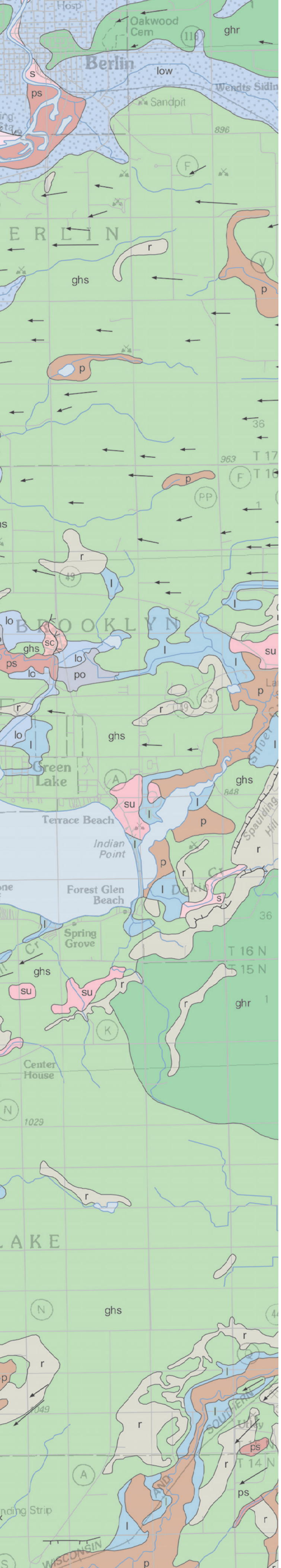

Quaternary Geology of Columbia, Green Lake, and Marquette Counties, Wisconsin

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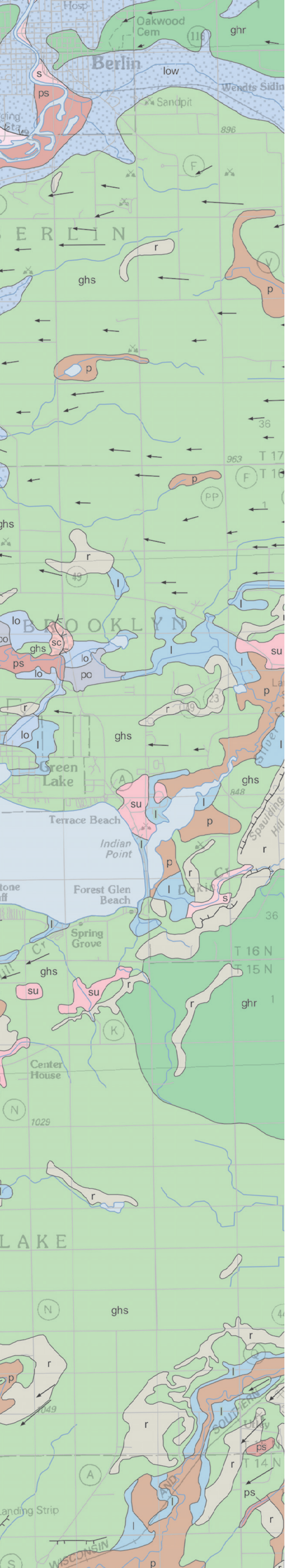
Front: St. Peter Sandstone, Arcade Glen, © William Mode

Back: Sinnipee Group dolomite, east end of Green Lake, © William Mode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Available separately at https://wgnhs.wisc.edu/pubs/000977.

Abstract

Columbia, Green Lake, and Marquette Counties, hereafter referred to as "the tri-county area," cover an area in south-central Wisconsin that was mostly covered by the Green Bay Lobe of the Laurentide Ice Sheet during its maximum extent, which occurred during the last part of the Wisconsin Glaciation around 24,000 to 21,000 years ago. A small area in northwestern Columbia County was not covered by the glacier and is part of the Driftless Area, but even this area contains glacial sediment that was transported and deposited by meltwater streams beyond the ice margin. The Johnstown (Hancock) moraine, deposited at the ice margin during the glacial maximum, is a high (>10 meters (m)), relatively continuous ridge composed mostly of sandy till of the Holy Hill Formation and contains significant quantities of sand and gravel. At its maximum position in west-central Columbia County, the glacier margin rested on the eastern end of the Baraboo Hills, impounding the drainage on the northern side of the Baraboo Hills and creating glacial Lake Wisconsin. The level of Lake Wisconsin rose until it reached a low point in the drainage divide and spilled northwestward into the Black River. Sediments deposited in glacial Lake Wisconsin were extensive and formed flat terraces or lake-plain surfaces largely underlain by sand with some silt. While the ice margin stood at the Johnstown moraine, subglacial processes in the tri-county area streamlined bedrock uplands, deepened bedrock lowlands, and ultimately blanketed the landscape in sediment. During this time, drumlins were created underneath the ice. Drumlins are common in the eastern portion of the tri-county area. In other areas, a blanket of till of the Holy Hill Formation was deposited over the pre-existing landscape without greatly modifying the relief. In western Columbia County, little to no glacial sediment was deposited on the extensive bedrock uplands, which are composed of Precambrian quartzite and early Paleozoic sandstone and dolostone.

Old granite quarry in Montello, Wisconsin

Most of the glacial landscape of the tri-county area was created as the ice margin of the Green Bay Lobe receded sometime between 23,000 and 18,500 years ago. A variety of ice-marginal glacial features formed when glacier recession temporarily halted or the glacier locally readvanced. Recessional moraines deposited during this time are smaller and more discontinuous than the Johnstown moraine. These moraines have been named the Milton, Lake Mills (Elderon), and Green Lake moraines in order from oldest (westernmost) to youngest (easternmost). These moraines are composed largely of till of the Holy Hill Formation. In other places, ice-marginal positions are marked by hummocky (collapsed) areas of meltwater-stream sediment or outwash fans with collapsed ice-contact faces. These features are particularly large where they formed at the mouth of a tunnel channel cut by meltwater at the base of the glacier. Another type of ice-marginal ridge in the tri-county area, one that is unique in Wisconsin, is a subaqueous morainal bank. These ridges, of which there are two in Columbia and Marquette Counties, formed where the ice margin terminated in glacial Lake Wisconsin's Lewiston Basin; they are distinguished by their flat tops that formed by wave action in the lake. Because they were formed by a combination of glacial, meltwater, and lacustrine processes, they contain a mixture of till, sand, and gravel.

Recession of the ice margin from the eastern end of the Baraboo Hills permitted the drainage of glacial Lake Wisconsin, the level of which declined from 296 to 253 m when the lake first drained and water spilled through the Alloa outlet. The lake level next declined from 253 m to 241 m when it drained through the Dekorra outlet into the lower Wisconsin River valley. Although this marked the end of the existence of glacial Lake Wisconsin, a new lake (glacial Lake Oshkosh) formed in front of the receding ice margin in the Fox River lowland. This lake initially spilled through the Dekorra outlet to the Wisconsin River; as the further recession of the Green Bay Lobe exposed lower outlets, the lake later spilled across the Niagara Escarpment to the Lake Michigan basin. By this time, the level of glacial Lake Oshkosh was too low to reach into the tri-county area. Later, the lake re-expanded into the area when the Green Bay Lobe readvanced around 15,500 and 14,000 years ago. Lake sediment deposited after the last glacial maximum is finer grained (largely silt and clay) and redder in color than earlier glacial Lake Oshkosh and glacial Lake Wisconsin sediment. These sediments underlie the lowlands in the tri-county area and can be more than 30 m thick.

The Green Bay Lobe exited the tri-county area after 19,000 years ago when it receded from the Green Lake moraine. Because it took some time for plants to colonize and completely cover the newly exposed sediment, wind erosion during the late glacial period moved considerable amounts of sand and silt, creating dune, sand sheet, and loess (silt) deposits. These widespread wind deposits are mostly thin (<1 m thick) but can reach 10 m in thickness where they occur as sand dunes, which are most often located on the plains of the two former glacial lakes.

Sand and gravel are extracted from several types of glacial settings in the tri-county area, including moraines, drumlins, eskers, collapsed topographic features, ice-contact fans, and meltwater-stream terraces. Sand is also available from lake plains and dunes.

Since the beginning of the postglacial period about 11,000 years ago, streams have deposited sediment on flood plains and organic deposits (peat) have accumulated in lowlands. These deposits can reach several meters in thickness. Flood-plain deposits are sandy in the Wisconsin River drainage basin and silty and clayey in the Fox River drainage basin. Minor (<1 m thick) amounts of windblown sediment probably were deposited in the postglacial environment.

By forces seemingly antagonistic and destructive Nature accomplishes her beneficent designs — now a flood of fire, now a flood of ice, now a flood of water; and again in the fullness of time an outburst of organic life.

John Muir, naturalist and explorer

Introduction

Although John Muir made the above comment when he was wandering California, little did he know that the landscape of his youth was formed by a "flood of ice and water" (Muir, 1894). Like Muir's beloved Sierra Mountains in California, the landscape of Columbia, Green Lake, and Marquette Counties was glaciated during the last ice age and large areas were inundated with water from proglacial lakes and large meltwater rivers that occupied the valleys of the existing Wisconsin and Fox Rivers. These processes resulted in rolling upland hills, including drumlins punctuated by low-lying areas dominated by marshes underlain by lake sediment.

This report describes the geology of Quaternary sediment deposited over the past two million years in Columbia, Green Lake, and Marquette Counties, located in south-central Wisconsin (fig. 1). Unless specified, these counties are subsequently referred to as "the tri-county area." Green Lake and Marquette Counties were originally mapped as part of a larger project that focused on the geology of the Fox River valley and the extent of glacial Lake Oshkosh (Hooyer and Mode, 2008). The study was expanded to include Columbia County mainly because of groundwater supply issues related to drinking water. For example, the type of sediment deposited above the bedrock controls the rate of infiltration to bedrock aquifers. It also controls the rate of runoff to rivers and streams, making it important in the siting of land-use activities such as large dairy farms. Understanding the distribution of Quaternary deposits ensures that state and local units of government have some information on the geology to implement effective land-use management practices aimed at preserving resources for the future.

The tri-county area covers approximately 3,348 square kilometers (km^2). The Quaternary deposits range in thickness from 0 to 100 m and overlie Precambrian, Cambrian, or Ordovician rock (Harr and others, 1978). In Columbia County, the surface soil was described by Mitchell (1978), and the groundwater geology of the area was

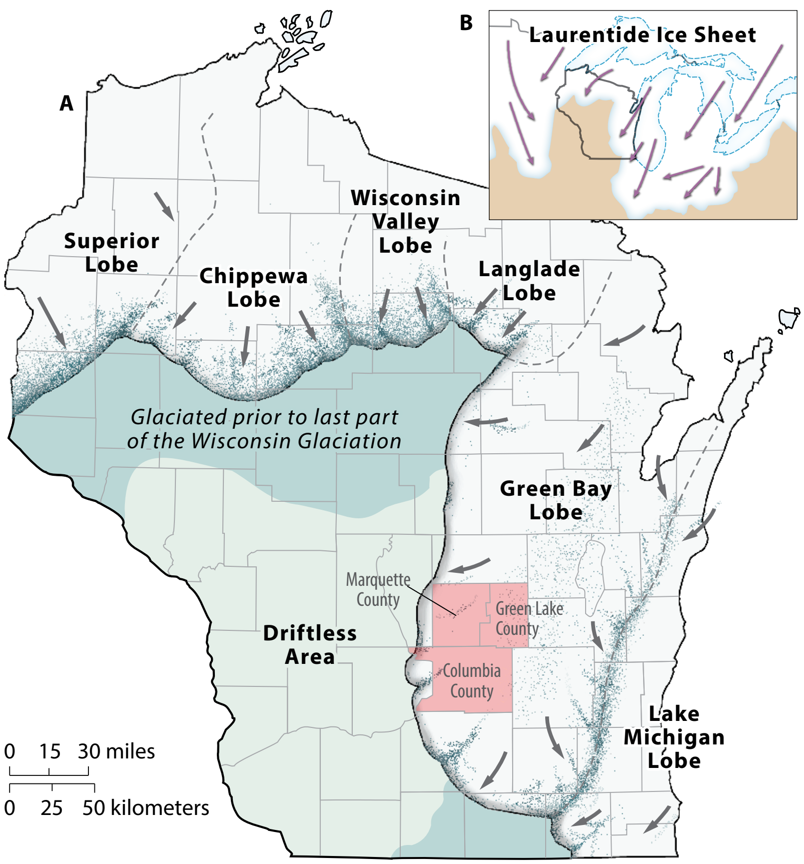
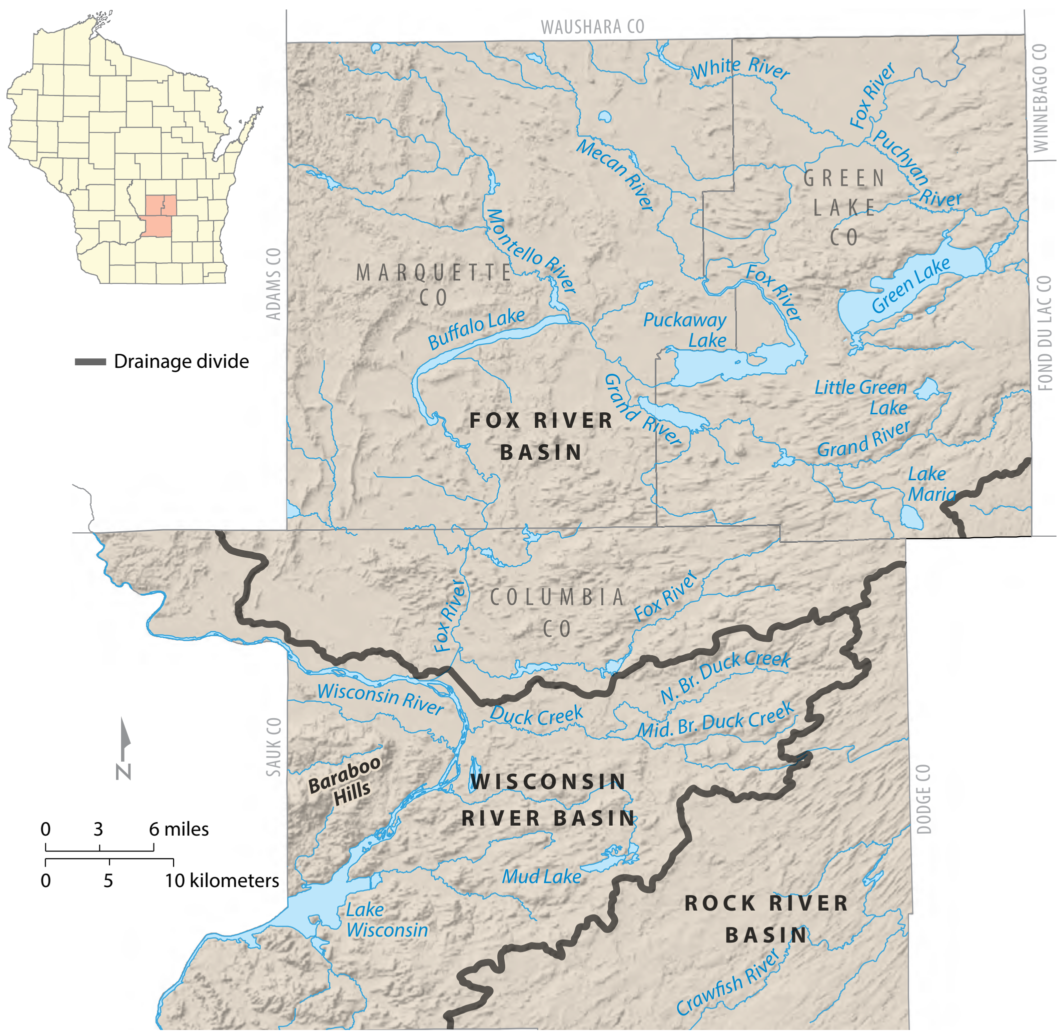


Figure 1. Location of Columbia, Green Lake, and Marquette Counties in Wisconsin (A) in relation to the Laurentide Ice Sheet, and (B) its lobes across the Great Lakes region of the United States and Canada during the most recent glaciation. Stippling in A indicates the edge of the ice sheet; arrows indicate direction of ice flow. Note that during the last part of the Wisconsin Glaciation, the tri-county area (light red) was almost entirely covered by ice.

initially described by Harr and others (1978). More recently, a preliminary water-table elevation map (Sellwood, 2012), a groundwater susceptibility map (Gotkowitz and Mauel, 2012), and a groundwater recharge map (Schoephoester and Gotkowitz, 2012) have been completed. The surface soils in Green Lake County have been described by Anderson and Gundlach (1977) and in Marquette County by Schmude (1975). Water-table elevation maps for Marquette County (Lippelt and Hennings, 1981) were constructed as part of a larger project on the Central Sand Plain of Wisconsin.

Surface water is contained by three main drainage basins (fig. 2): the upper Fox River, the lower Wisconsin River, and the upper Rock River. The majority of Green Lake and Marquette Counties drains to the lower Fox River, which begins in northern Columbia County and meanders northward through Buffalo and Puckaway Lakes before merging with the Wolf River at Lake Butte des Morts in Winnebago County. The lower Wisconsin River drainage basin captures runoff primarily in central and eastern Columbia County. The runoff joins the Wisconsin River, a braided river system that has a variable discharge given that it drains a large area of central Wisconsin. The southeastern part of Columbia County has poorly drained uplands and drains to the upper Rock River drainage basin.

Figure 2. Shaded-relief map of Columbia, Green Lake, and Marquette Counties showing drainage basins and their boundaries. Shaded-relief map was constructed from a 10-m digital elevation model dataset (U.S. Geological Survey, 2017).



Methods

The geologic map (plate 1) in this report is based on field work conducted from 2002 through 2007 by several investigators. The majority of the mapping in Marquette and Green Lake Counties was performed as part of a larger project focused on glacial Lake Oshkosh; John Attig contributed to the mapping of those counties. Lee Clayton mapped Columbia County as a separate effort. The geologic map was completed by evaluating a variety of datasets and drawing contacts onto 1:24,000-scale topographic maps with varying contour intervals. These contacts were plotted on the topographic maps while referencing 1:20,000-scale stereographic aerial photography images taken by the U.S. Department of Agriculture. The contacts on the topographic map were reduced to a scale of 1:100,000 for plate 1. Other evaluated datasets include soil surveys published by the U.S. Department of Agriculture (Schmude, 1975; Anderson and Gundlach, 1977; Mitchell, 1978) and lithologic information from unpublished Wisconsin Department of Natural Resources well-constructors' reports and field notes in Wisconsin Geological and Natural History Survey (WGNHS) files, including Road Materials Investigation Reports.

The most useful information, however, resulted from examining available exposures of sediment along fresh roadcuts, gravel pits, quarries, and building excavations. Additionally, shallow holes made with a shovel or a bucket auger were useful for understanding areas where no exposures were readily available. Direct observation of the landscape was also invaluable in that the presence of boulders at the land surface and the type of vegetation present were indicative of a specific type of sediment. For example, the presence of boulders in fields and along fence rows might be indicative of sediment deposited directly from glacier ice. In the tri-county area, four boreholes were drilled using rotary sonic (rotosonic) methods in key areas in an attempt to understand Quaternary materials and their history below the ground surface (fig. 3 and table 1) and along the Fox River valley.

Throughout this report, we present a few age estimates to constrain the geologic history of the tri-county area. These ages were derived using carbon-14 radiometric dating methods on extracted organic matter and have been calibrated to calendar years before present (cal yr BP) using the IntCal13 curve presented in Reimer and others (2013).

Figure 3. Geographic features of Columbia, Green Lake, and Marquette Counties, including major roadways, lakes, rotosonic borehole locations, and the approximate location of the low-relief escarpment formed by the Prairie du Chien Group.

Bedrock geology

Precambrian crystalline rock and Cambrian and Ordovician sandstones and dolostones lie beneath the glacial sediment in the tri-county area (Syverson and others, 2011; fig. 4). Precambrian rocks (Dalziel and Dott, 1970) form the Baraboo Hills, the most prominent landform on the western side of Columbia County; in places, these hills are more than 200 m above the adjacent Wisconsin River (fig. 2). Isolated patches (Smith, 1978) of Precambrian rocks are occasionally exposed at the surface in Marquette and Green Lake Counties. Otherwise, these rocks are unconformably overlain by younger Cambrian and Ordovician sandstones and dolostones deposited approximately 500 to 440 million years ago.

The Cambrian rocks in the tri-county area consist mainly of sandstones of the Elk Mound, Tunnel City, and Trempealeau Groups (fig. 4). This sandstone sequence can be up to 100 m thick and is usually permeable and saturated with water, forming one of the most productive deep aquifers in the tri-county area. Cambrian rock occasionally outcrops in northwestern Columbia County, Marquette County, and the western half of Green Lake County.

The Cambrian sandstone sequence is overlain by Ordovician rocks of the Prairie du Chien, Ancell, and Sinnipee Groups. Much of the rock exposed at the surface outside the vicinity of the Baraboo Hills consists of erosion-resistant dolostone of the Prairie du Chien Group. Occasionally Upper Cambrian sandstone is exposed beneath the dolostone. The exception to this is southeastern Green Lake County where the dolostone of the Sinnipee Group overlies the St. Peter Sandstone of the Ancell Group, forming a low-relief escarpment. Where bedrock is exposed at the surface or is buried by less than 2 m of sediment, it is represented in plate 1 as map unit **r**.

Table 1. Location, elevation, and depth of rotosonic wells.

Well Number	Latitude (decimal degrees north)	Longitude (decimal degrees west)	Elevation (meters)	Depth (meters)
RS–5	43.9090	89.0982	232	65
RS–9	43.5771	89.4176	239	45
RS–10	43.7703	89.1946	239	90
RS–11	43.6288	89.4131	236	35

Figure 4. Bedrock lithostratigraphic units in Columbia, Green Lake, and Marquette Counties, showing relative stratigraphic position and age (WGNHS, 2011). mya, million years ago.

Age (mya)	Era	Period	Group	Formation
444	Paleozoic	Ordovician	Sinnipee	Galena
				Decorah
				Platteville
			Ancell	Glenwood
				St. Peter
			Prairie du Chien	undivided
488		Cambrian	Trempealeau	Jordan
				St. Lawrence
			Tunnel City	undivided
			Elk Mound	Wonewoc
				Eau Claire
				Mount Simon
541	Precambrian		undifferentiated	

Regional Quaternary geology

The Quaternary geology of south-central Wisconsin is expressed as diverse landscapes and surficial deposits, including lowlands underlain by glacial-lake and meltwater-stream sediments and uplands composed of till and meltwater-stream sediments. Map units (plate 1) are defined by sediment genesis, stratigraphic position, and landform association.

During the last part of the Wisconsin Glaciation, south-central Wisconsin was covered by the Green Bay Lobe of the Laurentide Ice Sheet (fig. 1). In the tri-county area, only a small part of northwestern Columbia County was not glaciated at this time. There is no known record of previous glaciations in the tri-county area, which is attributable to the erosive nature of the Green Bay Lobe. When the lobe reached its maximum extent, it deposited sediment that formed the Johnstown moraine (known as the Hancock moraine north of the Baraboo Hills) (Syverson and Colgan, 2011; fig. 5). Recent work by Carson and others (2012) indicates that the Green Bay Lobe reached its maximum position in the area by about 26,400±5,100 years ago and began receding after about 21,400±3,300 years ago. Ullman and others (2015) dated the recession of the Green Bay Lobe from the Johnstown moraine in the Baraboo Hills at about 23,000±600 years ago and Attig, Hanson, and others (2011) dated this event to about 18,500 years ago.

Figure 5. Map of named moraines in Columbia, Green Lake, and Marquette Counties. The Johnstown (Hancock) moraine in northwestern Columbia County represents the maximum extent of the Green Bay Lobe in the tri-county area. Moraine crests are shown with a solid line, Vs point in direction of ice movement.

As the Green Bay Lobe ice margin receded with a rapidly warming climate, it stabilized enough to deposit a series of recessional end moraines. In the tri-county area, Alden (1918) named them (from west to east) the Milton, Lake Mills, and Green Lake moraines (fig. 5). North of the tri-county area, Thwaites (1943) mapped the Elderon and Bowler moraines as correlative with Alden's (1918) Lake Mills and Green Lake moraines, respectively. As the glacier was depositing the outermost end moraine, it was also forming drumlins at its base (Colgan and Mickelson, 1997). Meltwater streams deposited sand and gravel in proglacial and ice-contact settings associated with the Green Bay Lobe. Tunnel channels were also eroded by meltwater flowing beneath the ice (Attig and others, 1989). Radiocarbon dates from the Fox River lowland indicate that the Green Bay Lobe had receded from the eastern end of the map area well before 15,500 years ago (Mode and others, 2013).

All glacial sediment deposited during the Wisconsin Glaciation (Marine Isotope Stage 2; Martinson and others, 1987) maximum by the Green Bay Lobe is included in the Holy Hill Formation (Syverson and others, 2011; fig. 6). The Horicon Member of the Holy Hill Formation (Syverson and others, 2011) is the Pleistocene stratigraphic unit on the uplands in the tri-county area. The unit is characterized by its very sandy, yellowish-brown glacial sediment (till), which typically has 65 to 85 percent sand, 5 to 30 percent silt, 5 to 20 percent clay, and several percent gravel up to boulder size. Thirty-three grain-size analyses from the cores drilled as part of this project are within these limits, as are some from 17 other till samples from numerous shallow borings (WGNHS, 2008) (fig, 7). In addition to till, the Horicon Member also contains fluvial sand and gravel and lacustrine sand, silt, and clay. The fluvial deposits are extensive along the Wisconsin River in western Columbia County and in subaqueous morainal banks and ice-contact alluvial fans in Marquette and western Green Lake Counties (plate 1). These sediments, including the extensive lake sediment of glacial Lake Wisconsin, are an important component of the Horicon Member of the Holy Hill Formation. More information on the characteristics of the Horicon Member in adjacent areas can be found in reports by Clayton and Attig (1990, 1997).

Figure 6. General chronology of Pleistocene lithostratigraphic units and glacial events in Columbia, Green Lake, and Marquette Counties, showing relative stratigraphy and age.

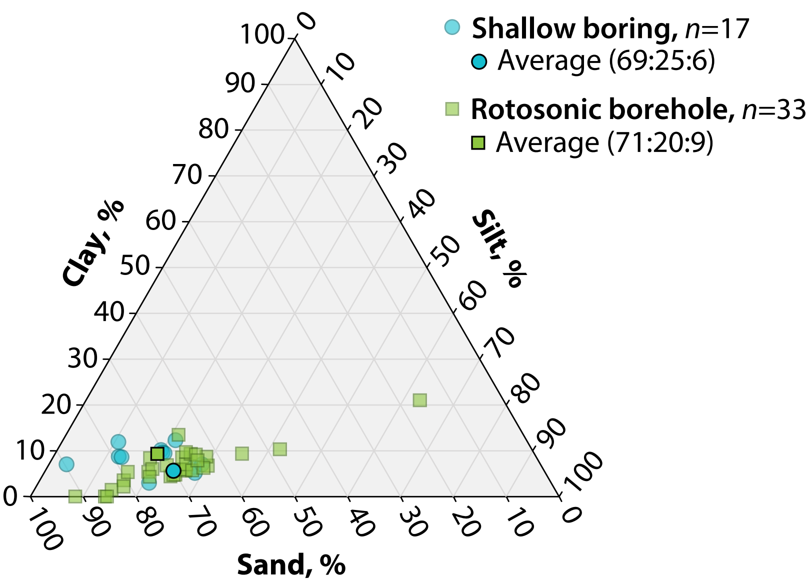
<table>
<tr><th>Age (years)</th><th colspan="2">Period/Epoch</th><th colspan="2">Glacial lithostratigraphic units in tri-county area</th><th>Events</th></tr>
<tr><td>0
11,700</td><td rowspan="6">Quaternary Period</td><td>Holocene Epoch</td><td colspan="2">unnamed units</td><td>postglacial events</td></tr>
<tr><td></td><td rowspan="5">Pleistocene Epoch</td><td rowspan="3">Kewaunee Formation</td><td>Middle Inlet Member</td><td rowspan="4">main part of the late Wisconsin glaciation</td></tr>
<tr><td>14,000</td><td>Two Creeks Forest Bed</td></tr>
<tr><td>15,500</td><td>Kirby Lake Member</td></tr>
<tr><td>30,000</td><td>Holy Hill Formation</td><td>Horicon Member</td></tr>
<tr><td>2,600,000</td><td colspan="2">other units may be present in subsurface</td><td>earlier glaciations?</td></tr>
<tr><td>5,300,000</td><td colspan="2">Pliocene Epoch</td><td colspan="3"></td></tr>
</table>

As the Green Bay Lobe advanced out of the Green Bay lowland and into the tri-county area, it impounded the drainage and thus created glacial lakes. The earliest lakes formed when the lobe was advancing to its maximum position at the Johnstown moraine. Lake sediment underlying till of the Holy Hill Formation in borehole RS–10 (fig. 3) was deposited in a glacial lake that formed in the Fox River lowland during the ice's advance. When the ice reached the Johnstown moraine, it created glacial lakes Wisconsin, Baraboo, and several other smaller lakes in the Driftless Area (Clayton and Attig, 1989). When the ice margin receded from the Johnstown moraine and from the Baraboo Hills, glacial Lake Wisconsin drained around the eastern end of the Baraboo Hills, cutting the Dells of the Wisconsin River (Clayton and Attig, 1989). As the Green Bay Lobe continued to recede, it impounded glacial Lake Oshkosh in the Fox River drainage basin (Hooyer and Mode, 2008). Initially, the outlet for glacial Lake Oshkosh was at Dekorra, where it spilled into the lower Wisconsin River valley (Wielert, 1980). With the further recession of the Green Bay Lobe, a sequence of lower outlets was opened into the Lake Michigan basin and glacial Lake Oshkosh was lowered and eventually drained (Hooyer and Mode, 2008). The distinctive red lake sediment deposited in glacial Lake Oshkosh is part of the Kewaunee Formation, which is another important stratigraphic unit in the tri-county area. The color of the Kewaunee Formation, which comes from iron oxides eroded from rocks or lake sediment located in the Superior basin (Syverson and Colgan, 2011), makes it easy to differentiate from lake sediment of the Horicon Member of the Holy Hill Formation.

As deglaciation proceeded, glacial sediment was exposed and easily eroded by wind. The sand was eroded and then deposited as sand sheets and dunes. Silt and clay were also transported and deposited as loess, which tends to be more widely distributed than eolian sand, which occurs locally. Sand dunes are nearly absent in the tri-county area, but they are prominent immediately to the west in Adams County (Clayton, 1987). Their formation has recently been dated between 14,000 and 10,000 years ago (Rawling and others, 2008). Eventually, vegetation anchored the glacial sediment to prevent further erosion.

The postglacial processes that have shaped the Quaternary geology of the tri-county area include the deposition of stream sediment (alluvium), slope sediment (colluvium), and organic sediment (peat). Because these deposits are the youngest, they cover considerable areas, but they do not constitute the largest proportion (by volume) of the Quaternary sediments in the region. The bulk of the Quaternary sediment was deposited by glacial and related processes.

Figure 7. Grain-size distribution chart of till of the Horicon Member of the Holy Hill Formation. Samples were collected either from rotosonic boreholes drilled as part of this project or from shallow borings in Columbia and Green Lake Counties. The average percentages of sand, silt, and clay in samples from the rotosonic boreholes and shallow borings are 71:20:9 and 69:25:6, respectively.



Glacial sediment and landforms

Moraines

A moraine, as the term is used here, is a ridge of glacial sediment deposited along the edge of an active (not stagnant) glacier. The four general forms of moraines in the tri-county area include minor, medium-sized, and large moraines and subaqueous morainal banks.

Minor moraines are very small moraines that often occur in clusters of closely spaced parallel ridges no more than a few meters high. They are inconspicuous in the field and on topographic maps with a 3-m contour interval, but they can often be seen on aerial photographs and on lidar imagery. Clayton and Attig (1997) mapped many small moraines in Dane County and discussed the possibility that they might be annual or push moraines. An alternative explanation is that they are subglacial crevasse fills similar to features that cover large parts of Iowa (Ankerstjerne and others, 2015; Cline and others, 2015). An example of a minor moraine can be observed in south-central Columbia County near the border (fig. 8).

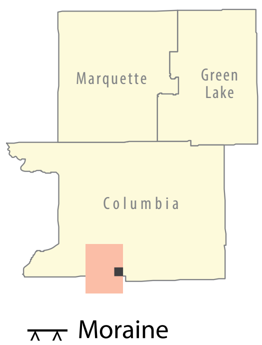
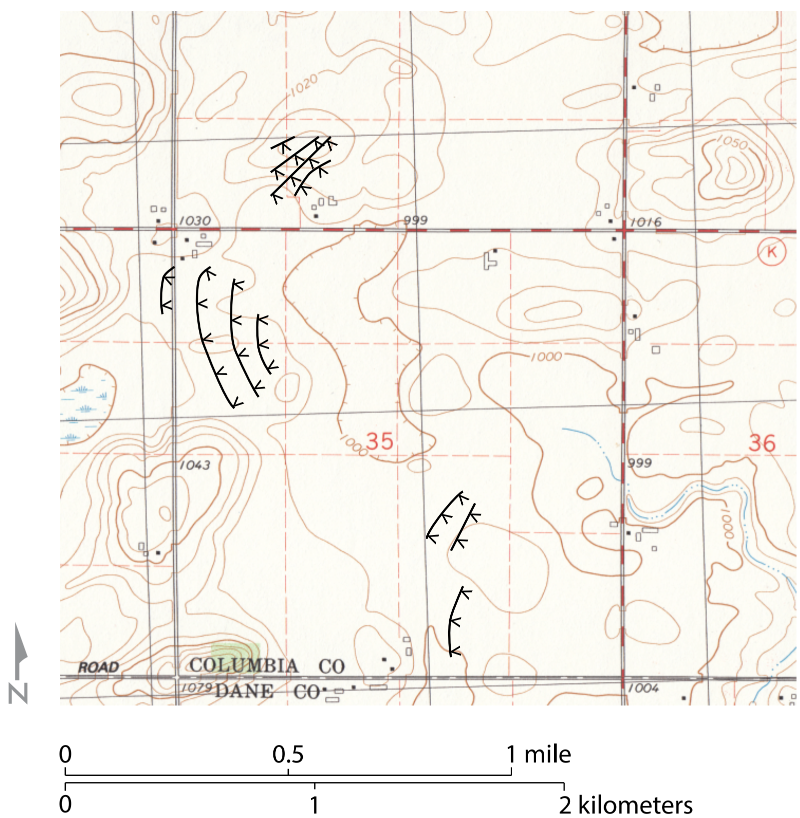
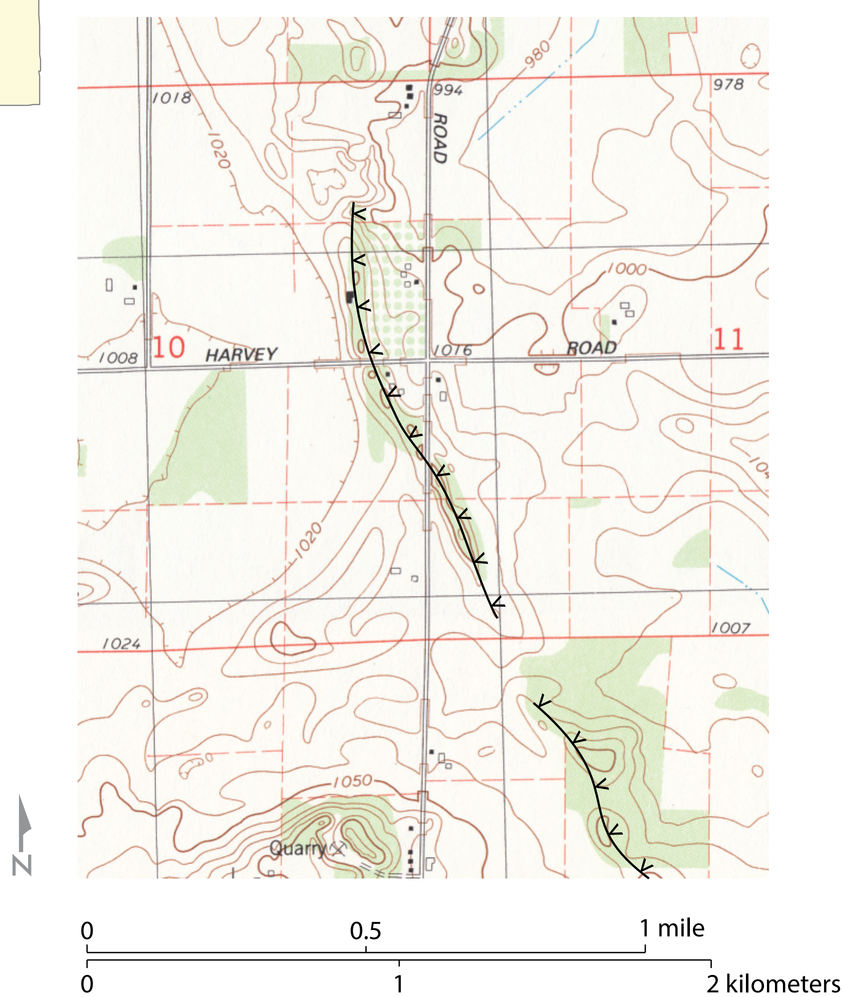


Figure 8. Very small moraines in the NW¼ sec. 35, T10N, R9E, in south-central Columbia County. The direction of the ice flow was to the west. Base is from U.S. Geological Survey, Arlington 7.5-minute topographic quadrangle (pink rectangle); location of figure shown by small black square. Contour interval is 10 feet (3 m).



Medium-sized moraines are solitary ridges that are more than a few meters high and roughly 100 m wide. Along with large moraines, they are shown on plate 1 by a line with Vs at right angles to the line. The line marks the crest of the moraine and the Vs show direction of ice movement. Medium-sized moraines are large enough to be recognized on topographic maps with a 3-m contour interval. They are more continuous over greater distances (kilometers) than the minor moraines (hundreds of meters) and presumably were deposited over longer periods than were the minor moraines. Two segments of the Lake Mills moraines can be observed on the topographic map from south-central Columbia County (fig. 9).

Figure 9. Two segments of the Lake Mills moraines in secs. 10, 11, 14, and 15, T10N, R10E, in south-central Columbia County. Base is from U.S. Geological Survey, Morrisonville 7.5-minute topographic quadrangle (pink rectangle); location of figure shown by small black square. Contour interval is 10 ft (about 3 m).



A large moraine marks the outermost extent of the Green Bay Lobe in far northwestern Columbia County. This moraine is substantially larger and topographically more irregular than the Lake Mills moraines (fig. 10). It is a few hundred meters wide and about 10 m high as viewed from the outwash plain directly to the west. The moraine appears to be about 30 m high when viewed from the east. In southern Wisconsin, Alden (1918) named the outermost moraine of the Green Bay Lobe the "Johnstown moraine" to the south of the Baraboo Hills and the "Hancock moraine" to the north of the Baraboo Hills. The moraine has been correlated with the Almond moraine in Portage County (Attig, Bricknell, and others, 2011).

Subaqueous morainal banks formed where the margin of the Green Bay Lobe calved into deep portions of glacial lakes (Attig and others, 2007). Two sets of morainal banks are located in the Lewiston basin of proglacial Lake Wisconsin in Marquette County. They are several tens of meters high and a few hundred meters wide. One such morainal bank of approximately 6 km in length is shown in figure 11. The tallest have flat tops that are at an elevation of about 293 m, which is just below the level of glacial Lake Wisconsin when it was at its maximum elevation. The tops are sharper where the crests of the morainal banks are at a lower elevation. The flat surfaces are interpreted to be the topset part of small deltas, which are composed of flatbedded and crossbedded sand and gravel (Socha, 1984). The western faces of these morainal banks usually contain delta foreset fans consisting of sand and gravel. In their description of the formation of morainal banks, Powell and Domack (1995) state that on the up-glacier flank where the ice abuts the bank, the sediment consists of a variety of material, including slumped till containing boulders.

Figure 10. Part of outermost moraine (Hancock Moraine) in northwestern Columbia County in sec. 5, T13N, R7E, in northwest corner of Columbia County. Base is from U.S. Geological Survey, Big Spring 7.5-minute topographic quadrangle (pink rectangle); location of figure shown by small black rectangle. Contour interval is 10 ft (about 3 m).

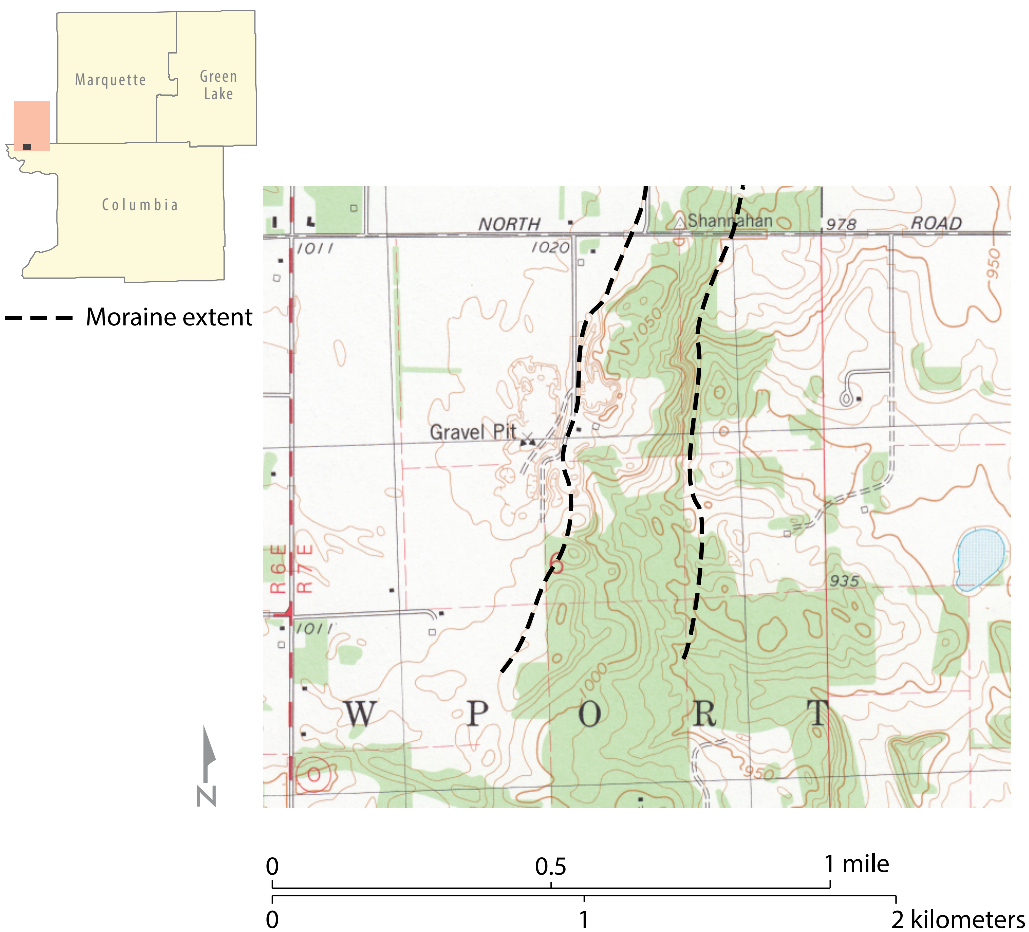
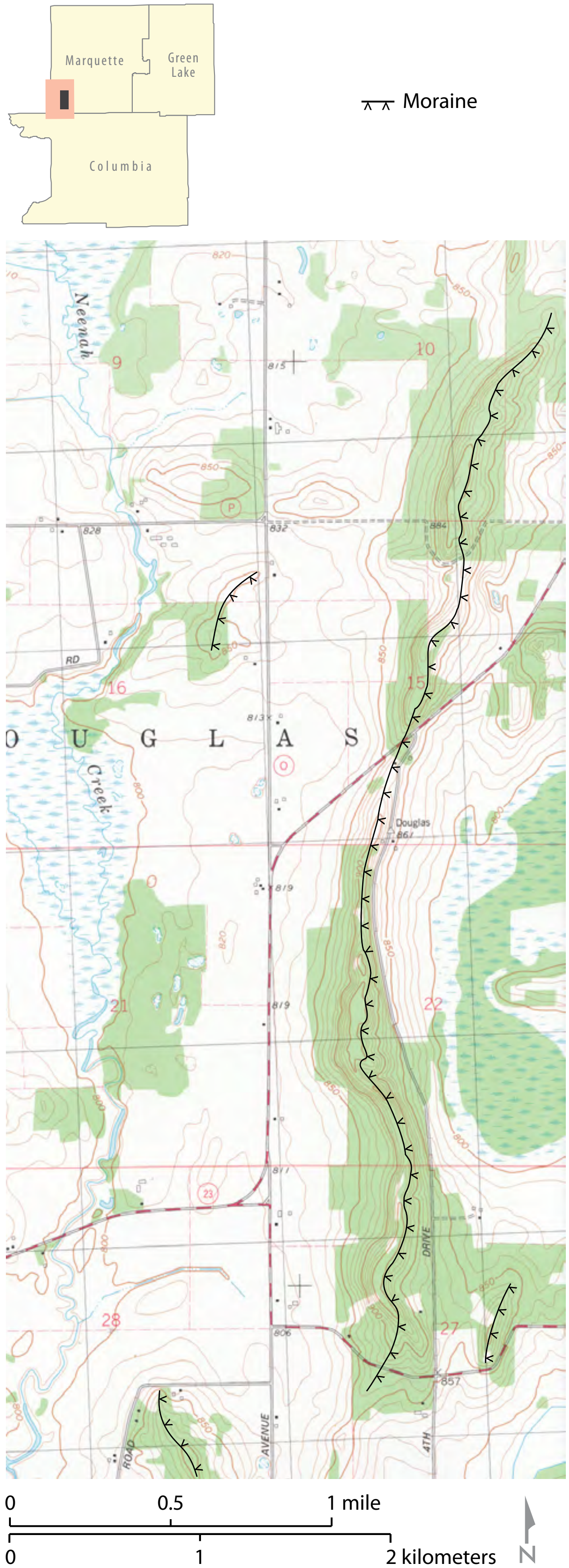


Figure 11. Map of part of Briggsville morainal bank that was formed in glacial Lake Wisconsin in southwestern Marquette County. The moraine is located in secs. 10, 15, 22, and 27, T14N, R8E. The topographic map shows a flat surface at the moraine crest (solid black line), which likely formed when waves from glacial Lake Wisconsin washed over it. Base is from U.S. Geological Survey, Briggsville 7.5-minute topographic quadrangle (pink rectangle); location of figure shown by small black rectangle. Contour interval is 10 ft (about 3 m).



Drumlins

As the glacier slid over its bed, in places it formed a series of elongated hills and ridges parallel to the direction of ice flow. If such an elongated hill is large enough to be considered a landform, it is designated a "drumlin." As time progressed, and the glacier continued to move over the hill, the hill gradually became streamlined until it finally evolved into a well-developed drumlin in the shape of an overturned canoe that is pointed in the direction of the ice flow. The intervening grooves between the hills go unnamed—perhaps because the grooves are commonly out of sight, buried under sediment deposited from meltwater lakes or streams and later by peat and sediment washed down off the drumlins.

The drumlins in the tri-county area are part of a larger field that includes drumlins formed by the Green Bay Lobe of the Laurentide Ice Sheet. This drumlin field contains nearly 15,000 drumlins (Colgan and Mickelson, 1997) and extends across south-central Wisconsin into Dodge, Jefferson, Waukesha, Dane, Winnebago, and Fond du Lac Counties. The sizes and shapes of drumlins vary across the tri-county area with the well-formed drumlins indicated by solid arrows and by dashed arrows (drumlinized hills of plate 1). Bedrock-cored drumlins are often less strongly streamlined than sediment-cored drumlins. The term "drumlinized hills" is used when pre-existing rock, not newly deposited sediment, was streamlined by the glacier. The longest and largest drumlins in the tri-county area are located in Columbia County and are approximately 3 km long, 0.3 km wide, and 25 m high. In the central and western parts of the tri-county area, the drumlins are less streamlined and less abundant than in the eastern part of Columbia County. They are absent in the far western area that would have been closer to the ice margin. Most of the drumlin irregularities are probably the result of inadequate streamlining, but some are the result of streamlining that was followed by irregular deposition of glacial debris on top of previously fully streamlined drumlins.

Drumlins are radially oriented in the tri-county area. Those in the northwestern corner of Marquette County trend N. 45° W., those along the northern county line of Columbia County trend east to west, and those in the southeastern corner of Columbia County trend S. 45° W. The locations of the drumlins with respect to each other seem haphazard in most areas, but some fairly well-developed ones in the eastern part of Columbia County are arranged *en echelon*, suggesting an earlier and more southerly glacial movement.

Many of the drumlins mapped in the tri-county area consist of till from the Horicon Member of the Holy Hill Formation and are located in terrain classified as map unit **ghs** on plate 1. The till content indicates that the landscape was formed subglacially. In areas devoid of drumlins, the nondescript, low-relief hills are represented by map unit **ghr** (rolling glacial topography, described below) on plate 1.

Although many drumlins are composed of till, other glacial sediments, as well as bedrock, are also found within drumlins. Drumlins frequently contain meltwater-stream sediment (sand and gravel), and several gravel pits are developed in drumlins to extract this material (fig. 12). Two gravel pits located west of Princeton (see Sand and Gravel Availability, below) contain both till and meltwater-stream deposits. Bedrock-cored drumlins also occur in the tri-county area. A dolostone and sandstone quarry in a drumlin is located about 5 km west of Green Lake, and many of the larger drumlins in the tri-county area contain bedrock cores veneered with till. Bedrock-cored drumlins with little or no till veneer occur in northern Columbia County. Their existence proves that, in addition to molding unconsolidated sediment, the sliding action of the glacier also streamlined some bedrock surfaces.

Rolling glacial topography

In parts of the tri-county area, the last glacier accomplished little besides eroding the pre-existing topography and covering the surface with glacial sediment. The resulting nondescript glacial topography is indicated by map unit **ghr** (plate 1). The area covered by this unit is without identifiable specific glacial landforms, except where drumlins or moraines are shown. In places where there was pre-existing stratified Pleistocene sand, silt, or clay, the only evidence that the area had been overrun by the glacier is scattered boulders on the land surface or deformed bedding in the surface sediment.

Nondescript glacial topography

Much like the landscape characterized by rolling glacial topography, areas of low-relief, nondescript, hummocky glacial topography (map unit **ghh)** consist of glacial sediment of varying thickness that is draped over the land surface. These areas usually contain enclosed depressions, many of which are actively and gradually filling with sediment and organic material. Locally, low-relief hummocks, less than 2 m high, resulted from till of varying thickness deposited during the ice's recession. These areas mark positions of the Green Bay Lobe during its recession and were mapped as end moraines by Alden (1918). Some areas of hummocky topography, such as the area that extends south from the southwestern corner of Green Lake, have higher relief and may be the result of buried ice blocks that subsequently melted out, leading to enclosed depressions.

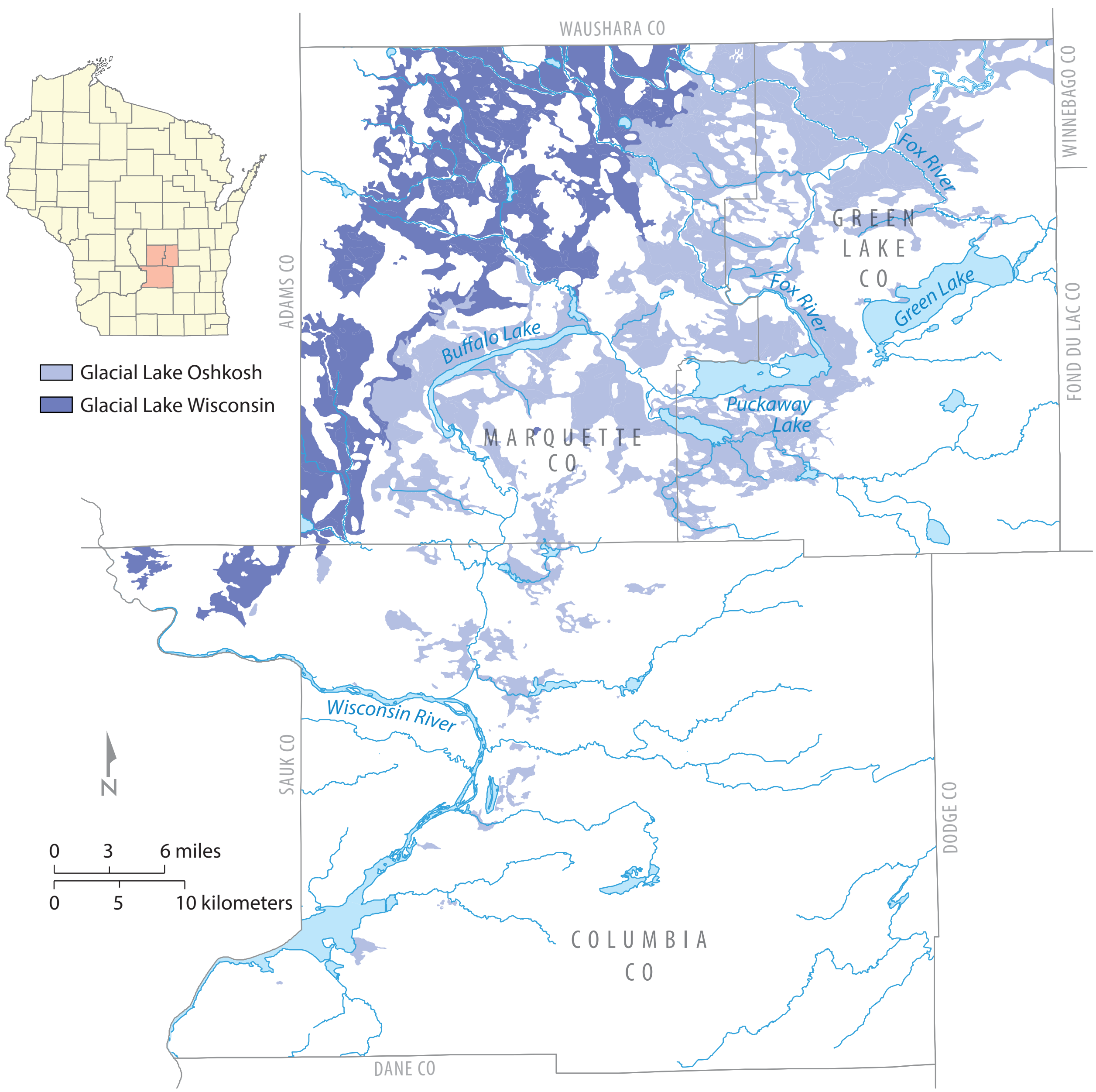
Figure 12. Gravel pit in a streamlined drumlin, exposing light-brown till and underlying gravel of the Holy Hill Formation. Such complex relationships among strata within drumlins were noted by Whittecar and Mickelson (1979) in Waukesha County. The till in the center appears red because soil has washed onto the exposure. Height of exposure is about 6 m. Located in SE¼NE¼SE¼ sec. 34, T16N, R11E, 4.5 km southwest of Princeton in the U.S. Geological Survey Princeton West 7.5-minute topographic quadrangle.

Lake sediment and landforms

Offshore sediment

Offshore lake sediment is a dominant feature in Green Lake, Marquette, and northern Columbia Counties because large areas of the land surface were inundated at different times by two different proglacial lakes: glacial Lakes Wisconsin and Oshkosh. Most of the offshore lake sediment is in flat lowland areas that are underlain by clay, silt, or sand (plate 1). Offshore sediment associated with glacial Lake Oshkosh tends to contain silt and clay (map unit **lo**) compared to glacial Lake Wisconsin, where the majority of offshore sediment is a bit coarser and consists of silt and sand (map unit **lw**). Lake sediment is prominent in the tri-county area, covering a large portion of the landscape (fig. 13). In many areas, especially in Marquette and Green Lake Counties, the lake sediments are covered with a thin veneer of windblown sediment (map units **low** and **lww**) up to 2 m thick. This sediment was likely deposited shortly

Figure 13. Distribution of lake sediment in the tri-county area. The light- and dark-purple areas represent sediment deposited in glacial Lake Oshkosh and glacial Lake Wisconsin, respectively.



after the Green Bay Lobe receded from the tri-county area when the climate was still cold, and the landscape was barren of vegetation. The timing of deposition is consistent with other studies where a veneer of sand covers a large area of central Wisconsin (Jacobs and others, 2011), and large sand dunes formed on the main plain of glacial Lake Wisconsin (Rawling and others, 2008). In other areas, the lake plain is covered by a layer of peat (map units **po** and **pw**) because the lake sediment and a high water table limit the surface-water infiltration. As a result, low-lying areas are perennially wet and form abundant wetlands throughout the tri-county area.

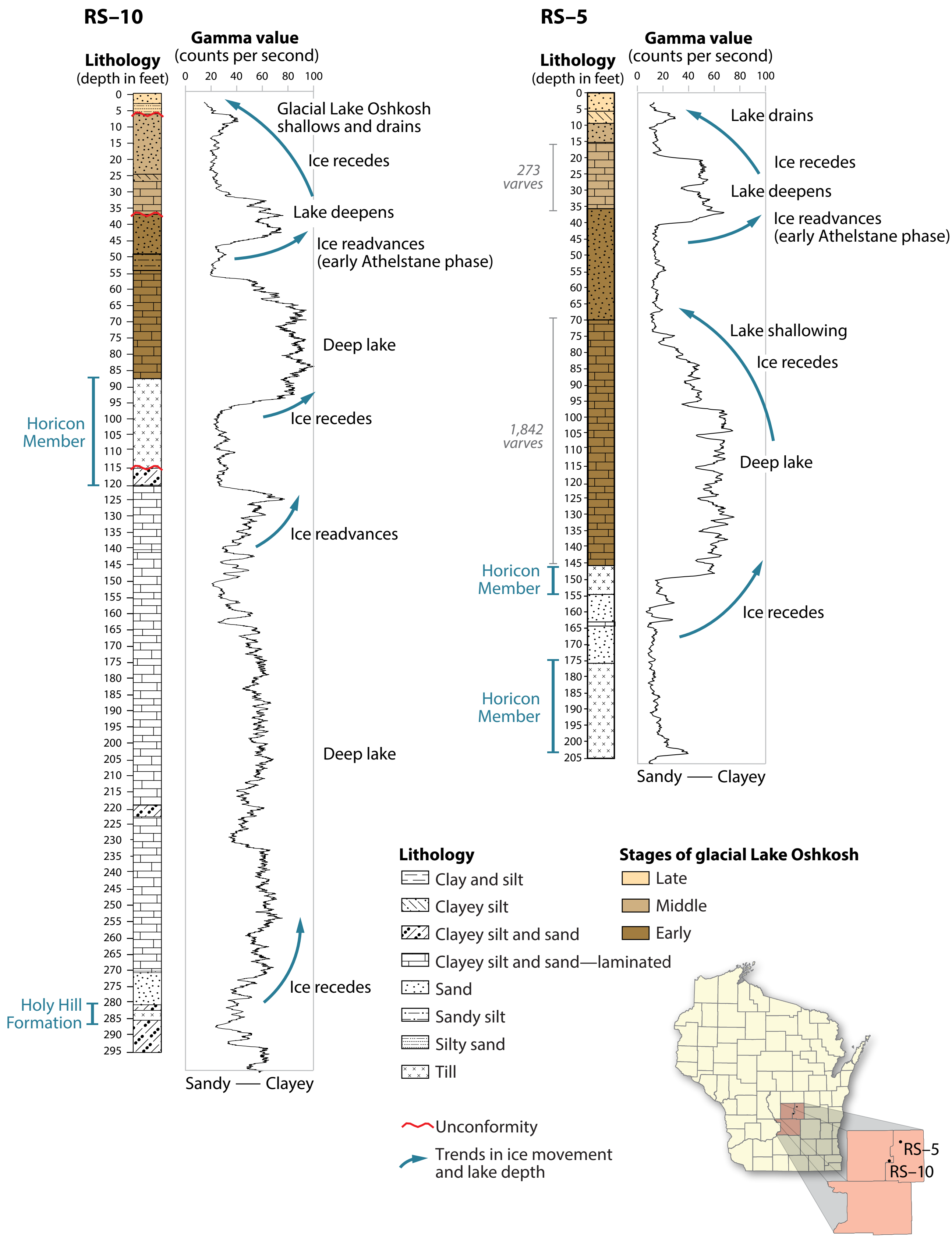
Most offshore lake sediment is now situated in areas that are too wet or covered with peat to have natural or artificial exposures. As a result, little information is available about this unit's characteristics except where noted on well construction reports and where encountered in four rotosonic boreholes that were drilled as part of this project. These four boreholes are located along the axis of the upper Fox River valley (fig. 3) and were part of a larger study to understand the extent of glacial Lake Oshkosh. Borehole logs indicate that lake sediment is over 80 m thick in places (for example, see the deep lake represented on the log for borehole RS–10 in fig. 14), especially in the deep preglacial valley that underlies the upper Fox River basin. Most of this lake sediment consists of silt and clay, and much of it is rhythmically laminated, which is typical of sediment deposited in a deep-water environment. Most of the laminated sediment contains varves that record yearly deposition (fig. 15). These varves consist of alternating red and gray layers, which indicate winter and summer depositional cycles. The red layers consist mainly of small clay-sized particles that settled out of the water column during the winter when the lake was covered by ice. The gray layers consist mainly of coarser-grained silt that settled out of the water column during the summer months when higher-energy conditions existed. Most of the red, fine-grained sediment remained suspended during this period due to the higher-energy conditions. The varves indicate a minimum number of years that the lake was in existence. Over 1,800 varves were counted in one of the lake-sediment sequences in borehole RS–5 (fig. 14).

Layers of fine-grained sediment in the boreholes are often overlain by a layer of sand, forming a coarsening-upward sequence. This increase in grain size is typical of a lake-sediment sequence, where offshore sediment was capped by nearshore sediment deposited in a higher-energy environment as the lake level fell with the opening of lower outlets. The downhole geophysical logs of natural gamma radiation from two boreholes confirm these transitions (fig. 14).

The lake-sediment sequences identified in rotosonic boreholes (fig. 14) document the history of glacial Lake Oshkosh as the Green Bay Lobe receded from the tri-county area. The boreholes specifically document the lake level's decrease and increase as it emptied and filled three different times (Hooyer and Mode, 2008). Rotosonic borehole RS–5 shows these three sequences overlying the till of the Horicon Member that was deposited when the Green Bay Lobe was at its maximum extent. The same sequence is observed in RS–10 with the exception that a thick sequence of lake sediment exists beneath the till of the Horicon Member. This lake sediment must represent an older lake phase that was deposited as the Green Bay Lobe advanced into Wisconsin; the sediment was somehow preserved beneath the ice lobe and is the only evidence in the basin of a proglacial lake in front of the Green Bay Lobe during its advance to its Wisconsin maximum position.


Wisconsin River, near Portage, Wisconsin

Figure 14.


RS–10
Lithology
(depth in feet)
Gamma value
(counts per second)
0 20 40 60 80 100
Glacial Lake Oshkosh
shallows and drains
Ice recedes
Lake deepens
Ice readvances
(early Athelstane phase)
Deep lake
Ice recedes
Ice readvances
Deep lake
Ice recedes
Horicon
Member
Holy Hill
Formation
Sandy —— Clayey
RS–5
Lithology
(depth in feet)
Gamma value
(counts per second)
0 20 40 60 80 100
273
varves
1,842
varves
Lake drains
Ice recedes
Lake deepens
Ice readvances
(early Athelstane phase)
Lake shallowing
Ice recedes
Deep lake
Ice recedes
Horicon
Member
Horicon
Member
Sandy —— Clayey
Lithology
Clay and silt
Clayey silt
Clayey silt and sand
Clayey silt and sand—laminated
Sand
Sandy silt
Silty sand
Till
Unconformity
Trends in ice movement
and lake depth
Stages of glacial Lake Oshkosh
Late
Middle
Early
RS–5
RS–10

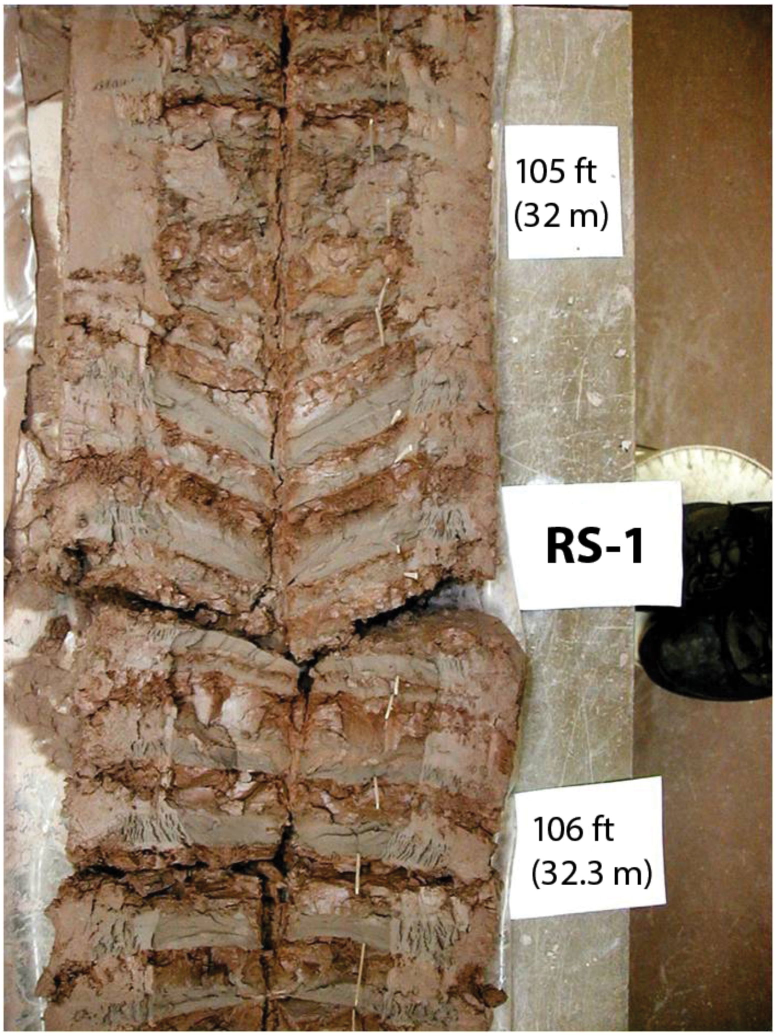
◀ **Figure 14.** Downhole geophysical logs of natural gamma radiation and associated lithologic logs for rotosonic boreholes RS–5 (Green Lake County) and RS–10 (Marquette County). Gamma radiation is measured in counts per second; low counts indicate sandy sediment and high counts indicate a greater amount of silt and clay. The lithologic logs, measured in feet, show thick sequences of laminated lake sediment deposited in glacial Lake Oshkosh. Several lake-sediment sequences (yellow, tan, and brown, representing discrete phases of glacial Lake Oshkosh's existence) can be attributed to the draining and refilling of glacial Lake Oshkosh as the Green Bay Lobe readvanced at least twice into the Fox River valley and dammed up the ancestral Fox River. The damming resulted in the lake draining southward through the Dekorra outlet into the lower Wisconsin River valley. Varves, annual sediment layers, were counted in the laminated silt and clay of RS–5; 1,842 varves were counted in the early stage of glacial Lake Oshkosh and 273 varves were counted in its middle stage.

Nearshore sediment

Nearshore sediment deposited in the shallow water (the littoral zone) was difficult to differentiate from offshore sediment, especially in areas covered by windblown sand, which includes large parts of the tri-county area (map units **l**, **lww**, and **low**). The sand covers nearshore features such as beaches and nearshore sand bars.

Few beaches are recognizable around the footprint of glacial Lake Wisconsin today because they were largely obliterated by the intense soil erosion that occurred during the period of periglacial climate immediately after the glaciation. Much of the evidence for nearshore deposits around glacial Lake Wisconsin was found in counties northwest of the tri-county area (Clayton and Attig, 1989).

Figure 15. Photograph of varves in offshore lake sediment of glacial Lake Oshkosh in core taken from rotosonic borehole RS–1 from 105 ft to 106 ft below ground level. One red layer (winter) and one gray layer (summer) together represent a varve that was deposited during one year. Approximately 20 varves are shown in the 0.3-m-thick layer of lake sediment.

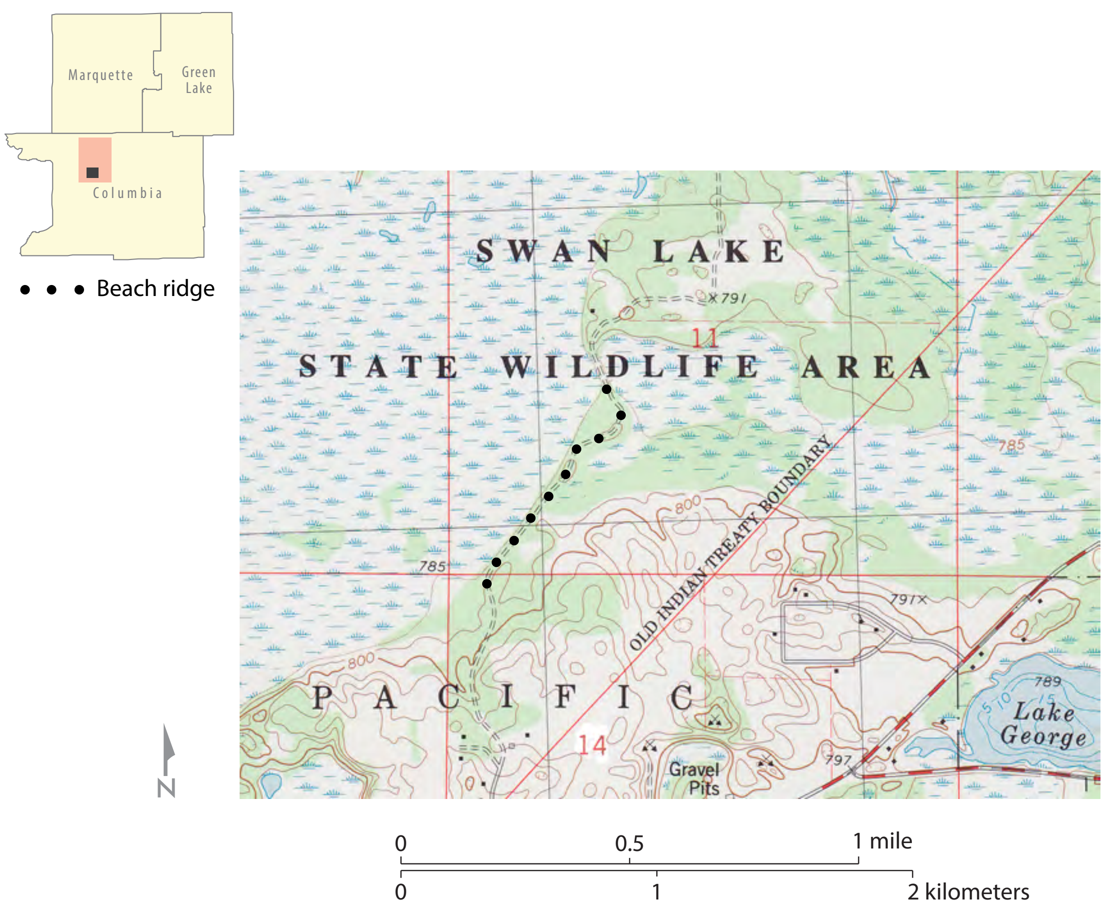


Glacial Lake Oshkosh formed later than glacial Lake Wisconsin, and its nearshore sediment underwent less erosion and has somewhat better-preserved beaches. For example, a sandy beach ridge 2 km northwest of Lake George and 3 km east of Portage (fig. 16) rises 3 m above the adjacent marsh. The ridge formed when the lake level stood at about 240 m. Numerous terraces, which document lake-level elevations, exist in the glacial Lake Oshkosh basin.

Although nearshore sediment is difficult to differentiate from offshore sediment in the tri-county area, rotosonic boreholes show that it is prominent in the subsurface. In most of the coarsening-upward lake-sediment sequences, each layer of offshore sediment is capped by sand that was likely deposited in a nearshore environment. For example, in borehole RS–5 from 10 to 21 m below the ground surface, an 11-m-thick layer of sand caps fine-grained sediment, which was deposited in deep water.

Although our results from the optically stimulated luminescence (OSL) dating of fine-grained sediment of glacial Lake Oshkosh (Hooyer and others, 2009) were mixed, OSL dating of these shallow-water sands may help constrain an age of deposition.

Figure 16. Beach ridge (dots) of glacial Lake Oshkosh located in sec. 11, T12N, R9E, in north-central Columbia County. Base map is from U.S. Geological Survey, Portage 7.5-minute topographic quadrangle (pink rectangle); location of figure shown by small black rectangle. Contour interval is 10 ft (about 3 m).



Pleistocene lakes

Glacial Lakes Wisconsin and Oshkosh

Glacial Lake Wisconsin (Clayton and Attig, 1989) occupied a large part of central Wisconsin every time the Green Bay Lobe advanced onto the eastern end of the Baraboo Hills to prevent drainage to the south and west down the lower Wisconsin River valley (fig. 17A) (Clayton and Attig, 1989). During these times, the lake drained to the northwest down the Black River in northeastern Jackson County through the Black River outlet (fig. 18). This proglacial lake was restricted to the main basin and several small basins at the southern end of the lake when the ice was at its greatest extent. As the ice receded, the lake then filled the Lewiston basin, which expanded eastward into Marquette and northwestern Columbia Counties (fig. 17B, C). During this time, glacial Lake Merrimac (also a proglacial lake) existed in the lower Wisconsin River valley in southwestern Columbia County and drained through an outlet just north of Sauk City. The Lewiston basin was the easternmost arm of glacial Lake Wisconsin. It expanded eastward, following the retreating edge of the Green Bay Lobe, until it reached an area near Portage. At this point, glacial Lake Wisconsin drained in its entirety. (Note that glacial Lake Wisconsin is unrelated to present-day Lake Wisconsin, a reservoir behind the dam on the Wisconsin River near Prairie du Sac in southwestern Columbia County.)

As the Green Bay Lobe started to recede off the eastern end of the Baraboo Hills, glacial Lake Wisconsin began to drain southward between the hills and the ice, which rapidly lowered the lake level from 296 to 252 m (for an elevation difference of 44 m). The lake level stabilized at the bedrock saddle at the interchange between Interstate 39 and Interstates 90 and 94 (fig. 17D). This feature has been called the Alloa outlet (Clayton and Attig, 1989) and occurs at an elevation of 252 m. The outlet elevations associated with glacial Lakes Wisconsin and Oshkosh are summarized in figure 18.

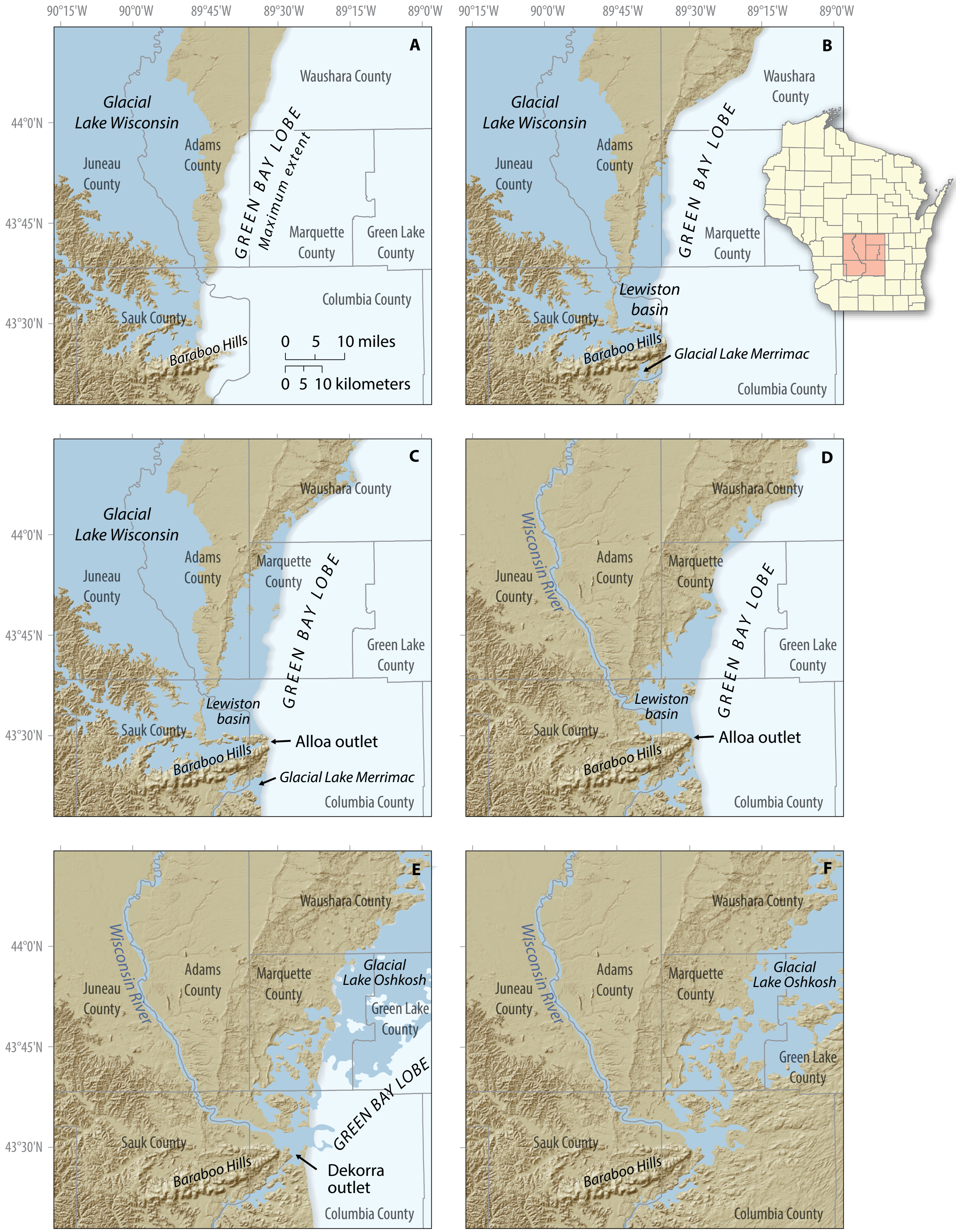
When the glacier receded another 4 km to the east, the lake level dropped another 12 m to the Dekorra outlet (Clayton and Attig, 1989). With this event, glacial Lake Wisconsin ceased to exist. As the ice margin receded another kilometer to the east, glacial Lake Oshkosh started to form at an elevation of about 242 m (fig. 17E, F). The controlling Dekorra outlet is thought to have been 5 km downstream, where the sandstone gorge narrows at St. Lawrence Bluff near the town of Dekorra. The lake level initially stabilized at 240 m and drained to the lower Wisconsin River valley (figs. 17E, 18). With the continued recession of the ice margin, a series of four lower outlets opened eastward across the Niagara Escarpment and into the Lake Michigan basin (fig. 18). The opening of these lower outlets lowered the lake level in the area occupied by glacial Lake Oshkosh (Wielert, 1980; Clark and others, 2008; Hooyer and Mode, 2008). As the Green Bay Lobe retreated north of present-day Lake Winnebago, the first eastward outlet to open was the Manitowoc outlet at 249 meters. Though the elevation of the Manitowoc outlet is now higher than that of the Dekorra outlet, this is an artifact of differential postglacial rebound. When the Manitowoc outlet was occupied during ice retreat, it was lower than the Dekorra outlet. As the Green Bay Lobe receded further north in the Green Bay lowland, the remaining three eastern outlets (Neshota, Kewaunee, and Ahnapee) were occupied in succession because each was lower than the preceding outlet. When glacial Lake Oshkosh was at the Neshota level (234 m), only a small area in northern Green Lake County was inundated with water. When the Kewaunee outlet opened, lowering the lake by 20 m, glacial Lake Oshkosh ceased to exist in the tri-county area because the outlet elevation was lower than the land-surface elevation. Glacial Lake Oshkosh finally ceased to exist when the Green Bay Lobe receded past Sturgeon Bay and the water in the Green Bay lowland equilibrated with that in the main Lake Michigan lowland.

The configuration of both glacial Lake Wisconsin and glacial Lake Oshkosh changed each time the ice receded far enough to uncover a lower outlet. When the Dekorra or any of the outlets across the Niagara Escarpment was used, the lake is referred to as "glacial Lake Oshkosh." When the outlet shifted to Sturgeon Bay, the connected bodies of water that are now referred to as "Green Bay" and "Lake Michigan" came into existence.

Green Lake

Unlike many other lakes in the tri-county area that are shallow and have been filled with sediment, Green Lake is the deepest inland natural lake in Wisconsin with water depths that exceed 70 m. The great depth of Green Lake along with the absence of thick sediments on its walls where bedrock is close to or at the surface suggest an erosional origin for the lake basin. Green Lake likely evolved as a tunnel channel that was formed by a subglacial river beneath the ice

Figure 17.

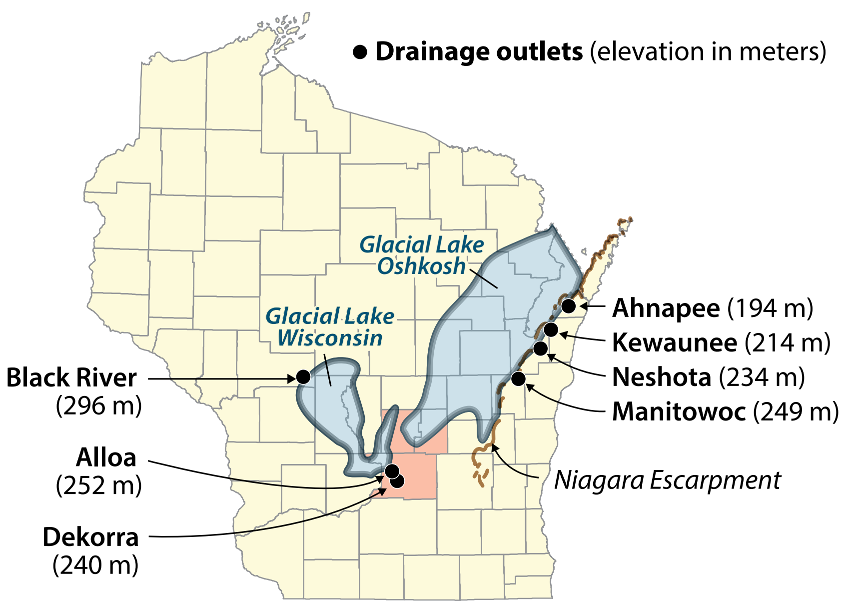

90°15'W
90°0'W
89°45'W
89°30'W
89°15'W
89°0'W
44°0'N
43°45'N
43°30'N
A
Glacial Lake Wisconsin
Juneau County
Adams County
GREEN BAY LOBE
Maximum extent
Waushara County
Marquette County
Green Lake County
Columbia County
Sauk County
Baraboo Hills
0 5 10 miles
0 5 10 kilometers
B
Lewiston basin
Glacial Lake Merrimac
C
Alloa outlet
D
Wisconsin River
E
Glacial Lake Oshkosh
Dekorra outlet
F

◀ **Figure 17.** Retreat sequence of the Laurentide Ice Sheet in Columbia, Green Lake, and Marquette Counties. **A,** Maximum extent of the Green Bay Lobe against the eastern edge of the Baraboo Hills, blocking the ancestral Wisconsin River and forming glacial Lake Wisconsin at an elevation of 296 m above sea level. **B,** Ice receded from its outermost marginal position with meltwater filling in the newly deglaciated area (Lewiston basin). **C,** With continued recession, the Alloa outlet, 252 m above sea level, opened around the eastern end of the Baraboo Hills. **D,** The opening of the Alloa outlet lowered the level of glacial Lake Wisconsin, significantly reducing its size. **E,** Glacial Lake Wisconsin completely drained when the Dekorra outlet, 240 m above sea level, opened along the ancestral lower Wisconsin River Valley. **F,** Glacial Lake Oshkosh formed between the Dekorra outlet and the receding ice margin. This lake increased in size as ice continued to recede to the northeast.

as it was receding to the northeast. Although it is difficult to imagine a subglacial river being as wide as Green Lake (greater than a kilometer), it may have been occasionally fed by the draining of a subglacial lake (Clayton and others, 1999). A plausible alternative origin is that Green Lake represents a subglacial valley that was cut by a migrating subglacial river and it was formed over a longer period rather than by catastrophic drainage of a subglacial lake. Like other tunnel channels, a large alluvial fan, represented by sand and gravel deposits (map unit **sc**), exists at the end of the tunnel channel at the western end of Green Lake. These sand and gravel deposits are quite hummocky, indicating that outwash buried some large ice blocks that had separated from the ice margin and subsequently melted out. Given the number of abandoned gravel pits located in the area covered by map unit **sc**, it appears that much sand and gravel historically was removed from this alluvial fan.

Green Lake was never part of glacial Lake Oshkosh simply because the elevations of the alluvial fan (about 251 m) and the surrounding topography are well above the highest outlet elevation for glacial Lake Oshkosh. Had glacial Lake Oshkosh reached into Green Lake, it would have been filled with sediment. Puckaway Lake, for example, is a shallow lake located 3 km west of the western end of Green Lake. Because its elevation is 10 m lower than Green Lake, it was filled with glacial Lake Oshkosh sediment, as indicated in rotosonic borehole RS–10, which was located on the northern shore of the lake and yielded over 80 m of lake sediment (figs. 3, 14). Because Green Lake was isolated from glacial Lake Oshkosh, it retained its bathymetry and original shape.

Figure 18. Generalized outlets and elevations for glacial Lake Wisconsin and glacial Lake Oshkosh. The four outlets on glacial Lake Oshkosh opened across the Niagara Escarpment.




Portage Canal

Other small former lakes

The last glacier left behind numerous lakes as it receded from the tri-county area. Many were filled with offshore silt and clay or with coarser sediment closer to the shore. Only the largest areas of lake sediment are indicated by map unit **l** on plate 1. When meltwater no longer reached these small lakes, sediment from shore erosion, soil erosion, and erosion along streams continued to fill the lakes with sediment, but at a reduced and declining rate. Eventually, most of these small lakes were shallow enough for marsh or swamp plant debris to accumulate as peat. Some, like Mud Lake in Columbia County (5 km southwest of Rio) and Grand Lake in Marquette County (immediately adjacent to Kingston), have fluctuated between lake and marsh as the climate changed along with the water-table levels.

Other deep lakes occur where the glacial outwash was thick enough to insulate and preserve the buried glacial ice. Such ice blocks ultimately melted and left a natural depression (kettle) that filled with groundwater and local surface-water runoff. Examples include Little Green Lake and Twin Lakes in Green Lake County; Tuttle Lake, Wood Lake, and Crystal Lake in Marquette County; and Silver Lake and Swan Lake in Columbia County.

Artificial lakes

Most artificial lakes in the tri-county area are usually associated with low-head dams that were built to power grain mills. One such mill pond, located adjacent to Neshkoro in Marquette County, dams the White River. Such mill ponds are often shallow because they have filled with sediment over the years. Other low-head dams were built to create wildlife habitats, such as the French Creek Wildlife Area in northern Columbia County and the Grand River Marsh in Marquette County. Still other low-head dams were constructed to create lakes for recreational opportunities, such as Buffalo Lake in Marquette County.

Buffalo and Puckaway Lakes lie along the upper Fox River valley and are extremely shallow (2 to 3 m) compared to Green Lake. The entire Fox River valley has been filled with lake sediment from glacial Lake Oshkosh, as shown by cores collected from boreholes drilled adjacent to the river (fig. 13). Even though the levels for both Buffalo and Puckaway Lakes are currently controlled by dams at Montello and Princeton, respectively, there must have been standing water in these low-lying areas following the draining of glacial Lake Oshkosh. Because the climate has fluctuated since that time, it would not be surprising if both lakes varied between a marsh and standing water because the ground-water recharge to these low areas also changed.

Stream sediment and landforms

Stream transport sorts detrital sediment by weight, with the lightest particles being carried the farthest downstream and the heaviest carried short distances, if at all. Because it reduces the amount of sorting and washing required before commercial use, this natural sorting is the reason that stream deposits of sand and gravel are valued by the aggregate industry. In the landscape, most economic deposits lie beneath graded surfaces that represent alluvial fans (steeply graded; map unit **sa**, plate 1) and flood plains (gently graded; map unit **su**, plate 1) formed by meltwater streams whose locations were determined by the ice margin and meltwater drainage systems of the Green Bay Lobe. These graded surfaces may be interrupted by kettles (map unit **sc**, plate 1**)**. Finer particles, including silt and clay, remain in suspension in meltwater streams until the flow velocity markedly decreases. This reduction in flow often occurs when meltwater rivers flow into standing water such as a lake, where the flow velocity approaches zero and the fine-grained sediment settles to the bottom.

Modern streams in Wisconsin do not have the large discharge or velocity that characterized glacial meltwater rivers, and they also lack a source of large volumes of sediment that is usually available at a glacier margin. As a result, modern streams rarely transport sediment coarser than sand; these deposits (map unit **s**, plate 1), which formed on flood plains, are restricted to areas adjacent to the streams.

Meltwater streams

The thermal and hydrologic characteristics of glaciers determine whether meltwater will flow on, in, or under the glacier. The Hancock (Johnstown) moraine in the northwestern corner of Columbia County marks the maximum extent of the Green Bay Lobe. The cold temperatures that prevailed at the time of its formation made it difficult, even in summer, for the entire glacier to warm to the melting point (Attig and others, 1989). Meltwater produced by basal melting under the thicker ice that was 5 km or more behind the ice margin was forced toward the ice margin by hydrostatic pressure. The base of the near-marginal ice was colder than the meltwater, which then eroded tunnel channels into the substrate (Clayton and others, 1999; Cutler and others, 2002; Zoet and others, 2019). Several tunnel channels occur within the former position of the Green Bay Lobe, and they are often fronted by outwash fans that were deposited at and beyond the channel mouth (fig. 19). Later, when climate warming had caused the glacier to begin receding and thinning, the glacier was warmer and not frozen to its bed. Most water produced by surface melting flowed into crevasses in the ice and melted its way to the bottom where it flowed in conduits that melted either upward into the base of the ice or into channels eroded down into the subglacial material. The water pressure within the glacier caused basal meltwater to flow toward the margin of the ice where it emerged from a conduit. At that point, the flow velocity dramatically declined away from the glacier because the water was no longer confined to a narrow channel under abnormally high pressure. The decline in velocity also caused the sediment-carrying capacity of the stream to decrease enough for the coarser sediment to be deposited at that point (Cutler and others, 2002). Hence, past positions of the Green Bay Lobe are marked by such meltwater-stream deposits that take the form of fans or deltas that are linked to an ice margin (fig. 19, map unit **sa**, plate 1).

If the land surface beyond the edge of the glacier sloped away, the meltwater streams flowed away from the glacier margin and deposited sediment on flood plains. Today, these former flood plains stand well above valley bottoms and are often distant from modern streams; such surfaces, which are sloped even though they are referred to as "plains," are called outwash terraces (map unit **su**, plate 1). As the Green Bay Lobe receded, outwash sometimes buried the glacier ice. When the buried ice finally melted out, the outwash collapsed into the space left by the melted ice and kettles formed (map unit **sc**, plate 1). Kettled outwash terraces are also called pitted outwash plains. In several locations within this area, such as the Wisconsin River valley south of the Baraboo Hills, meltwater-stream terraces contain large quantities of sand and gravel. In certain areas, especially around margins of glacial lakes, intense downcutting of graded alluvial surfaces produced numerous gullies (map unit **se**, plate 1).

If the land surface beyond the edge of the glacier sloped back toward the glacier, one of two situations developed with respect to meltwater emerging from the glacier. Where meltwater was able to flow along the margin of the ice in an upland area, an ice-marginal meltwater stream formed. Its flood-plain deposits formed a type of terrace known as a kame terrace because the sediments have characteristics (such as collapse structures) that reflect deposition in contact with the edge of the ice. Where meltwater was unable to flow away from the ice margin, it became impounded by the topography and formed ice-marginal lakes. This scenario was how glacial Lake Wisconsin formed in the area north of the Baraboo Hills and glacial Lake Oshkosh formed in the Fox River valley. These lakes drained only when glacial recession exposed low areas through which lake water could spill.

Ice-contact fluvial outwash fans

Whenever the margin of the Green Bay Lobe stood at a particular position for an extended period (tens to hundreds of years), large (often more than 1 km across) outwash fans (map unit **sa**, plate 1) formed along the glacier terminus (fig. 20). The proximal edge of these fans was deposited in contact with the glacier and the fan prograded into the proglacial environment through deposition by subaerial distributary channels. When the Green Bay Lobe stood at the Johnstown moraine in northwestern Columbia County, outwash fans prograded away from the ice margin and into the Driftless Area (Attig and others, 1989). An example of such a fan occurs in Columbia County in sec. 6, T13N, R7E, where a gravel pit is operating at the apex of the fan (fig. 19). Fans are often located at the mouth of a tunnel channel, which formed as the subglacial channel of a meltwater river (Attig and others, 1989). Fans were deposited along the margin of the Green Bay Lobe anytime it stood at a recessional marginal position for more than a few years (map unit **sa**, plate 1). The large collapsed fan that impounds the western

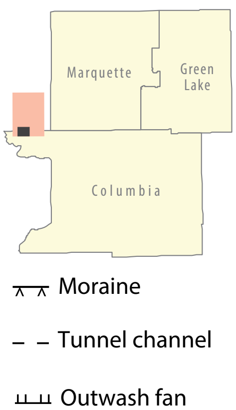
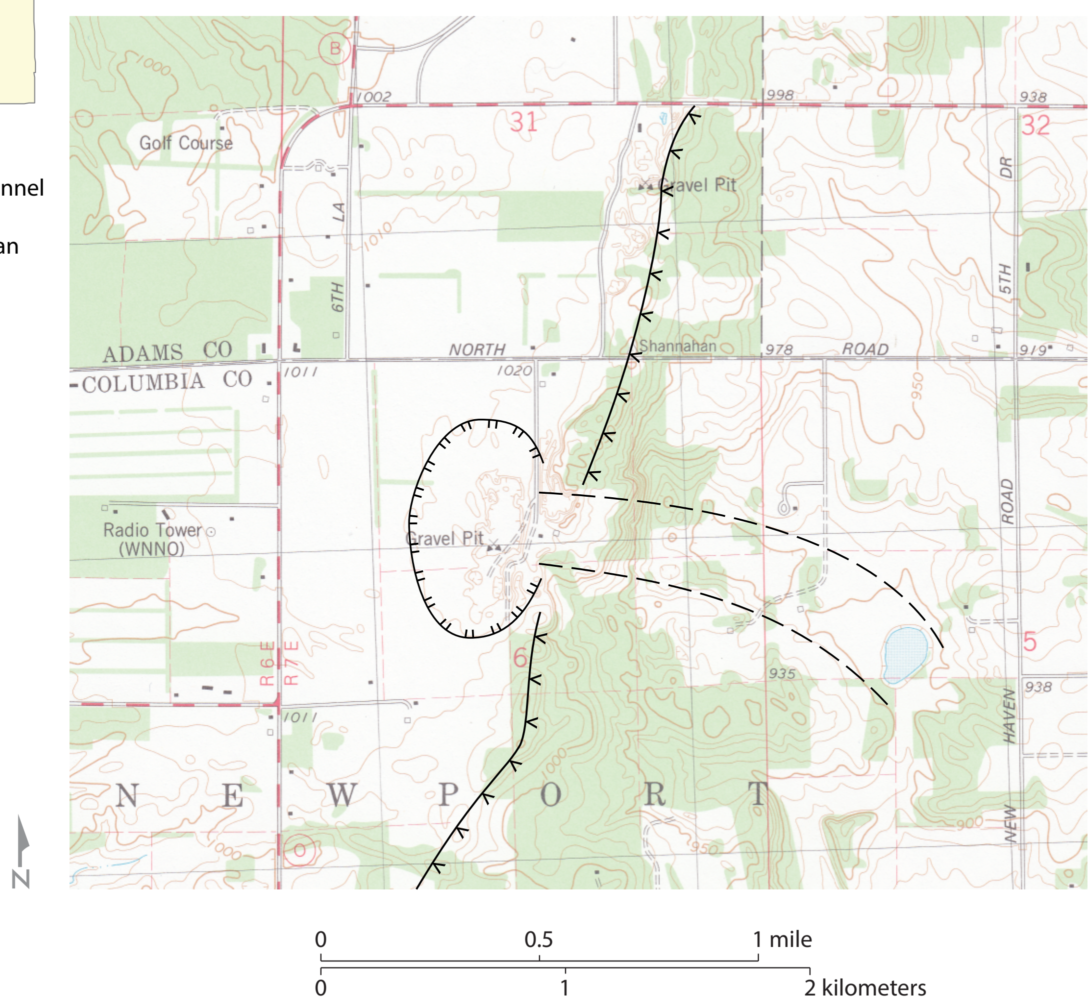


Figure 19. Tunnel channel (dashed line) and outwash fan (hachured line) located along part of the outermost moraine (line with V's) in northwestern Columbia County in secs. 5 and 6, T13N, R7E. Base map is from U.S. Geological Survey, Big Spring 7.5-minute topographic quadrangle (pink rectangle); location of figure shown by small black rectangle. Contour interval is 10 ft (about 3 m).



end of Green Lake also formed at the mouth of a tunnel channel. This fan is mapped as unit **sc** because it has many enclosed depressions, indicating that blocks of ice were buried and eventually formed kettles when they melted. Many other ice-contact fans are located throughout the map area, and some gravel pits have been developed in them; an example of such a pit is shown in figure 20.

Eskers

At times, subglacial meltwater-stream sediment was deposited under the glacier, forming an esker instead of being transported to the ice margin. Eskers are shown on the map (plate 1) as a nested series of V's pointing in the direction of flow.

The eskers of southeastern Wisconsin have been studied since the 1890s and are commonly understood to be ridges of sand and gravel that were deposited by meltwater rivers flowing in tunnels at the base of the glacier (Chamberlin, 1893). They were first mapped by Alden (1918, plate 3). The eskers of eastern Columbia County were generally small, tens of meters wide and several meters high. Since Alden's time, however, most of the ridges have been converted into long, narrow gravel pits a few meters deep. The bottoms of the pits are a few meters below the adjacent land surface, indicating that the subglacial river was incising the substrate before it aggraded to form the ridge. A few segments that have never been mined and never had a ridge can be recognized as a narrow band of surface sand and gravel that is a continuation of an esker ridge. The eskers are typically 2 to 3 km long, not including a few short gaps. In map view, they have a meandering shape that is typical of rivers. The stratification indicates that the water flow was up the regional slope, generally from east to west in the northeastern part of Columbia County. In detail, however, the eskers tend to be oriented about 20° clockwise from the drumlin orientation. The reason for this variation is unknown.

The only eskers in Marquette County are located in an area of collapsed topography in the northwestern corner of the county. No eskers were identified in Green Lake County.

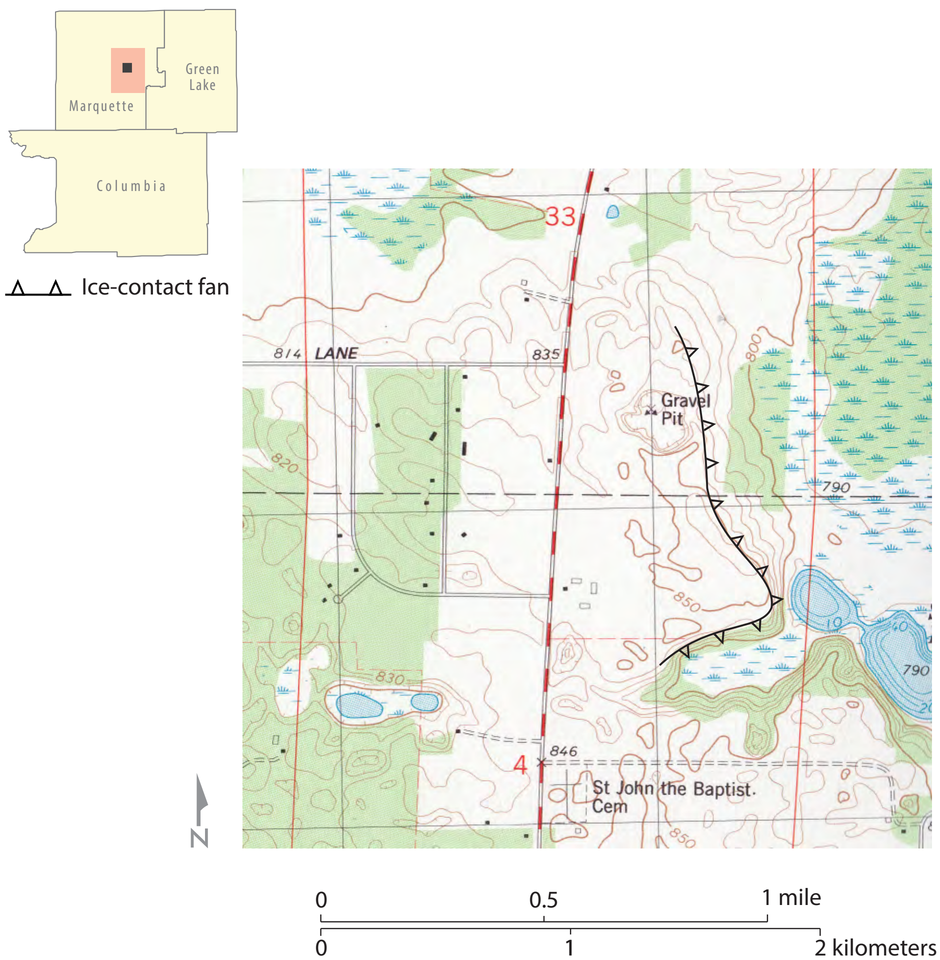


Figure 20. Ice-contact fan containing gravel pit located in sec. 33, T16N, R10E and sec. 4, T15N, R10E, in east-central Marquette County. Line with V's marks an ice-contact face. Base map is from U.S. Geological Survey, Montello 7.5-minute topographic quadrangle (pink rectangle); location of figure shown by small black square. Contour interval is 10 ft (about 3 m).

Subaqueous morainal banks

In places where the margin of the Green Bay Lobe terminated in glacial Lake Wisconsin, sediment was deposited below the water line (subaqueously) along the edge of the ice. Ice-marginal ridges formed in this way resemble moraines and are composed largely of meltwater-stream sediment. Two recessional positions of the Green Bay Lobe are recorded by subaqueous morainal banks (map unit **sg**, plate 1) in the southwestern corner of Marquette County, where the glacier terminated in the Lewiston basin of glacial Lake Wisconsin. The higher portions of the crests of these ridges have flat tops due to wave washing (fig. 11); the lower portions are not as flat. These ridges connect to moraines and ice-contact faces formed subaerially, demonstrating that they do indeed mark a stillstand of the ice margin.

Wisconsin River diversions

Soon after glacial Lake Wisconsin drained, the Wisconsin River changed its course at least once, as evidenced by the landforms and sediments in the area surrounding Portage. Figure 21 shows the present route of the Wisconsin and Fox Rivers and Neenah Creek (including its tributary, Big Slough). A flat area to the northwest of Portage is the site of postglacial diversions of the Wisconsin River. This flat area slopes from an elevation of about 262 m at its southwestern side (only a meter or so above the present level of the Wisconsin River) to about 259 m at its northern end, a slope of about 0.3 m/km, which is about the same as the slope of the adjacent Wisconsin River. In places, the flat area is underlain by several tens of meters of offshore lake sediment, including sediment of glacial Lake Wisconsin and the Wisconsin River. The land surface retains traces of river channels that have been obscured by a discontinuous layer of windblown silt, river silt, and peat.

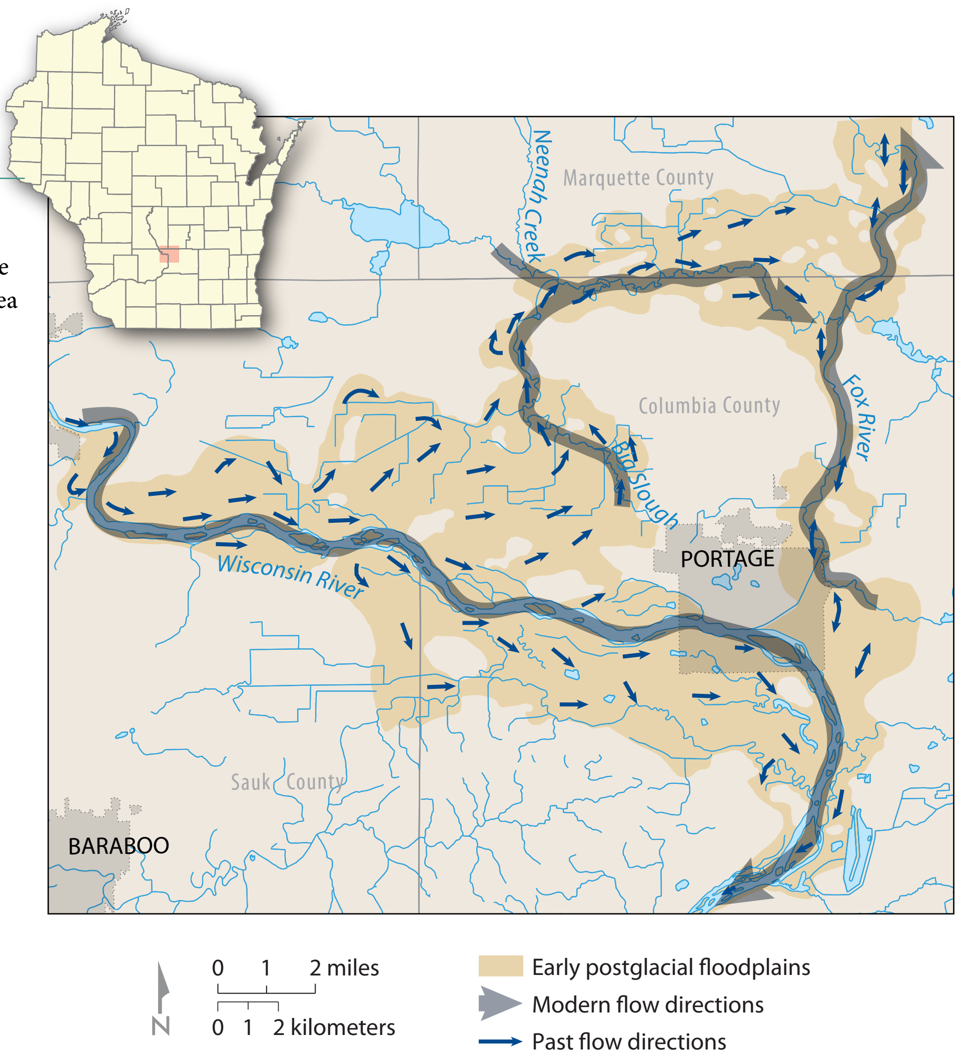


Figure 21. Routes followed by the Wisconsin River at various times after glacial Lake Oshkosh drained from this area for the last time. Thick gray arrows indicate modern flow directions; short blue arrows indicate past flow directions; dark-tan area indicates early post-glacial floodplains.

The river-channel meanders have about the same radius of curvature as those on the modern flood plain of the Wisconsin River (fig. 22).

The direction of slope and the orientation and size of these large channel scars indicate that the Wisconsin River once flowed northeast across the flats to Big Slough, then eastward down Neenah Creek to the Fox River. From there it could have flowed northward down the Fox River toward Lake Michigan or southward down the Fox River to rejoin the present path of the Wisconsin River south of Portage. These flow patterns could have happened at various times after glacial Lake Oshkosh drained. During the 19th century (before modern flood control), several Wisconsin River floods spilled across the flats, down Big Slough to Neenah Creek and the Fox River (Jones, 1914), or northward down the Fox River north of Portage.

Figure 22. Map and aerial photograph showing an oversized meander of the Wisconsin River. A, Neenah Creek and its tributary, Big Slough, showing an oversized, old meander of the Wisconsin River. Point-bar ridges (dashed lines) are seen on the inside of the oversized meander; houses are located on the higher, dryer natural levee on the outside of the meander. The meander is located in secs. 3 and 4, T13N, R8E, and secs. 33 and 34, T14N, R8E, in northwest Columbia County. Base map is from U.S. Geological Survey, Briggsville 7.5-minute topographic quadrangle (pink rectangle); location of figure shown by small black square. Contour interval is 10 ft (about 3 m). B, Aerial photograph taken in 2013 showing the oversized meander (U.S. Department of Agriculture—Farm Service Agency's National Agriculture Imagery Program).

Modern streams

When the last ice melted at the end of the Pleistocene, meltwater rivers were replaced by the current streams. Except for the Wisconsin River, their flood plains are a minor part of the landscape. Sediment deposited on the flood plain of the Wisconsin River tends to be sand, whereas flood-plain sediment in the Fox River drainage basin tends to be silt and clay. The type of sediment reflects the difference in materials over which these streams are flowing: the Wisconsin River flows largely over sand deposited by meltwater streams, wind, and shallow glacial lakes. The Fox River flows over the silt- and clay-rich offshore sediment of glacial Lake Oshkosh. Modern stream sediments (map units **s** and **ps**, plate 1) may be tens of meters thick, but more commonly they are no more than a few meters thick. These sediments are distinguished from meltwater-stream sediments by the presence of peat, wood, and dispersed fine-grained organic material. Steep slopes created by lateral stream erosion on the outside banks of existing or past meanders are shown as cutbanks in plate 1.

In several areas, the proximity of flood plains to the water table causes flood plains to be so poorly drained that standing water is present for long periods, which causes wetlands to form. The presence of water inhibits the decay of dead plant material, which leads to the accumulation of organic sediment mapped as peat (map unit **ps**, plate 1). Though peatlands are commonly present on flood plains, they are also found in low areas other than flood plains.

Organic sediment

Surficial organic sediment (peat) that is thicker than 1 m is usually shown on plate 1, although there are many other areas where organic sediment accumulations are thinner; these thinner deposits are not shown. The various map units used for peat on plate 1 are distinguished by what lies under the peat. Where the underlying material is organic sediment related to glacial Lake Oshkosh, the map unit is **po**; where it is related to glacial Lake Wisconsin, the map unit is **pw**; and where it is modern stream sediment, the map unit is **ps**. Sometimes the material underlying the peat is unknown, in which case the map unit is shown as **p** on plate 1. Approximately one-tenth of the map area is underlain by peat. Typically, 1 to 3 m of peat blankets the flat lowland basins that were once the beds of glacial lakes, but the peat may be thicker in places. The lakes filled with offshore sediment until they were shallow enough for swamp, marsh, and bog vegetation to grow and accumulate as peat.

Windblown sediment and landforms

The surface sediment in much of the tri-county area consists of 1 m or less of fine sand and silt (loess) deposited by the wind after the Green Bay Lobe receded from the area (Jacobs and others, 2011). Unlike the thick (up to 7 m) deposits of sand that form dunes to the west in Adams County (Rawling and others, 2008), up to 1 m of windblown sand blankets the landscape in Marquette County, western Green Lake County, and north-central Columbia County. The sand that covers these areas generally lacks any distinctive topographic expression such as dunes. The sand is easily identified on aerial photographs by its lighter tones, especially on cultivated fields in dry weather. In Columbia County, the sand can occur as wind streaks tens of meters wide, up to a few kilometers long, and oriented N. 55°–60° W., suggesting a prevailing northwesterly wind direction when they were active. In a few places, the windblown sand is thick enough to exhibit distinct blowout dunes a few meters high; the absence of topsoil indicates that some blowouts have been active in historic time and even at present. Though uncommon in the tri-county area, dunes containing up to 7 m of eolian sand (map unit **w** in plate 1) occur in a few places, such as in southwestern Columbia County near Lake Wisconsin. Relief on dunes can be up to 5 m.

The finer-grained windblown loess differs from the sand in that it is more susceptible to mass movement when it covers hill slopes. This loess covers level to gently sloping upland surfaces throughout much of the tri-county area, but it is thinner on steeper upland slopes and absent on the steepest hillsides. As a result, aprons of resedimented silt thicken towards the base of these slopes where the silt loses its identity as it interfingers with lowland deposits such as peat, stream sediment, and lake sediment. The loess can be up to 3 m thick on level upland surfaces near the Wisconsin River in Columbia County, especially south of the easternmost part of the Baraboo Hills. Significant thicknesses of loess have also been observed along the southern border of Columbia County and in southeastern Green Lake County (Jacobs and others, 2011).

Most of the fine sand that covers the landscape in the tri-county area undoubtedly originated from the lakebed of glacial Lake Wisconsin after it drained. Permafrost conditions existed immediately following glaciation (Clayton and others, 2001; Attig and Rawling, 2018); thus, plant growth was slowed and unable to stabilize the surface material, making it available for wind transport. Large sand dunes that range in height from 3 to 20 m exist on the former lakebed immediately to the west in Adams County. The source of the loess is farther away, along the Mississippi Valley, according to clay mineralogy analysis (Jacobs and others, 2011). The loess certainly traveled the same pathway as the sand but mainly accumulated on a low-relief bedrock escarpment that cuts across Green Lake and Columbia Counties (Jacobs and others, 2011). The relief of this escarpment (fig. 3) was enough to slow the transport of sand and deposit the finer silt-sized particles.

Sinnipee Group dolomite, east end of Green Lake

Summary of events during the Wisconsin Glaciation

Except for a small area in northwest Columbia County, the tri-county area was completely covered by the Green Bay Lobe of the Laurentide Ice Sheet during the maximum extent of the Wisconsin Glaciation (fig. 17A). The lobe most likely eroded the majority of pre-existing sediment from the surface and sculpted the underlying bedrock surface as evidenced by bedrock knobs that exist in some areas (for example, the Berlin rhyolite knobs at Berlin in the northeastern corner of Green Lake County). However, not all sediment was eroded from the landscape, especially along the axis of preglacial valleys as shown in rotosonic borehole RS–10, which contains a sequence of older lake sediment. Drumlins in the upland areas indicate that after a period of glacial erosion, deposition must have occurred. Most of these drumlins consist of till of the Horicon Member, indicating deposition and subsequent erosion by the Green Bay Lobe (Vreeland and others, 2015). Most of the till in these drumlins (map unit **ghs**) was probably deposited at the base of the ice when the lobe was at its maximum extent. The drumlins are oriented to the southeast in Columbia County and to the west in Green Lake and Marquette Counties, indicating a divergent flow of the Green Bay Lobe towards its margin. The remaining deposits (including stream, lake, and windblown sediments) were deposited as the Green Bay Lobe receded across the landscape.

During the recession of the Green Bay Lobe, large morainal banks were deposited in glacial Lake Wisconsin. These unique features consist of sand and gravel, and their flat tops indicate that the elevation of the lake was at 296 m. The two sets of parallel morainal banks in Columbia and Marquette Counties indicate that the Green Bay Lobe was relatively stable at two points in time. Once glacial Lake Wisconsin drained, the receding ice formed many ice-contact alluvial fans that are especially common in Marquette County. Many of these fans were deposited in upland areas above the level of glacial Lake Oshkosh and are excellent resources of sand and gravel. A large part of the tri-county area was inundated with water from glacial Lakes Wisconsin and Oshkosh. The history of these lakes in the tri-county area is as follows.

Glacial Lake Wisconsin

Glacial Lake Wisconsin (Clayton and Attig, 1989) formed when the Green Bay Lobe advanced onto the Baraboo Hills in western Columbia County, blocking the Wisconsin River from flowing southward and into the lower Wisconsin River valley (Clayton and Attig, 1989). The lake filled to an elevation of about 307 m before spilling over to the Black River, a tributary of the Mississippi River located in southwestern Wood County. Several smaller but interconnected basins filled with water in the Baraboo Hills in Sauk County (fig. 17A). OSL dates from four small ice-marginal lakes in the Baraboo Hills indicate that the Green Bay Lobe was at its maximum extent until about 18,500 years ago (Attig, Hanson, and others, 2011) when it started to recede. This is supported by dates on glacial Lake Wisconsin sediment in Adams County that range between 19,300 to 13,600 years ago. However, the timing of the start of the Green Bay Lobe's recession is controversial because other studies of samples collected south of the Baraboo Hills in Dane County indicate that the lobe was at its maximum position from about 26,400 to 21,400 years ago and receded shortly thereafter (Carson and others, 2012; Ullman and others, 2015). It is certainly possible that the margin of the Green Bay Lobe receded at different rates, but that scenario is not consistent with the formation of recessional moraines that (1) are parallel both to the outermost moraine and to each other and (2) indicate that the lobe receded at an even rate across its areal extent.

Once the Green Bay Lobe started to recede from its maximum extent, the Lewiston basin opened inside the terminal moraine and glacial Lake Wisconsin grew proportionally larger (fig. 17B). This basin extended along the western margin of both Columbia and Marquette Counties. Just south of the Baraboo Hills, glacial Lake Merrimac formed in front of the ice margin. This lake was relatively small and collected local meltwater from the lobe. The Lewiston basin grew in size as the ice continued to recede (fig. 17C). Eventually, the Green Bay Lobe receded off the eastern end of the Baraboo Hills, resulting in the opening of the Alloa outlet at an elevation of 252 m. The level of glacial Lake Wisconsin precipitously dropped about 43 m as the water catastrophically drained from the main basin of the lake. The discharge from the lake cut through the terminal moraine and the soft Cambrian sandstone, forming the Dells of the Wisconsin River. After this event, which probably occurred over 2 weeks (Clayton and Attig, 1989; Clayton and Knox, 2008), the main basin was completely drained and glacial Lake Wisconsin only existed at the lower level in the Lewiston basin (fig. 17D). With the continued recession of the ice eastward, water in the Lewiston basin drained as a lower outlet near the town of Dekorra opened up at an elevation of about 240 m. The opening of the Dekorra outlet signifies the transition between glacial Lake Wisconsin and glacial Lake Oshkosh because the majority of the water flowing through this outlet was originating from the latter.

Glacial Lake Oshkosh and Green Lake

Glacial Lake Oshkosh formed with the continued recession of the Green Bay Lobe eastward, opening the outlet at Dekorra. Early in its existence, glacial Lake Oshkosh occupied portions of the Lewiston basin that were below 240 m in elevation (fig. 17E). As the ice receded to the northeast, the lowlands along the upper Fox River valley were flooded, covering large areas of the tri-county area (fig. 17F). Lower outlets eventually opened to the Lake Michigan basin and glacial Lake Oshkosh ceased to exist in the tri-county area. However, the Green Bay Lobe readvanced twice into the Fox River valley, covering the lower outlets to the Michigan Basin and reactivating the outlet at Dekorra (Hooyer and Mode, 2008). These readvancements occurred at approximately 15,500 and 14,000 years ago. As a result, the basin was flooded, and thick layers of lake sediment were deposited throughout the tri-county area.

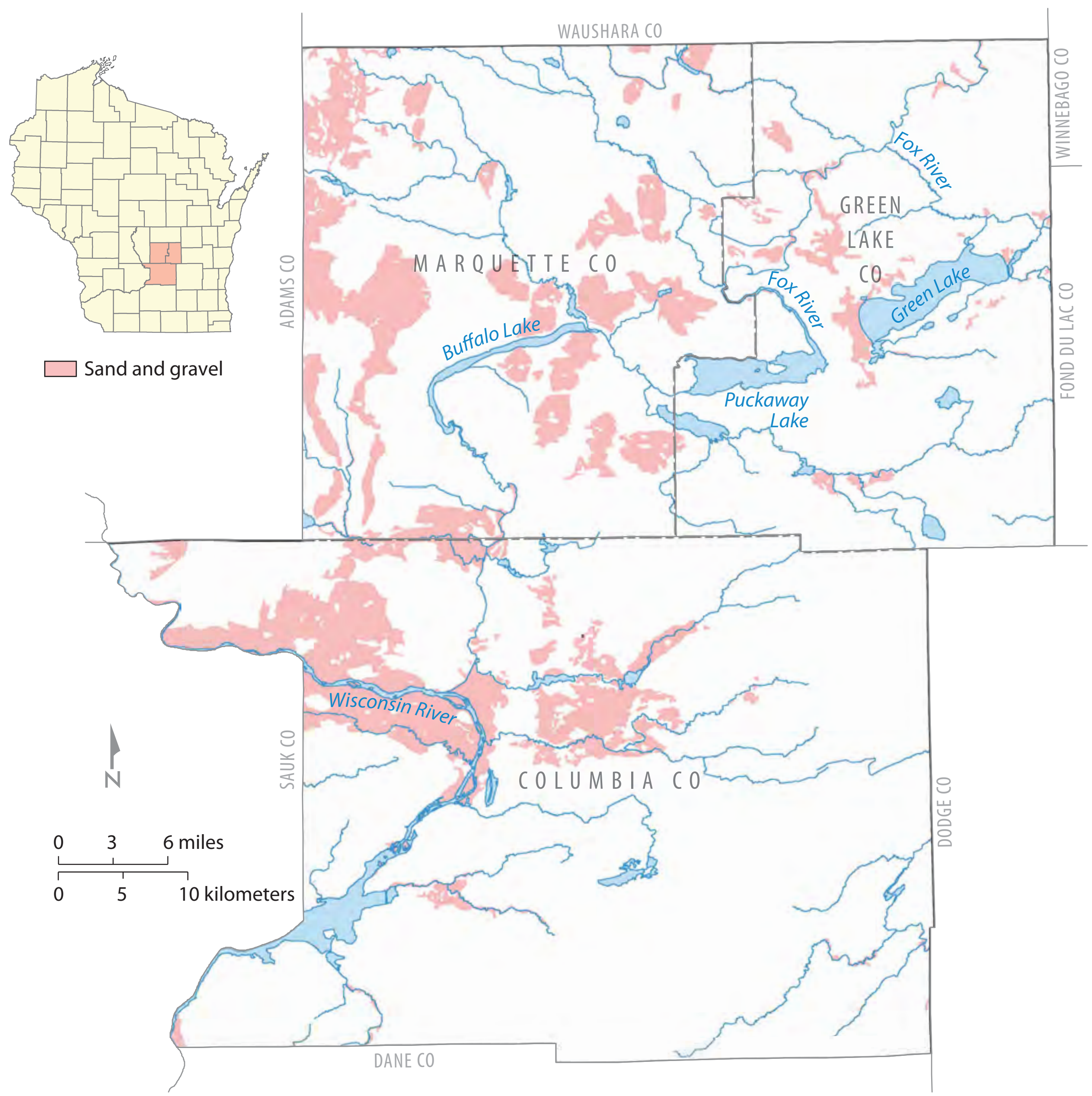
When the ice was receding across Green Lake County, a tunnel channel containing a large river must have formed, eroding existing sediment from what now is Green Lake. Although tunnel channels rarely occupy bedrock valleys, Green Lake certainly occupies a preglacial valley that was eroded into the rock before the last glaciation. At the mouth of the tunnel channel located at the southwestern end of the lake, an outwash fan formed, elevating the area so it was higher than glacial Lake Oshkosh and thus never filled.

Green Lake

Sand and gravel availability

Economic deposits of sand and gravel were most often deposited by meltwater streams near the glacier, either in contact with the ice or on proglacial outwash plains. These deposits are mapped as units **sa**, **su**, **se**, **sc**, and **sg** (plate 1), and their combined distribution is highlighted in figure 23. Several sand and gravel pits, some of which have been mentioned earlier in this report, occur in these deposits. Glacial lake sediment (map units **l, low, lo, lww,** and **lw**; plate 1) deposited close to shore tends to be sandy and locally may provide a source of sand. In certain instances, sandpits may be developed in the dunes (map unit **w**, plate 1). Proglacial meltwater-stream deposits typically lie beneath surfaces that grade to a position of the ice margin. Such deposits are mapped as unit **su** (plate 1). Extensive outwash plains are located adjacent to the Wisconsin River in western Columbia County. Ice-contact stratified deposits are recognizable because they bear

Figure 23. Distribution of sand and gravel (pink) in the tri-county area.



evidence of collapse, which occurred when sediment-bearing glacier ice melted and left the sediment behind. The sediment collapsed and thus resulted in pitted outwash plains (map unit **sc**). The area of collapsed topography bordering the western side of Green Lake is a good example of a pitted outwash plain. This area has been extensively mined for sand and gravel. The ice-contact face of alluvial fans and deltas (fig. 20; map unit **sa**) is marked by the angle of repose for these slopes. Many such features occur in Marquette County, and active sand and gravel mining occurs in some of them. Morainal bank deposits (map unit **sg**) may also be important sources of sand and gravel. Large volumes of meltwater sediment were deposited right at the ice margin where it terminated in a standing body of water, such as the Lewiston basin, creating morainal banks. One example of a sand and gravel pit is developed in the western-most of the two morainal bank ridges in Marquette County in sec. 31, T15N, R8E.

Sand and gravel can be found in drumlins (map unit **ghs**, plate 1) (for example, Whittecar and Mickelson, 1979). Two pits located southwest of Princeton, both in drumlins, expose till as well as sand and gravel (fig. 12 shows one of these two pits). As long as a large majority of material exposed in a drumlin pit is sand and gravel, the deposit may be economic. Till usually is not an economic source of sand and gravel because it contains too much fine material (silt and clay), which is inappropriate for construction uses.

Filled land

Near Portage are two areas of filled land (map unit **f**, plate 1) where low-lying land has been filled in order to reclaim it to a new land use. The fill consists of materials that were available at the time (gravel, sand, silt, and clay).

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The Survey conducts earth-science surveys, field studies, and research. We provide objective scientific information about the geology, mineral resources, water resources, soil, and biology of Wisconsin. We collect, interpret, disseminate, and archive natural resource information. We communicate the results of our activities through publications, technical talks, and responses to inquiries from the public. These activities support informed decision making by government, industry, business, and individual citizens of Wisconsin.