Ice-walled-lake plains: Implications for the origin of hummocky glacial topography in middle North America

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Abstract

Ice-walled-lake plains are prominent in many areas of hummocky-till topography left behind as the Laurentide Ice Sheet melted from middle North America. The formation of the hummocky-till topography has been explained by: (1) erosion by subglacial floods; (2) squeezing of subglacial till up into holes in stagnant glacial ice; or (3) slumping of supraglacial till. The geomorphology and stratigraphy of ice-walled-lake plains provide evidence that neither the lake plains nor the adjacent hummocks are of subglacial origin. These flat lake plains, up to a few kilometers in diameter, are perched as much as a few tens of meters above surrounding depressions. They typically are underlain by laminated, fine-grained suspended-load lake sediment. Many ice-walled-lake plains are surrounded by a low rim ridge of coarser-grained shore sediment or by a steeper rim ridge of debris that slumped off the surrounding ice slopes. The ice-walled lakes persisted for hundreds to thousands of years following glacial stagnation. Shells of aquatic molluscs from several deposits of ice-walled-lake sediment in south-central North Dakota have been dated from about 13 500 to 10 500 B.P. (calibrated radiocarbon ages), indicating a climate only slightly cooler than present. This is confirmed by recent palaeoecological studies in nearby non-glacial sites. To survive so long, the stagnant glacial ice had to be well-insulated by a thick cover of supraglacial sediment, and the associated till hummocks must be composed primarily of collapsed supraglacial till.

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1. Introduction

In many places in the mid-continent area of North America, ice-walled-lake plains are a conspicuous component of tracts of hummocky-till topography. The purpose of this paper is to detail evidence that the ice-walled-lake plains are of supraglacial origin, including palaeontological evidence that they could not have formed subglacially. Because of the close association of
ice-walled-lake plains and the hummocky-till topography, we argue that the hummocky till was also primarily of supraglacial origin.

Till hummocks have been interpreted to have formed in several different ways, including by erosion in subglacial floods (Munro and Shaw, 1997), by squeezing of subglacial material up into holes through stagnant glacial ice (Stalker, 1960; Eyles et al., 1999; Boone and Eyles, 2001), and by slumping of supraglacial material down into holes through stagnant glacial ice (Gravenor and Kupsch, 1959; Johnson et al., 1995; Johnson and Clayton, 2003).

The ice-walled-lake plains in these tracts of hummocky topography have typically been overlooked or unrecognized, and they are rarely mentioned in regional reports or textbooks on glacial geology. Yet they are widespread in areas of thick glacial sediment along the southern and southwestern marginal zone of the Laurentide Ice Sheet (Fig. 1). Here we review the morphology and sedimentology of ice-walled-lake plains in mid-continental North America and evaluate what they tell us about the origin of hummocky till.

Many ice-walled-lake plains can be identified with confidence because they have distinctive characteristics. They typically consist of offshore sediment surrounded by a ring of shore-zone sediment (Fig. 2a,b). Commonly, the outward-facing ice-contact face at the edge of the plain slumped when the support was removed as the surrounding ice melted (Fig. 2b). In many places, the lake sediment is tens of meters thick. In contrast to typical lake sediment, the ice-walled-lake sediment today is not in a basin, but is elevated above the surrounding topography.

A variety of names has been applied to these features, typically using various combinations of words such as dead-ice or stagnant-ice, ice-walled or perched, lake or lacustrine, and plains or plateaus. Parizek (1969) called them moraine lake plateaus.

2. Sources of information

Much of the information about ice-walled-lake plains is scattered in local reports on the glacial geology of specific areas, many not widely available. Our intent here is to summarize observations from several decades past and bring them up to date with more recent findings. Our emphasis is on North Dakota, Minnesota, and Wisconsin, because this area has abundant ice-walled-lake plains, most of which have been inventoried in reports of the three state geological surveys (Fig. 1), although we know of numerous examples in Iowa, South Dakota, Illinois, Manitoba, Saskatchewan, and Alberta as well as in Denmark, Sweden, Norway,
Poland, Lithuania, Germany, and Russia (Johnson and Clayton, 2003; Johnson et al., 2004).

The purpose of those reports was to map and describe the geology of an area, generally a county or regional study. Some of these contain detailed discussions of ice-walled-lake plains and were based on interpretations of aerial photographs and large numbers of observations of shallow exposures, generally roadcuts, with some drill holes and excavations.

3. Description

3.1. Abundance

In North Dakota (Fig. 1), 170 ice-walled-lake plains larger than about 1 km have been shown on a 1:500 000 state-wide compilation (Clayton, 1980; many smaller ones exist) derived from 1:125 000 maps in bulletins published by the North Dakota Geological Survey in the 1960s and 1970s. All occur on either the Turtle Mountains, a 60-km-wide upland in northern North Dakota and southern Manitoba, or on the Coteau du Missouri (Missouri Coteau), an upland 20 to 50 km wide, extending 1000 km southeast across Saskatchewan, North Dakota, and South Dakota (Fig. 1). Numerous ice-walled-lake plains are shown on 1:125 000 maps in bulletins of the South Dakota Geological Survey (Koch, 1975; Christensen, 1977; Leap, 1988; Hammond 1991). All are on either the Coteau du Missouri or the Coteau des Prairies (Prairie Coteau), a triangular upland that extends into Minnesota (Fig. 1).

In Minnesota, hundreds of ice-walled-lake plains formed in broad zones along the west flank of the Des Moines Lobe on the Coteau des Prairies in southwestern Minnesota (Patterson, 1992, 1995, 1997; Patterson et al., 1999) and along its east flank in the southeast and south-central part of the state (Patterson and Hobbs, 1995; Lusardi, 1997; Lusardi et al., 2002). They also occur, but less abundantly, in other parts of the state, where they tend to be more subtle and of lower relief than those formed on the flanks of the Des Moines Lobe (Fig. 1; Meyer, 1985, 1993a, 1993b; Hobbs et al., 1990; Meyer et al., 1990, 2001; Patterson, 1992; Meyer and Hobbs, 1993; Harris and Knaeble, 1999; Meyer and Lusardi, 2000; Patterson and Knaeble, 2001; Lusardi et al., 2002; Syverson et al., 2005). About 330 ice-walled-lake plains have been identified and shown on 1:100 000 maps of the Wisconsin Geological and Natural History Survey (Clayton, 1986, 1987, 2001; Johnson, 1986, 2000; Mickelson, 1986; Attig and Muldoon, 1989; Attig, 1993; Ham and Attig, 1997; Mickelson and Syverson, 1997).

3.2. Morphology

Like present-day lakes, ice-walled lakes tend to have rounded outlines, especially the smaller ones. Few ice-walled-lake plains are more than 5 km in diameter. Many less than 0.5 km have been recognized but have generally not been mapped. Many ice-walled-lake plains are as high as, or even twice as high as, the surrounding till hummocks (in the concluding remarks, we argue that the correlation between the height of hummocks and the height of ice-walled-lake plains is evidence that the hummocks are of supraglacial origin).

Ice-walled-lake plains form a morphologic continuum with low to high relief (Clayton and Cherry, 1967;
Ham and Attig, 1996, 1997; Syverson et al., 2005). The lower ones, less than about 20 m high, tend to be slightly dished, gently sloping downward from an outer rim into a central level area. Many low ones have a distinct ridge around the edge of the plain, some of which are several meters above the middle of the plain (Figs. 3 and 4). The higher ice-walled-lake plains (20 to 50 m high) tend to be flat to slightly convex, gently sloping from a central flat area down past a rim that lacks a ridge (Fig. 5a,b). Rim ridges might have originally existed but slumped away from the higher ice-contact faces.

Some ice-walled-lake plains appear to have had more than one phase of development (Johnson, 1986; Attig and Muldoon, 1989; Attig, 1993). For example, in Fig. 4a, ice walls apparently at first surrounded the lake plain above

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![Figure 3](image-url)

**Fig. 3.** Two low-level ice-walled-lake plains with rim ridge beaches, surrounded by hummocky collapsed till. Dotted lines mark the crest of ice-contact faces; 8 km north of Medford, Taylor County, Wisconsin; sec. 36, T. 32 N., R. 1 E.; from Attig, 1993, Figs. 24 and 25. (a) View to west. (b) Part of the U.S. Geological Survey Medford 7.5-minute topographic quadrangle; contour interval 3 m (10 ft). The large dashed V symbol marks the view of the photograph. Star symbols show location drill holes mentioned in text. North is to right in the photograph. Photograph by John Attig.
Fig. 4. (a) Two-phase terraced ice-walled-lake plain. Part of the U.S. Geological Survey Rosholt NW 7.5-minute quadrangle. Contour interval is 10 ft (∼3 m). Located in sec. 34, T. 26 N., R. 9 E. in Marathon County, Wisconsin (Attig and Muldoon, 1989). (b) Ice-walled-lake plain, cultivated, surrounded by hummocky till. Dotted line marks the crest of the ice-contact face around the lake plain. Located 19 km southwest of Ross, North Dakota, in sec. 6 and 7, T. 154 N., R. 94 W. (Clayton, 1972, Plates 1 and 2). U.S. Department of Agriculture aerial photograph BAL-4 V45. (c) Oblique aerial photograph of ice-walled-lake plain surrounded by till hummocks with central depressions, located 11 km south-southwest of Stanley, North Dakota, in sec. 23 and 26, T. 155 N., R. 92 W. The plain is 0.5 km wide. Dotted line marks the crest of the ice-contact face. Photograph by Lee Clayton.
the 1280 ft (390 m) contour. The ice walls receded and a lower lake plain formed at the 1230 ft contour.

3.3. Sedimentology

The central part of most low-lying lake plains is underlain by offshore clay, silt, and fine sand, grading to coarser near-shore sand, with beach sand and gravel at the rim (Figs. 5a,b and 6a,b; Clayton and Cherry, 1967; Johnson, 1986; Attig, 1993; Ham and Attig, 1997; Johnson, 2000; Syverson et al., 2005). The offshore sediment is horizontally laminated, and near the margin the bedding in the coarser sediment dips at a few degrees toward the centre. Faults are commonly observed near the ice-contact faces of the lake plains.

Some of the lower-level ice-walled-lake plains have rim ridges with steep outer slopes (ice-contact faces) but with gentle inner ones. These rim ridges are typically composed of beach sediment, but some have poorly sorted debris flows interbedded with the shore or near-shore sediment (Fig. 6a,b; Attig, 1993; Attig et al., 1998). The gently sloping rims of some ice-walled-lake plains have bodies of sand and gravel interpreted to be deltas with high-angle foreset beds dipping toward the centre of the lake plain (Fig. 5a,b). A delta extending into a lake plain is visible in the southwest part of the lake plain shown in Fig. 4a.

Other low-lying ice-walled-lake plains have rim ridges that are steep on both sides. They are composed of material that is similar to the till surrounding the ice-walled-lake plain and is thought to be material slumped off the surrounding ice.

3.4. Thickness of lake sediment

Few ice-walled-lake plains have been systematically investigated, but the thickness of lake sediment in outcrops or drill holes has been noted in several regional studies. In North Dakota and Wisconsin, the lake sediment is often reported to be as thick as or thicker...
than the height of the plain above adjacent inter-hummock depressions. The following paragraphs detail the observations of thickness known to us in these two states. Lake sediment is 15 to 30 m thick in drill holes in ice-walled-lake plains of North Dakota where typical till hummocks are 5 to 15 m high, with some 30 m high (Clayton, 1962; Clayton and Cherry, 1967; Clayton and Freers, 1967). Clayton (1962) mapped an ice-walled-lake plain in the same area with more than 23 m of horizontally laminated clay and silt exposed in a roadcut on one side and a similar thickness of stratified sand, gravel, and lacustrine clay and silt with numerous gravity faults in gravel pits on its other side. Royse and Callender (1967) found about 5 m of lake sediment in the concave middle of three large but low-relief ice-walled-lake plains in northwest North Dakota. They found more than 17 m in the middle of a large high-level ice-walled-lake plain in the same area, where the surrounding till hummocks are up to 20 m high.

In northwest Wisconsin, Johnson (1986) reported drill holes with 7 to 10 m of lacustrine silt with interbedded debris-flow sediment in low-level ice-walled-lake plains, where the surrounding till surface has about 10 to 15 m of local relief. Cahow (1976) reported 23 m of lake silt in a drill hole in an ice-walled-lake plain in northwestern Wisconsin, where the local till relief is ‘tens of feet’. Attig (1993; unpublished data) drilled...
through 3 to 4 m of laminated clayey silt and fine sand overlying gravelly sand and till at three sites in the middle part of the lake plain shown in Fig. 3, and 4 m of gravelly sand in the rim ridge. Twelve additional sites with 3 to more than 20 m of laminated lake sediment observed in drill holes in ice-walled-lake plains are known to us (Ham, 1994; Attig et al., 1998).

The presence of thick offshore sediment in high-relief ice-walled-lake plains indicates an abundant source of silt and clay up the slope above lake level. These observations of lake-sediment thickness confirm that lake processes shaped these features, which are not flat-topped till hills with only a thin layer of postglacial sediment on top.

4. Identification

Ice-walled-lake plains generally have a distinctive morphology (Fig. 2). They are commonly first recognized because they are much flatter than surrounding areas of hummocky till (Figs. 2, 3, 4, 5c and 6c), and because they are perched well above the present-day wetlands in the surrounding depressions, and because farm fields are free of pebbles, cobbles, and boulders (Figs. 3a,b, 4a–c, 5c and 6c). Many are conspicuous because they are cultivated land surrounded by grazing land (Fig. 4b) or by woodland (Fig. 3a).

Hummocky collapsed supraglacial outwash or supraglacial lake deposits are common in some hummocky-till regions (Attig, 1993). Their morphologies are similar and may be hard to distinguish from each other and from hummocky till without subsurface information. In one roadcut through till hummocks in north-central Wisconsin, Attig (1993) noted that crude bedding plains could be seen to dip downward toward the high points in the landscape. He interpreted this to indicate that at least the upper parts of the hummocks were of supraglacial origin and that all the hummocks are gradational with ice-walled-lake plains.

5. Fossils, climate, and chronology

The period of treeless tundra vegetation and permafrost in the proglacial environment during active-ice deglaciation at the end of the Wisconsin Glaciation is poorly known in the mid-continent area, because of the scarcity of wood for radiocarbon dating (Clayton et al., 2001). However, this generally frigid scene ended during the better-dated Pleistocene–Holocene transition, perhaps several hundred years after active-ice deglaciation, with a marked warming of the climate (Fig. 7; Yansa, 2006). This is significant in understanding ice-walled-lake plains because many persisted through the transition and into earliest Holocene time.

In hummocky-till areas of the northeast Great Plains this striking change has been documented in two sets of palaeoecologic studies. One is based on mollusc shells preserved in the youngest ice-walled-lake deposits in the hummocky-till area of south-central North Dakota. The other is based on organic remains in non-glacial lake deposits of the same age and in the same region as the ice-walled-lake plains.

Together these two suites of fossils show that some of the ice-walled lakes persisted for hundreds or thousands of years in a temperate climate. This indicates an insulating blanket of thick debris on top of the surrounding stagnant glacial ice.

5.1. Ice-walled lake suite

At the time of the Pleistocene–Holocene transition, the climate warmed, and the ice-walled lakes that survived were colonized by a variety of organisms. The shells of 28 species of mollusc were recognized in ice-walled-lake sediment, as well as in hummocky collapsed supraglacial lake sediment and in hummocky collapsed supraglacial outwash at 40 sites in south-central North Dakota (Clayton, 1961, 1962; Tuthill, 1967). Most of these fossils are unleached and retain well-preserved morphologic details, permitting identification to species level. Also present are the shells of at least ten species of ostracods and the oogonia (reproductive bodies) of charophytes (a bushy green alga). Generally, only calcareous fossils have been preserved; lime has been leached from only the upper several centimeters of soil in this area. Most non-calcareous fossils have been destroyed because all the fossil sites are above the water table and are well oxidized, but the presence of fish is indicated by the presence of the glochidia (larvae) of mussels, which are obligate parasites of fish. Recently, Brandon Curry (Illinois State Geological Survey) has...
found shells of ostracods that lived in ice-walled lakes in Illinois.

Most of these fossil sites were roadcuts, and all were well above any nearby bodies of water. All the fossils were found in sediment that could only have been deposited in depressions that were walled or floored by stagnant glacial ice. Few of the shells show any evidence of transport; many of the mussel shells were still articulated, indicating they remain where they lived, died, and were subsequently buried by lake or stream sediment.

According to Tuthill et al. (1964) and Tuthill (1967), the climate at the time molluscs lived in the ice-walled and supraglacial environments in south-central North Dakota was moist enough to support a mixed conifer and deciduous woodland and was only slightly cooler than at present. It may have been like present-day north-central Minnesota, 400 km to the northeast, where freshwater lakes have outlets and stable water levels. In contrast, the environment of the Coteau du Missouri today and through most of Holocene time had dry hot summers with prairie vegetation. Modern sloughs and most lakes are ephemeral, lack outlets, and are alkaline, and harbour a different association of molluscs than those that lived in the ice-walled lakes.

Mussel shells in seven of the ice-walled deposits have been radiocarbon dated: 10123±399; 10966±365; 11298±195; 11531±494; 11711±505; 12944±279; 13497±302 B.P. (Moran et al., 1973). In addition, radiocarbon dates of 12 088±482 and 12 119±477 B.P. from white-spruce wood in hummocky till on the Coteau du Missouri in northwestern North Dakota probably mark the time of tree burial during the collapse of supraglacial till (Pettyjohn, 1967). All dates presented here have been calibrated using the method described by Fairbanks et al. (2005).

5.2. Non-glacial-lake suite

The fossils just described from the ice-walled and supraglacial stream and lake deposits on the Coteau du Missouri are now in high positions in the landscape, well above, and unrelated to, present-day sloughs, lakes, and streams. However, complementary climatic evidence comes from studies of pollen and macrofossils collected from non-glacial lake sediment underlying the modern slough deposits, in the same general area as the ice-walled-lake plains.

Most sloughs in south-central North Dakota contain several meters of Holocene sediment, which consists of faintly bedded or non-bedded silt and clay with few non-calcareous fossils as a result of bioturbation and oxidation during widely fluctuating Holocene water levels. Below the faintly bedded sediment in many sloughs is finely laminated organic lake clay, containing abundant well-preserved plants and animals that lived at the same time as the molluscs in the ice-walled lakes.

This lake sediment occurs under the slough sediment in less-hummocky places where the stagnant glacial ice melted earlier than the ice around nearby better-insulated ice-walled lakes. This lake sequence was deposited in deeper water with more-stable water levels and less-oxidizing bottom conditions, resulting in better fossil preservation than in the later Holocene sloughs. At one site in south-central North Dakota (Cvancara et al., 1971), more than 160 species have been identified, including beaver, muskrats, frogs, molluscs, numerous yellow perch and other fish, 81 species of beetles, aspen leaves, and white-spruce cones and needles, with beaver-gnawed wood radiocarbon dated at 11155±182 B.P. (calibrated date). Yansa (2002, 2006) studied several sites like this and concluded that south-central North Dakota may have had tundra vegetation for a short time following deglaciation, which was replaced by a white-spruce parkland (savanna) from about 14 500 to about 13 500 B.P. (calibrated radiocarbon dates), followed by a deciduous parkland until about 11 500 B.P., which in turn was replaced by grassland through the Holocene. The parkland vegetation resembled the aspen parkland existing today 400 km to the north and northeast in northwest Minnesota and southern Manitoba.

This corroborates Tuthill’s (1967) interpretation that the climate that exists today just northeast of the prairie—woodland boundary is similar to the climate that existed in south-central North Dakota during at least the final stages of many of the ice-walled lakes. This is also the conclusion reached by Florin and Wright (1969) and Wright (1980) in northern Minnesota, where forest-floor litter occurs at the bottom of Holocene pond and lake sequences, indicating that buried ice lasted into a time of moderate climate and that trees growing on the debris-covered ice were let down into the final collapse depressions as the ice melted.

Although the fossil preservation in these non-glacial lakes was very different from the preservation in the ice-walled lakes, the two suites of organisms were contemporaneous and lived in the same general area, and for that reason their ecological conditions were very similar. Together they indicate that the ice-walled lakes persisted into the early Holocene warm period and were not subglacial.

6. Discussion

Reasoning by analogy with permafrost thaw lakes gives some insight into the formation of supraglacial
and ice-walled lakes (Attig, 1993; Ham, 1994; Ham and Attig, 1998). Both ice-walled lakes and permafrost thaw lakes (thermokarst lakes) occur where ice is present below the surrounding land surface. The basin of a thaw lake deepens because the ground ice continually thaws beneath the lake if it is too deep to freeze solid during the winter. Where unfrozen, the average annual temperature at the bottom must stay above the freezing point. The flow of heat downward from the lake water and upward from within the earth will cause the permafrost or stagnant glacial ice to gradually melt away beneath the lake. However, if everything is frozen solid up to the land surface or lake surface during the winter, conduction of heat to the atmosphere will prevent the permafrost or glacier ice from melting. Therefore, once a supraglacial lake is deep enough to remain unfrozen during the winter, the lake will eventually melt its way through underlying stagnant glacial ice, initially resting on a small area of solid ground, eventually becoming an ice-walled lake, and then perhaps merging with adjacent ice-walled lakes before final drainage.

An explanation is needed for the way the lake is initiated and becomes deep enough for the bottom water to remain unfrozen in the winter. A starter lake might appear where the thickness of supraglacial debris is irregular, causing differential insulation and melting, which could result in depressions with lakes too deep to freeze solid. However, the distribution of individual ice-walled-lake plains within a group of ice-walled-lake plains generally has no obvious relationship to any known pattern of debris irregularity. Some ice-walled-lake plains are arranged in rows parallel to rows of lakes in ice-block depressions. However, their distribution generally seems to be haphazard, depending on the irregular arrangement of glacial debris on stagnant glacial ice. If the initial surface of the supraglacial debris is too flat for supraglacial starter lakes, such as on a supraglacial outwash plain, no ice-walled lakes can form. The presence of collapse hummocks composed of supraglacial lake sediment between many ice-walled-lake plains indicates that these supraglacial lakes were too shallow or short lived to melt their way to the bottom of the ice (Attig, 1993).

Permafrost may have played an important role in the development of ice-walled-lake plains by inhibiting the melting of the debris-covered ice (Ham and Attig, 1996). For example, Attig (1993), Clayton et al. (2001) and Attig et al. (2003) argued that some of the highest ice-walled-lake plains, 4 km from the outermost limit of the late Wisconsin glacial advance, at least 60 m above the limit, could not have existed unless the drainageways through the glacier and through the coarse-grained till under the ice were frozen shut. Ham et al. (1993) and Ham and Attig (1996) also proposed a landscape model for the deglaciation of hummocky areas in northern Wisconsin, suggesting that permafrost delayed the melting of stagnant buried glacial ice for a few thousand years after active glaciation and stabilized the ice-cored landscape, allowing the formation of large, well-developed ice-walled lakes.

7. Conclusions

In the previous sections, we have described the morphology, sedimentology, palaeontology, and chronology of these flat-topped hills in enough detail to demonstrate that they are ice-walled-lake plains. Their elevated position above the surrounding till hummocks and the distribution of lake-sediment facies within them are possible only if the sediment was deposited within ice walls that have subsequently melted. The presence of molluscs in the lakes and the radiocarbon dates indicate that the glacial ice was well-insulated from the surrounding ice. The insulating material could only have been the same supraglacial till that makes up the hummocks around the lake plains.

Any explanation of hummocky-till topography must accommodate associated ice-walled-lake plains. Molluscs could not live under a glacier, and ice walls could not have survived during hundreds or thousands of years of temperate climate unless they were well-insulated. Although it is certainly possible that there is some subglacial component of hummocky-till topography in the mid-continent area, the geomorphology and stratigraphy of ice-walled-lake plains argue for a primarily supraglacial origin for the lake plains and much of the surrounding hummocky topography.

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