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Late Pleistocene deltas in the Lower Peninsula of Michigan, USA

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ABSTRACT

U.S. Geological Survey (USGS) Monograph 53 by Frank Leverett and Frank Taylor identified more than 20 deltas of late Pleistocene age in the Lower Peninsula of Michigan. To that list, we add many additional deltas discovered during the course of our research. These "relict" deltas are important proxies for paleoenvironmental conditions, particularly wave energies, as well as prevailing wind and longshore drift directions. If dated, they can help to constrain the chronologies of ice retreat and proglacial lake stages. In plan view, relict delta morphologies usually protrude from a paleolake shoreline and are often elongate or cuspate shaped. Most of the deltas identified by Leverett and Taylor have this morphology and are located at the junction of a major present-day river and a relict paleolake shoreline. In this chapter, we map and discuss these deltas, first identified by Leverett and Taylor, while also identifying and describing the other, newly found deltas. All of these deltas formed during the marine isotope stage 2 ice retreat, roughly 28–13 ka. To identify and characterize them, we utilized a variety of data within a geographic information system, mainly a statewide USGS 7.5′ digital raster graphic, a 10 m digital elevation model (DEM), county-level Natural Resources Conservation Service soil data, and schematic lithologic depth profiles interpreted from descriptive water well and oil/gas logs. DEMs were particularly useful, because they can be "flooded" to various elevations of paleolakes. Maps of soil wetness and textural characteristics were also useful in detecting and delineating deltas. In sum, we mapped 61 deltas; 27 had been known from previous works, whereas 34 are newly reported in this study. Most are composed of sandy, well-drained sediments and have smooth, graded longitudinal profiles. Of these, most are perched above a relatively low-relief, poorly drained lake plain. However, unlike several deltas recognized by Leverett and Taylor, we found that many of the newly reported deltas are (1) adjacent to one or more formerly unknown shorelines, (2) not associated with a modern river, (3) complex, and/or (4) broad, coalesced features, deposited by more than one river, with fan-like morphologies. The methods that we used to identify and delineate these deltas can be applied to other regions. Mapping like the kind reported here will aid in a better understanding of the paleocoastal and terrestrial conditions during the late Pleistocene.

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INTRODUCTION

Deltas, which form when a river deposits more sediment at its mouth than can be removed by the nearshore water body in longshore drift, are valuable environmental proxies (Lyell, 1832; Galloway, 1975). Relict deltas are no longer graded to an active shoreline and thus provide evidence of paleolake levels and conditions (Gilbert, 1885, 1890). The shape and sedimentary characteristics of relict deltas are also excellent proxies for certain paleoenvironmental conditions, such as wave energies, and dominant wind and longshore drift directions (Leverett and Taylor, 1915; Coleman and Wright, 1975; Orton and Reading, 1993; Suter, 1994; Milligan and Chan, 1998; Bhattacharya and Giosan, 2003; Woodroffe and Saito, 2011; Vader et al., 2012; Blewett et al., 2014; Gobo et al., 2014). Such deltas can also provide proxy data for paleoterrestrial conditions within their catchment areas, such as sediment load and landscape stability (Oldale et al., 1983; Shipp et al., 1991; Barnhardt et al., 1995, 1997; Walker, 1998; Mangold and Ansan, 2006; Bell, 2009). The wide variety of paleoenvironmental proxies associated with relict deltas merits their thorough study. Our focus in this chapter is on relict deltas associated with paleolakes, most of which were formed in association with glacial meltwater sources. In some ways, such deltas are unique from others: They have minimal tidal influence and form under the influence of highly variable discharge regimes with respect to both water and sediment.

In U.S. Geological Survey (USGS) Monograph 53, Leverett and Taylor (1915) documented more than 20 relict deltas in the Lower Peninsula of Michigan. These deltas (and others discussed in this chapter) formed during ice retreat after the Last Glacial Maximum, in a paraglacial environment where rivers discharged into nonmarine, pro- and postglacial lakes (Leverett and Taylor, 1915). Leverett and Taylor had minimal subsurface information and relied heavily on topographic signatures in their interpretation. Based on their findings, the locations of the majority of known relict deltas are shown on Plate VII of the *Glacial Map of the Southern Peninsula of Michigan* (Leverett and Taylor, 1915). For example, using dashed lines in a fan-shaped pattern, Leverett and Taylor (1915) highlighted the Allendale and Zeeland Deltas, both located nearly 10–15 km inland from the present-day mouths of the Grand and Macatawa Rivers, respectively, in Ottawa County, Michigan. The massive (~475 km^2) Jackpines Delta, located in Iosco County, was also originally identified by Leverett and Taylor (1915), as well as many deltas of Glacial Lake Maumee, in southeastern Michigan.

Forty years after USGS Monograph 53 was published, Helen Martin (1955) published the *Map of the Surface Formations of the Southern Peninsula of Michigan*. On this map, she labeled many (but not all) of the same deltas mentioned in USGS Monograph 53. Martin also identified another delta, the Chippewa River Delta, located between Mount Pleasant and Midland. Roughly 20 years after Martin's map was published, Wendy Burgis' (1977) dissertation on the glacial landforms in northeastern Lower Peninsula of Michigan was published. Burgis focused on the relict deltas associated with the glacial Au Sable River, originally discussed in USGS Monograph 53. Like Martin before her, Burgis added to the list of known deltas. More recently, Vader et al. (2012) identified and discussed the origin of the Black River Delta, another relict delta in northeastern Lower Peninsula of Michigan that had gone undocumented in previous research.

As discussed herein, history has shown that detailed study of Michigan's physical landscape can lead to discoveries of previously undocumented landforms. We build upon these previous works to develop a new, more thorough inventory of relict Pleistocene deltas in the Lower Peninsula of Michigan. In our study, we employed current geologic maps and spatial data, viewed and profiled in a geographic information system (GIS), to identify and describe dozens of relict deltas in the Lower Peninsula of Michigan. We attempt here to provide information about the age and physical characteristics for a few typical examples, using the categories identified by Luehmann (2015) via a principal components analysis. Although other deltas certainly will be found in the future, our study nonetheless provides the most complete inventory of relict deltas in the Lower Peninsula of Michigan to date.

METHODS

Data Sources

Our mapping effort began by examining the geologic literature on the Great Lakes region (Leverett and Taylor, 1915; Farrand and Eschman, 1974; Karrow and Calkin, 1985; Larson and Schaetzl, 2001). Each delta mentioned in this literature was marked as a point feature using ArcMap 10.1 (ESRI©, Redlands, California) and stored in a GIS project (.mxd). Maps published by Martin (1955) and Farrand and Bell (1982) were georeferenced, and the deltas and shorelines on those maps were digitized within the GIS project. In addition, water well and oil/gas log data for each county in the Lower Peninsula of Michigan, downloaded from the Michigan Geographic Data Library (http://gis.michigan.opendata.arcgis.com/), were added to the project. Well locations were formatted as point features within the GIS, whereas attribute data were saved in a spreadsheet. Well-log attributes were joined to the well-log locations to aid in identifying the primary lithology, depth, thickness, and color of the well strata. In order to more efficiently interpret and describe the subsurface sediments, a graphical depth plot was created for each well log using the R software package (version 3.1.2, http://www.r-project.org/). An R script, coded specifically for this study, was used to read in the well-log information and construct lithologic logs (Fig. 1). Individual logs were saved as portable document format (PDF) files. The original point-feature shapefile of wells, developed on a county-by-county basis, was then converted to a peninsula-wide geodatabase, and the depth plot images were joined to the associated well-log point using the "add attachments" tool in ArcGIS. This geodatabase allowed the "HTML popup" tool in ArcGIS to be employed to show stratigraphic and textural characteristics of wells, sometimes exceeding 150 m. This tool and the data it

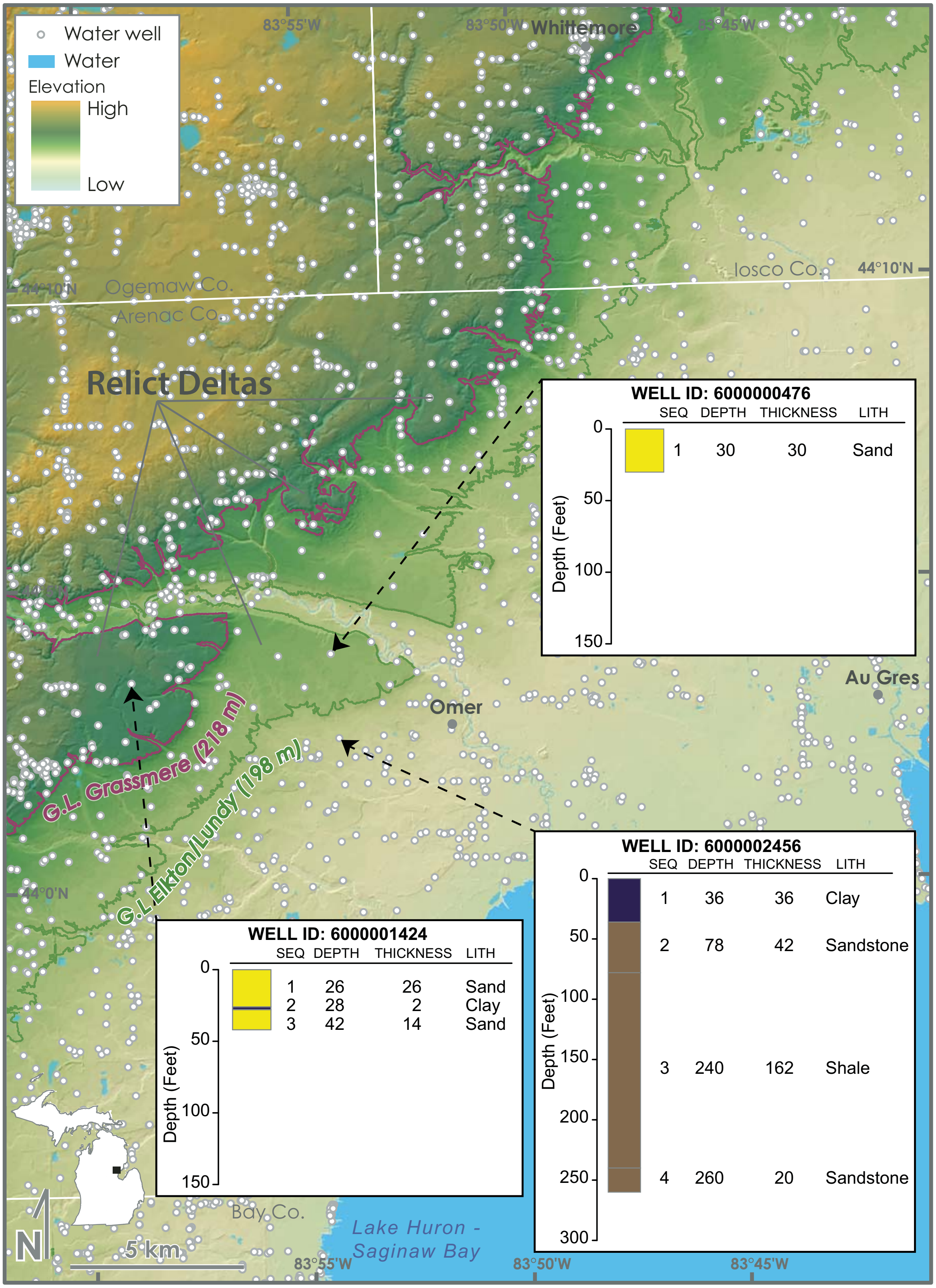

Figure 1. Location of water wells from the Michigan Geographic Data Library database, and the lithologic logs of selected wells using the ArcGIS "HTML Popup" tool, revealing the texture and depth of lithologic contacts. The base map is a 10 m digital elevation model (DEM) that is overlaid on a hillshaded DEM. White inset at bottom left shows map location in the state of Michigan.

provides are useful for exploring sedimentary (grain-size) characteristics of landforms.

In addition to the data listed above, several of the geographic data layers listed in Schaetzl et al. (2013) were also included in the GIS project. In particular, a statewide USGS 7.5′ topographic map, a seamless 10 m National Elevation Data set (NED) and digital elevation model (DEM), and a hillshade DEM (Gesch et al., 2002) were added to the GIS. Several derivative data sets, which are based on Natural Resources Conservation Service (NRCS) soil map data, were also included, e.g., the natural soil drainage index (Schaetzl et al., 2009, 2013), and the textures of the uppermost mineral, and deepest subsurface horizons. These data were originally derived from the NRCS Soil Survey Geographic (SSURGO) database.

The majority of the deltas mentioned in the literature were identified using the geospatial data layers mentioned here; we searched for landforms that formed a bulge along a relict shoreline, often with a fan-shaped or elongated outline (Vader et al., 2012). Because many of the deltaic landforms identified in previous works were composed of sandy, well-drained sediments and had one or more clear paleochannel(s) and a graded longitudinal profile, we focused on exploring sites with these characteristics. Furthermore, our focus was on sites that were located on relatively low-relief and (usually) wet lake plain areas.

Identifying Additional Deltas

Within the GIS, in many cases, we "flooded" sections of the landscape using a 10 m DEM to help find areas where an upland or area of contrasting soil texture or wetness occurred along a probable relict shoreline and/or an escarpment that could be interpreted as a relict shoreline (Fig. 2). This exercise facilitated the identification and description of the overall shape and area of any additional deltas or subdeltas. It also helped us to refine the extents of deltas previously reported in the literature (Luehmann et al., 2013); the names of such deltas were retained. However, each newly identified delta was named after a river/creek or formerly named geologic feature within the region that was likely

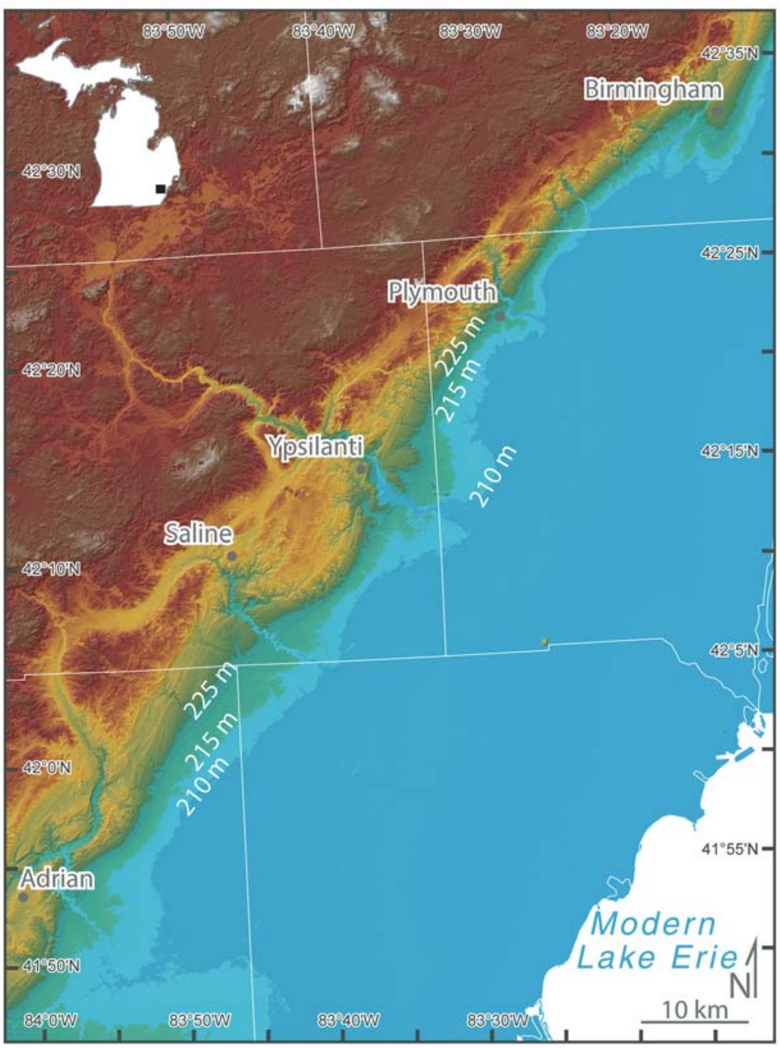

Figure 2. Example of a digital elevation model (DEM) "flooded" to the 225, 215, and 210 m levels of Glacial Lakes Maumee and Arkona (Karrow and Calkin, 1985). This area, in southeastern Lower Michigan, illustrates that relict deltas may form conspicuous terraces along relict shorelines. Deltas are located near the cities of Adrian, Saline, Ypsilanti, Plymouth, and Birmingham. Note: Lake symbology (i.e., blue fill) has no reference to water depth. White inset at top left shows map location in the state of Michigan.

associated with the delta during its formation. A Roman numeral was added to the delta name (with Roman numeral "I" being oldest) for situations in which multiple deltas had formed from a single fluvial system.

The longitudinal profile of each delta, both those under review and those previously reported, was examined using data from a 10 m DEM and employing the "profile" tool in ArcMap. Each profile began near the apex of the delta and ended beyond the delta front, approximately at the start of the prodelta position.

Martin's (1955) *Map of the Surface Formations of the Southern Peninsula of Michigan*, which was georeferenced in a GIS for this project, was often used in combination with the profile information to determine the shoreline to which each delta was graded, i.e., the upper end of each profile. This information was then used to assign each delta to a lake stage and/or phase, and to infer an estimated age range (Table 1).

RESULTS AND DISCUSSION

Relict Deltas in the Lower Peninsula of Michigan

Based on morphological and soil characteristics, we identified 61 relict deltas in the Lower Peninsula of Michigan (Fig. 3; Table 1). In total, 23 of these deltas were originally recognized by Leverett and Taylor in USGS Monograph 53, four additional deltas were acknowledged by subsequent studies and researchers, and this study, along with Luehmann (2015), identified 34 more unique deltas (Table 1). Many of the newly identified deltas are not associated with a large, present-day fluvial system, and hence the word "creek" is often applied to the deltas (e.g., Brown, Cedar, and Deer Creek Deltas). The lack of a large, contemporary river at some delta heads may explain why they had not previously been reported.

Although additional sedimentological criteria (e.g., topset and foreset bedding, and basinward textural fining trends) could have helped confirm whether each feature has deltaic origins, we lacked such data. Thus, it is possible that some of the "deltas" we identified may have formed at least partially subaerially and thus are better termed alluvial/colluvial fans and fan deltas. We nonetheless believe that each of the features we report has deltaic properties.

Presumably, each of the relict deltas discussed in this study formed during the marine isotope stage 2 ice retreat. Of the 61 deltas, 17 occur in the Lake Erie drainage basin (15,016 km^2; one delta per 883 km^2), 29 in the Lake Huron drainage basin (38,250 km^2; one delta per 1319 km^2), and 15 in the Lake Michigan drainage basin (53,195 km^2; one delta per 3546 km^2; note: the number of deltas per drainage area is based on the shaded regions illustrated in Fig. 4). We labeled the deltas in Figures 3 and 4, and listed them in Table 1, incrementally from south to north within each basin. However, deltas in a delta complex were labeled first, before assigning the next closest delta a number. Therefore, deltas are not listed exactly in order by latitude; there are eight delta complexes in the Lake Erie and Lake Huron Basins (Table 1).

Distribution of Deltas

Eastern Lower Michigan has the densest concentration of deltas (Fig. 3). This distribution likely occurs because paleolakes were more expansive on this side of the peninsula, and these lakes experienced wider lake-level fluctuations. For example, at least 11 and 12 different lake elevations existed for the Lake Huron and Erie Basins, respectively, between the Crown Point–Port Bruce and Two Rivers–Onaway phases (Fullerton, 1980; Karrow and Calkin, 1985; Colman et al., 1994; Larson and Schaetzl, 2001; Kincare and Larson, 2009). Conversely, throughout roughly the same time period, the paleolakes in the Lake Michigan Basin reflect primarily two (main) paleolake elevations of Lake Chicago (Glenwood and Calumet; Evenson, 1973; Hansel et al., 1985; Clark et al., 1994; Colman et al., 1994). The wider range of paleolake fluctuations in the Lake Erie and Huron Basins, as opposed to the Lake Michigan Basin, implies that fluvial systems draining to the eastern Lower Peninsula of Michigan had to make more base-level adjustments. Thus, more deltas and subdeltas had the potential to form. Figures 3 and 4 illustrate this point; many of the deltas in the Lake Erie and Huron drainage basins are complex features and are closely spaced or stacked (i.e., delta complexes), even when they are associated with a single fluvial system. We could find no evidence of similar situations for relict deltas within the Lake Michigan drainage basin (Figs. 3 and 4).

Another possible reason for the greater number of deltas in the eastern Lower Peninsula of Michigan may be related to the strength or persistence of waves and/or longshore currents within individual lake basins. Stronger waves and currents along the western margins of the Lower Peninsula of Michigan may have been able to carry away more of the load that was being transported to the coast, slowing or preventing deltas from forming. The strength and persistence of longshore drift would have been governed by the dominant wind strength and direction. Proxy data for wind direction and strength for the Great Lakes region during this fairly large time span are, understandably, equivocal. Evidence from many Midwestern U.S. loess and dune deposits suggests strong westerly and northwesterly winds during the time period when deltas may have formed in the Lower Peninsula of Michigan (Muhs and Bettis, 2000; Rawling et al., 2008; Schaetzl et al., 2014; Arbogast et al., 2015). Conversely, data from spits and other coastal features within Glacial Lake Algonquin (somewhat later in time) point to strong easterly winds for areas within a few hundred kilometers of the ice margin (Krist and Schaetzl, 2001; Vader et al., 2012; Schaetzl et al., 2016). Evidence is also mounting that locally strong, katabatic winds could have dominated, or at least been more prevalent, near former ice margins (Krist and Schaetzl, 2001; Luehmann et al., 2013; Schaetzl and Attig, 2013). Regardless of directionality, winds within the Lower Peninsula of Michigan at the time of delta formation were likely considerably stronger than at present, potentially leading to strong longshore currents and wave energies at exposed shoreline locations. Thus, delta formation may have been promoted mainly in sheltered areas and embayments (Vader et al., 2012).

TABLE 1. LIST OF THE 61 DELTAS ANALYZED DURING THIS STUDY, ALONG WITH THEIR GENERAL LOCATION, ELEVATION, AND THE PALEOLAKE(S) TOWARD WHICH THEY ARE MOST LIKELY GRADED

Map ID	Delta name	Latitude and longitude of delta center	Delta plain elevation (m asl)	Glacial lake (phase)	Estimated age range (cal k.y. B.P.)	Reference(s)
E-1	Raisin River	41°52′1″N, 83°55′50″W	221–212	Arkona (I–III)	16.0–15.5	Leverett and Taylor (1915); Martin (1955)
E-2	Saline River	42°5′32″N, 83°43′54″W	221–217	Arkona (I–III)	16.0–15.5	Leverett and Taylor (1915)
E-3	Huron River I	42°14′43″N, 83°35′9″W	233–230	Maumee (I–III)	17.1–16.3	Leverett and Taylor (1915); Scherzer (1916); Bay (1937, 1938); Martin (1955)
E-4	Huron River II	42°13′4″N, 83°33′34″W	220–213	Arkona (I–III)	16.0–15.5	Leverett and Taylor (1915); Scherzer (1916); Bay (1937, 1938)
E-5	Huron River III	42°9′34″N, 83°26′2″W	199–197	Warren (I–II), Wayne	15.1–14.7	Leverett and Taylor (1915); Scherzer (1916); Bay (1937, 1938)
E-6	Middle River Rouge	42°22′3″N, 83°26′24″W	220–211	Arkona (I–III)	16.0–15.5	Leverett and Taylor (1915); Scherzer (1916); Bay (1937, 1938)
E-7	Tarabusi Creek	42°26′15″N, 83°22′50″W	220–215	Arkona (I–III)	16.0–15.5	Leverett and Taylor (1915)
E-8	Rochester	42°30′21″N, 83°15′0″W	219–212	Maumee (I–III)	17.1–16.3	Leverett and Taylor (1915); Scherzer (1916); Bay (1937, 1938); Howard, 2010
E-9	Clinton River	42°39′1″N, 83°4′12″W	220–210	Maumee (I–III), Arkona, Warren, Wayne	17.1–14.7	Leverett and Taylor (1915); Martin (1955)
E-10	North Branch Clinton River	42°47′27″N, 82°57′11″W	225–215	Arkona (I–III)	16.0–15.5	Leverett and Taylor (1915)
E-11	Belle River	42°50′4″N, 82°39′60″W	206–203	Warren (I–III)	15.1–14.7	Leverett and Taylor (1915)
E-12	Smiths Creek	42°56′10″N, 82°38′24″W	208–206	Warren (I–III)	15.1–14.7	Leverett and Taylor (1915)
E-13	South Pine River	42°58′21″N, 82°36′53″W	208–203	Warren (I–III)	15.1–14.7	Leverett and Taylor (1915)
E-14	Black River I	42°59′30″N, 82°31′57″W	206–198	Warren (I–III)	15.1–14.7	Leverett and Taylor (1915)
E-15	Black River II	43°0′27″N, 82°29′56″W	196–192	Warren (I–III)	15.1–14.7	Leverett and Taylor (1915)
E-16	Black River III	43°0′47″N, 82°27′57″W	190–188	Grassmere, Lundy	14.7–14.3	Leverett and Taylor (1915)
E-17	Pine River	43°0′9″N, 82°36′16″W	210–206	Warren (I–III)	15.1–14.7	Leverett and Taylor (1915)
H-1	Flint River	43°13′11″N, 83°56′2″W	197–191	Lundy	14.7–14.3	Luehmann (2015)
H-2	Cass River	43°35′47″N, 83°7′40″W	238–225	Saginaw	15.1	Leverett and Taylor (1915); Martin (1955); Larson and Kincare, 2009
H-3	Chippewa River I	43°36′54″N, 84°44′1″W	232–226	Early Saginaw	16.3–16.0	Martin (1955)
H-4	Chippewa River II	43°36′36″N, 84°34′41″W	219–212	Warren (I–III)	15.1–14.7	Luehmann (2015)
H-5	Gladwin	43°59′0″N, 84°26′56″W	241–230	Early Saginaw	16.3–16.0	Luehmann (2015)
H-6	Rifle River I	44°3′19″N, 83°58′47″W	227–220	Warren (I–III)	15.1–14.7	Luehmann (2015)
H-7	Rifle River II	44°4′5″N, 83°54′2″W	207–200	Grassmere	14.7–14.3	Luehmann (2015)
H-8	Big Creek	44°6′26″N, 83°54′26″W	227–220	Warren (I–III)	15.1–14.7	Luehmann (2015)
H-9	Cedar Creek I	44°7′50″N, 83°51′47″W	227–225	Warren (I–III)	15.1–14.7	Luehmann (2015)
H-10	Cedar Creek II	44°8′18″N, 83°49′7″W	207–200	Grassmere	14.7–14.3	Luehmann (2015)
H-11	Johnson Creek	44°11′43″N, 83°47′3″W	208–205	Lundy	14.7–14.3	Luehmann (2015)
H-12	Au Gres River I	44°14′0″N, 83°45′56″W	218–210	Grassmere	14.7–14.3	Luehmann (2015)
H-13	Au Gres River II	44°13′10″N, 83°45′13″W	208–206	Lundy	14.7–14.3	Luehmann (2015)
H-14	West Branch Rifle River	44°13′42″N, 84°10′15″W	265–255	Early Saginaw	16.3–16.0	Luehmann (2015)
H-15	Jackpines	44°26′8″N, 83°37′32″W	260–245	Warren (I–III)	15.1–14.7	Leverett and Taylor (1915); Martin (1955); Burgis (1977, 1981)

(*Continued*)

TABLE 1. LIST OF THE 61 DELTAS ANALYZED DURING THIS STUDY, ALONG WITH THEIR GENERAL LOCATION, ELEVATION, AND THE PALEOLAKE(S) TOWARD WHICH THEY ARE MOST LIKELY GRADED (*Continued*)

Map ID	Delta name	Latitude and longitude of delta center	Delta plain elevation (m asl)	Glacial lake (phase)	Estimated age range (cal k.y. B.P.)	Reference(s)
H-16	Sevenmile Hill	44°27′35″N, 83°29′21″W	235–220	Grassmere	14.7–14.3	Leverett and Taylor (1915); Martin (1955); Burgis (1977, 1981)
H-17	South Branch	44°32′44″N, 84°36′15″W	375–368	?	<17.1	Luehmann (2015); Schaetzl et al. (2017)
H-18	Beaver Creek I	44°35′35″N, 84°45′45″W	402–393	?	<17.1	Luehmann (2015)
H-19	Beaver Creek II	44°33′46″N, 84°46′27″W	386–371	?	<17.1	Luehmann (2015)
H-20	Bull Gap	44°38′40″N, 84°1′5″W	310–295	?	<15.1	Luehmann (2015)
H-21	Kneeland	44°40′26″N, 84°4′3″W	326–317	?	<15.1	Burgis (1977, 1981)
H-22	Elk Hill	44°43′34″N, 84°22′23″W	389–380	?	<15.1	Luehmann (2015)
H-23	Indian Creek I	44°49′34″N, 83°48′38″W	262–259	?	<15.1	Luehmann (2015)
H-24	Indian Creek II	44°50′40″N, 83°47′10″W	249–241	?	<15.1	Luehmann (2015)
H-25	Turtle Lake	44°54′22″N, 83°56′6″W	245–238	?	<15.1	Luehmann (2015)
H-26	Brush Creek	45°4′11″N, 83°58′10″W	260–255	?	<15.1	Burgis, 1977, 1981
H-27	Sturgeon–Pigeon River	45°23′7″N, 84°35′40″W	219–205	Algonquin	13.2–11.5	Luehmann (2015)
H–28	Black River	45°25′45″N, 84°19′49″W	214–207	Algonquin	13.2–11.5	Vader et al. (2012)
H-29	McPhee Creek	45°26′46″N, 84°47′60″W	219–210	Algonquin	13.2–11.5	Luehmann (2015)
M-1	Fair Plain	42°5′42″N, 86°25′34″W	195–189	Chicago (Calumet)	14.1–12.6	Leverett and Taylor (1915); Martin (1955); Kincare (2007)
M-2	Zeeland	42°47′55″N, 86°1′28″W	204–198	Chicago (Glenwood I & II)	16.8–15.0	Leverett and Taylor (1915); Martin (1955); Evenson (1973)
M-3	Allendale	42°58′28″N, 85°57′46″W	201–198	Chicago (Glenwood I & II)	16.8–15.0	Leverett and Taylor (1915); Bretz (1953, 1964); Martin (1955); Hough (1958, 1963); Kehew (1993)
M-4	Maple River	43°2′28″N, 84°29′17″W	224–222	Chicago (Glenwood I)	16.8–15.0	Luehmann (2015)
M-5	Sanborn Creek Fan	43°54′23″N, 85°44′46″W	280–276	?	<17.1	Luehmann (2015)
M-6	Lake City–Harrison Ridge	44°16′31″N, 85°1′12″W	372–370	?	<17.1	Luehmann (2015)
M-7	Slagle Fan	44°17′33″N, 85°48′58″W	311–252	?	<17.1	Luehmann (2015)
M-8	Cole Creek Fan	44°24′45″N, 85°39′43″W	310–295	?	<17.1	Luehmann (2015)
M-9	South Higgins Lake Ridge	44°26′57″N, 84°46′38″W	385–375	?	<17.1	Luehmann (2015)
M-10	Cottage Grove	44°30′30″N, 84°42′54″W	384–381	?	<17.1	Luehmann (2015); Schaetzl et al. (2017)
M-11	Platte River	44°40′8″N, 86°1′50″W	220–210	Algonquin	13.2–11.5	Luehmann (2015)
M-12	Boardman River	44°43′51″N, 85°37′11″W	220–210	Algonquin	13.2–11.5	Luehmann (2015)
M-13	Rapid River	44°50′17″N, 85°17′45″W	206–190	Algonquin	13.2–11.5	Luehmann (2015)
M-14	Deer Creek	45°8′6″N, 85°6′22″W	191–190	Algonquin	13.2–11.5	Luehmann (2015)
M-15	Brown Creek	45°9′24″N, 85°7′11″W	198–195	Algonquin	13.2–11.5	Luehmann (2015)

Note: The map ID values indexed in this table relate to the deltas labeled in Figures 3 and 4.

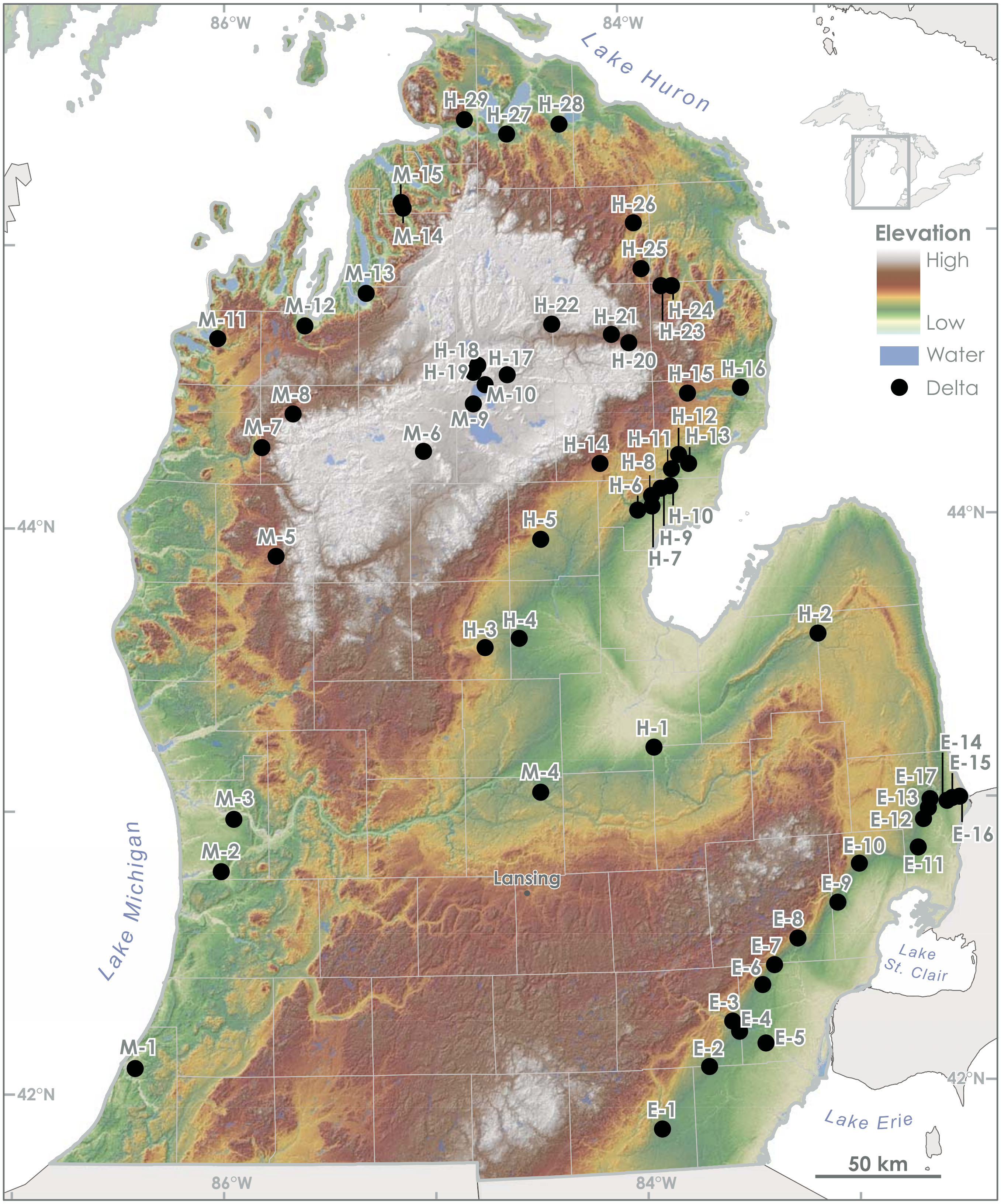

Figure 3. Locations of the 61 deltas reported in this study. Labels refer to the delta ID numbers; the letter prefixes refer to the modern watershed (E = Lake Erie, etc.). Additional information on each delta is provided in Table 1. White inset at top right shows map location in the state of Michigan.

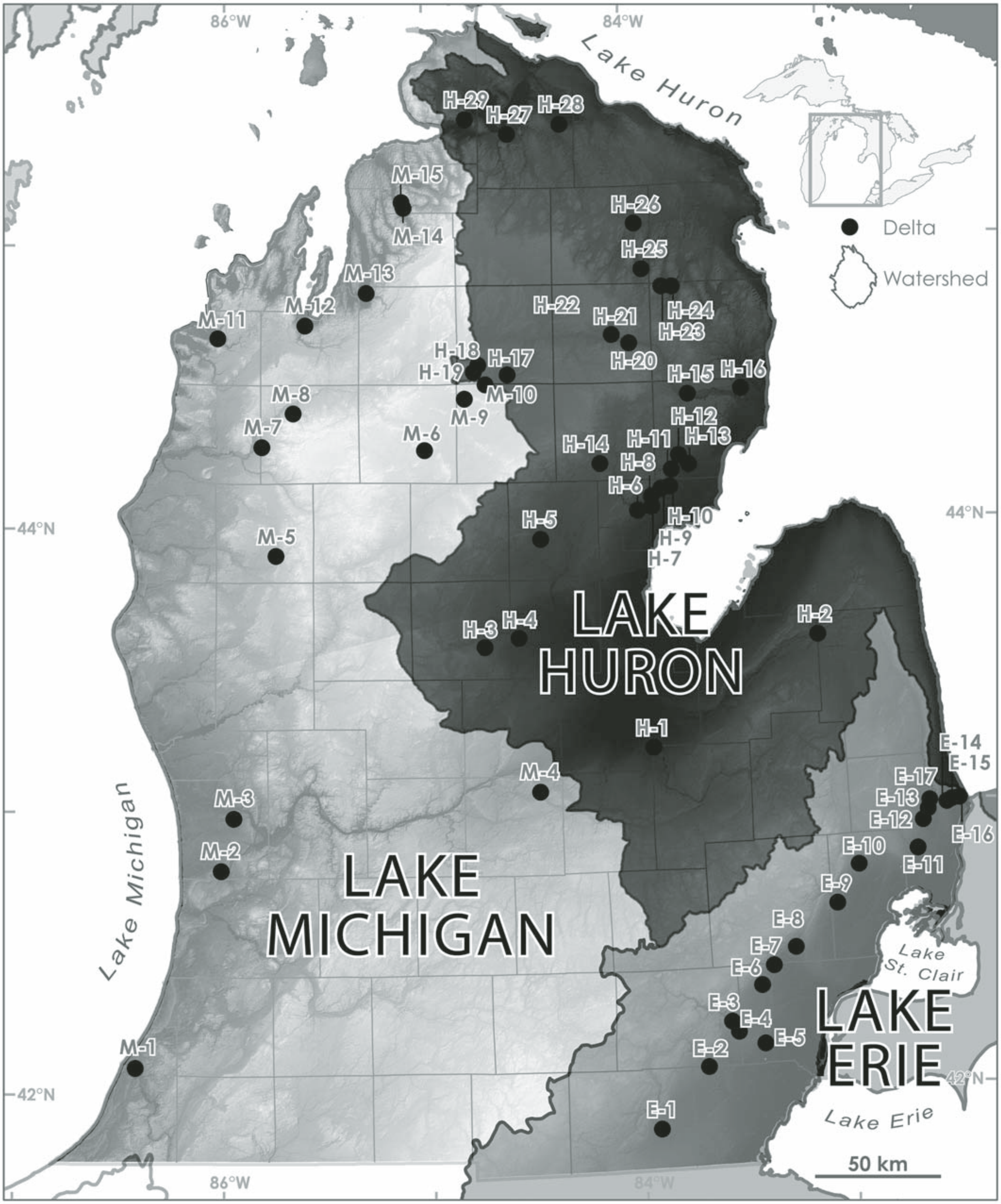

Figure 4. Extent of the (modern) Great Lakes drainage basins within the Lower Peninsula of Michigan, and the locations of Pleistocene deltas reported in this study. White inset at top right shows map location in the state of Michigan.

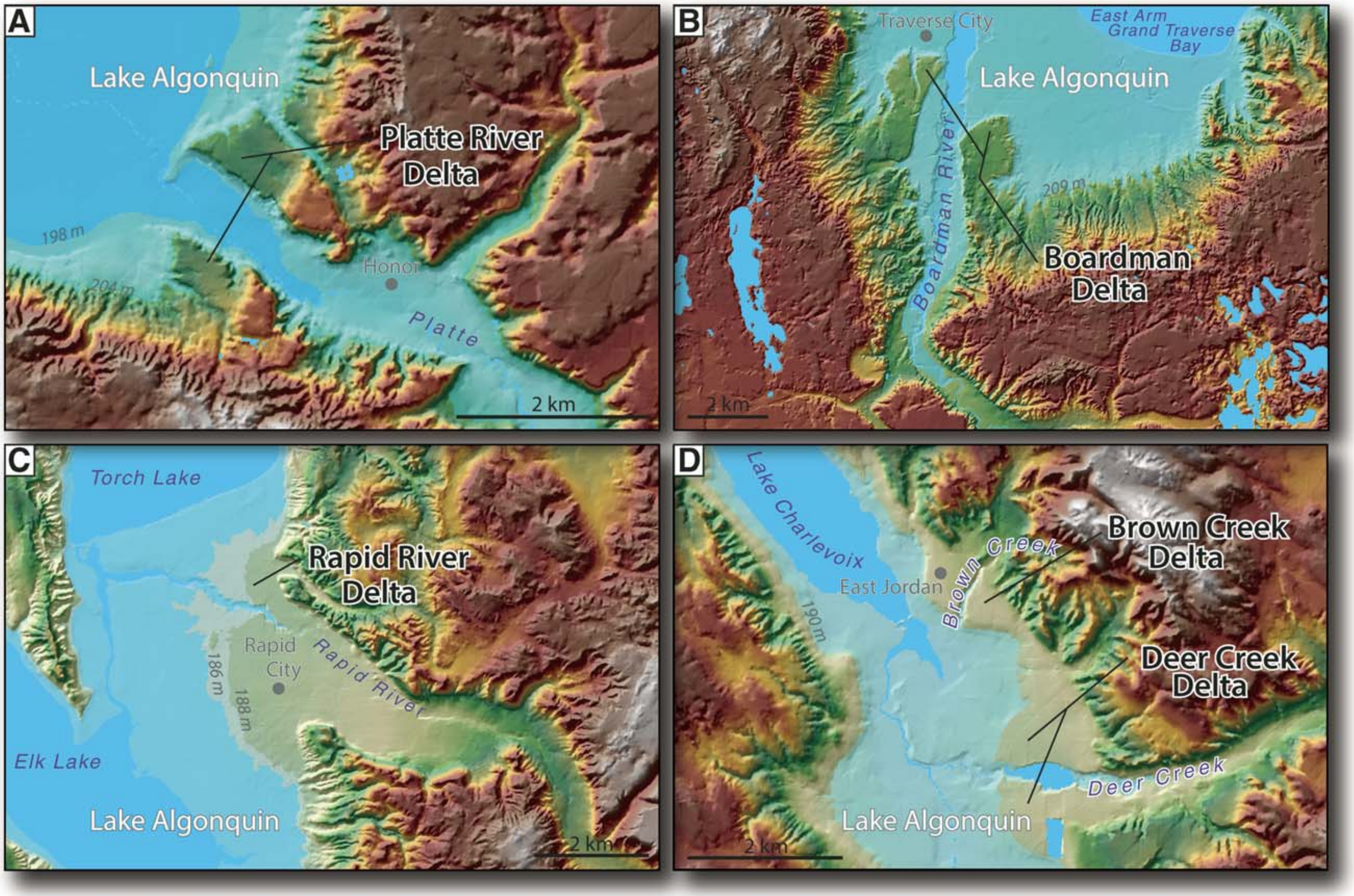

Figure 5. (A–D) Digital elevation model (DEM) flooded to one or more Lake Algonquin paleolake-level elevations (Drzyzga et al., 2012), illustrating the well-defined, symmetrical deltas characteristic of NW Lower Michigan. The approximate coordinates of the Platte River, Boardman, Rapid River, Brown Creek, and Deer Creek Deltas are 44°40′N/86°1′W, 44°43′N/85°37′W, 44°50′N/85°17′W, 45°9′N/85°7′W, and 45°8′N/85°6′W, respectively.

Categories of Deltas

When examining the deltas, we observed that certain groups of deltas had similar topographic and textural characteristics. For example, many of the deltas in northern Michigan have characteristics similar to the Black River Delta (Vader et al., 2012). The Black River Delta is a sandy, nearly symmetrical, arcuate-shaped landform, with one paleodistributary channel. It also has a relatively steep delta front and a low-gradient delta plain. According to Galloway's (1975) delta classification system, modern wave-dominated deltas often have one main feeder channel, with a smooth, arcuate outer margin, and a relatively steep, subaqueous, delta front, due to strong wave action along the margins of the delta. We agree with Vader et al. (2012), who suggested that the Black River Delta is best characterized as a wave-dominated delta. Based on similar morphology, we have interpreted a wave-dominated origin for the Platte River, Boardman River, Rapid River, Brown Creek, and Deer Creek Deltas, all located in the northwestern Lower Peninsula of Michigan (Fig. 5). The McPhee Creek, Turtle Creek, and Indian Creek I and II Deltas also have characteristics of wave-dominated deltas and are located in the northern Lower Peninsula of Michigan (Fig. 3; Table 1).

Some deltas that we mapped are not associated with an as-yet reported paleolake. The Cottage Grove and South Higgins Lake River Deltas are examples of deltas in the northern interior of the Lower Peninsula of Michigan, known as the High Plains. They are also sandy and generally arcuate shaped, and they were only recently identified by Luehmann (2015), and the Cottage Grove Delta later studied by Schaetzl et al. (2017; see also Fig. 6 herein). These deltas are unique because they are located on the distal sides of ice-marginal (kamic) ridges. Schaetzl et al. (2017) concluded that these deltas formed as the retreating ice margin temporarily paused, forming large ice-contact, kamic ridges, and because the ice margin was subaqueous at the time, these kame deltas formed in preferred locations. Nonetheless, the lake name(s) and stage(s) associated with these deltas are still unclear. Today, both the ridges and the deltas are relict, and thus, the deltas lack a contemporary catchment area. Like other deltas in the northern Lower Peninsula of Michigan, the deltas within this area are sandy and have steep outer margins, suggestive of a wave-dominated depositional environment.

Deltas in the southeastern Lower Peninsula of Michigan are often different than the sandy, wave-dominated deltas discussed in the previous paragraph. Like the deltas farther north, the deltas here have relatively large catchments and are often symmetrical and arcuate shaped, and primarily have one paleodistributary channel, e.g., the North-Branch, and the Clinton River Deltas. However, unlike the sandy deltas in northeastern Lower Michigan, many of the relict deltas in southeastern Michigan are composed of sediments with a variety of textures, ranging from clayey to sandy. We refer to such deltas as being "texturally mixed." Additionally, these deltas often have muted, or gently sloping, delta fronts. Leverett and Taylor (1915) interpreted the fairly subtle topographic characteristics associated with a few of these deltas to mean that, once formed, they were then inundated by higher, succeeding lake levels. Erosional processes associated with the later lakes may have led to a gradually sloping, wave-beveled, outer delta slope.

Other previously reported deltas in southern Michigan are more elongate-shaped features, with multiple paleodistributary channels and distinct midchannel bars (Fig. 7). Like the deltas in southeastern Lower Michigan, these deltas are also texturally mixed and are composed of sandy and gravelly textured sediments near the surface. Examples include the Allendale and Zeeland Deltas (Fig. 7). Both the Allendale and Zeeland Deltas have deep channels cut into the delta plain. Leverett and Taylor (1915) contended that the Allendale and Zeeland Deltas formed when the Glacial Grand River functioned as a spillway between the Huron and Lake Michigan Basins. The Cass River Delta, located in the "thumb" of the Lower Peninsula of Michigan, has similar topographic and sedimentological characteristics to the Allendale and Zeeland Deltas. The Cass River Delta also presumably formed in a meltwater/spillway setting, when the Cass River was the spillway between Glacial Lakes Whittlesey (within the Lake Erie Basin) and Saginaw (within the Lake Huron Basin; Kincare and Larson, 2009). The gross morphology and composition of these deltas, and their occurrence at the mouth of a meltwater spillway, best fit Galloway's (1975) fluvial-dominated delta category.

The Sturgeon–Pigeon River Delta, located in northern Lower Michigan, is an example of another type of relict delta identified in this study (Fig. 3; Table 1). Similar to the wave-dominated deltas, these deltas are sandy and have a relatively steep delta front (Fig. 8). Also like the fluvial-dominated deltas, they have multiple distributary and/or feeder channels. We interpreted these

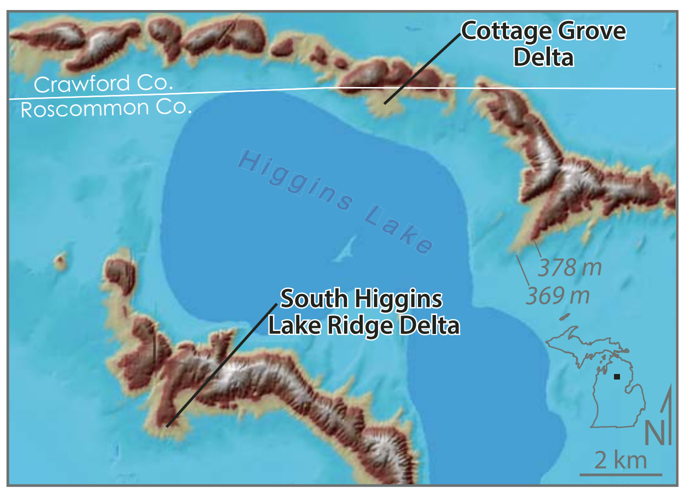

Figure 6. Digital elevation model (DEM) flooded to two potential paleolake-level elevations, illustrating the South Higgins Lake Ridge and Cottage Grove Deltas (Schaetzl et al., 2017) and the way in which they grade southward from the heads of outwash features in this area. These deltas are likely ice-contact features that formed as a retreating ice margin temporarily paused at the E-W–trending ridges. The approximate coordinates of the South Higgins Lake Ridge and Cottage Grove Deltas are 44°26′N/84°46′W, and 44°30′N/84°42′W, respectively. Co.—County.

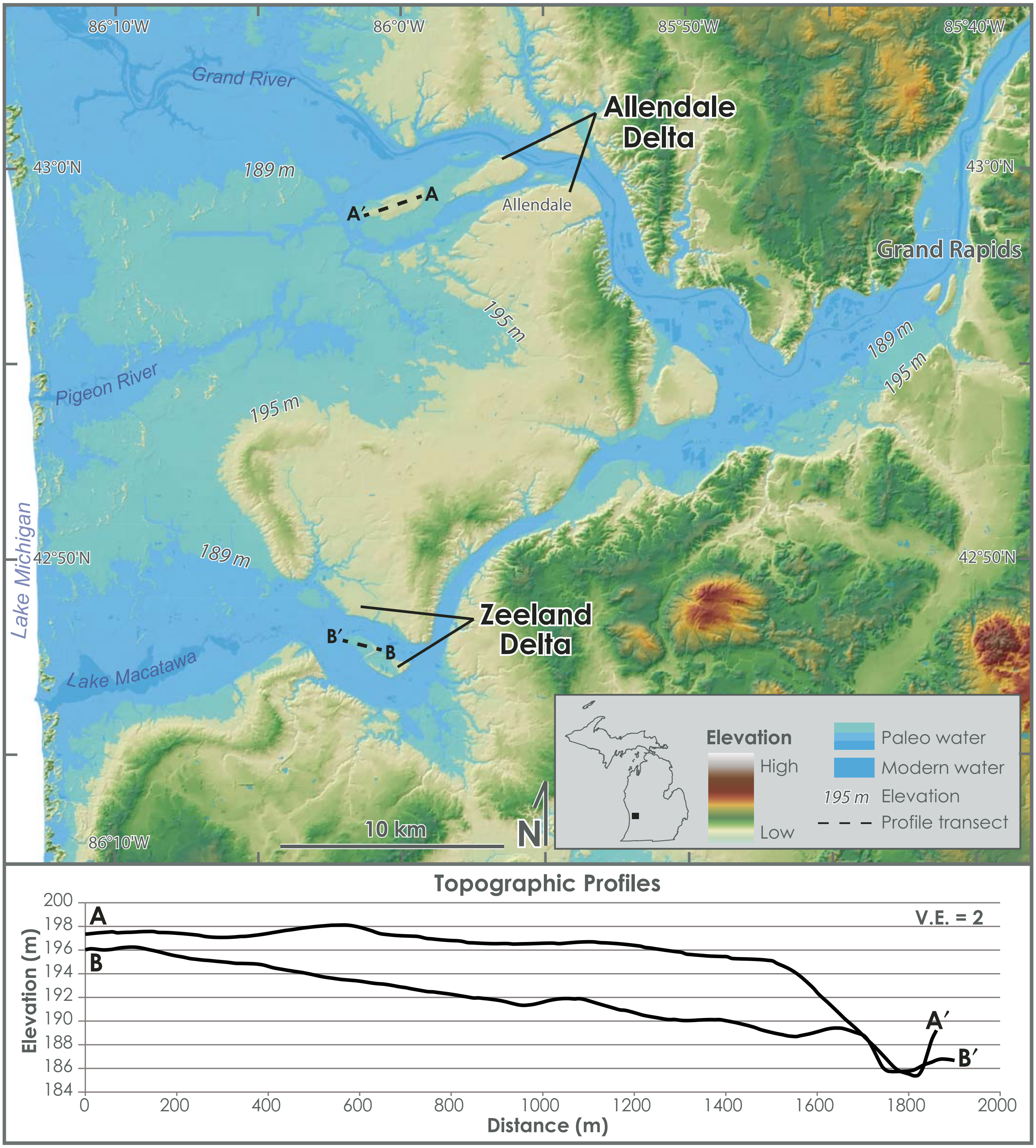

Figure 7. Digital elevation model (DEM) flooded to the Glenwood level of Glacial Lake Chicago (Hansel et al., 1985), illustrating the elongate shape and general profile of the Allendale and Zeeland Deltas. Black outline in legend shows map location in the state of Michigan. V.E.—vertical exaggeration.

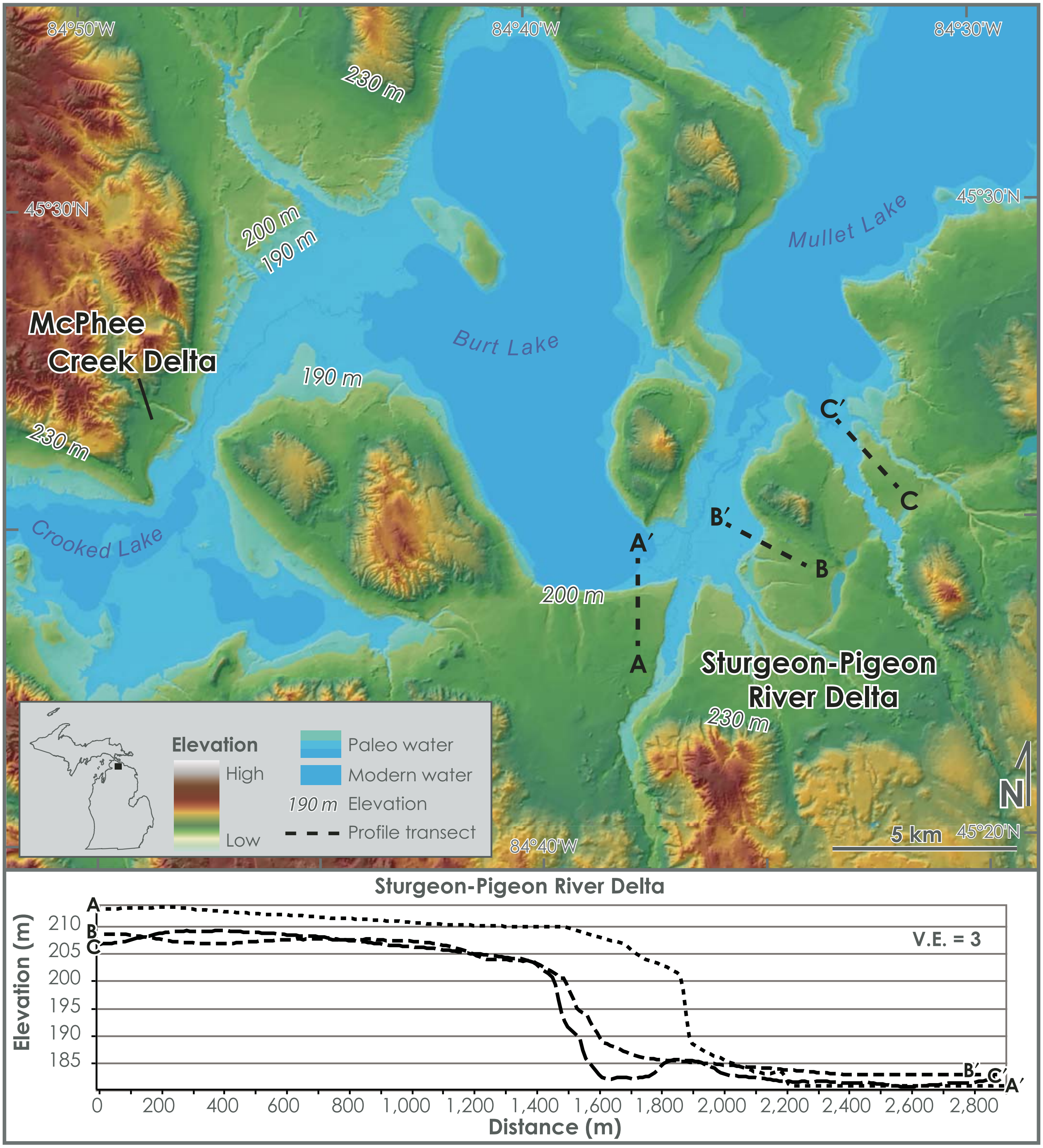

Figure 8. Digital elevation model (DEM) flooded to a likely Lake Algonquin level, illustrating multiple feeder channels and the broad, continuous delta plains of the Sturgeon–Pigeon River Delta. The steep delta front, which is also commonly associated with the coalesced deltas, is illustrated in the longitudinal profiles. Black outline in legend shows map location in the state of Michigan. V.E.—vertical exaggeration.

landforms' topography to be reflective of a delta composed of several broad, continuous, and overlapping delta plains. These deltas likely formed by the coalescence of several smaller deltas (Fig. 8); we refer to these types of deltas as coalesced deltas. They formed as large amounts of sediment were being deposited in a lake from several, closely spaced feeder streams. These types of deltas may also occur where the receiving basin is confined, and hence there is a limited amount of space and/or wave energy along the shoreline to distribute the large quantities of sediment away from the river mouths. The Slagle and Cole Creek Fan Deltas in Wexford County reflect additional examples of coalesced deltas in northern Lower Michigan (Fig. 3; Table 1).

CONCLUSIONS

When viewed collectively in a GIS, topographic, water well, and soils data have proven useful in identifying a number of previously unreported relict deltas in Michigan. The abundance of relict deltas in the Lower Peninsula of Michigan arises because of several contributing factors: (1) The region was home to several large, long-lived, proglacial lakes, many of which exhibited abrupt and/or large changes in lake level, and (2) many of the rivers that were tributary to these lakes were fed by glacial meltwater that transported copious amounts of sediment under flashy hydrological conditions, particularly during the spring. The late Pleistocene landscape had the potential to contribute massive amounts of sediment to fluvial systems because of (1) the lack of vegetation on the recently deglaciated surfaces, (2) buried ice that kept many landscapes unstable for considerable periods of time, and (3) potentially widespread permafrost, which promoted runoff and sediment production (Schaetzl, 2008; Lusch et al., 2009). The large number and, in some cases, vast size of these deltas suggest that the deglacial landscapes of southern Michigan were unstable for several hundreds to even thousands of years following deglaciation.

We hope that our study of relict Pleistocene deltas in the Lower Peninsula of Michigan will encourage further, more focused, research on these deltas, especially of their stratigraphy and sedimentology. We also encourage further work on the dating of these features, as has been done for the Cottage Grove Delta in central Lower Michigan (Schaetzl et al., 2017). Detailed analyses, and improved chronologies and dating methods, combined with better knowledge of deltaic processes across the region, will aid in our understanding of ice-marginal positions, lake-level history, and paleoenvironmental conditions in the late Pleistocene landscapes of Lower Michigan.

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