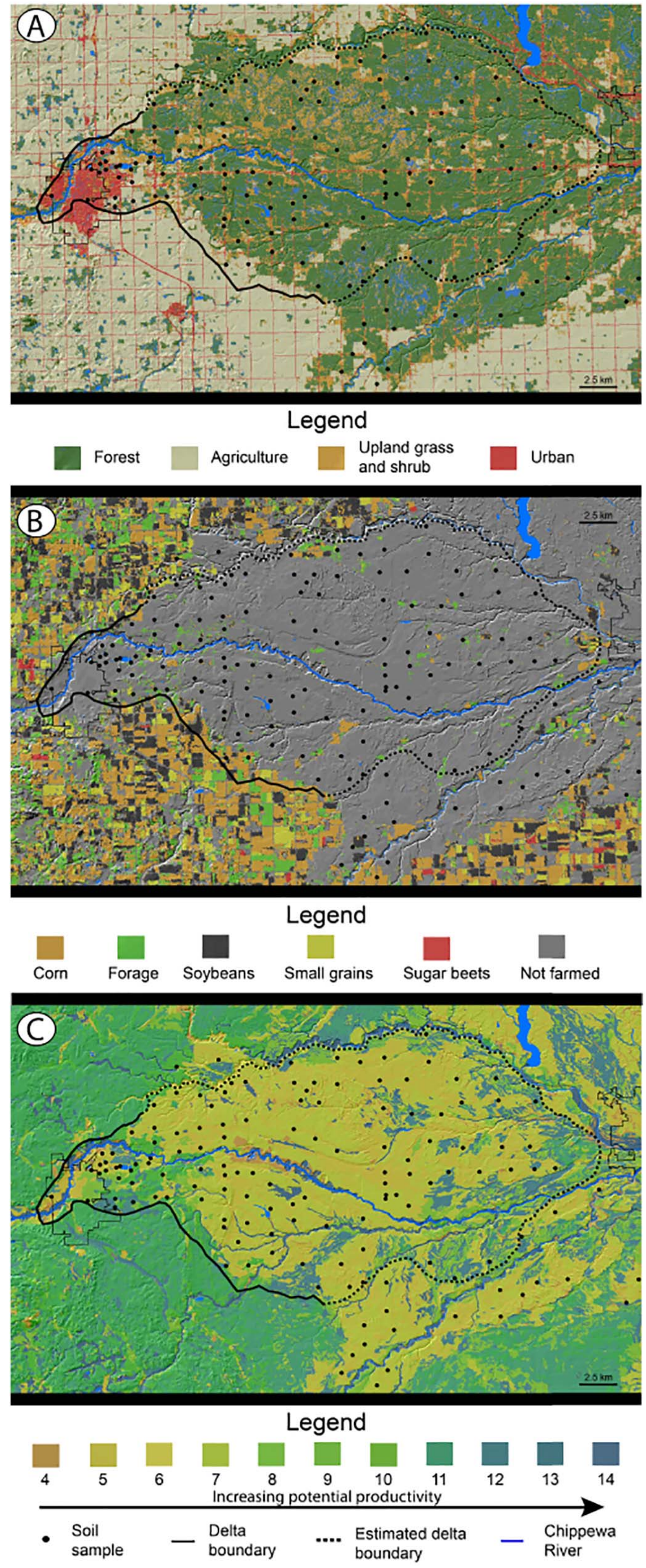

Fig. 5. Locations of sample points across the delta on backgrounds of (A) land use, (B) crops, and (C) soil productivity index (PI; Schaetzl et al., 2012). Higher PI values indicate higher inherent fertility and productivity for crop and forest growth.

into the same point shapefile. For the delta and areas nearby, we determined the thickness of the sands from 3285 water well logs. Measurements of the thickness of sandy deposits were recorded for wells that reported sand, gravel, or *sand and gravel* at the surface. For each such well, the terminal depth (sand thickness) was determined based on the presence of a thick (> 1 m) intervening stratigraphic unit of composition other than sand, e.g., clay, clay loam, loam. Also, in ArcMap we placed 185 additional points, roughly evenly spaced, onto sites within the delta (after its extent had been determined) that had been mapped by the NRCS with two-storied soils. For each site, the thickness of sand was determined from its OSD and the value recorded in the shapefile.

Records of former shorelines and their elevations were collected and analyzed from the literature and published maps, primarily Leverett and Taylor (1915) and Martin (1955). The GIS analyses of these shorelines were accentuated by overlaying them onto a hillshade DEM and digitized topographic maps (DRGs) in a GIS. Leverett and Taylor (1915) recorded many detailed descriptions of shoreline features across the study area, including their elevations and their locations relative to towns and villages. These features were identified and recorded in a shapefile. Additional data came from a digitized and georectified scan of the 1955 Martin map. This map is especially useful because Martin symbolized some of the shoreline features with an indication of their associated lake stage, e.g., Arkona, Warren, and Saginaw; this information was omitted from the Farrand and Bell (1982) map. Shorelines from the Martin (1955) map were entered into a polyline shapefile and smoothed slightly in ArcMap, with a 100-m smoothing tolerance, to improve the aesthetic quality of the layer. We also imported the Quaternary Features shapefile from the Farrand and Bell (1982) 'Quaternary Geology of Michigan' map, which had been digitized by the Michigan Natural Features Inventory and is available from the Michigan Geographic Data Library (http://gis.michigan.opendata.arcgis.com/). Finally, a shapefile of the highest shoreline of Glacial Lake Saginaw, originally used in a study by Lusch et al. (2009), was obtained and included in the GIS project. Because these shoreline data sets were derived from small-scale maps, we next evaluated them for spatial accuracy by comparing the location of the mapped shorelines with topographic features and with other linear or curvilinear features on the DEM. Within the study area, shoreline features vary between strongly expressed beach ridges to more subtle wave-cut bluffs or bars. Most of these features have fairly distinct lateral continuity on the landscape, which helps to identify them as coastal landforms. Many also are readily identifiable based on soil data; they show up as sandy areas or as areas of slightly better-drained soils. When applied to the NRCS data, the Drainage Index of Schaetzl et al. (2009) was especially helpful in identifying shoreline features. Locations of relict shorelines often corresponded with narrow, linear soil map units of sandy soils, many with loamy substrata. Comparing and overlaying the previously mapped shorelines with topographic and soil data enabled us to create a new shoreline shapefile, and many of these shorelines could be associated with a particular lake stage or stages.

4. Results and discussion

4.1. Extent and boundaries of the delta

The large, elongate Chippewa delta is ≈ 18 km wide and ≈ 38 km long (Fig. 3). The delta heads near the city of Mt. Pleasant, where the Chippewa River enters the Saginaw Lowlands, and ends at the city of Midland, near the confluence of the Chippewa and Tittabawassee Rivers. The northern delta boundary roughly follows the highest elevation terraces of the Salt River, which eventually discharges into the Titabawassee River. The southern margin of the delta appears to overlap with deltaic sediments from another, smaller delta associated with the Pine River (see below).

The thin sandy character of the delta, coupled with a lack of outcrops and detailed LiDAR topographic data, necessitated a mapping effort focused on soils and sediments (rather than stratigraphy or relief) for identifying, defining, and characterizing the Chippewa delta. This strategy has proven effective for relict Pleistocene deltas elsewhere (Vader et al., 2012; Luehmann and Schaetzl, 2017; Schaetzl et al., 2017).

In most places, the Chippewa delta has a diffuse, gradual distal boundary rather than a sharp delta front. Deltas that have formed in more *stable* paleolakes (e.g., the Black River delta in Glacial Lake Algonquin) have wave-worked, steep delta fronts (Vader et al., 2012; Schaetzl et al., 2017). We believe that the gradual slope of the delta margin here was formed in part by fluctuating lake levels, which effectively reworked the sands and splayed them out in the swashzones of the various lakes.

Because of its weak topographic expression, the margin of the delta was correlated to the extent/boundaries of sandy deposits on the otherwise loamy lake plain (Hutchinson, 1979; McLeese and Tardy, 1985; Schaetzl et al., 2013). In a GIS, we mapped the sandy deposits using a combination of NRCS soils data, stratigraphic logs from water well data, and textural data from field samples (Fig. 3). The delta boundary is shown as a dashed line in Figs. 3 and 5, in locations where our confidence in its exact location is low. In such locations, the delta grades into other deltas or into sandy alluvium from parallel-flowing streams. In most places, the margins of the delta represent a transition from thick (> 2 m) sands, to two-storied soils (< 2 m sand over loamy materials at depth), to loamy soils formed in Saginaw lobe till. The sands become more discontinuous and interspersed with areas of loam-textured parent materials near the delta periphery. Although the delta boundary is not sharp or even noticeable in most places on the ground, we argue that our estimation is as accurate as currently possible and is supported by land use; across the boundary, land use typically changes from forest (on the delta) to agriculture (on the loamy lake plain) (Figs. 3, 5).

Very little of the delta surface is currently used for agriculture, as most of the soils are sandy and wet (Figs. 2, 5A). Most of the delta is currently in low-density residential land use or state-owned forest; the Chippewa River State Forest and Tittabawassee River State Forest account for much of the northwestern, north-central, and south-central parts of the delta. General Land Office surveys compiled during the 1850s also reported forest cover dominated by hemlock (*Tsuga canadensis*) and white pine (*Pinus strobus*) on the delta (Comer et al., 1995). The Productivity Index of Schaetzl et al. (2012) clearly illustrates the lower productivity of the sandy soils on the delta, vis a vis the surrounding landscape (Fig. 5C). Areas of *upland grass/shrub* in Fig. 5A typically represent abandoned farm fields, indicating that many areas on the delta that were once farmed are now in pasture or have been left fallow.

4.2. Geomorphology, sediments, and soils

The delta surface is best characterized as a broad, relatively flat, sandy plain (Fig. 2B) with widely spaced, incised stream valleys. It slopes very gradually (generally < 1% slopes) from west to east. In the central part of the delta, the Chippewa River is slightly incised (ca. 2–5 m below the delta surface) within a shallow paleovalley that ranges in width from ≈ 2.2 to 3.6 km. We named this paleovalley the Glad Tidings valley, for the only cultural feature of note within it: the Glad Tidings Church. Inset within the Glad Tidings paloevalley is a meandering, inset valley of the more recent Chippewa River. This later valley is incised almost 8 m below the level of the Glad Tidings valley, with one or two additional inset terraces (Fig. 2A). The Salt River flows approximately along the northern margin of the delta, whereas the Pine River flows along the southern margin, cutting into the delta about 14 km east of the village of Shepherd.

As is typical for many of the sandy areas in the Saginaw Lowlands (Arbogast et al., 1997; Schaetzl et al., 2013), a small dune field, roughly

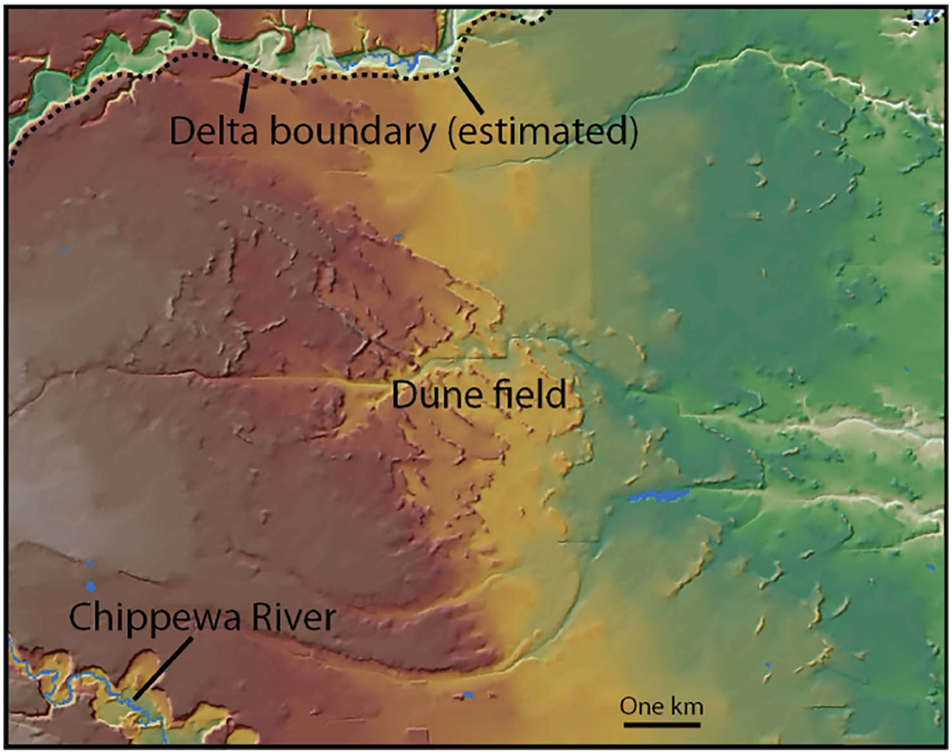

Fig. 6. Hillshade DEM of the dunes in the north-central part of the Chippewa delta.

5 × 8 km in area, occurs in the north-central part of the delta. The field contains a number of broad (≈ 700 m wide) but low (< 3 m in height), closely spaced, parabolic dunes (Figs. 2C, 6). To the east and southeast of this dune field, dunes appear more sporadically and are more widely spaced.

Except for the dunes, large portions of the delta are swampy, with most of the soils in somewhat poorly or poorly drained drainage classes (Hutchinson, 1979; McLeese and Tardy, 1985). Most soils classify as Mollic Psammaquents, Typic Endoaquolls, or Typic Endoaquods. Soils on slightly higher areas are usually Oxyaquic Haplorthods, whereas soils on dunes are Typic Udipsamments. Loamy soils on the lake plain of the Saginaw Lowlands, just outside of the delta proper, are typically Mollic Endoaquepts or Aeric Glossaqualfs.

4.3. Delta thickness

Data from water well logs and two-storied soils were used to estimate the thickness of the delta. We obtained well log data before the boundary of the delta was determined; as a result, many data points fell outside of the final delta boundary. Nonetheless, these data add to our confidence in the thickness data near the delta's periphery, as determined by kriging.

Overall, the sands in the Chippewa delta are fairly thin, averaging only 2.9 ± 2.4 m thick. As interpreted by the kriging routine, delta sands range in thickness from < 2 m at the northern and southern margins of the delta, to > 6 m in the central part (Fig. 7). Two areas of particularly thick sands are present: (i) near the head of the delta within and east of the City of Mt. Pleasant and (ii) in the north-central part of the delta (Fig. 7). The latter area, with mean thicknesses of 5–6 m or more, is bisected by the present-day Chippewa River. This thickest-sand area thins but continues toward the eastern margins of the delta, at Midland, where the sands thicken slightly to 2.0–2.5 m.

In order to better evaluate the variation in sand thickness across the delta, in ArcMap we took a random sample of 200 points across the kriged sand thickness layer. These data (Fig. 7B) provide detail on the delta's thickness and better represent the thickness of this landform, which has a very uneven distribution of wells/data. (A random sample of well data, taken from the wells shapefile alone, would under-represent areas of the delta where few wells exist.) The delta averages 2.3 m thick, with a median thickness of 2.0 m (Fig. 7C). The majority of these points fell on locations where the sands were 1–2 m thick.

We attribute the overall thin but wide character of the delta to the preexisting shallow accommodation space of the lake plain, combined with strong sorting and reworking of the delta sands by waves and currents in the shallow lake waters, which acted to splay the sediments out across the lake plain. As outlined below, frequent changes in lake level also impacted the delta by creating lakeward regressions and landward transgressions. These fluctuations were apparently very effective in redistributing sands across the shorezone areas and obscuring any wave-cut bluffs or scarps that may have existed.

The two main areas of thickest sand are typically associated with former shorezones of Glacial Lake Saginaw, as discussed below. A third area of slightly thick sands, outside and immediately south of the Chippewa delta, appears to be associated with the delta of the Pine River (Fig. 1).

4.4. Textural patterns

As has been done previously (Vader et al., 2012; Schaetzl et al., 2017), spatial patterns of the delta sediments were examined to gain insight into paleodepositional processes. Although the delta is sand-textured throughout, patterns of various gravel and sand fractions revealed interesting and important information.

Of the 180 auger samples, 127 are within the sand textural class (Soil Survey Division Staff, 1993). Of the remaining 53, 29 classify as coarse sand or loamy coarse sand, and 20 as either fine sand, very fine sand, loamy fine sand, or fine sandy loam (Fig. 8A). The majority of coarser samples are in the upper portion of the delta, clustered near Mt. Pleasant. Many of the fine and very fine sand samples are near the extreme margins of the delta — a trend that appears consistently in the field. Modal values for all the samples (Fig. 8B) peaked in the sand fraction. The spatial distribution of modes shows a similar spatial

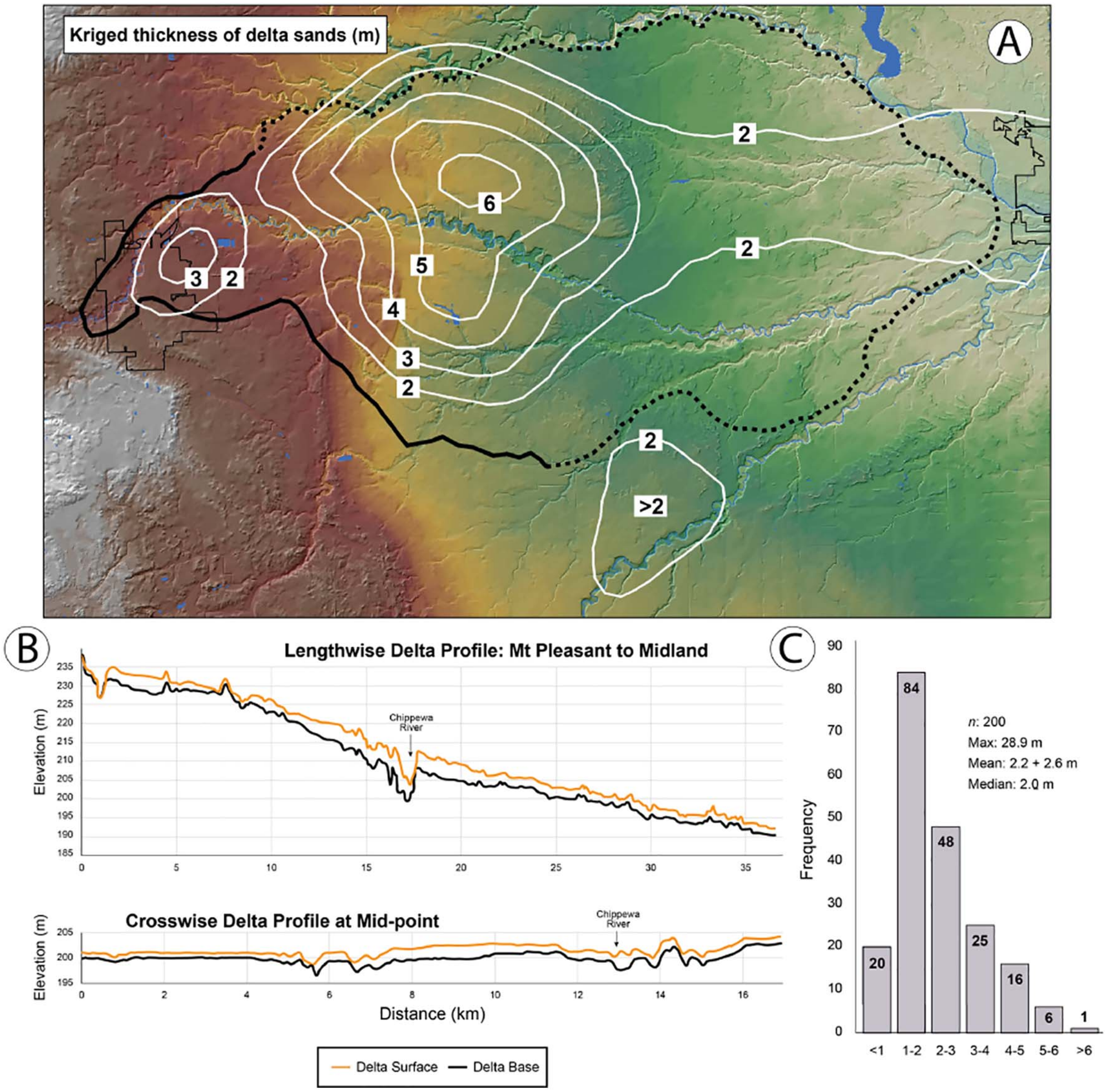

Fig. 7. Thickness of the sands in the Chippewa delta. (A) Kriged map of the data obtained from well logs and two-storied soils. (B) Profiles of the delta surface (top line), determined from a DEM, along with an estimate of the base of the delta (bottom line), determined by subtracting the kriged sand thickness interpolation surface from the DEM. The A-A′ profile generally follows a west to east transect from Mt. Pleasant to Midland, whereas the B-B′ profile is along a north to south transect about two-thirds of the way to the margin of the delta. (C) Histogram of sand thicknesses, derived from 200 randomly placed points on the delta, as extracted from the kriged thickness layer in (A).

pattern to the data for texture classes – peaking near the head of the delta. Only 66 of 180 samples have > 2% gravel, and they are again primarily located in the upper part of the delta near Mt. Pleasant (Fig. 8C). Data for very coarse sand contents (Fig. 9) have similar spatial patterns to those for gravel.

Based on these data, we identified two distinct coarse textured zones on the delta (Fig. 9). The first zone is coincident with the modern Chippewa River, near the head of the delta, where it is spatially restricted. This upper delta area was indicated generally on Martin's (1955) map. Sediments here are very coarse textured, with comparatively high contents of gravel, very coarse sand, and coarse sand and correspondingly low contents of fine and very fine sand. Aggregate extraction operations can be found in this area. Modes in this zone are dominantly within the coarse sand fraction (Fig. 8B). In the NRCS soil data, soils within the Thetford series (Aquic Arenic Hapludalfs), described with coarse sand subsurface textures, are widely mapped here. A second zone is associated with the Chippewa River in the central part of the delta. Here, the river has incised ca. 2–5 m below the general delta upland, forming the previously mentioned Glad Tidings paleovalley. The modern, meandering Chippewa River is incised almost 8 m below this valley (Fig. 2A). Sediments within and immediately beyond this channel are also coarser textured than those of the surrounding delta regions (Fig. 9), suggesting that an erosional event, late in the formation interval of the delta, carried coarser sediment eastward, onto the prograding surface.

4.5. Paleoshorelines and shorezones

The discussion below presupposes that the relative isostatic adjustment across the Chippewa delta has been minimal (M. Lewis, Geological Survey of Canada, pers. comm.; see also Lewis et al., 2005). Rebound values since ca. 11 ka·BP vary across the delta, north-to-south, by < 1 m. Thus, we proceed with the assumption that paleoshorelines here should all be nearly horizontal.

Between ≈ 17.1 and ≈ 15 ka·BP, the Saginaw, Arkona, and Warren stages of Glacial Lake Saginaw inundated all or various parts of the study area, respectively. During this period, waters within the Saginaw Lowlands were assumed to have been widely fluctuating, as indicated by the indistinct shorelines and facilitated by the generally low-relief character of the basin (Leverett and Taylor, 1915; Bretz, 1951; Kincare

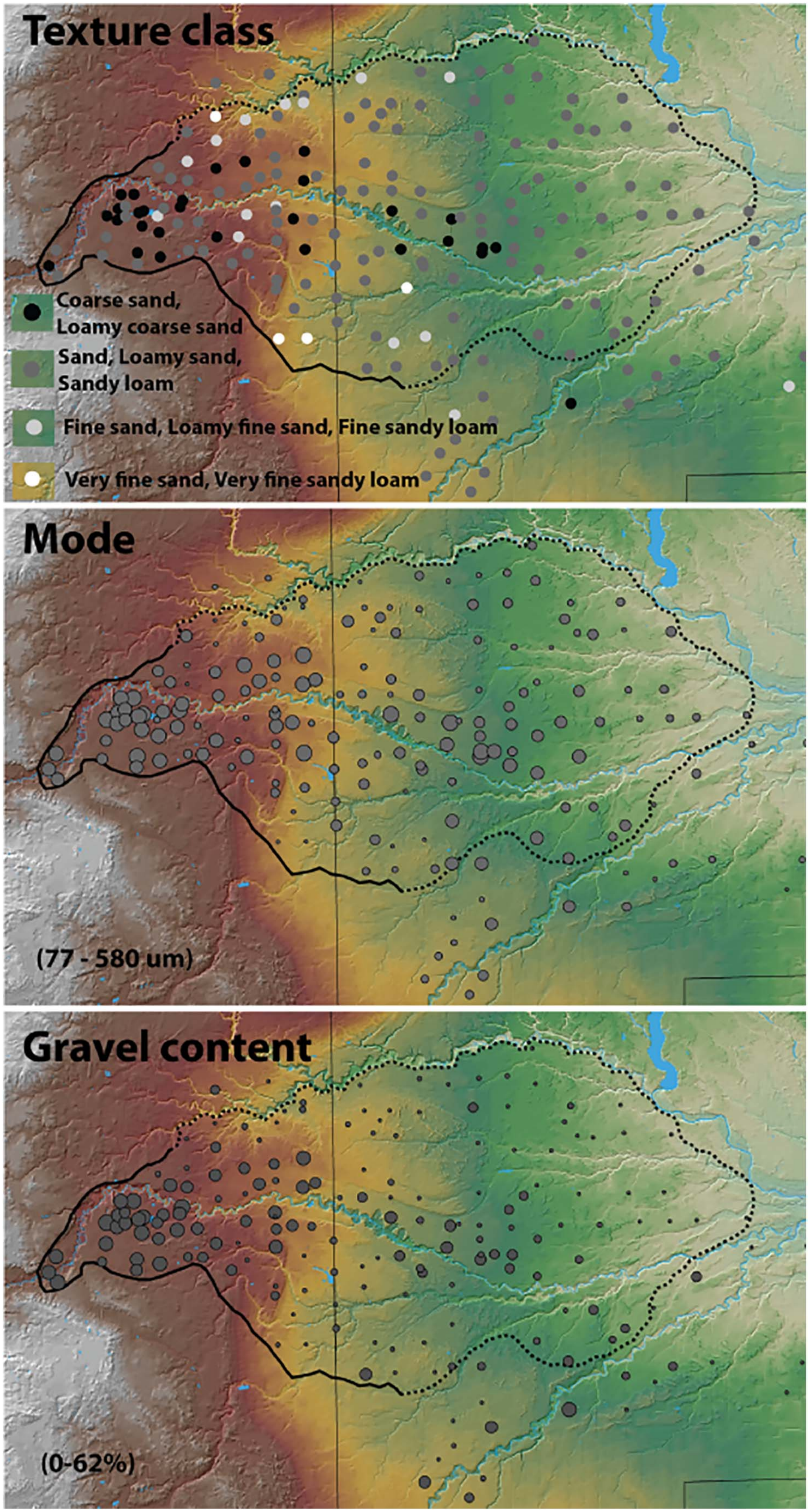

Fig. 8. Texture data across the delta for the 180 auger samples, shown as filled circles and (A) sorted by texture class, (B) according to particle size mode and (C) gravel content.

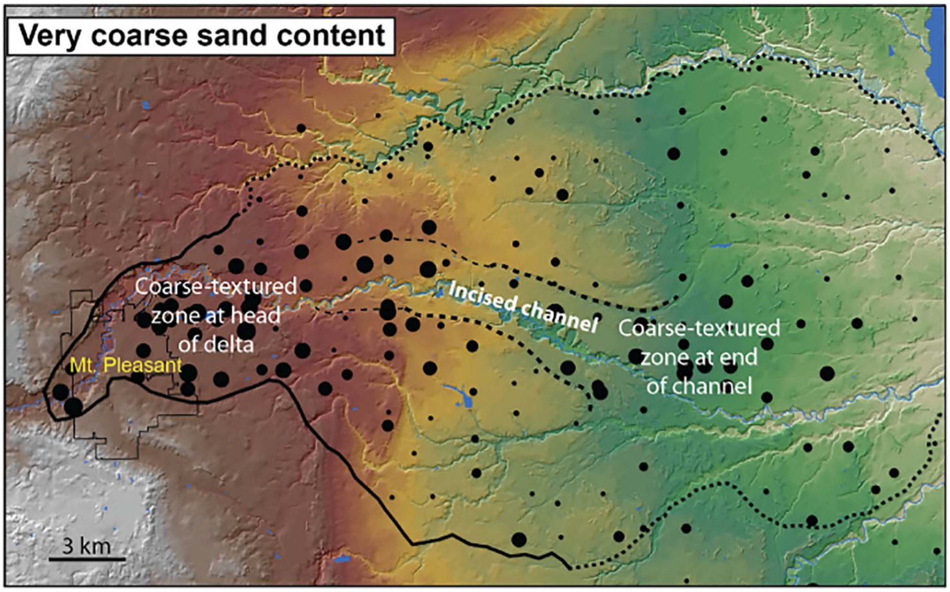

Fig. 9. Map of the upper delta, showing contents of very coarse sand (1–2 mm·dia.), as related to the incised channel in the center of the delta.

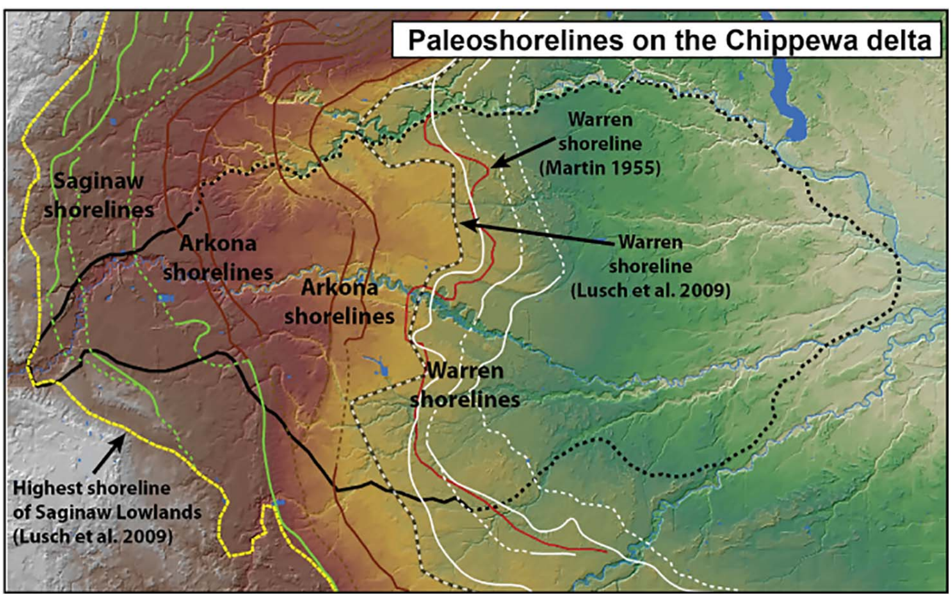

Fig. 10. Shorelines in the vicinity of the Chippewa delta, showing the delta outline and the Chippewa River. The shorelines primarily reflect data taken from Martin (1955) and Farrand and Bell (1982), but their positions were slightly modified in a GIS, based on topographic attributes. Dashed lines reflect areas of less certainty, drawn by connecting shorelines of roughly similar elevations across the delta.

and Larson, 2009). Lake levels were mainly controlled by downcutting in the Maple-Grand Valley but also by oscillations at the ice margin that uncovered (and recovered) lower elevation outlets outside of the study area. Fluctuating lake levels would have had a considerable impact on delta progradation, by changing the discharge point of the Chippewa River onto the delta proper. Key to the growth of the delta was the progradation and regression of shorezones as lake levels fell and rose.

Shorelines are difficult to observe and only intermittently mapped across the delta and surrounding lake plain because of the short-lived nature of each individual shoreline, coupled with the sandy nature of the sediments. The latter created a situation whereby shorezone features were easily destroyed by rising lake levels, as well as by subaerial erosion and eolian activity after the lakes had drained (Eschman and Karrow, 1985; Arbogast et al., 1997). Thus, the data we report here have mainly been gleaned from the small-scale maps of Martin (1955) and Farrand and Bell (1982) as well as the high-level shoreline reported by Lusch et al. (2009). On the former two maps, shorelines have been mapped primarily in off-delta areas where finer-textured sediments prevail, leading to better topographic expression. We modified the locations of these shorelines subtly, in locations where an obvious topographic break (as shown on the DEM) justified it, and then extended them across the delta as dashed lines (following contours of similar elevation) because few topographic features are apparent on the 10-m DEM of the delta proper (Fig. 10).

4.6. Geomorphic history of the Chippewa delta

The geomorphic history of the Chippewa delta revolved around deposition of sandy sediment into the various stages of Glacial Lake Saginaw, as these stages frequently rose and fell within the basin. Most paleodeltas in the Great Lakes region have formed in one stage of a paleolake and thus lack mid-delta shorelines, which can complicate interpretations.

Commensurate with this basin-filling event were periods of shoreline progression and regression, which led to diminution of any shoreline features such as wave-cut bluffs or offshore bars and concomitant transport of sands into the shallow waters of nearshore areas, splaying the delta sands out across the lake floor. The result is a broad, sandy delta with sands that are typically only 2–3 m in thickness, except in areas of preferred deposition, and few distinct shoreline features.

Sediments of the upper delta, in and near Mt. Pleasant, are comparatively thick and coarse textured (Figs. 7, 8, 9). This area appears to represent delta formation into Early Lake Saginaw, associated with the oldest and highest elevation shorelines in the study area (Fig. 10). Here, the delta is only ≈ 4.5 km wide, moderately (≈ 2–3 m) thick, with comparatively high contents of gravel and very coarse sand. The shoreline history here is complex, mainly due to incrementally lowering lake levels (pre-Lake Arkona) caused by downcutting of the outlet at the Maple-Grand River valley. The lowest elevation shoreline of Glacial Lake Saginaw was also nearly coincident with the highest Arkona shoreline (Fig. 10). Glacial Lake Arkona (≈ 16.5 to ≈ 15.5 ka·BP) also drained through the Maple-Grand River valley outlet.

The delta is thickest in an area ca. 13 km ENE of the upper delta (Fig. 7). This area of thick sands is generally coincident with some of the lower Arkona shorelines (Fig. 10). Sediments here are coarse textured above the Arkona shorelines, but become finer textured in what may have been the shallow waters offshore (Figs. 8, 9, 10). We interpret sediments here as near-shore deltaic deposits associated with a pulse in delta progradation during the Arkona phase. At this time, the delta widened and thickened, likely incorporating sediments from the preexisting delta. When a low outlet for the lake opened in the Trent Lowlands (Ontario), Glacial Lake Arkona drained and was replaced by an eastward-draining lake –Lake Ypsilanti (Kunkle, 1963; Larson and Schaetzl, 2001). At this time, the Saginaw Lowlands may have been completely subaerial, leading to fluvial incision. The Port Huron readvance at 15.5 ka·BP then closed off the Trent outlet, reforming a lake in the Saginaw Lowlands.

Clear evidence for a period of incision is preserved in the Chippewa delta, in the deep, wide Glad Tidings valley mentioned above (Fig. 9). This valley bisects the thickest sediments of the delta, implying that it post-dates Glacial Lake Arkona. We believe that this channel was cut as the lake fell from Arkona (and Saginaw) levels to those of Glacial Lake Warren, as the upper part of the delta became subaerial. (The Warren stage formed as the tip of Michigan's *thumb* became ice free, merging the two lakes in the Erie and Saginaw basins.) Sediments eroded from the upper delta would then have been redeposited as the delta prograded farther into Glacial Lake Warren. Evidence for these sediments is shown in Figs. 7, 8, and 9 as a relatively thick, coarse-textured zone that extends from the end of this channel almost to Midland.

An alternate hypothesis for the formation of the Good Tidings valley is associated with the Lake Ypsilanti low stage. Evidence supporting the Ypsilanti low stage was first identified in the Lake Erie basin by Kunkle (1963) but had been previously suggested by Hough (1966) for the Michigan and Huron lake basins. Evidence for the Ypsilanti low has never, however, been documented for the Saginaw Basin. During the Ypsilanti low, the Saginaw Lowlands would have presumably been entirely subaerial, causing rivers in the basin to incise. The Glad Tidings valley may, in part, be relict from this erosion event. The valley may then have aggraded as lake levels subsequently rose. Following this rise, lake levels in the Saginaw Basin dropped to the Lake Warren stage and the Chippewa River may have again incised into any aggradational deposits in the valley, making the floor of the Glad Tidings valley a fill terrace.

As mentioned above, following the Ypsilanti low stand, readvance of the ice margin blocked the Trent outlet and reestablished Glacial Lake Saginaw. Subsequent retreat of the ice margin led to the coalescing of Glacial Lake Saginaw with Glacial Lake Whittlesey in the Erie Basin, forming Glacial Lake Warren in the Saginaw basin, which formed as the Maple-Grand River outlet was downcut (Kehew, 1993). Most sources cite at least two or three Warren shoreline elevations (Bretz, 1951; Kunkle, 1963; Barnett, 1985; Kincare and Larson, 2009); in our study area we identified three (Fig. 10). Opening of new outlets to the east, outside the study area, eventually led to the drainage of Glacial Lake Warren and the establishment of lakes in the Saginaw Lowlands that were at levels below those of the Chippewa delta. Delta growth during the Warren stage appears to have been dominated by fine sands, with minimal gravel content, having been eroded from the upper delta and redeposited into the shallow waters of Glacial Lake Warren and splayed out by waves and currents. This depositional event caused the delta to widen and lengthen considerably. Growth of a delta on the Pine River, south of the Chippewa delta, may have also been occurring at this time.

After drainage of Glacial Lake Warren, the Chippewa delta appears to have undergone little additional growth. Geomorphic activity was limited to eolian activity associated with parts of the delta that were vulnerable to deflation (Fig. 6).

5. Conclusions and implications

Data from water well logs, NRCS digital soils data, and field-collected samples were used to confirm the presence of the Chippewa delta, first identified by Martin (1955). In this study we identify, characterize, and interpret the geomorphic history of the Chippewa delta in central Lower Michigan. Our work represents the first use of these types of spatial data sets and methods in the geomorphic study of a relict delta. The sandy, low relief Chippewa delta developed in stages, forming in various lakes that occupied the Saginaw Lowlands between ca. 17 and 15 ka·BP. Coarse-textured zones on the delta are associated with former shorezones and/or erosional channels.

As in most research, our work answers some questions and generates others. For years, the sandy deposits on the Saginaw Lowlands were an enigma, as the sediments of the Saginaw lobe are primarily loamy. Our work confirms that this area of sands, and likely most others, represent thin deltaic deposits associated with rivers entering the many proglacial lakes that occupied the basin (Luehmann and Schaetzl, 2017).

The modern-day Chippewa River is a medium-sized river that at present carries little bedload. For it to have built the extensive Chippewa delta, the Chippewa River would have to have had a much larger discharge and a ready supply of sand. These conditions could have been met by positing either a glacial meltwater source and/or extensive permafrost within the basin to facilitate runoff. Evidence of permafrost during the late Pleistocene does exist for nearby areas (Schaetzl, 2008; Lusch et al., 2009), leading us to conclude that much of the upland landscapes to the west of the Chippewa delta were, at least for some part of the 17–15 ka timespan, experiencing permafrost. Preliminary work on a large lake in central Lower Michigan, north of the study area, appears to suggest that outflows from this lake may also have contributed to the discharge of the paleo Chippewa River (Schaetzl et al., 2017). Work on other sandy areas in the Saginaw Lowlands may help to better understand the geomorphic, hydrologic, and paleoclimatic environments of this region during the immediate post-glacial period.

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