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Glacial landscapes *of the* southern Green Bay Lobe *and the* northern Kettle Moraine

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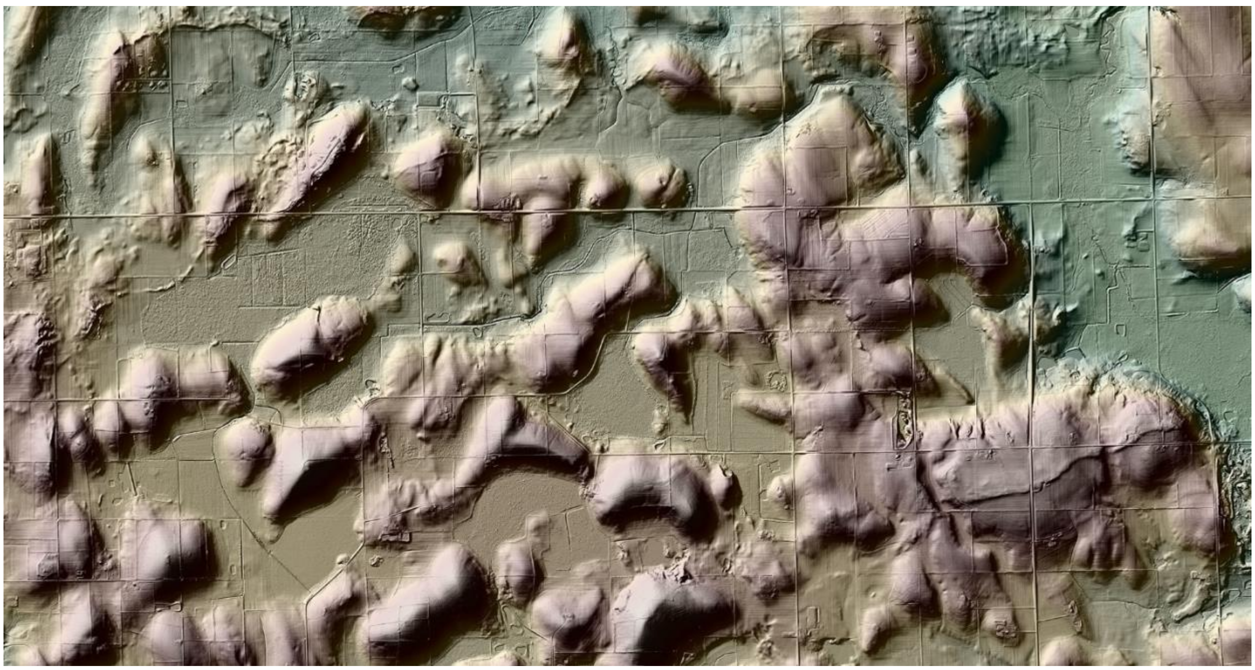

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Introduction

Madison lies close to the outermost edge of the former Green Bay Lobe of the Laurentide Ice Sheet. To the immediate west is the Driftless Area, which apparently was never glaciated, and to the south are older glacial deposits of Illinoian age (Marine Isotope Stage, hereafter MIS, 6–8) (fig. 1). The all-day field trip will concentrate on the glacial geology of the southern Green Bay Lobe and the adjacent Kettle Moraine (figs. 2 and 3). All of the glacial deposits we see are late Wisconsin age (MIS 2), or between about 30,000 and 18,000 years old. (Note: all radiocarbon ages in this guidebook are expressed in calendar years).

Madison lies about 15 km inside the outermost moraine (Johnstown Moraine) of the Green Bay Lobe, between Lakes Mendota and Monona. These lakes and several others downstream occupy a preglacial valley that was not completely filled with glacial deposits during the last glaciation. The isthmus between the two lakes, where the conference is being held, is underlain by lake sediment and till of the last glaciation. The hills are drumlins that stood as islands in the ice-marginal lake that formed in this basin as ice retreated. The hill beneath the State Capitol is a drumlin, as are Bascom Hill and Observatory Hill on the UW–Madison campus.

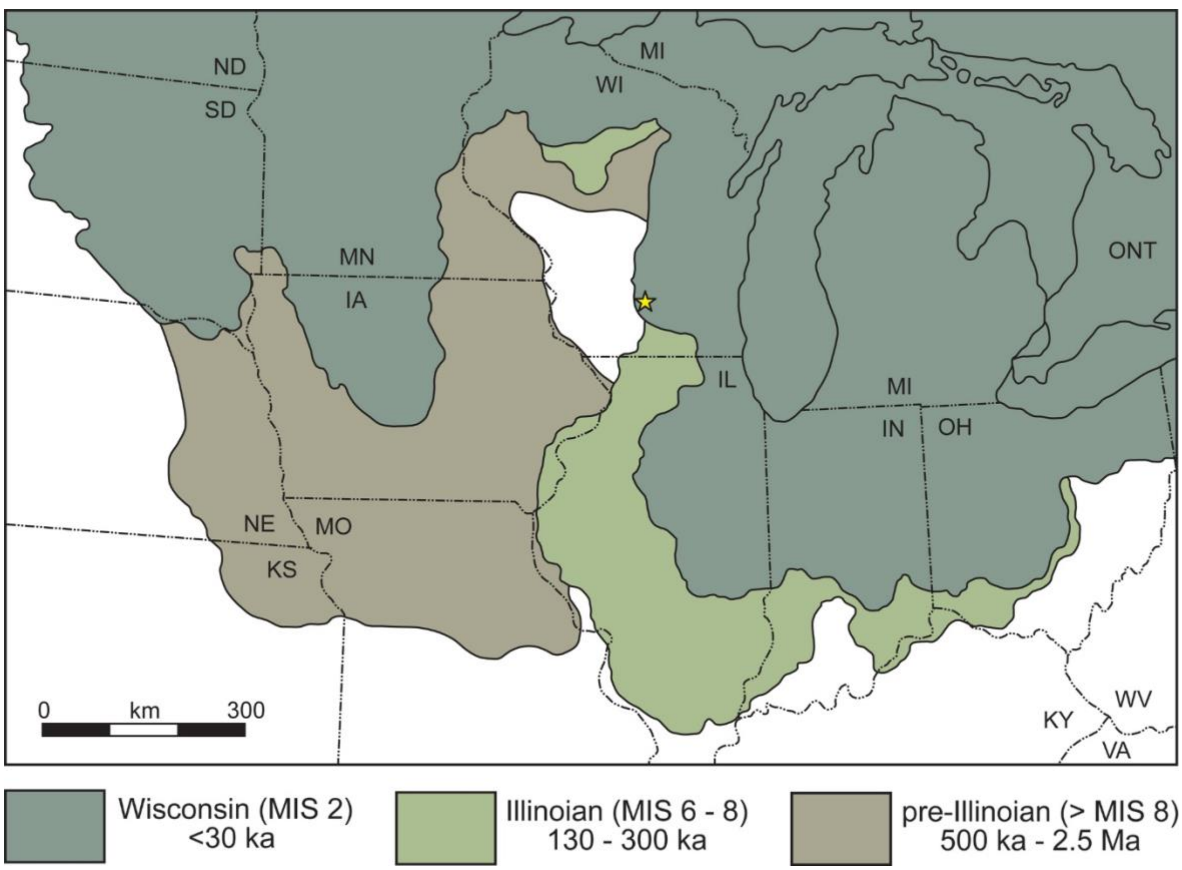

Figure 1. Glacial deposits map of the western Great Lakes area.
The star shows the location of Madison near the southwest edge of the Green Bay Lobe.
The white area surrounded by glacial deposits is the Driftless Area. (Modified from Prior, 1991, by Eric Carson.)

Figure 2. Map of Wisconsin showing areas covered by lobes of the southern Laurentide Ice Sheet during the Late Wisconsin (MIS 2) glaciation. The star shows the location of Madison near the southern edge of Green Bay Lobe deposits. Dashed box shows approximate location of figure 5.

The southern Green Bay Lobe formed over 14,000 drumlins that exhibit a wide range of shapes and sizes; the reasons for this will be one topic for discussion. On its eastern side, the Green Bay Lobe abutted the Lake Michigan Lobe. As the two lobes receded, meltwater streams deposited sand and gravel in the interlobate zone. This landscape has been called the Kettle Moraine since the 1870s (Chamberlin, 1877). In this area, we will view and discuss what we interpret to be very large moulin kames, eskers, and high-relief hummocky topography with deep kettles. This guide is not meant to be exhaustive descriptions of the features or their genesis. To learn more about these features, we recommend the following publications from the Wisconsin Geological and Natural History Survey (WGNHS), available from https://wgnhs.org:

Glaciation of Wisconsin—2011, 4 p., WGNHS Educational Series 36, by Attig, J.W., Bricknell, M., Carson, E.C., Clayton, L., Johnson, M.D., Mickelson, D.M., and Syverson, K.M.

Laurentide Ice Sheet: Ice-margin positions in Wisconsin (second edition)—2017, 46 p., WGNHS Educational Series 56, by Mickelson, D.M., and Attig, J.W. *Set of 43 maps, also available as a video (https://youtu.be/rq90Qv0-tbo).*

Bedrock geology of Wisconsin—1981, WGNHS Map 78 (full-size map) and Map 67 (page-size map), by Mudrey, M.G., Jr., Brown, B.A., and Greenberg, J.K.

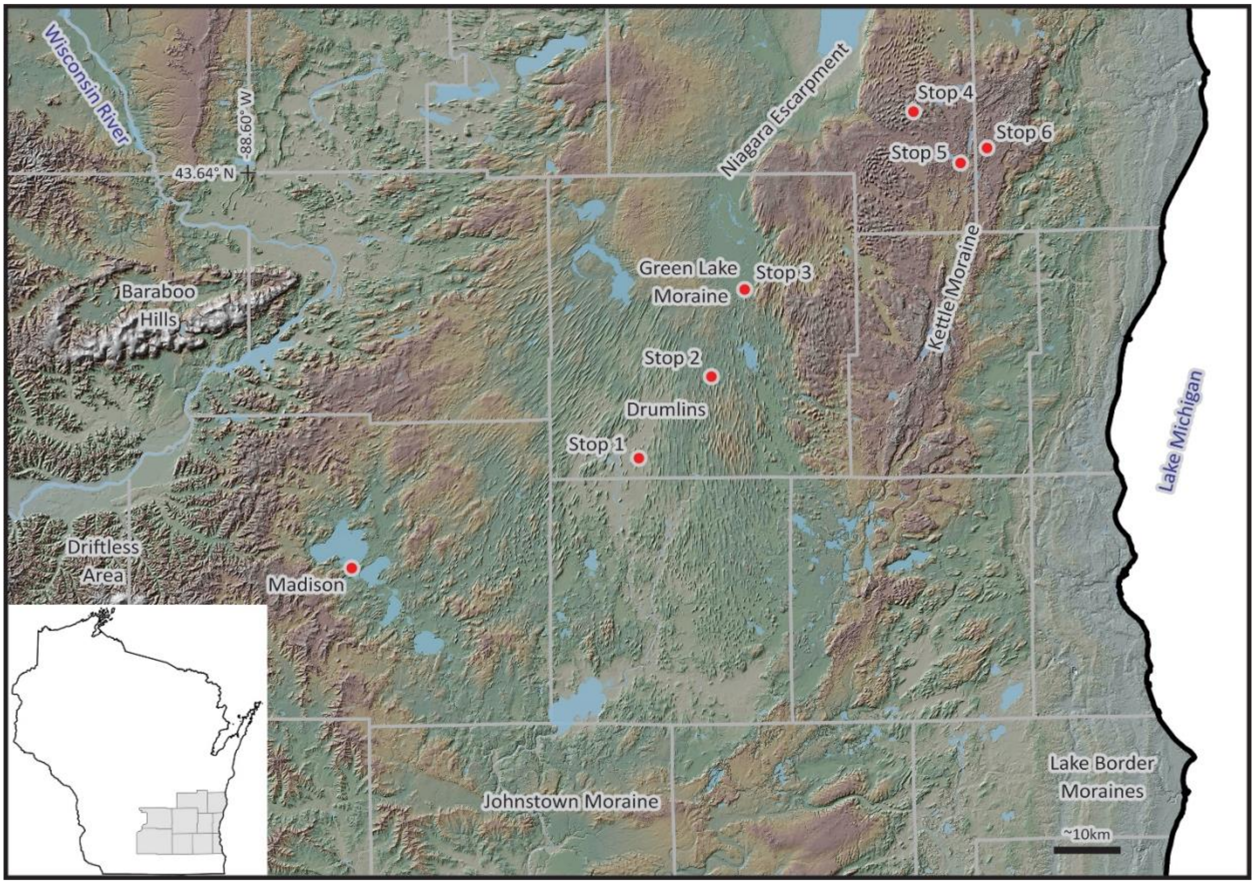

Figure 3. Shaded-relief map of southeastern Wisconsin showing fieldtrip stop locations (red dots).

The southern Green Bay Lobe

During the late Wisconsin Glaciation ice flowed southward and southwestward across eastern Lake Superior, the low and narrow part of the Upper Peninsula of Michigan, and into what is now the basin of Lake Michigan and Green Bay (figs 1 and 2). The flow path of the ice was obviously influenced by the underlying topography of the Great Lakes.

It seems likely that the Green Bay Lobe eroded a substantial amount (meters to tens of meters) of bedrock from the lowland. The Niagara Escarpment, on the east side of Green Bay must have already been a prominent landscape feature and, therefore, a major influence on ice-flow direction. There is little evidence of earlier glaciations covering this area except at one location just east of Madison. South of the outermost moraine there are older glacial deposits that are now thought to be MIS 6–8, or Illinoian age (fig. 1).

Bedrock lithology

Wisconsin lies in the stable midcontinent (craton) with gently dipping sedimentary rocks of Paleozoic age. The stratigraphic column for rocks in southern Wisconsin is shown on the Bedrock Geology of Wisconsin map (WGNHS Map 067). Paleozoic sedimentary rocks underlie all of the southern Green Bay Lobe except for a small area near the northern edge, where Precambrian metamorphic rock is present at the surface. The lowlands in the western part of the southern Green Bay Lobe are underlain by Cambrian rocks that are dominated by sandstone. The sandstone is poorly cemented and erosion of the sandstone has influenced the grain-size composition of the till derived from it. The Cambrian sandstone forms a major aquifer beneath the southern Green Bay Lobe.

The hills on the western side of the lobe are typically capped with Ordovician dolomite. Many of these dolomite-topped hills form the cores of drumlins. The more gently rolling central part of the lobe is underlain by Prairie du Chien Group rocks that are dominated by dolomite and limestone. Above these, and farther to the east, the St. Peter Formation is mostly sandstone. Above the St. Peter and exposed even farther East there is widespread Sinnipee group dolomite. There are very limited outcrops of Maquoketa shale in the lowest part of the lowland just east of and beneath Green Bay and Lake Winnebago. The Maquoketa Formation is overlain by Silurian age dolomite. This dolomite is quite resistant to erosion and it forms the Niagara (Silurian) Escarpment. This asymmetrical ridge is in places over 75 m high. The rock here dips gently to the east. The Niagara Escarpment forms a distinctive landform that begins in southern Wisconsin and arcs across part of the northern Great Lakes to Niagara Falls where Lake Erie empties into Lake Ontario.

Generalized depth to bedrock

As far as we know, there is no evidence of older glacial deposits present between the bedrock surface and the late Wisconsin deposits in the southern Green Bay Lobe except one location quite close to the southern margin of the lobe near Madison. In general, the Late Wisconsin till thickness varies from less than 1 m to about 5 m between moraines. In the moraines, till thickness can be as much as 15 m. Till may be thicker in some drumlins but there are few exposures and there has been very little drilling to determine till thickness. There are several deep preglacial valleys that are mostly filled with deposits associated with the last glaciation, but this appears to be mostly outwash sand and gravel rather than till.

Glacial deposits

The first detailed mapping of glacial deposits within the Green Bay Lobe was done by Alden (1918). His glacial deposits map (1:250,000) agrees remarkably well with mapping done about 100 years later. Colgan (1999) used air photos to produce a detailed map of landforms of the southern Green Bay Lobe. Since 1980, the Wisconsin Geological and Natural History Survey has produced numerous county maps of the area at a scale of 1:100,000 and established a stratigraphic framework of Quaternary deposits for the state (Syverson and others, 2011).

The southern Green Bay Lobe deposits belong to the Horicon Member of the Holy Hill Formation (Syverson and others, 2011). The till is generally brown to reddish-brown and sandy. Sand content varies, but it generally makes up between 60 to 80% of the less-than-2-mm fraction. Clasts of local dolomite are common in the southern Green Bay Lobe, and Precambrian metamorphic and igneous rocks typically makeup less than 20% of clasts. The underlying sandstone is friable enough that clasts of sandstone in the till are rare. Younger advances of the Green Bay Lobe deposited till containing substantially more silt and clay.

Sand and gravel of the Horicon Member of the Holy Hill Formation is common throughout the area covered by the southern Green Bay Lobe. Most was deposited as outwash, but there are a few small eskers that were deposited in tunnels beneath the ice. Several deep valleys in the bedrock surface are filled with over 100 m of sand and gravel. Large rivers that drained the outermost part of the ice sheet deposited huge volumes of sand and gravel in front of the ice. The Rock River, which flows southward from the southern margin of the lobe has an outwash plain that is more than 20 km wide and over 100 m thick. Presumably fine-grained sediments were washed farther downstream to the Mississippi River and then to the Gulf of Mexico. Another important river that drained the western part of the Green Bay Lobe is the Wisconsin River. That also has outwash sand and gravel over 100 m thick and up to 20 km wide.

Chronology of ice advances

There is little evidence of the initial advance of the Green Bay Lobe, especially in this part of Wisconsin (Carlson and others, 2018; Ceperley and others, 2019). One radiocarbon date from wood from a drill hole east of the Kettle Moraine (therefore Lake Michigan Lobe) indicates glacier ice was advancing down the Lake Michigan basin and depositing Holy Hill Formation till by about 31,000 years ago (Carlson and others, 2011 and 2018). It seems likely that Green Bay Lobe ice was advancing at close to the same time (Ceperley and others, 2019). Lake sediment between two layers of Holy Hill till in Madison has OSL dates of about 26,000 years ago, indicating that the Green Bay Lobe advanced southwest of Madison and then had retreated at least as far as the present location of the University of Wisconsin by 26,000 years ago (Mickelson and others, 2007. It then re-advanced an unknown distance, covering the lake sediment with more till. Carson (verbal comm., 2019) reports that near Devil's Lake, about 50 km northwest of Madison, ice reached its maximum position prior to 24,600 years ago OSL ages reported by Attig and others (2011) and Carson and others (2012) suggest the ice margin had retreated about 15 km from its outermost position by shortly after 18,500 years ago. The minor advances and retreats that took place between about 30,000 and 18,000 years ago were likely accompanied by a slow warming of ice in the southern Green Bay Lobe and ultimately a transition from a frozen to a thawed bed (discussed in next section).

Climate during ice advance and retreat

It seems highly likely that permafrost was present when the Green Bay Lobe advanced into southern Wisconsin. Patterned ground produced by ice-wedge casts has been documented on outwash in front of the maximum position of the Green Bay Lobe, as well as on outwash and till surfaces that were deglaciated before about 14,000 years ago (Clayton and others, 2001), and perhaps several thousand years later in northern Wisconsin (Attig and Rawling, 2018). Evidence of permafrost during the last glaciation is also documented by a recent study of speleothems in Cave of the Mounds, about 25 km west of Madison in the Driftless Area (Batchelor and others, 2018). They used a U-series geochronometer to develop a record of speleothem growth over the last 250,000 years. For thousands of years there was precipitation of calcium carbonate on the speleothems indicating penetration of water through the overlying soil and bedrock. Speleothem growth did not occur between 33,000 and 14,000 years ago, which argues for a lack of liquid water entering the cave from above and suggests that permafrost was continuous during that time.

Because it is hypothesized that the formation of drumlins and tunnel channels among other features are in part dependent on thermal conditions at the base of the ice, Cutler and others (2000) developed a two-dimensional, time-dependent model of permafrost and glacier ice dynamics along the flowline down the axis of the Green Bay Lobe. These simulations of ice advance over permafrost suggest that the bed of the glacier was frozen from 60 to 200 km behind the ice margin at the glacial maximum. The permafrost was tens of meters thick, likely thick enough to prevent groundwater moving toward the ice margin in the shallow sandstone aquifer. We hypothesize that by about 18,000 years ago most permafrost beneath the southern Green Bay Lobe had melted, and that water was present at the bed of the ice all the way to the ice margin. Thus, we speculate that conditions after the last glacial maximum in the southern Green Bay Lobe were very different than during ice advance and relative ice margin stability, from about 30,000 to about 18,000 years ago. Presumably, the transition from frozen-bed conditions to wet-bed conditions took place over thousands of years, first occurring beneath thick ice near the interior and eventually thawing near the ice margin. At the northern end of Lake Winnebago, on top of the Niagara Escarpment, tundra plants are preserved between Horicon Formation till and overlying Kewaunee Formation till (Mickelson and others, 2007; Socha, 2007). These are dated at about 16,000 years ago, so by that time, except possibly for some buried ice in moraines, the southern Green Bay Lobe was deglaciated. The tundra plant assemblage suggests that shallow permafrost likely developed on freshly deglaciated surfaces in front of the retreating ice margin.

Ice surface profiles

There have been several attempts to estimate the thickness of the Green Bay Lobe in various places and to reconstruct ice surface profiles (fig. 4). Colgan (1999) reconstructed ice surface profiles based on moraine surface elevations along the Baraboo Hills at the west edge of the southern Green Bay Lobe region as well as the moraine crest elevations along the west side of the Green Bay Lobe. He also used a force-balance method (Ridky and Bindschadler, 1990). His reconstructions are slightly steeper than previous reconstructions by Clark (1992) and Alden (1911). Calculated average basal shear stresses ranged between 7 and 25 kPa, except for an ice margin position at the Lake Mills moraine (fig. 5), which was somewhat lower. These profiles (fig. 4) were estimated for retreat positions when presumably the bed was wet and the glacier was actively sliding. Details of the reconstruction process are included in Colgan (1999).

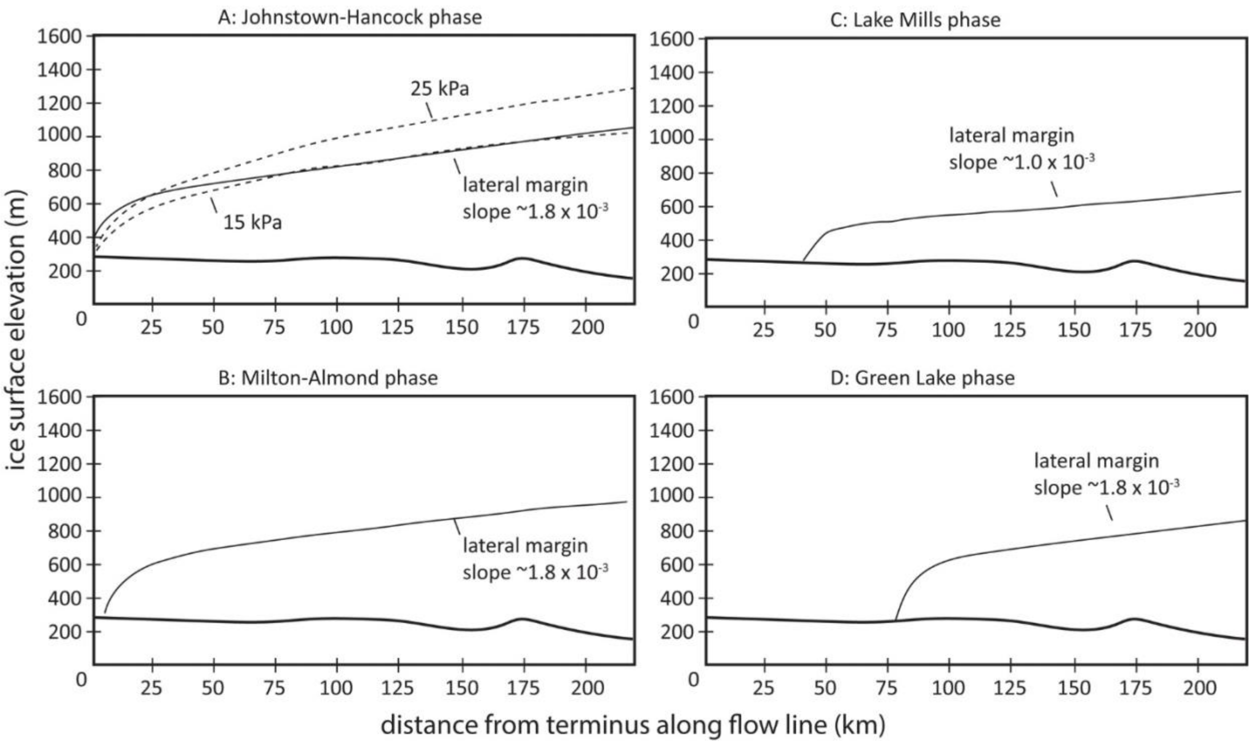

Figure 4. Reconstructed profiles of the Green Bay Lobe during four phases—A: Johnstown-Hancock phase (maximum extent of lobe), B: Milton-Almond phase, C: Lake Mills phase, and D: Green Lake phase. Solid lines are profiles derived from estimates of slope near terminus (terminus to 50 km) and slopes of moraine crests along the western margin of the lobe (50–200 km from terminus); dashed lines show profiles reconstructed using force-balance method (Ridky and Bindschadler, 1990) assuming a constant basal shear stress of 15 and 25 kPa. (Modified from Colgan, 1999).

Moraines

Unlike the landscape of the Lake Michigan Lobe in Illinois that, except for low moraines, is dominated by low-relief till plains, the Green Bay Lobe created a wide variety of landforms. Figure 5 shows named moraines of the southern Green Bay Lobe. The end moraines of the southern Green Bay Lobe are less continuous than those of the Lake Michigan Lobe (Clayton and Attig, 1997). While the Lake Michigan Lobe moraines are composed mainly of thick, uniform till, end moraines of the Green Bay Lobe are composed of both till and sorted sediments (Lundqvist and others, 1993). Moraines of the southern Green Bay Lobe have lower internal relief than moraines to the north, indicating that less sediment was carried on the surface of the glacier than in the north. Moraines in Illinois are generally wider and have lower internal relief than those in the southern Green Bay Lobe. Green Bay Lobe end moraines are commonly 200 to 500 m wide and 5 to 20 m high (Colgan, 1996). Figure 6a shows representative lidar images of the Green Lake Moraine east of Horicon, Wisconsin, just east of the Niagara Escarpment. The hills just south of the moraine are dolomite hills with a thin till cover. Note the quarries in two of them. Figure 6b shows the Johnstown Moraine, the outermost moraine of the late Wisconsin advance of the Green Bay Lobe. This image shows the moraine just southwest of Madison.

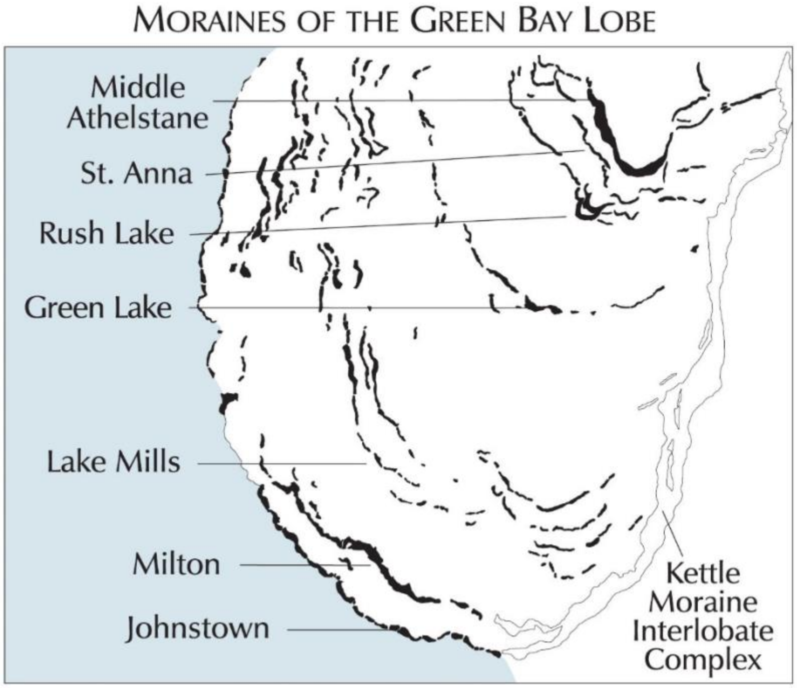

Figure 5. Map showing end moraines of the southern Green Bay lobe of Wisconsin. Approximate location is indicated on figure 2. (Modified from Colgan, 2003.)

The outermost moraines (Johnstown and Milton) are the largest and most continuous of all of the moraines in the southern Green Bay Lobe area, although there are gaps where no end moraine formed or are preserved. This is the case with the Johnstown Moraine for a distance of almost 20 km just northwest of Madison. Here the only evidence of glacial extent on the uplands is a scatter of erratic boulders. In figure 5, the Middle Athelstane Moraine, just south of Lake Winnebago, is composed of till of the Kewaunee Formation, which has considerably less sand and more silt and clay than till of the Horicon Formation. Its formation likely followed a major retreat and re-advance. Minor moraines with heights less than about 2 m and widths less than 10 m are present in a few places on the till surface of the southern Green Bay Lobe. Colgan (2003) mapped these from air photos.

Drumlins of the southern Green Bay Lobe

Theories on origins of drumlins

Like many parts of the world where drumlins are present, the origin of Wisconsin drumlins has been speculated upon for many years. How much has our understanding of drumlin origins changed in the last 113 years? In their 1906 classic textbook (p. 360–361, first edition) Chamberlin and Salisbury wrote:

> "The origin of drumlins has been much discussed, but there is as yet no generally accepted conclusion, and the subject is still under active inquiry. Opinion is chiefly divided between the views (1) that they were accumulated beneath the ice under special conditions and (2) that they were developed by the erosion of earlier aggregations of drift, much as roches moutonnées are developed. Under the first of these general views, it has been suggested (1) that the bars of rivers give the clue to their origin; (2) that protuberances of rock gave occasion for the lodgment; (3) that the balance between load and strength of movement furnishes the key to their explanation, a slight but not excessive overload being the conditions necessary for their development; and (4) that they may be, in some way, connected with longitudinal crevasses."

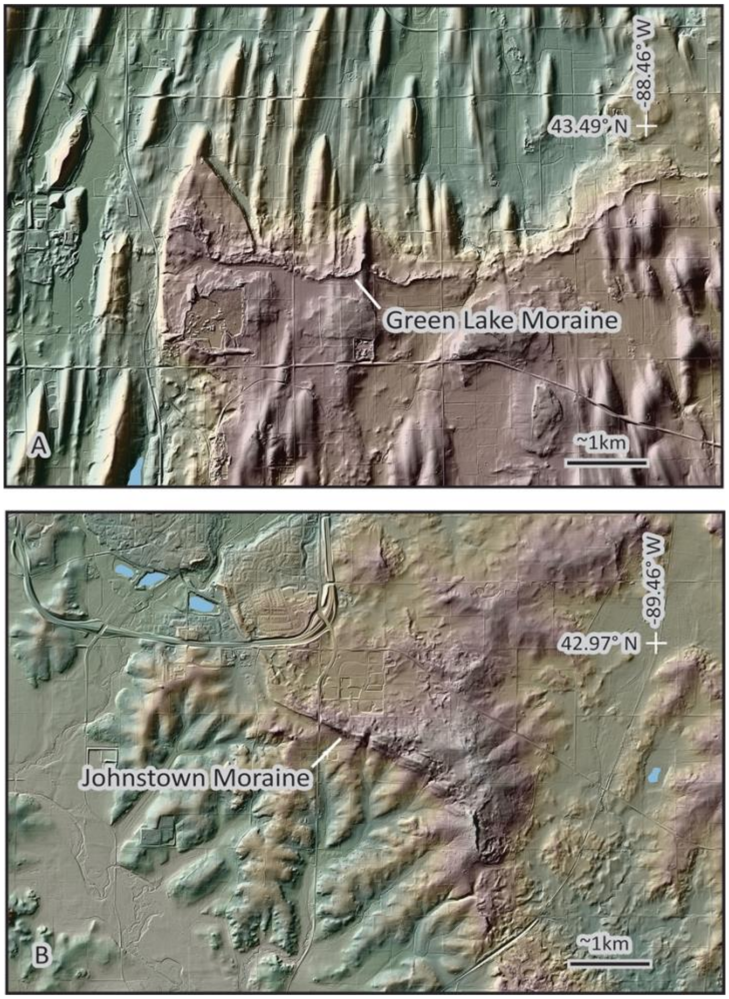

Figure 6. Lidar-derived hillshade of end moraines in two places covered by the southern Green Bay Lobe. A: Green Lake Moraine, a recessional moraine east of Horicon Wisconsin. B: Johnstown Moraine south of Madison, Wisconsin, the outermost moraine of the late Wisconsin (MIS 2) ice advance. The area to the south was glaciated, but likely during MIS 6.

Long before both Chamberlin and Salisbury became very well-known and respected geologists, both grew up just at the edge of the southern Green Bay Lobe.

In 1892, Warren Upham, another well-known geologist of his time, visited UW–Madison for a conference at the time when underground steam pipes were being installed to the university buildings then on Bascom and Observatory Hills. He saw till over gravel in the excavations and also recognized that the hill upon which the State Capitol sits contains thin till over sand and gravel (Upham, 1894). He described these as “Madison-type drumlins,” but the name never came into general use.

The first major detailed mapping of the Green Bay Lobe drumlins and description of their content was done by Alden (1911, 1918). Since that time, there have been numerous papers on various aspects of drumlins in Wisconsin.

The Madison drumlin field of the Green Bay Lobe contains thousands of drumlins with greatly varying width-to-length ratios and heights (fig. 7). At any given time, there are relatively few exposures in the drumlins, but those that have been observed by the authors are extremely variable. Some drumlins appear to be composed of uniform till, others are till interbedded with sand and gravel, and others are all sand and gravel with a thin till cover. The sand and gravel in the drumlin cores varies from horizontally bedded or uniformly dipping beds of sand and gravel to greatly deformed beds with overturned folds and diapirs of fine-grained sediment. In areas north of Madison, most of the drumlins have a core of dolomite with a complete cover of till that ranges from a few meters to a few tens of meters thick.

Drumlins are not unique to the southern Green Bay Lobe. There are thousands of drumlins to the north in Wisconsin and westward into Minnesota. They are not present south of approximately the latitude of Chicago. Instead, glacial ice in most of Iowa, Illinois, Indiana, and Ohio left a nearly flat till plain broken only by broad and relatively high end moraines and meltwater channels.

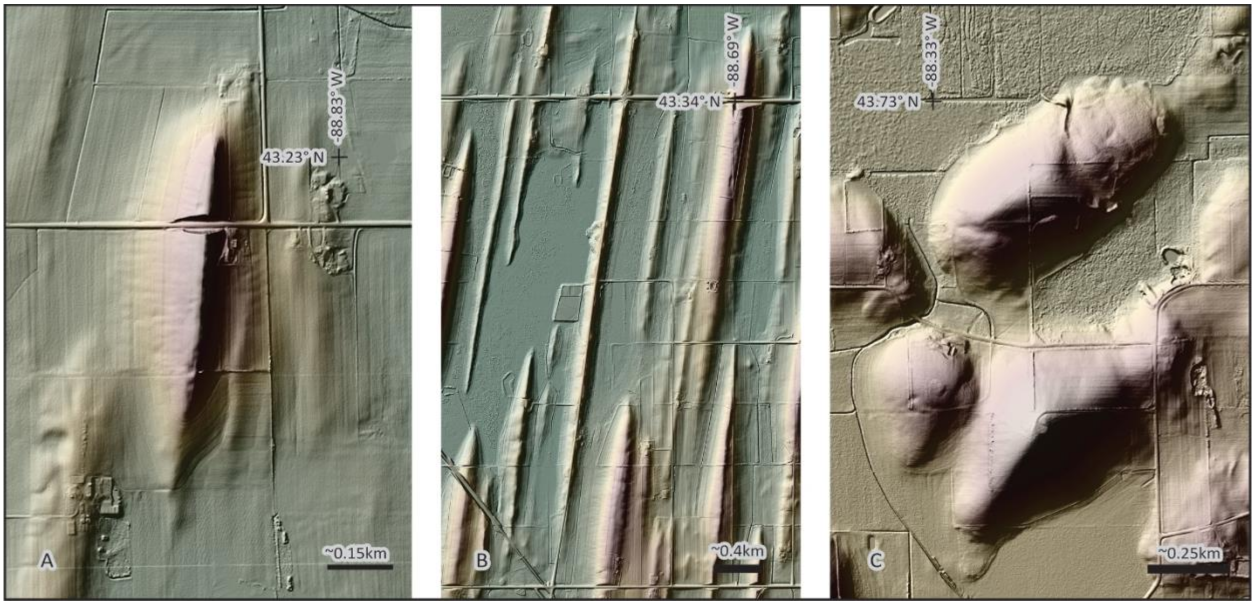

Figure 7. Examples of drumlin morphology. A: A classic steeper up-ice slope drumlin (Stop 1). B: Extremely elongated drumlins (Stop 2). C: Short and tall drumlins (near stop 4).

Drumlin formation in the southern Green Bay Lobe

We suggest that about 30,000 years ago the Green Bay Lobe advanced over permafrost that was tens of meters thick. The glacier was cold-based and there was likely very little modification of the landscape. In the next several thousand years geothermal heat produced warming and finally melting at the bed under the thicker central part of the lobe, while the outermost part of the lobe was still frozen to its bed. By the time the frozen bed zone around the edge of the Green Bay Lobe was about 20 to 30 km wide, water had found its way along the glacier bed out to the ice margin and large flows of water cut channels down into the bed (Nye channels).

As the boundary between the frozen and thawed bed migrated toward the ice margin, an intermediate zone of partly frozen bed existed. This heterogeneous mix of frozen and unfrozen state in the partially thawed region created randomly spaced spots that were easily eroded and others that were resistant. The cores of the drumlins are the zones that remained frozen while the melted zones became the inter-drumlin regions. Eventually all of the bed was sliding and drumlins continued to be shaped by the sliding ice. By this time (about 18,000 year ago) ice had warmed, water flowed in channels at the bed and eskers formed in places. The ice margin retreated and readvanced a number of times producing small recessional moraines. It is possible that during periods of retreat shallow permafrost reformed.

Using high-resolution lidar data, approximately 14,000 drumlins were mapped in the footprint of the southern Green Bay Lobe (Barrette and others, 2017). Nearest neighbor analysis of the drumlin distribution on the lobe-scale found that with a 95% probability the drumlins were spatially clustered owing to a variety of large-scale factors such as local geology, distance from the ice margin, time under the ice, and post-glacial erosion. Analysis of a smaller region (about 30 x 30 km) that contained about 1,900 drumlins where effects of large-scale factors were minimal (leaving only the glaciological effects such as ice-flow variability, subglacial hydrology, and basal temperature variations to affect spacing) indicated with 95% probability that the drumlins were randomly spaced (fig. 8). The observations of random drumlin spacing when large-scale factors were minimized supports the hypothesis that randomly spaced frozen and unfrozen patches at the ice-bed interfaced served as the mechanism for drumlin initiation.

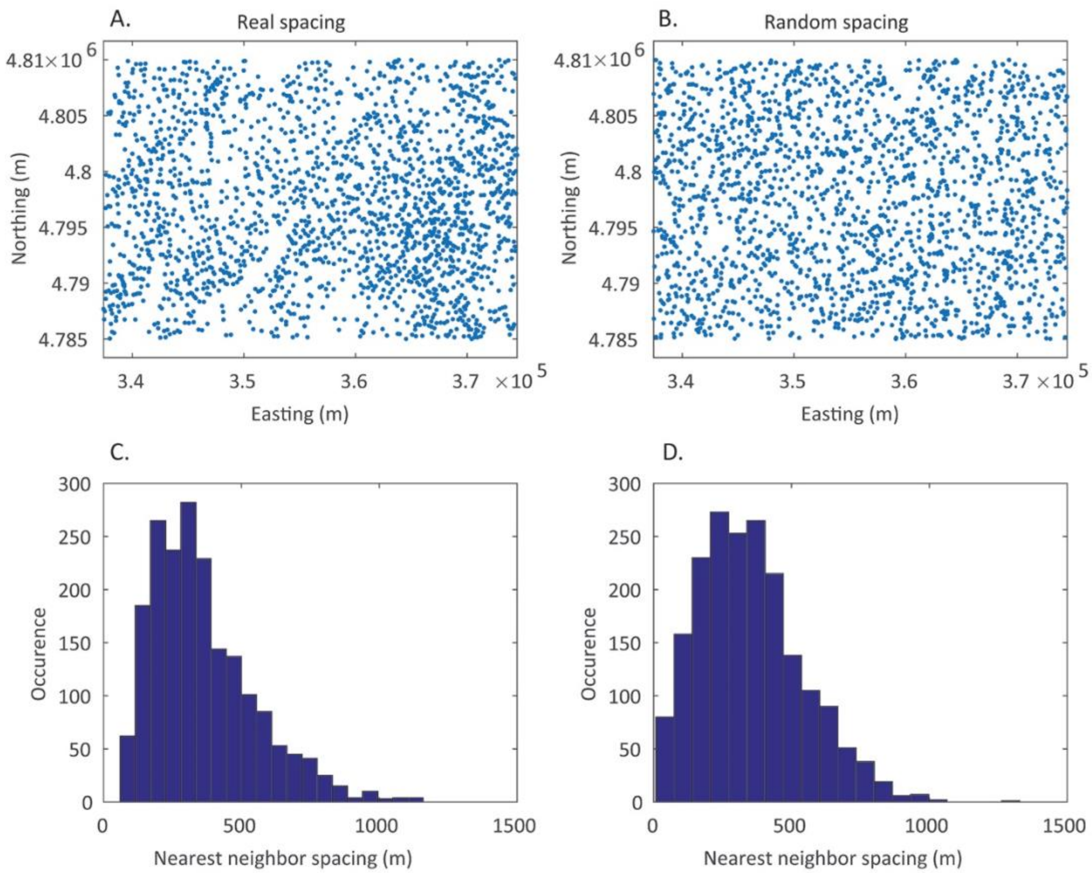

Figure 8. Panels A and B show a map of spatial distribution drumlins for (a) a real subsection of the Green Bay Lobe drumlin field and (b) a randomly generated section of the bed. Each blue dot is the centroid of one drumlin. Panels C and D show a histogram of nearest neighbor distance from panels A and B, respectively. The two spatial distributions are similar with a 95% confidence indicating the distribution of drumlins is random with 95% confidence.

The northern Kettle Moraine

The Kettle Moraine is among the best-known landform zones in Wisconsin and formed where the Lake Michigan Lobe and the Green Bay Lobe collided in the eastern part of the state (fig. 3). Recognized as a unique part of our landscape since the late 1800s, it was known as the Potash Kettle Range before T.C. Chamberlin published an exhaustive study of glacial deposits in 1878. He correctly interpreted the feature as an accumulation of sediment where the two lobes came together. He named the feature the Kettle Moraine. These days the feature would be more appropriately called an interlobate area or interlobate zone because the term “moraine” is generally restricted to features composed mostly of till, whereas the Kettle Moraine is composed almost entirely of sand and gravel. Chamberlin (1877) used the term “kettle moraine” to describe the terminal moraine of what we call the late Wisconsin glacial advance all the way from New England to the Dakotas. “Kettle Moraine” now refers exclusively to the interlobate zone between the Lake Michigan and Green Bay Lobes.

Alden (1918) assigned more specific names to landforms in the Kettle Moraine, but maintained the mainly proglacial or wasting ice (as opposed to subglacial) model of Chamberlin (1877, 1878) that most subsequent research has supported (Thwaites, 1943; Thwaites and Bertrand, 1957; Black, 1970, 1974; Mickelson and Syverson, 1997; Carlson and others, 2011).

Age and general setting

A major control on the shape of ice lobes (fig. 2) in eastern Wisconsin during the last glaciation was the earlier differential erosion of the underlying bedrock by preglacial rivers and earlier glaciations. The high area between the Lake Michigan basin and the Green Bay basin is the Niagara Escarpment, which is composed of resistant Silurian dolomite. Ice was funneled down the Lake Michigan basin into southern Illinois and down the Green Bay–Lake Winnebago basin to southern Wisconsin. The Kettle Moraine in most places does not lie directly on the Niagara Escarpment, although the escarpment clearly influenced the shape of this part of the ice sheet. The escarpment is about 10 km west of the Kettle Moraine in the area of this field trip, and just east or west of the Kettle Moraine south of there.

The overall model developed by Chamberlin (1878), and by several researchers since, is that the Green Bay Lobe and Lake Michigan Lobe advanced more or less simultaneously. We now think that took place about 30,000 years ago based on radiocarbon ages, and likely the lobes were in contact in the northern Kettle Moraine area by about that time (Carlson and others, 2011). We don’t know how thick the ice was over what is now the Kettle Moraine, but we do know the ice surface was lower there than over the central part of either of the adjacent ice lobes based on the ice flow directions indicated by drumlin orientations on both sides of the interlobate area. Glacier ice flows in the direction of the ice surface slope, and drumlins indicate ice flow toward the west and southwest east of the Kettle Moraine and toward the southeast west of the Kettle Moraine. The ice had to be thick enough to easily overtop the highest hills that are present there now. Colgan (1999) estimated an ice thickness on the order of 600 to 900 m at the axis of the Green Bay Lobe this distance back from the outermost ice margin position. We also know that this valley on the ice surface sloped toward the southwest. Meltwater produced on the surface of both lobes carried sediment down to the central valley on the ice surface and then southwestward (Alden, 1918). In places along the Kettle Moraine gravel at least 100 m thick was deposited by this process. A huge volume of sediment was carried and ultimately deposited in the Kettle Moraine and in the large outwash plain south of the outermost late Wisconsin Johnstown Moraine at the southern end of the Kettle Moraine (Alden, 1918).

As is the case along most of the Kettle Moraine, the land surface regionally slopes eastward toward Lake Michigan. As ice of the Lake Michigan Lobe retreated from the Kettle Moraine, several successively lower channels carried meltwater along the ice margin and eventually to Lake Michigan. For the most part these have only small (underfit) streams in them now. Part of one of these, the Mink Creek channel, is shown in figure 9.

The Kettle Moraine extends about 30 km farther northward from the location described here. There the Kettle Moraine is a more-or-less single hummocky ridge without the low central area and without the large conical moulin kames that are present between stops 5 and 6.

Genesis of individual landforms in the Kettle Moraine

As suggested by the name Kettle Moraine, kettles are an obvious and widespread landform throughout the area. These depressions were produced where masses of glacial ice previously covered by sand and gravel melted out. Where they occur on otherwise nearly flat surfaces we use the term “pitted outwash” to describe the surface. Where a surface has collapsed, leaving hardly any nearly flat former streambeds, we use the term “hummocky” and the hills between the kettles are called “hummocks.”

Generally, hummocky topography forms where large amounts of debris, meters to tens of meters thick, is on the glacier surface. This debris partly insulates the ice below, but the ice below slowly melts out in an irregular pattern, producing topography on the debris-covered glacier. As this debris slips and slides, various parts of the ice surface are exposed to varying amounts of warming and melting from the sun. This pattern produces a very irregular land surface after the buried ice has completely melted out. Hummocky topography is common in many places in the Kettle Moraine, particularly along the edges in this area.

When glacial ice melts and becomes thinner, water produced by melting on the glacier surface flows across the ice and then down crevasses or, in places where crevasses intersect, near-vertical shafts in the ice called moulins. These near-vertical shafts in the ice allow water and sediment to plunge into the glacier and eventually all the way to the bed. Gravel and rocks that fall into moulins may accumulate in conical hills called moulin kames. Kames in the Kettle Moraine area are among the largest in the world. These large-scale features were probably produced by collapse of gravel into a large moulin or a collapsed ice tunnel at the base of the glacier.

By the time the Laurentide Ice Sheet was retreating from eastern Wisconsin, temperatures had risen and huge amounts of water must have passed through the moulins to the base of the glacier. It then flowed out to the ice edge through tunnels. In places where streams flowing in these tunnels deposited sand and gravel, the tunnel partly or even completely filled with sediment. When the ice surrounding the sediment-filled tunnel finally melted, it left the ridge of sand and gravel that now traces the path of that former tunnel. These ridges are called eskers, and there are superb examples in the Kettle Moraine (fig. 9). These are often winding ridges that can be several km to tens of km long and tens of meters high. Because they are an excellent source of sand and gravel, many in Wisconsin have been mined away.

Genesis of the northern Kettle Moraine

As mentioned above, almost all of the northern Kettle Moraine is composed of sand and gravel. This indicates that the sediment was carried by water. Based on the amount of rounding of the particles, it suggests significant distance of transport. Why did so much gravel get pushed relatively high in the glacier to ultimately be released by surface melting? When glaciers flow with little obstruction, debris-rich ice stays close to the base of the glacier and debris is not released until the wasting ice is very thin. However, when a glacier finds resistance at its margin, as happened when the two lobes flowed against each other, there is an increased upward component of flow (compressive flow) and sediment is carried higher in the ice to later be released by surface melting. A similar upward component of ice flow occurs when glaciers advance up a regional slope, such as occurred along the west side of the Green Bay Lobe where it encountered the Niagara Escarpment.

Much of the Kettle Moraine north and south of here is made up of supraglacial sediment throughout, but in this area it is different. Here, much of the flat to gently rolling central area of the Kettle Moraine in figure 9 represents the base of the glacier without a thick cover of supraglacial or ice-marginal sediment (Carlson and others, 2011). Part of the low area between the kames appears to be basal till or till with a thin cover of outwash. The Parnell Esker (fig. 9) and other eskers must have formed at the base of the ice, as indicated by their continuity, narrow crest and steep sides. If they had formed in a tunnel up in the ice, much of the gravel would have been dispersed as underlying ice melted out. The same argument can be made for the formation of the moulin kames (fig. 9) in this area. If the sand and gravel in them had been deposited with ice beneath, it would have collapsed into a dispersed hummocky pile of gravel instead of distinctive, mostly cone-shaped, moulin kames. This indicates that the flatter areas between the kames represents the base of the glacier and that there was no significant thickness of sediment on the glacier’s surface as it melted away at this location. Contrast that with the high relief hummocky topography on the east and west sides of the Kettle Moraine here. Our interpretation of the genesis of this part of the Kettle Moraine is illustrated in figure 10 and summarized in Carlson and others (2004).

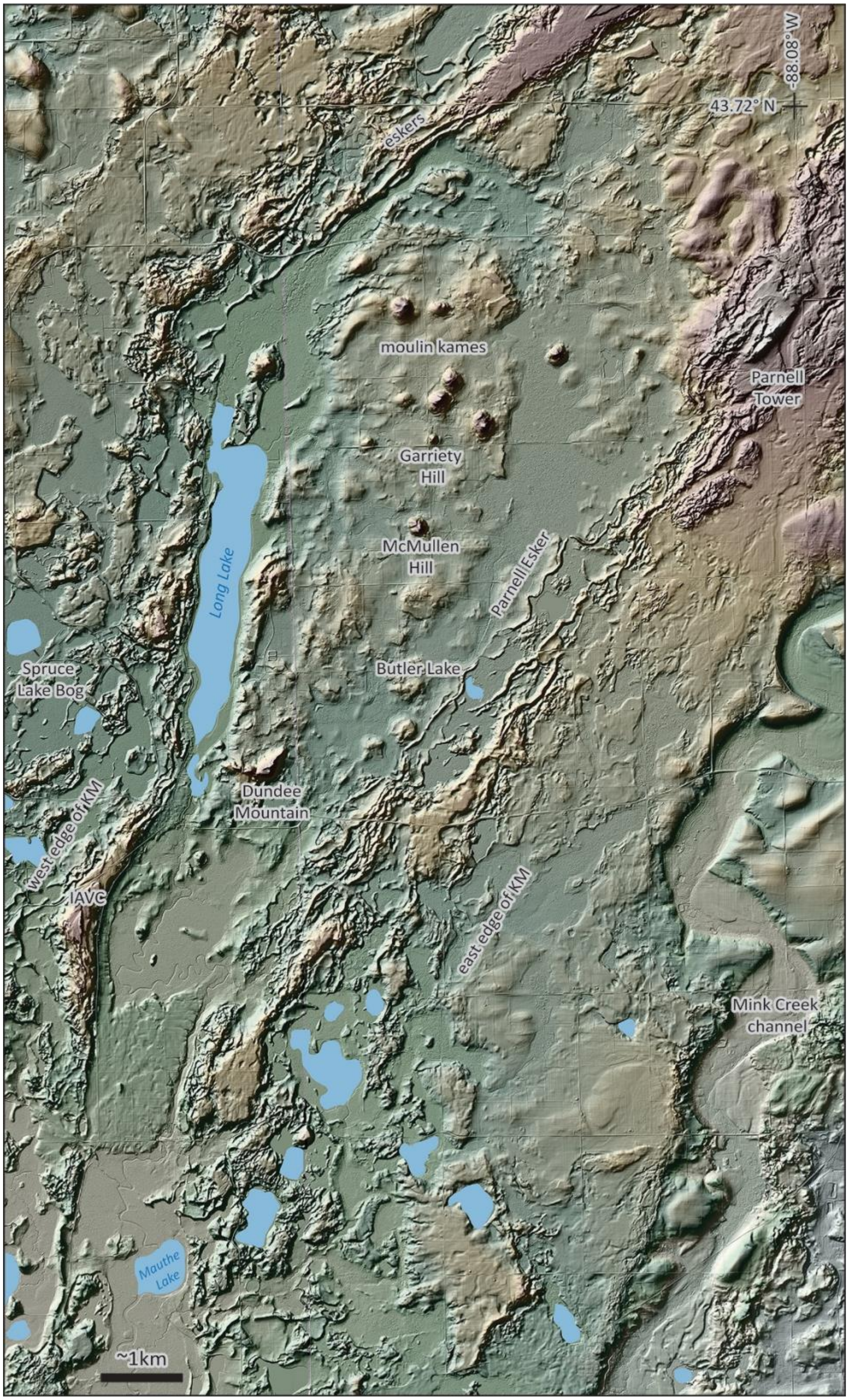

Figure 9. Shaded relief map of part of the northern Kettle Moraine showing large moulin kames, the Parnell Esker in the low central part of the Kettle Moraine and high-relief hummocky topography on the edges of the Kettle Moraine (IAVC = Ice Age Visitor Center).

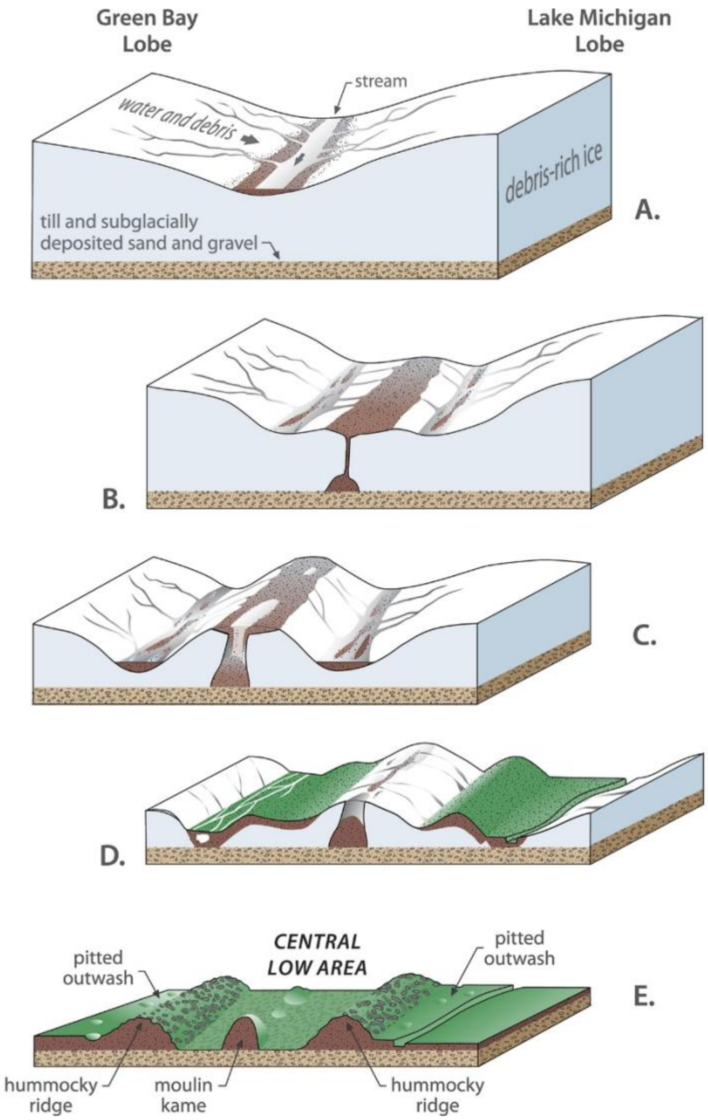

Figure 10. Interpretation of the formation of much of the northern Kettle Moraine, where it is a double ridge with a low area in between.

A. As the Green Bay and Lake Michigan Lobes thin, water and sediment flow down the surface of the ice towards a central depression. That water and sediment moves southwestward toward the ice margin.

B. Stream sediment on top of the ice in the central area becomes thick enough that it insulates ice below. This debris limits melting while cleaner ice on either side continues to melt downward. Vertical shafts, called moulins, open and gravel accumulates in kames at the base of the ice.

C. The central area becomes higher relative to the troughs on either side and sediment is shed from the central area into low areas. These areas will eventually become the hummocky ridges on the Green Bay Lobe and Lake Michigan Lobe sides of the Kettle Moraine.

D. Sediment continues to slide and wash off the high central area and accumulate in the troughs on either side, creating a thick deposit of sand and gravel on top of the ice.

E. All of the underlying ice has melted out. High-relief hummocky topography remains in the former troughs on the ice surface. The low area is present in the central part of the Kettle Moraine. This area has till and sand and gravel interpreted to have been formed at the base of the glacier and not accumulated from above with the exception of the kames and eskers. As the glacier edge retreated away from the debris-covered ice, streams deposited sand and gravel on top of isolated ice masses that eventually melted out to produce kettles.

(Modified from Carlson and others, 2004; drafted by Mary Diman.)

Stop descriptions

1. Waterloo (Long Rd.) Drumlin

(private property—stay in right-of-way)

43.22673, -88.83485

The Waterloo Drumlin is oriented nearly directly north–south and is in the middle of the Green Bay Lobe (fig. 11). The exposed part of this classic drumlin is composed entirely of Horicon Formation till. Note the uniformity of the material suggesting that it is till deposited at the base of the ice. Was the till deposited during ice advance and then overridden and shaped into the drumlin form? Or was it deposited directly beneath the ice as a streamlined feature? Vreeland and others (2015) measured magnetic fabrics of till in five drumlins in the southern Green Bay Lobe drumlin field. Their overall conclusion was that, with the exception of a thin layer on top, the bulk of the till was deposited when ice had a somewhat different flow direction than the orientation of the drumlin. They concluded that the till was deposited during ice advance and that the drumlin shaping took place later.

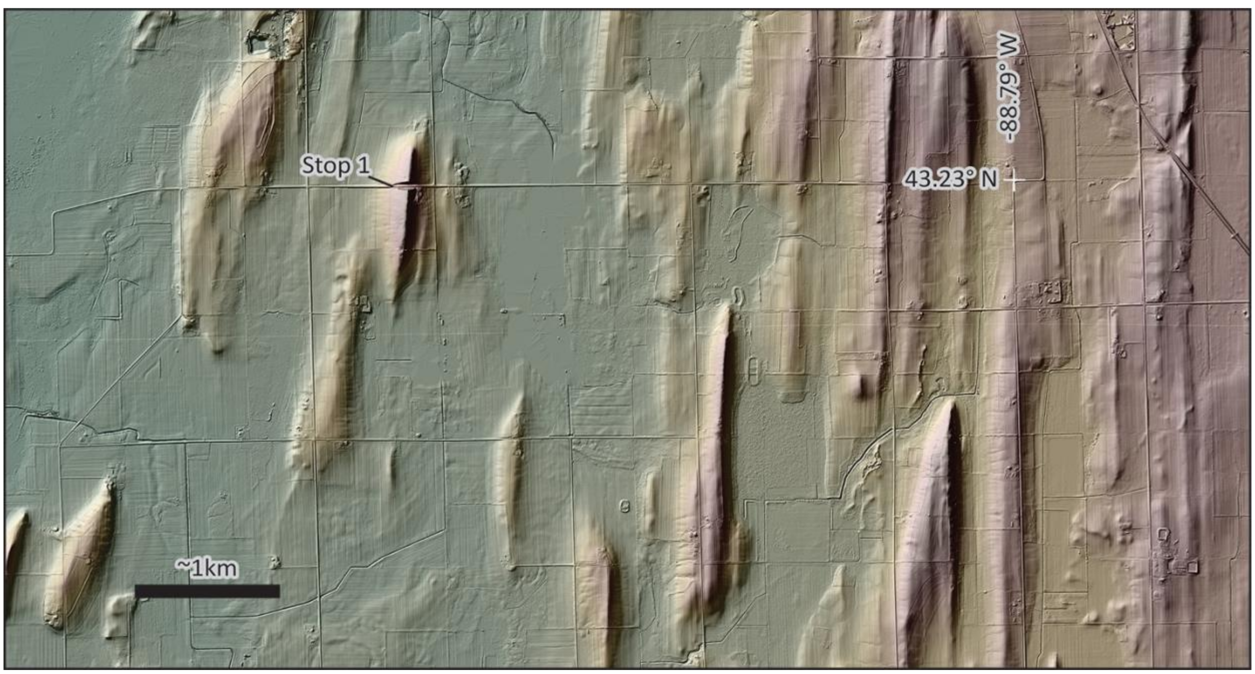

Figure 11. Waterloo Drumlin (Stop 1)

2. Clyman Drumlin

43.342419 -88.689722

This is one of the longest and narrowest drumlins in the Green Bay Lobe. We are only a few kilometers south of the inner edge of the Madison drumlin field. Figure 12a is a lidar image showing this drumlin and adjacent drumlins. Figure 12b shows a lidar image with what appear to be flutes or grooves parallel to flow. Unless destroyed by plowing, these grooves are commonly present on drumlins, although they can usually only be seen on lidar.

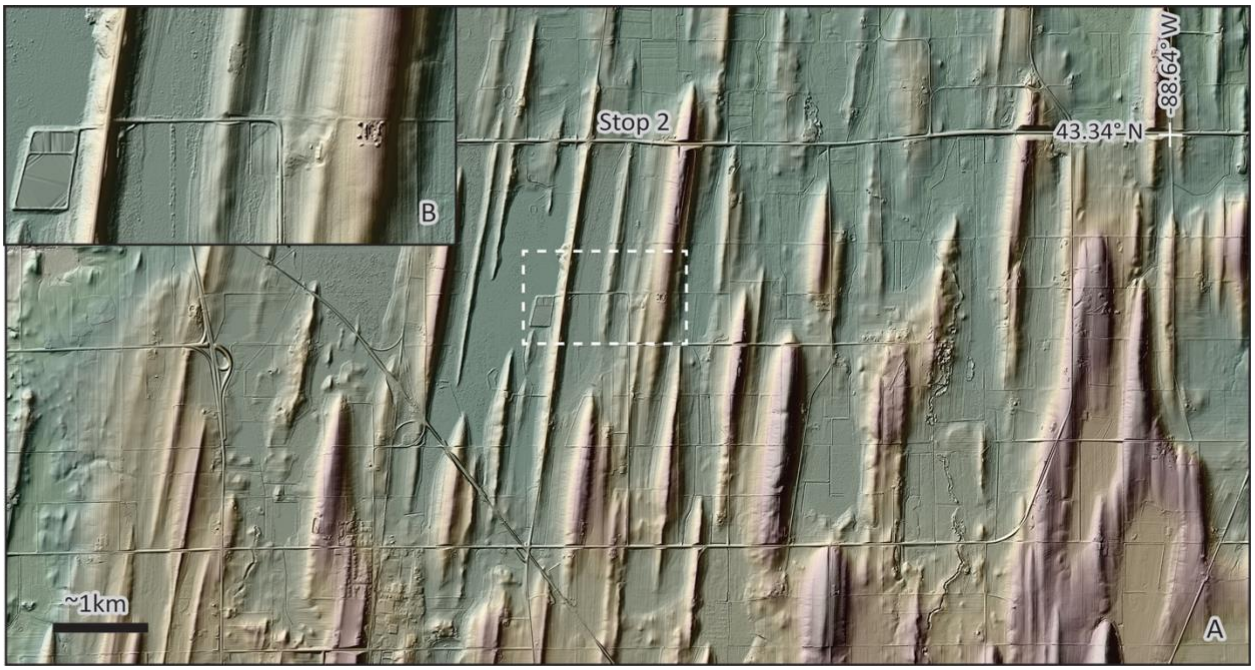

Figure 12. Clyman Drumlin. Dashed box shows location of inset map.

3. Horicon Marsh Department of Natural Resources station

43.46688, -88.62130

This stop is on the top of a drumlin in the southern end of Horicon Marsh (fig. 13). Other drumlins to the north were also islands in the large glacial lake that was here as the Green Bay Lobe retreated. Note that Horicon Marsh is not a kettle lake as are many of the lakes in Wisconsin, but a lake dammed by a small moraine, the Green Lake Moraine, just south of the marsh. To the east is the Niagara Escarpment. The marsh itself is underlain by Maquoketa shale. Lake sediment with molluscs is about 15 m thick and was overlain by several meters of peat. Most of the peat has been oxidized since the marsh was drained by European settlers. A short trail is available to hike (20–30 minute) between here and the visitor center ***(43.474074, -88.600425)***, which includes a rest room.

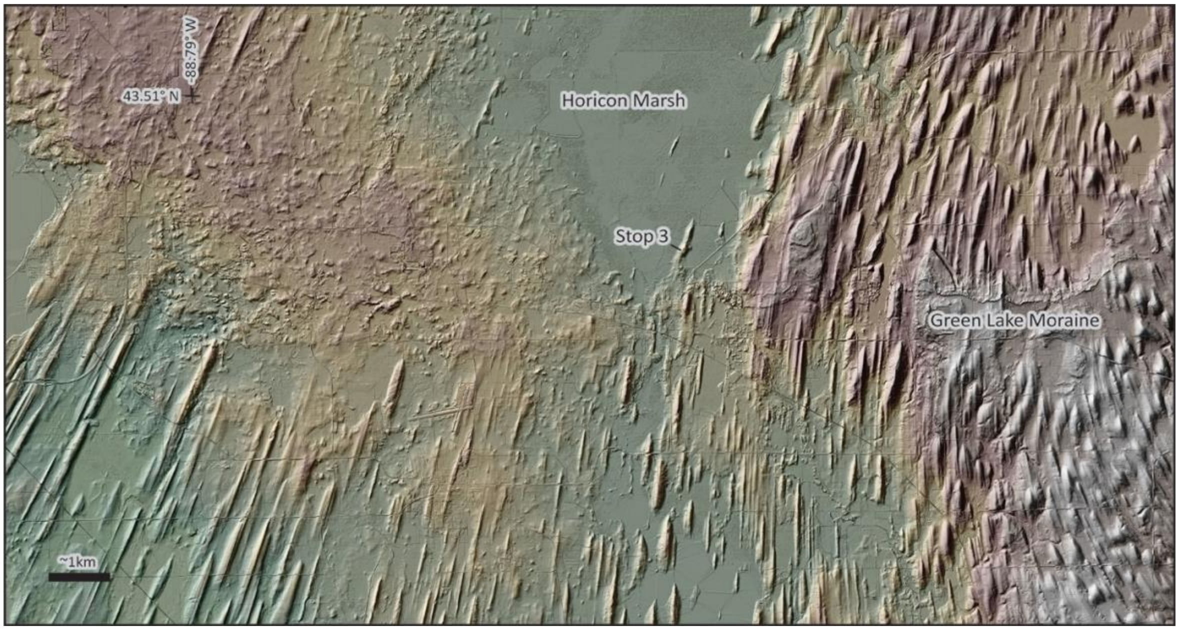

Figure 13. Horicon Marsh (Stop 3)

4. Seven Hills Drumlin

(private gravel pit—do not enter without permission; pit face is visible from road)

43.717789, -88.280813

Overview of gravel pit with several meters of till over outwash sand and gravel adjacent to drumlins on Niagara Escarpment (fig. 14). These and the Campbellsport drumlins to the south are the highest drumlins in the state. Their short, stubby nature may relate to the intense compressive flow that took place here, just west of the Kettle Moraine and on top of the Niagara Escarpment. Colgan (1999) suggested that the Campbellsport drumlins may have been created first by a Lake Michigan Lobe advance that created drumlins that were then overridden by Green Bay Lobe ice that partly reshaped them.

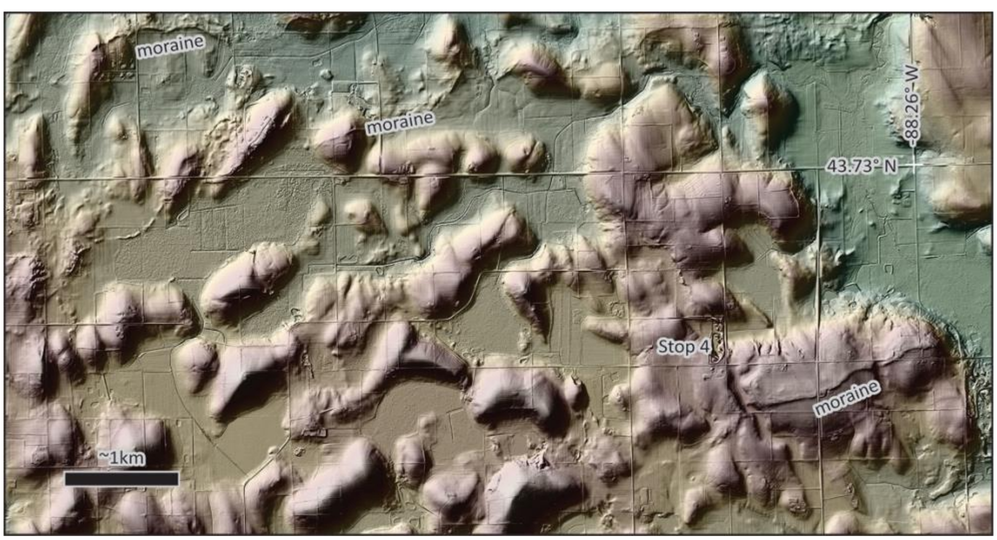

Figure 14. Seven Hills Drumlin (Stop 4)

5. Henry S. Ruess Ice Age Visitor Center in Dundee
43.642703, -88.189745
Administered by the Wisconsin Department of Natural Resources and the National Park Service. Visitor center has restrooms, lecture hall, exhibits, and views from a deck. The visitor center (fig. 9) is on the hummocky, Green Bay Lobe side of the Kettle Moraine. From here we can see ***Dundee Mountain (43.654963, -88.164220)***, the low central part of the Kettle Moraine, and the hummocky Lake Michigan side of the Kettle Moraine beyond. Before you leave, look at the rocks in the fireplace and chimney. They are from Kettle Moraine gravel.

6. Drive HWY V South through the Kame Field to Parnell Esker
Continue North on 67 to Hwy V to view Kames including ***McMullen Hill (43.679812, -88.141865)*** and **Garriety Hill** ***(43.68864, -88.13963),*** and several unnamed kames (fig. 9). Turn west on Butler Lake road to **Parnell Esker** ***(43.663347, -88.13658)***. The esker was deposited by a stream flowing southward through a tunnel at the bottom of the glacier. Stop includes a short hike on the Ice Age Trail along crest of esker (includes some stairs and uneven ground).

Alternative Kettle Moraine stops:
Spruce Lake Bog (43.46688, -88.62130) is a classic kettle peat bog (fig. 9). It formed in pitted outwash on the Green Bay Lobe side of the Kettle Moraine. This was an open lake when it formed from a melting ice block about 15,000 years ago. Since then sphagnum and associated plants have filled the edges of the pond and produced a floating mat near its edge. Pitcher plants (*Sarracenia purpurea*) and sundews (*Drosera* sp.) are common insectivorous plants here. There may be native orchid species in bloom as well. Please stay on the walkway.

Parnell Fire Tower (43.69758, -88.08978) lies in high-relief hummocky topography on the Lake Michigan Lobe side of the Kettle Moraine and provides an overview of many landforms including large moulin kames and the Parnell Esker (fig. 9).

Garriety Hill (43.68864, -88.13963), a moulin kame, has an elevation of 1,140 ft/347 m (fig. 9). Note chaotic bedding, poorly sorted sediment masses surrounded by cleaner gravel, and a steep dip from west to east. Most of the rocks are local dolomite, but there are far-traveled rocks as well. These kames formed when huge volumes of sand and gravel carried by streams flowing southwestward on ice above collapsed into cavities at the base of the ice. The gravel here is not as well rounded as it is in the hummocky topography along the edges of the Kettle Moraine (Carlson, 2002).

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