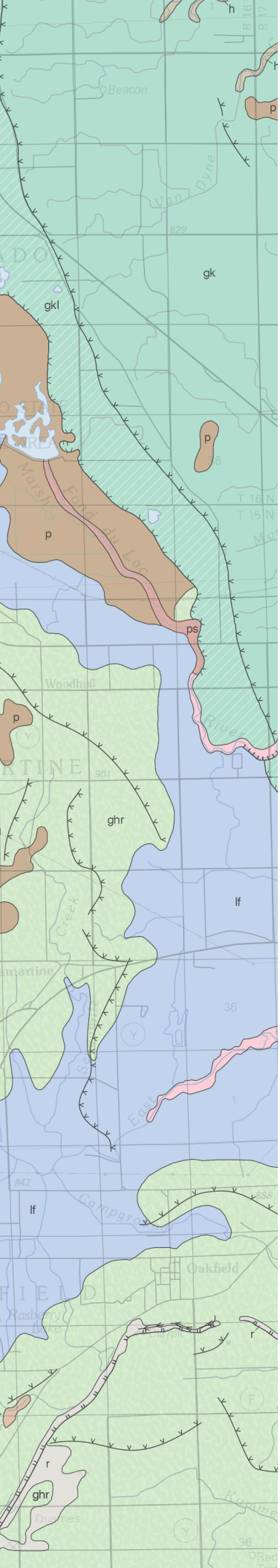

Quaternary Geology of Fond du Lac County, Wisconsin

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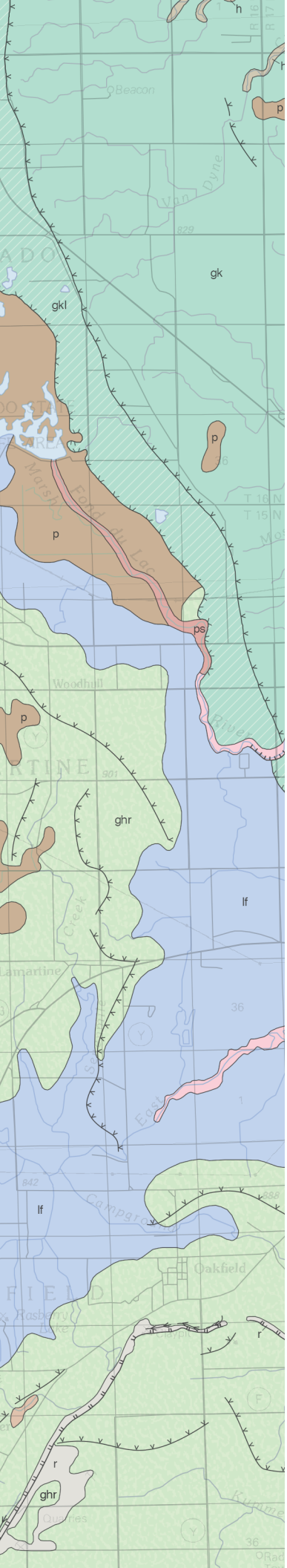
Cover photos

Front: Kettle interlobate moraine in eastern Fond du Lac County and adjacent Sheboygan County. Hills are moulin kames, © William Mode

Back: Large gneiss erratic in Kettle interlobate moraine, © William Mode



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Niagara Escarpment

Abstract

The Quaternary geologic map of Fond du Lac County, Wisconsin (plate 1) reveals diverse landscapes and surficial deposits, including lowlands underlain by glacial lake sediment and meltwater-stream sediment and uplands composed of till and meltwater-stream sediment. The map units are defined by sediment type and genesis, stratigraphic position, and landform association. Glacial sediments were deposited by the Green Bay and Lake Michigan Lobes of the Laurentide Ice Sheet from about 20,000 to 12,000 years before present (yr BP), when ice receded from the region. Glacial strata consist of two formations—the Holy Hill and Kewaunee Formations—that are distinguishable by the color and texture of the tills they contain. Kewaunee Formation deposits are restricted to the north-central part of the county. Holy Hill Formation deposits are the surficial material in the southern part of the county and also occur beneath Kewaunee Formation deposits in places. Glacial landforms include active-ice features (drumlins and end moraines) as well as ice-disintegration features (kettles, kames, ice-walled outwash plains, and eskers). Ice-disintegration features dominate the Kettle interlobate moraine in the eastern part of the county where the Green Bay and Lake Michigan Lobes intersected. Lake sediment was deposited in glacial Lakes Fond du Lac and Oshkosh. Glacial Lake Fond du Lac was impounded when the Green Bay Lobe readvanced (during the overall ice recession) into Fond du Lac County. This advance terminated at the Eureka moraine and deposited till of the Kirby Lake Member of the Kewaunee Formation. A new accelerator mass spectrometry ^{14}C date on plant macrofossils from the base of the glacial Lake Fond du Lac sediments indicates that the lake and the Eureka moraine formed at 15,500 calibrated years before present (cal yr BP) and that glacial Lake Fond du Lac likely existed for 500–1,000 years, after which the ice margin receded from the Eureka moraine. The next readvance (13,000 cal yr BP), which buried the Two Creeks Forest Bed farther north, terminated north of the county. Glacial Lake Oshkosh persisted in Fond du Lac County until the margin of the Green Bay Lobe receded from the state by 12,500 cal yr BP.

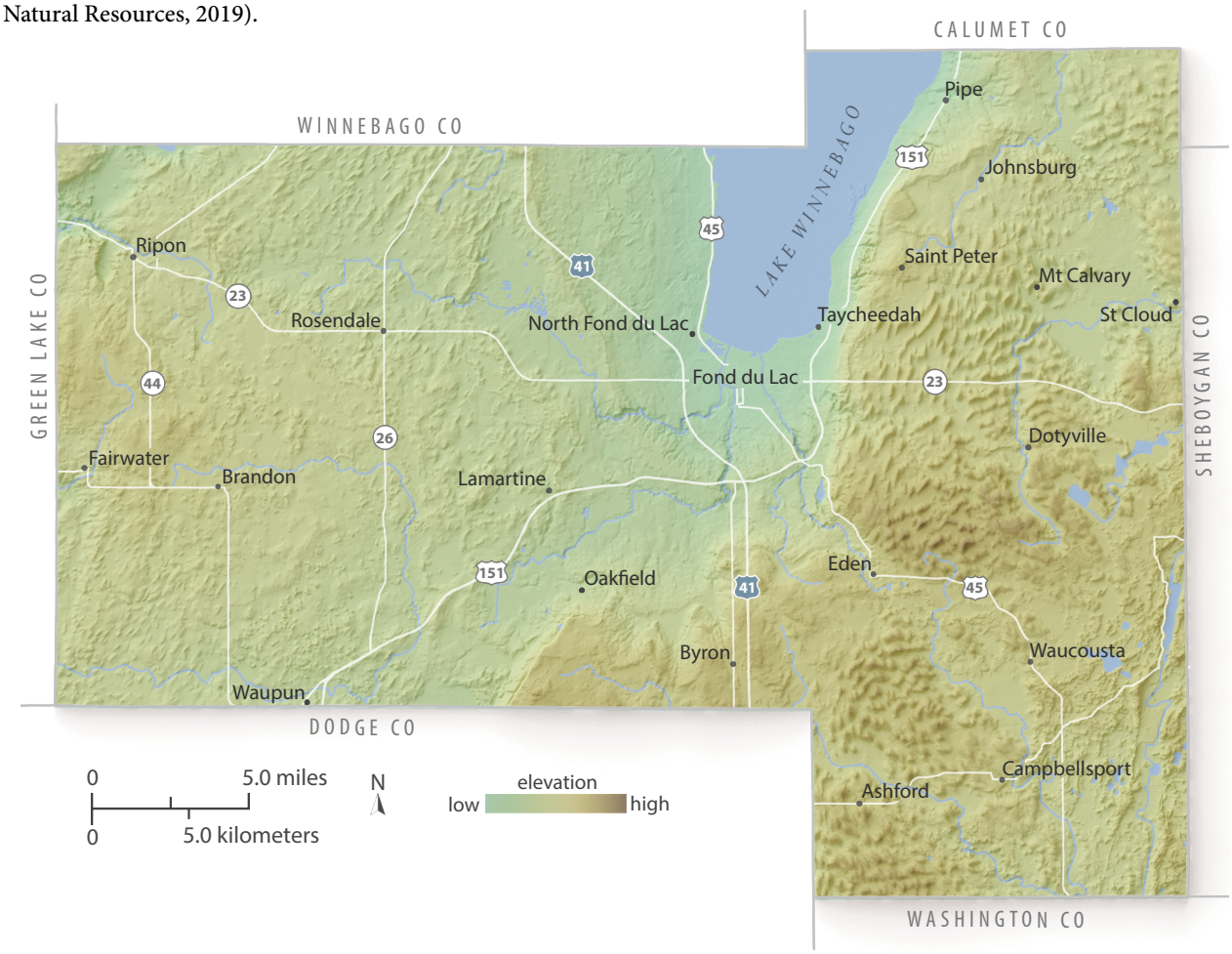
Drumlin

Introduction

Knowledge of surficial materials is required by land-use planning agencies and resource developers. Updated Quaternary mapping is required for many reasons, including the need to incorporate new concepts in glacial geology, stratigraphy, and modern technology (such as digital elevation models; fig. 1). The Quaternary geology of Fond du Lac County was previously mapped by Alden (1918). Thwaites (1943) mapped adjacent parts of the lower Fox River basin. Both maps were produced at a scale of 1:250,000. More recently, the Wisconsin Geological and Natural History Survey published several Quaternary geologic maps of parts of the Fox River basin at a scale of 1:100,000 (Need, 1985; Hooyer and Mode, 2008; Mickelson and Socha, 2017; Hooyer and others, 2021). The major Quaternary deposits in Fond du Lac County include a wide variety of Pleistocene glacial, glacial-lake, and meltwater-stream sediments. Less common deposits include postglacial (Holocene) stream, slope, and peatland sediments. The ages of the glacial sediments exposed at the surface range from 32,000 to 14,000 cal yr BP (last part of the Wisconsin glaciation; Syverson and Colgan, 2011). These sediments were deposited by the Green Bay Lobe of the Laurentide Ice Sheet, except in the southeastern corner of the county where they were deposited by the Lake Michigan Lobe (fig. 2). Glacial lake sediments overlie the bedrock lowland that includes and surrounds Lake Winnebago. This lowland is the former location of two major glacial lakes—glacial Lakes Fond du Lac and Oshkosh—and numerous smaller lakes. Till and meltwater-stream sediments characterize the areas east (the upland of the Niagara Escarpment) and west (the upland of the Sinnipee escarpment) of this lowland.

Bedrock topography strongly influenced glacial processes and the resulting distribution of glacial deposits and landforms. The bedrock

Figure 1. Shaded-relief map of Fond du Lac County derived from a 10-m digital elevation model (Wisconsin Department of Natural Resources, 2019).



lowlands are relatively flat-floored because of the presence of glacial lake sediment and meltwater-stream sediment. The bedrock uplands are dominated by several landscapes: (1) gently rolling topography where thin (less than 15 meters (m)) glacial sediments drape the surface; (2) streamlined topography with drumlins that often contain up to 15 m of till; (3) end moraines with till and stratified drift that is often 10 m or more thick; and (4) collapsed topography consisting of meltwater-stream sediment of variable thicknesses that was originally deposited on stagnant glacial ice. The Kettle interlobate moraine in the southeastern corner of the county consists largely of collapsed meltwater-stream sediment. This area was overlain by stagnant ice as indicated by the presence of collapsed topography (kettles), kames, and eskers. Other moraines in the county, such as the Eureka moraine, were formed at the margin of active glacial ice. Streamlined topography (drumlins) and rolling glacial topography, usually composed of till, formed subglacially before the ice receded. Recessional moraines and collapsed topography drape the subglacial topography in several areas. Meltwater-stream terraces also formed in front of the glacier during ice recession.

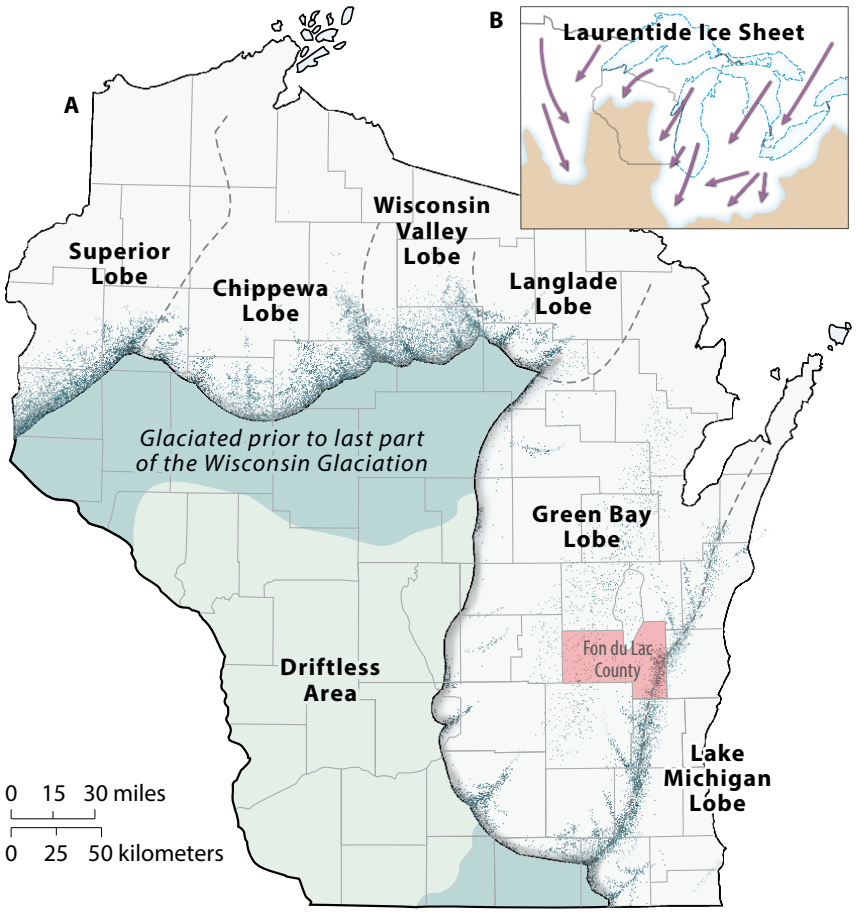


Figure 2. Location of Fond du Lac County in Wisconsin (A) in relation to the Laurentide Ice Sheet, and (B) its lobes across the Great Lakes region of the United States and Canada during the most recent glaciation. Stippling in A indicates the edge of the ice sheet; arrows indicate direction of ice flow. Note that during the last part of the Wisconsin glaciation, Fond Du Lac County was largely covered by ice of the Green Bay Lobe.

Methods

U.S. Geological Survey (USGS) 7.5-minute topographic maps, aerial photographs, soil surveys and maps (Link, 1973), and well construction reports were studied and formed the basis for the first approximations of the Quaternary geology. Field-work campaigns were then planned and executed to test the first approximations. Field work entailed visiting exposures in gravel pits, quarries, foundation holes, and roadcuts to record and sample glacial deposits. Where no exposures were available, excavation was by shovel, bucket auger, or power drill. Cores were taken from 12 hollow-stem auger boreholes (split-spoon cores) and one rotosonic core (table 1 and dataset 1). The cores were described in the field and again in the WGNHS Core Repository, where samples were taken for subsequent analysis.

To create the Quaternary geologic map (plate 1), contacts were drawn on USGS 7.5-minute topographic maps (1:24,000 scale), digitized, and generalized to a scale of 1:100,000. No attempt was made to reconcile the line work with the lidar-derived digital elevation maps that became available several years after the mapping was completed. The minimum thickness for material to be mapped was 1 m. In areas where the surface material was less than 1 m thick, the underlying material is shown.

In this report, the geochronology of the glacial and post-glacial periods is reported in calibrated radiocarbon years before present (cal yr BP) based on the calibration program of Stuiver and others (1998). These dates will not match those in earlier publications (for example, Mickelson and others, 1984) where dates were not calibrated. The calibrated geochronology for the last part of the Wisconsin glaciation is available in Mickelson and Attig (2016).

Table 1. Locations of boreholes and rotosonic drill hole in Fond du Lac County (except as noted).

Site ID	Site name[a]	WGNHS identifier (WID)	Land survey location	Name of 7.5-minute topographic quadrangle	Depth drilled	
					Feet	Meters
1	McDermott	71002757	SE¼SE¼SW¼ sec. 32, T17N, R17E (Winnebago County)	Fahrney Point	12.0	3.7
2	Entringer	60003196	NE¼NE¼NW¼ sec. 31, T16N, R20E (Sheboygan County)	St. Cloud	30.0	9.1
3	O'Laire	20003034	NW¼SW¼SE¼ sec. 31, T15N, R17E	Oakfield	22.3	6.8
4	Hausmann	20003035	NW¼SW¼NW¼ sec. 26, T15N, R16E	Oakfield	26.8	8.2
5	Loduha	20003036	NW¼NW¼SW¼ sec. 5, T14N, R16E	Oakfield	10.0	7.6
6.1	Swast 1	20003044	NW¼SW¼NE¼ sec. 2, T14N, R17E	Byron	20.0	6.1
6.2	Swast 2	20003037	same as Swast 1	Byron	40.0	12.2
7	Beltz	20003038	SW¼SW¼SE¼ sec. 1, T14N, R17E	Byron	55.0	16.8
8	Schmitz	20003039	SW¼SE¼SW¼ sec. 19, T15N, R17E	Oakfield	30.0	9.1
9	Miller	20003040	SE¼SW¼SW¼ sec. 27, T16N, R19E	St. Cloud	12.0	3.7
10	Schultz	20003041	NW¼NW¼NW¼ sec. 13, T16N, R16E	Eldorado	16.0	4.9
11	S. Immel	20003042	NW¼NW¼NW¼ sec. 14, T14N, R19E	Dundee	29.0	8.8
12	J. Immel	20003043	SE¼NE¼SE¼ sec. 14, T14N, R19E	Dundee	29.0	8.8
13	Boyke (rotosonic)	20003045	SE¼SE¼NE¼ sec. 36, T15N, R17E	Byron	155.0	47.3

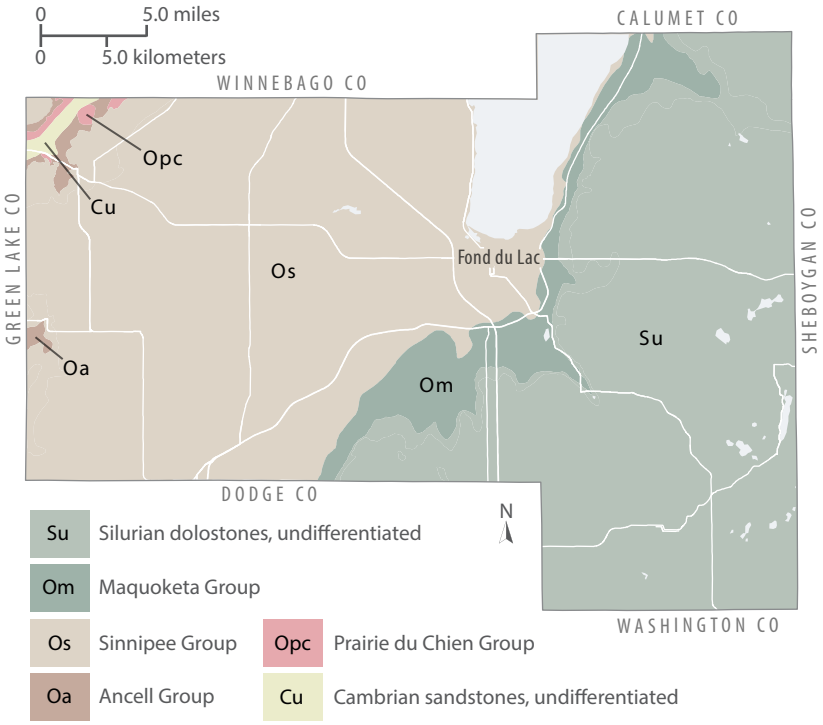
[a] Hollow-stem auger drilling used at all sites, except as noted.

Bedrock

The bedrock in Fond du Lac County ranges in age from Cambrian through Silurian (fig. 3; Batten, 2018). In places such as the Niagara Escarpment, the bedrock is exposed at the surface; however, in most of the county, it is buried by glacial and postglacial deposits that are locally more than 45 m thick. In the subsurface, beneath the Cambrian rocks, well-drilling records indicate the presence of Precambrian quartzite, granite, gneiss, and schist (Newport, 1962). Steep slopes that extend linearly across the landscape (escarpments) have formed where the western edge of a resistant rock unit reaches the surface. Typically, a less-resistant rock unit occurs beneath the resistant layer. Running southwestward from the northeastern corner of the county to the middle of the southern edge of the county is the Niagara Escarpment (fig. 4), in which the resistant layer is Silurian dolostone and the less-resistant layer beneath it is Ordovician Maquoketa Shale (Luczaj, 2013). Near the western edge of the county is the Sinnipee escarpment, where the Ordovician Platteville Formation (Sinnipee Group) overlies shale and sandstone of the Ordovician Ancell Group. In the northwestern corner of the county, the Prairie du Chien escarpment is where dolostone of the Ordovician Prairie du Chien Group overlies the Cambrian sandstone (see cross section in Batten, 2018). In each escarpment, the steep slope occurs at the western end of a gently east-dipping layer of dolostone that is more resistant than the sandstone or shale beneath it. This bedrock topography was modified by glacial erosion during the Quaternary, but much of its configuration was acquired during a long interval of preglacial erosion. The presence of these alternating escarpments and lowlands led early physiographers (for example, Martin, 1932) to name this region of the state "the Eastern Ridges and Lowlands."

The Niagara Escarpment, the highest of the three, divides the county into two regions: the upland of the southeastern one-third, which is supported by Silurian dolostone, and the lowland of the western two-thirds, which is underlain by mostly Ordovician rocks and a small area of Cambrian rocks (fig. 3; Batten, 2018). The bedrock topography influenced the pattern of glaciation and glacial deposition. The westward flow of the Lake Michigan Lobe was restricted by the dip slope of the Silurian dolostone. The southward and southeastward flow of the Green Bay Lobe was

Figure 3. Simplified Paleozoic bedrock geologic map of Fond du Lac County (modified from Batten, 2018). Strata dip gently (5 degrees) toward the east into the Michigan basin.



restricted by the Niagara Escarpment. This pattern of ice flow led to the deposition of the Kettle interlobate moraine near the crest of the Niagara Escarpment (fig. 4). By contrast, the lowland west of the Niagara Escarpment funneled the flow of the Green Bay Lobe southwestward, creating an asymmetric pattern of diverging ice flow that is easily seen in the direction of the long axes of the drumlins in that area (plate 1; Colgan and Mickelson, 1997).

Figure 4. Shaded-relief map of Fond du Lac County showing approximate locations of the Niagara Escarpment (eastern red line), the Prairie du Chien escarpment (western red line), drumlin long-axis orientation trends (arrows), western portion of the Kettle interlobate moraine (pink area), and major moraine crests (bold lines with Vs). Moraine names are from Alden (1918), although he referred to the Eureka moraine as the "Outer Margin of Red Drift."

Pleistocene geology

Thickness of unlithified sediment

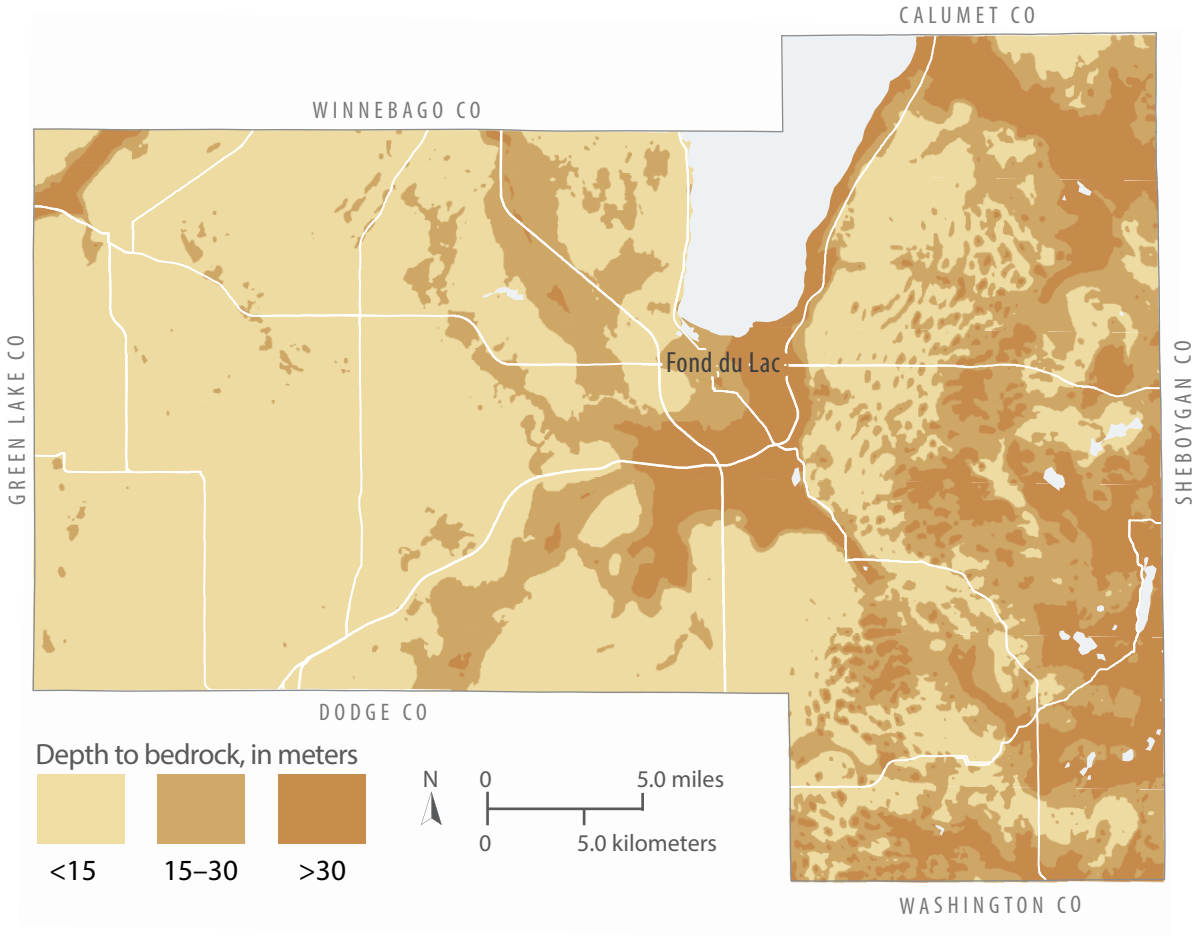
Unlithified sediment is less than 15 m thick in much of Fond du Lac County (fig. 5). It is thicker than 30 m in several spots, including (1) a buried bedrock valley in the northwestern part of the county near Rush Lake; (2) a buried bedrock valley under the present-day Fond du Lac River, which flows into the southern end of Lake Winnebago; and (3) in the Kettle interlobate moraine in the southeastern corner of the county, where it exceeds 45 m in thickness. The only areas where bedrock is exposed at the surface or is covered by less than 2 m of sediment are along the Niagara Escarpment in eastern Fond du Lac County and the Sinnipee and Prairie du Chien escarpments in the northwestern corner of the county.

Stratigraphy

The surficial Quaternary materials of Fond du Lac County were deposited during the last part of the Wisconsin glaciation and the postglacial (Holocene) period (fig. 6). Glacial deposits are assigned to either the Holy Hill Formation or the Kewaunee Formation (Syverson and others, 2011). The Horicon Member is the only member of the Holy Hill Formation known to be present in the county, although it is possible that older members (as well as stratigraphic units older than the Wisconsin glaciation) may be present in the subsurface. The Kewaunee Formation is divided into two members of the same age: (1) the Kirby Lake Member, which occurs on the western side of Lake Winnebago; and (2) the Chilton Member, on the eastern side of Lake Winnebago. Deposits of the Holy Hill Formation cover a large part of the county, whereas deposits of the Kewaunee Formation are restricted to areas adjacent to Lake Winnebago.

Although there are no radiocarbon dates to support the timing of the initial deposition of the Horicon

Figure 5. Simplified map showing depth to bedrock in Fond du Lac County (modified from Batten, 2018).

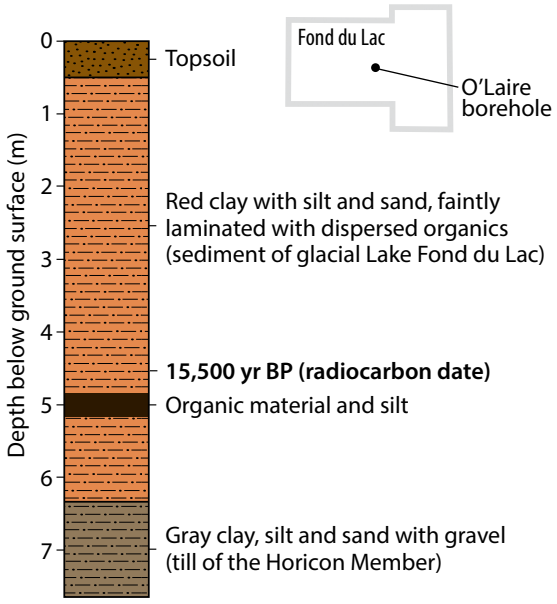


Member in Fond du Lac County, it had ceased being deposited by about 15,500 cal yr BP, when deposition of the Kewaunee Formation (Chilton phase) began in the county. A new radiocarbon date taken from material in the O'Laire borehole (fig. 7, table 2) shows that the Green Bay Lobe reached the Eureka moraine in Fond du Lac County at about 15,500 yr BP, a somewhat older age for the Chilton phase (deposition of the Kirby Lake and Chilton Members of the Kewaunee Formation) than previously thought (around 15,000 years ago; Syverson and Colgan, 2011). The reddish-brown color of the lake sediments in the split-spoon core from the O'Laire borehole (fig. 7), which is located within the basin of glacial Lake Fond du Lac, indicates that they are part of the Kewaunee Formation (Syverson and Colgan, 2011). The level of glacial Lake Fond du Lac reached 259 m in elevation, 18 m higher than the level of glacial Lake Oshkosh (241 m). To impound glacial Lake Fond du Lac, the Green Bay Lobe margin must have stood at the Eureka moraine. When the ice margin receded from this position, glacial Lake Fond du Lac drained and was replaced by glacial Lake Oshkosh (Hooyer and Mode, 2008). The new radiocarbon date is reliable because the dated material consisted of plant macrofossils picked from a peaty silt layer that was deposited in the shallow-water margin of the lake. A second radiocarbon date from 1.5 m deeper in the same core (table 2) is unreliable and yielded an older date because the material dated was bulk organic matter concentrated from slightly organic-rich silt and sand. It is likely that the bulk organic matter included old carbon from pre-Quaternary organic material. Mode (unavailable lab reports, 2012) found an Ordovician acritarch and a Mesozoic spore in a similar sample from a drill core in glacial Lake Fond du Lac sediments.

Figure 6. Stratigraphy of Quaternary deposits in Fond du Lac County (modified from Hooyer and Mode, 2008).

Calendar years ago	Period/epoch		Glacial lithostratigraphic units in Fond du Lac County			Events
0	Quaternary Period	Holocene Epoch	unnamed units			postglacial events
11,700						
14,500		Pleistocene Epoch	Kewaunee Formation	Kirby Lake Member	Chilton Member	main part of the late Wisconsin Glaciation
16,000						
			Holy Hill Formation	Horicon Member		
30,000						
2,600,000			*other units may be present in subsurface*			earlier glaciation?

Figure 7. Geologic log of O'Laire borehole on the O'Laire Farm in central Fond du Lac County. The site is located in the basin of glacial Lake Fond du Lac, which was impounded when the Green Bay Lobe reached the Eureka moraine. Glacial Lake Fond du Lac sediment taken from the O'Laire borehole contains disseminated organic material throughout with a more concentrated layer of organic material at 5 m depth. The organic content represents deposition in a shallow wetland environment. The sample taken for radiocarbon dating was from 4.6 m depth and consisted of plant macrofossils. The date was 15,485±175 cal yr BP (table 2). See location in figure 12A.



Properties of unlithified sediment

Till of the Horicon Member is most often gravelly sandy silt (the average sand, silt, and clay percentages for six samples are 23, 53, and 23 percent, respectively). Its brown to yellowish-brown (7.5YR to 10YR hues) coloring reflects the dominance of light-colored Silurian dolostone; however, where it lies on or near the Maquoketa Shale, it is a gray (5Y hues), clayey sandy silt (average sand, silt, and clay percentages for three samples are 17, 55, and 28 percent, respectively). This till is much richer in silt and clay in Fond du Lac County than elsewhere, which we attribute to the glacial erosion and incorporation of sediments derived from the Maquoketa Shale into the till. Hooyer and Mode (2008) reported that the till in the broader region of east-central Wisconsin is a silty sand (average sand, silt, and clay percentages for 28 samples are 65, 27, and 8 percent, respectively).

Till of the Kirby Lake Member in Winnebago County is reddish brown (5YR hues) and usually richer in silt and clay than till of the Horicon Member (Hooyer and Mode, 2008). The single analyzed sample of till of the Kirby Lake Member from Fond du Lac County was too small to provide meaningful results. However, field and laboratory descriptions of till of the Kirby Lake Member in Fond du Lac County indicate it is rich in silt and clay, a texture similar to that in Winnebago County.

Glacial lake sediment is most often clayey silt, but can be well-sorted clay, silt, or sand depending upon where it was deposited in the glacial lake. Nearshore and shoreline deposits are sandy, whereas offshore deposits are silty and clayey. Varves are common in the basins of glacial Lakes Oshkosh and Fond du Lac. These coarse-grained to fine-grained couplets of lake sediment represent deposition over one full year. In each couplet, the coarser-grained layer is silty or sandy and represents deposition during the summer, and the finer-grained layer is clayey and represents deposition during the winter (fig. 8). The evidence that these couplets are varves is that while measuring, describing, and counting the thousands of couplets in drill cores from the glacial Lake Oshkosh basin, we never found any graded beds that would indicate an origin other than varves. Additionally, counts of the couplets agreed with other estimates (Syverson and Colgan, 2011) of the duration of the glacial lake.

Glacial sediment and landforms

Till is the major component of the landforms and landscapes of the majority of the county, and glacial lake sediment also covers large areas. In the eastern part of the county, the Kettle interlobate moraine and adjacent areas consist largely of meltwater-stream sediment.

Moraines

End moraines are curvilinear ridges consisting of sediment that is deposited at the edge of a glacier. As long as the glacier is actively flowing, it creates, transports, and deposits unsorted sediment (known as diamict). Moraines formed by active ice consist of diamict, some of which is till, along with interbedded meltwater-stream and lacustrine deposits. However, the terminus of a glacier can become stagnant. When stagnation occurs, no more till is created and the sediment is deposited mainly in glacial meltwater streams and lakes. Ridges formed in this manner are known as disintegration or hummocky moraines. Both end moraines and hummocky moraines are present in Fond du Lac County (fig. 4).

Table 2. Radiocarbon dates for O'Laire borehole in Fond du Lac County.

Material dated	Lab identification number[a]	Depth below surface (m)	Measured radiocarbon age (yr BP, ±σ)[b]	$\delta^{13}C$ (‰, VPDB)[c]	Calibrated radiocarbon age (yr BP, 2σ range)[b,d]
Plant material	Beta-296589	4.3	13,110±60	–26.5	15,310–15,660
Organic sediment	Beta-296590	5.8	18,890±100	–27.7	22,260–22,560

[a]Analysis completed at Beta Analytic (Miami, Fla.)
[b]The abbreviation "yr BP" indicates calendar years before present, where present is CE 1950.
[c]VPDB refers to the isotopic reference standard Vienna Pee Dee Belemnite.
[d]Calibrated using Stuiver and others (1998).

Alden (1918) mapped and named three discontinuous end moraines (the St. Anna, Rush Lake, and Waupun moraines) and two hummocky moraines (both of which are parts of the Kettle interlobate moraine) in Fond du Lac County (fig. 4). Plate 1 shows a number of additional (unnamed) moraines, but we found only a few short segments of the Waupun moraine where Alden (1918) mapped it (fig. 4). These end moraines mark the extent of the brief stillstands or readvances of the Green Bay Lobe during its overall recession from the state sometime between about 20,000 and 15,500 yr BP. The till that composes these moraines is part of the Horicon Member of the Holy Hill Formation (map unit **ghr** on plate 1).

The easternmost of the two hummocky moraines that compose the Kettle interlobate moraine in the southeastern corner of the county formed at the margin of the Lake Michigan Lobe while the hummocky moraine to its west formed at the margin of the Green Bay Lobe (Carlson and others, 2005). Both are composed primarily of collapsed meltwater-stream sediment (map unit **sc** on plate 1), signifying that the sediment was deposited on or against stagnant glacier ice, which eventually melted and caused the sediment to collapse. Landforms that are characteristic of these hummocky moraines include kettles, kames (hummocks), and eskers. Clayton (2001) provides a thorough review of the development of ideas about the formation of the Kettle interlobate moraine.

The Eureka moraine (fig. 4) is a ridge of thick (25 m in places) till of the Kirby Lake Member (map unit **gk** on plate 1) that marks the extent of the Green Bay Lobe's readvance during the Chilton phase (Hooyer and Mode, 2008). Alden's (1918) map labels this feature as the "outer margin of the red drift," but we believe it is, at least in most areas, an end moraine (Hooyer and Mode, 2008).

Drumlins

Drumlins are streamlined, linear ridges that form at the base of a sliding glacier and whose long axes are parallel to the direction of ice flow (fig. 9). They are often composed of till, although they may contain meltwater-stream sediment (fig. 10). Nearly all the drumlins in Fond du Lac County are located within the area mapped as till of the Horicon Member (plate 1). The very few drumlins that are located within the area mapped as till of the Kirby Lake Member are often cored with till of the Horicon Member and are simply veneered by till of the Kirby Lake Member (Hooyer and Mode, 2008). Most areas of abundant drumlins are represented on plate 1 by map unit **ghs**; however, a few are scattered in areas of predominantly rolling glacial topography (map unit **ghr** on plate 1).

Because they are molded by the sliding action of the glacier, drumlins are excellent indicators of ice-movement direction. In Fond du Lac County,

Figure 8. Photograph of varves in sediment from glacial Lake Oshkosh exposed in neighboring Winnebago County. Scale bar is approximately 0.5 m.

Figure 9. Digital elevation maps showing orientation of drumlins in Fond du Lac County. A, Drumlins in the lowland west of the Niagara Escarpment, indicating flow of the Green Bay Lobe to the southwest. B, Drumlins on the Niagara Escarpment with two dominant axes, indicating flow to the south and southeast.

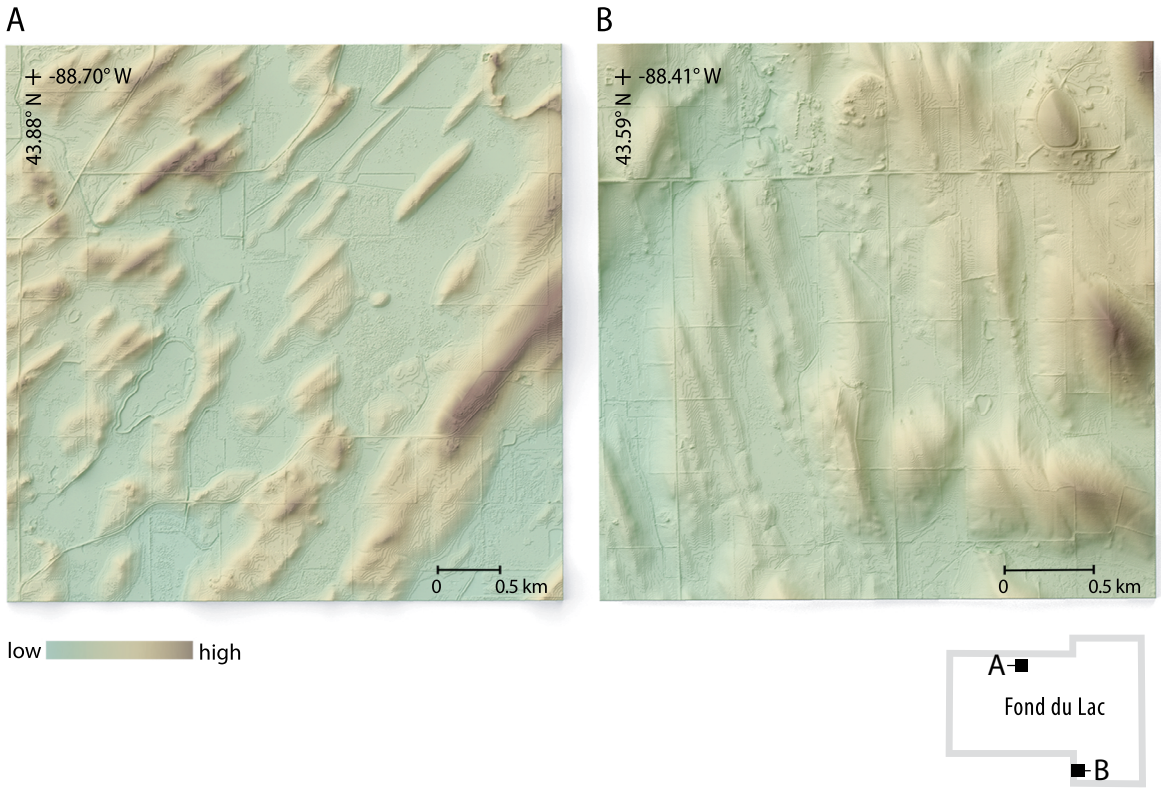


Figure 10. Vertical wall of gravel pit in drumlin located in Fond du Lac County. Wall is about 8.3 m high and exposes gravelly meltwater-stream sediment beneath till of the Horicon Member. Dashed line shows the contact between the two sedimentary units. Scale bar is approximately 1 m.

their long-axis directions document the diverging glacial flow that fans out toward the southeast, south, and southwest from Lake Winnebago (plate 1; Colgan and Mickelson, 1997). Upon closer examination, there may be considerable local variation in long-axis directions, which is often attributable to the variable elevation of the bedrock surface over which the glacier moved (fig. 9). In several cases, drumlins with bifurcating long axes can be seen in eastern Fond du Lac County (fig. 9B); they have been explained as representing two different flow directions, one older and one more recent (Alden, 1918).

Rolling glacial topography

Areas that are overlain by till of the Horicon Member and are largely lacking drumlins are mapped as rolling glacial topography (map unit **ghr** on plate 1). Most end moraines are located within this map unit. The local relief is less than 30 m, often substantially less. Deposits of the Horicon Member are typically less than 15 m thick (thickest in moraines), and most of the topography reflects the shape of the buried pre-Horicon-Member surface. Small areas of meltwater-stream sediment and windblown deposits are included within this map unit, but they are too patchy and (or) too thin to be mapped.

Nondescript glacial topography

The till of the Kirby Lake Member underlies nondescript glacial topography (map unit **gk** on plate 1) where local relief is usually less

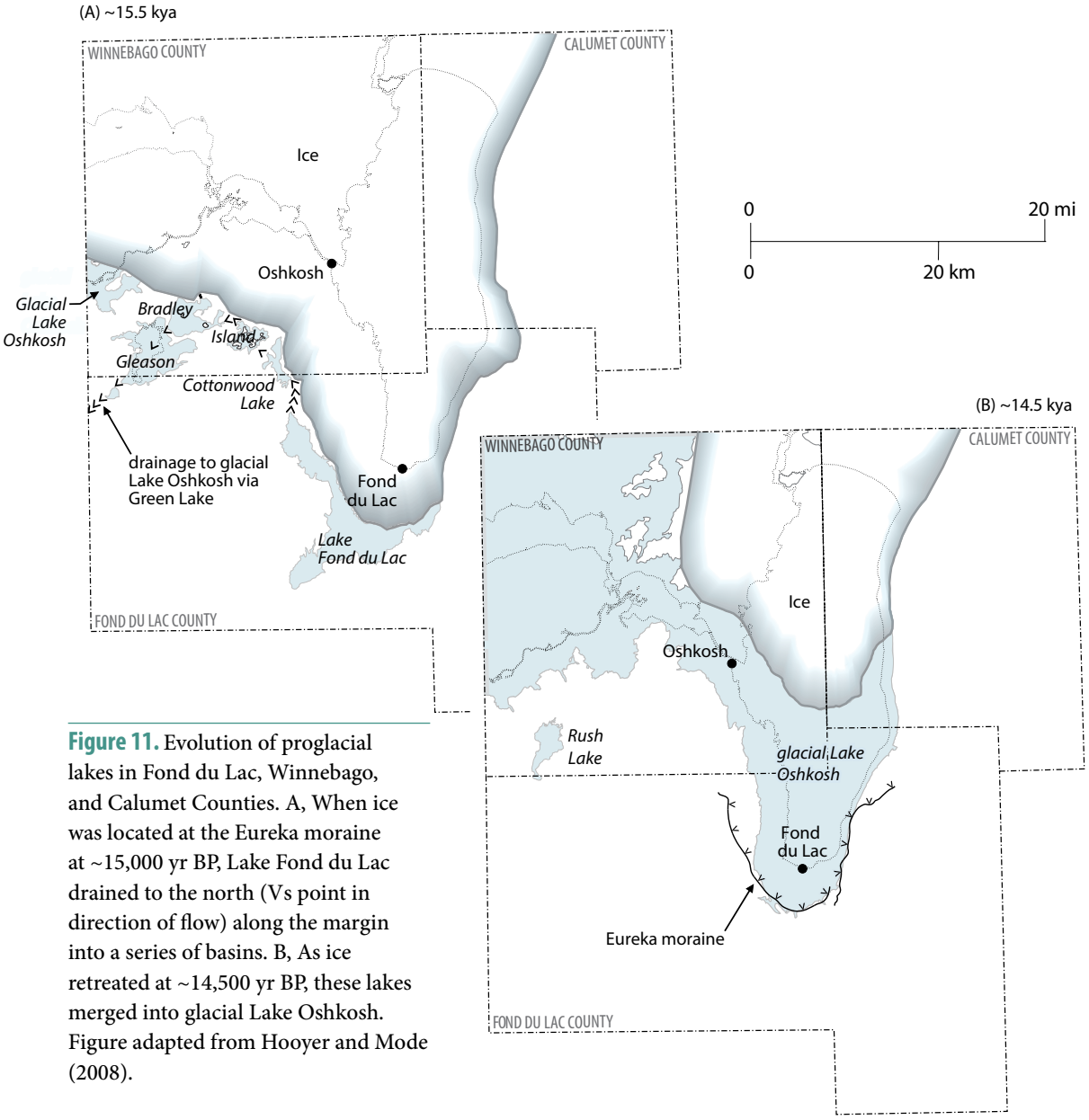


Figure 11. Evolution of proglacial lakes in Fond du Lac, Winnebago, and Calumet Counties. A, When ice was located at the Eureka moraine at ~15,000 yr BP, Lake Fond du Lac drained to the north (Vs point in direction of flow) along the margin into a series of basins. B, As ice retreated at ~14,500 yr BP, these lakes merged into glacial Lake Oshkosh. Figure adapted from Hooyer and Mode (2008).

than 15 m. An exception is the Eureka moraine, which is located within this map unit and has relief up to 22 m. Deposits of the Kirby Lake Member are typically less than 15 m thick (thicker in the Eureka moraine), and most of the topography reflects the shape of the buried pre-Kirby-Lake-Member surface. A substantial portion of the area in which the Kirby Lake Member was deposited was subsequently inundated by glacial Lake Oshkosh. As a result, there are large areas where small patches of the Kirby Lake Member are mingled with small patches of glacial Lake Oshkosh sediment. These areas are represented by map unit **gkl** on plate 1.

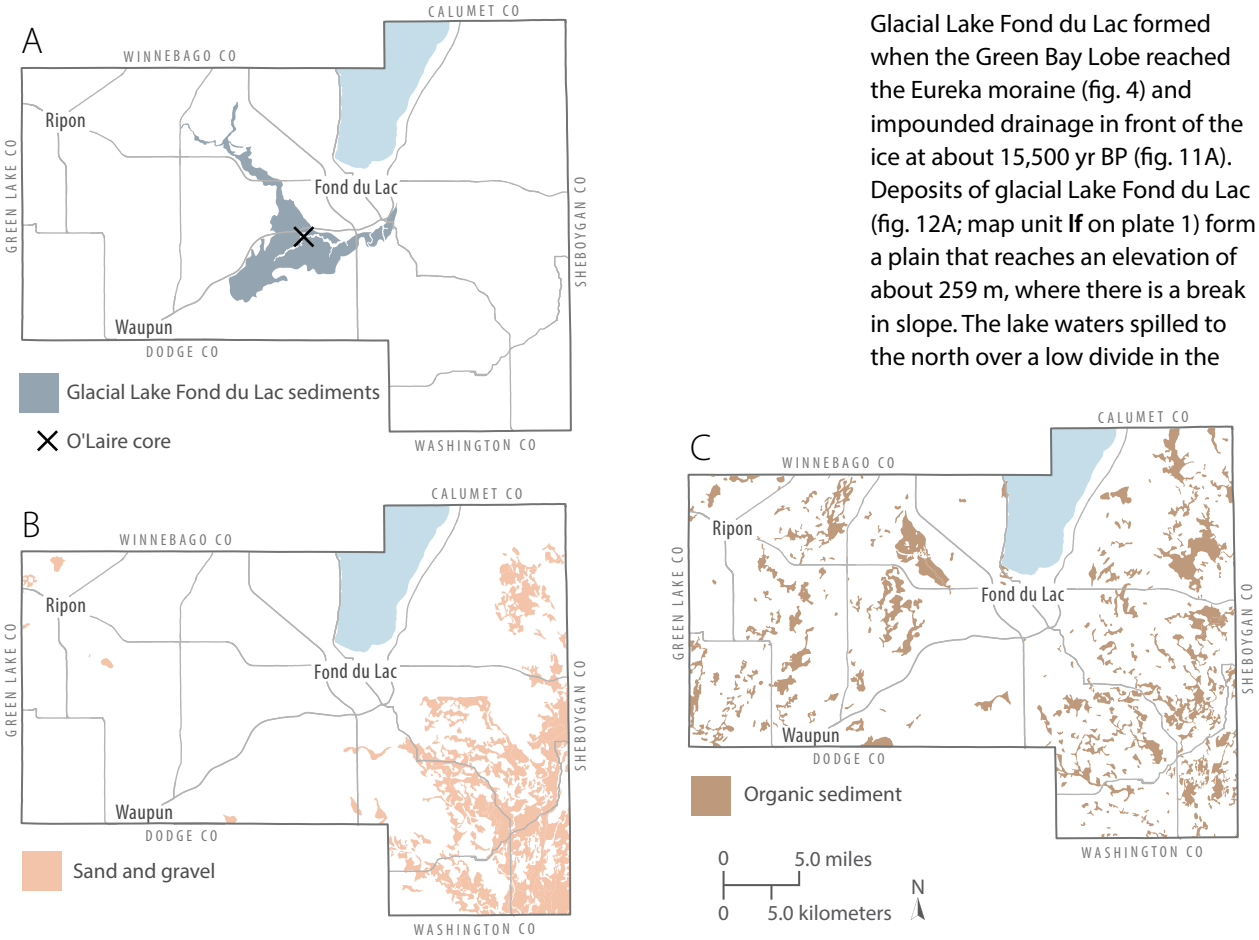
Lake sediment and landforms

East of the Niagara Escarpment (fig. 4), meltwater drainage was eastward and southward away from the Green Bay Lobe. West of the escarpment, the bedrock slope was toward the ice margin, which caused the meltwater to be impounded against the ice to form proglacial lakes (glacial Lakes Fond du Lac and Oshkosh). As a result, extensive areas of glacial lake sediment were mapped west of the escarpment. By contrast, in the area east of the escarpment, the bedrock surface slopes eastward, so drainage from the Green Bay Lobe was unimpeded and resulted in an abundance of meltwater-stream sediment deposits east of the escarpment.

The low-relief, relatively flat ground (representing a former lake plain) in central Fond du Lac County is most often underlain by sediment that was deposited in glacial lakes. These deposits are stratified, often thin to medium bedded, and consist of sand where the glacial lake was shallow and silt and clay where the water was deeper. In buried valleys, such as the one underlying the Fond du Lac River, clayey lake sediment can be as thick as 30 m. Where glacial lake sediments are thin (less than 3 m), they are more often sandy with silty interbeds. Thin glacial lake sediments are often found resting on or adjacent to till of the Kirby Lake Member (map unit **gkl** on plate 1), forming a patchy pattern of lake sediment and till.

Glacial Lake Fond du Lac formed when the Green Bay Lobe reached the Eureka moraine (fig. 4) and impounded drainage in front of the ice at about 15,500 yr BP (fig. 11A). Deposits of glacial Lake Fond du Lac (fig. 12A; map unit **lf** on plate 1) form a plain that reaches an elevation of about 259 m, where there is a break in slope. The lake waters spilled to the north over a low divide in the

Figure 12. Maps showing distribution of surficial sediments in Fond du Lac County. A, Glacial Lake Fond du Lac sediments. B, Sand and gravel. C, Organic sediment (peat).



north-central part of Fond du Lac County, traversed through a series of small ice-marginal lakes (map unit **l** on plate 1), and eventually reached glacial Lake Oshkosh (fig. 11B). As soon as the Green Bay Lobe began receding from the Eureka moraine, the lake level of glacial Lake Fond Du Lac dropped and the water body merged with glacial Lake Oshkosh, whose outlet was at the divide between the Fox River and the Wisconsin River near Portage. The plain of glacial Lake Oshkosh extends to an elevation of about 241 m, where its shoreline is marked by a break in slope. Neither glacial Lake Fond du Lac nor glacial Lake Oshkosh created significant beach deposits (beach ridges), probably because they were short-lived lakes. Glacial Lake Oshkosh persisted in Fond du Lac County until the Green Bay Lobe receded north of the Neshota outlet (elevation 255 m) and disappeared from Fond du Lac County when the ice receded sufficiently to expose the Kewaunee outlet (elevation 228 m). At that point, an early version of Lake Winnebago existed. Because glacial Lake Oshkosh was a relatively shallow lake (mostly less than 15 m deep) in Fond du Lac County, its deposits (map unit **gkl** on plate 1) are thin and scattered, having filled in occasional low spots.

When the Green Bay Lobe readvanced into the Fox River lowland one final time at about 13,100 yr BP (Panyushkina and others, 2017), glacial Lake Oshkosh re-formed and briefly reoccupied its 241-meter level. At this time, the ice reached only as far as present-day Appleton. The same sequence of outlets drained glacial Lake Oshkosh as the Green Bay Lobe receded for the final time from the Fox River valley beginning at about 12,500 yr BP (Mickelson and Attig, 2016).

Other small proglacial lakes formed as the ice margin receded from the county. For example, one such lake existed in the area of present-day Sheboygan Marsh in Sheboygan County (Carlson and others, 2011) because meltwater was impounded by the Lake Michigan Lobe. The borehole drilled in Sheboygan County (site number 2 in table 1), approximately 0.5 km east of Fond du Lac County, revealed thinly laminated, silty lake sediment underlying peat in the headwaters of the Sheboygan River.

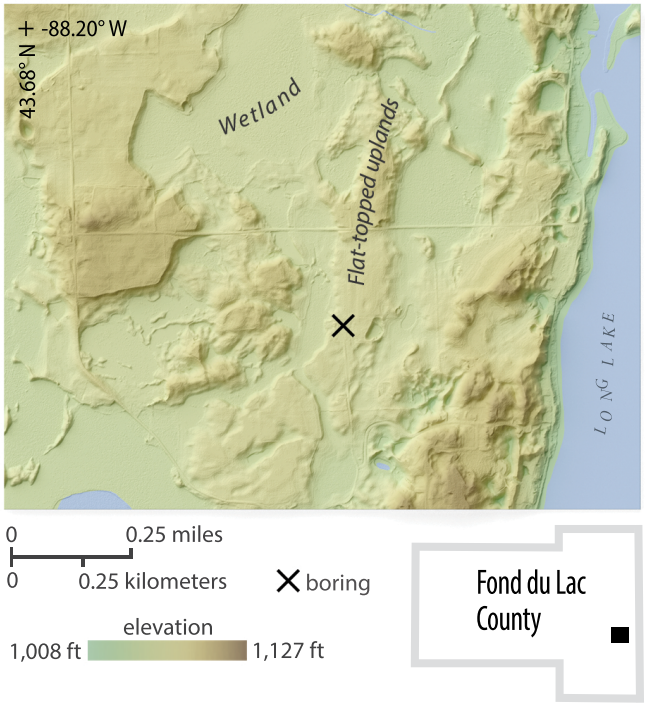
Stream sediment and landforms

Glacial meltwater streams deposited sand and gravel that constitute important sources of construction aggregate. Postglacial (Holocene) streams in the county are generally not competent enough to transport gravel, and much of their sediment load is suspended silt and clay, which has been deposited on flood plains adjacent to stream channels.

Meltwater-stream sediment

Meltwater streams draining away from the glacier's ice margin deposited sand and gravel in channels and on bars. Ice-contact fans (map unit **sa** on plate 1) and proglacial terraces (included in map unit **su** on plate 1), which are especially common in the eastern part of the county, consist of meltwater-stream sediments. Because these sediments were deposited as the glacier margin receded, they are concentrated between drumlins (and in some places partially bury drumlins), signifying that the drumlins formed earlier than the proglacial stream terraces. Some of the surfaces that are underlain by meltwater-stream sediments can be traced upstream to ice-margin positions that are now marked by end moraines (indicating active ice) or ice-contact faces (indicating stagnant ice).

Figure 13. Flat-topped uplands with steep sides occur on the eastern and western sides of a wetland in the eastern part of Fond du Lac County. These uplands were formed as stream-channel deposits in ice-walled channels. The borehole, located on the western ice-walled channel, revealed well-rounded gravel.



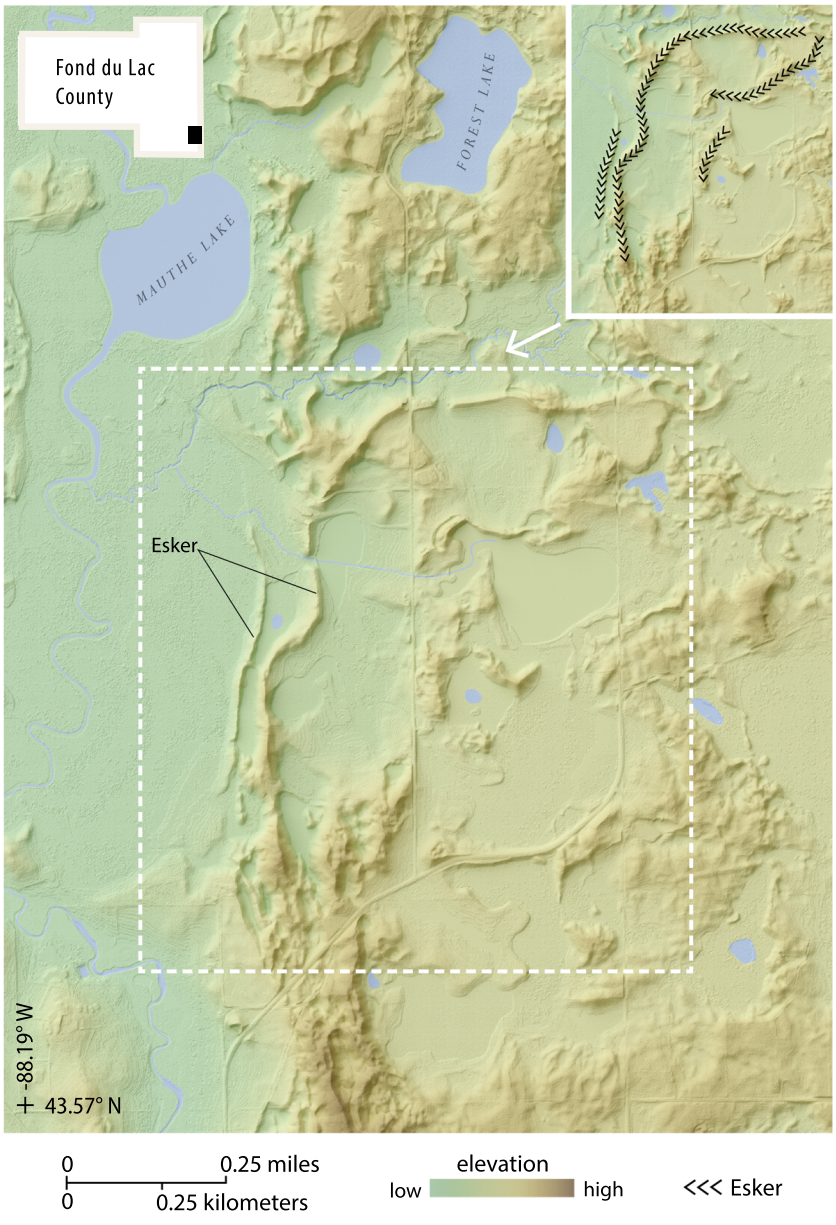
Meltwater streams also flowed on, in, and under stagnant glacier ice. The sand and gravel deposits (map unit **sc** on plate 1) of these streams are mainly found in the eastern part of the county in and near the Kettle interlobate moraine. Where a meltwater stream flowed on the glacier surface, its channel walls would have been glacier ice and it may have been floored either by glacier ice (ice-floored) or by solid ground (ice-walled; Parizek, 1969). Ice-floored meltwater-stream deposits are kettled because they collapsed when the ice beneath them melted. Ice-walled meltwater-stream deposits are flat-topped instead of being kettled, and they have steep, collapsed slopes at their margins that mark the positions of the ice walls that once contained the channel and the channel deposits (Parizek, 1969; Attig and Rawling, 2018; fig. 13). A borehole drilled in an ice-walled meltwater channel (J. Immel, table 1; fig. 13) yielded well-rounded, moderately sorted, coarse to very coarse gravel.

Eskers form where meltwater streams flow at or near the base of the ice in conduits. Eskers are sinuous ridges composed of sand and gravel (map unit **sc** on plate 1) whose long axes parallel the ice-flow direction because the water flow was driven by the hydraulic head in the glacier, which slopes in the same direction as the ice surface. Mickelson and Syverson (1997) described the formation of eskers in the southern part of the Kettle interlobate moraine, where the eskers trend in the same direction as the interlobate moraine because the conjunction of the Lake Michigan and Green Bay Lobes forced the meltwater southward. Eskers formed in this manner are located in eastern Fond du Lac County. In places, they formed as extensions of eskers created by meltwater flowing toward the interlobate moraine, down the gradient of the individual ice lobe. Figure 14 shows eskers with east-west-trending long axes that transition to north-south-trending where they reach the interlobate moraine.

Sand and gravel resources

Abundant sand and gravel resources are located in eastern Fond du Lac County where meltwater-stream deposits occur widely at the surface (fig. 12B). Also located in the eastern half of the county are active gravel pits in drumlins, where the gravel underlies the till of Horicon Member (fig. 10). West of Fond du Lac, the surficial material is mainly till and lake sediment, limiting the availability of sand and gravel.

Figure 14. Eskers in the southeastern part of Fond du Lac County formed in and near the Kettle interlobate moraine when westward-flowing meltwater of the Lake Michigan Lobe was diverted southward and converged with eastward-flowing meltwater from the Green Bay Lobe.



Holocene geology

The Pleistocene Epoch ended at 11,700 yr BP and was followed by the current Holocene Epoch (fig. 6). The ice sheet had receded from Fond du Lac County by about 15,000 yr BP; therefore, some nonglacial deposits, such as hillslope sediment (map unit **h** on plate 1), may be partly Pleistocene and partly Holocene in age. Hence, although this section describes the Holocene postglacial or nonglacial deposits, they may include older sediments.

Hillslope sediment and landforms

Hillslope sediment may have been deposited any time since deglaciation at about 15,000 yr BP. The sediment is more likely to date from times when vegetative cover on the landscape was minimal or disturbed or times of widespread permafrost (Clayton and others, 2001), both of which allowed accelerated hillslope erosion. Because steeply sloping landforms composed of silty till of the Kewaunee Member, such as the Eureka moraine, are easily eroded, light-gray to reddish-brown, silty hillslope sediment is found in stream banks and flood plains that drain such landforms. The light-gray color is inherited from the eroded soil's A-horizon. In one auger hole, a pollen grain from corn was found at a depth of 1.3 m in light-gray, silty hillslope sediment. This indicates that at least 1.3 m of hillslope sediment was deposited after humans began to settle in the area. Hillslope sediment is shown as unit **h** on the map (plate 1).

Modern stream sediment

Several streams—Fond du Lac River, De Neveu Creek, Taycheedah Creek, Milwaukee River, and Sheboygan River—have created flood plains since the retreat of the ice sheet. These flood plains are occupied by fine-grained deposits (map unit **s** on plate 1), which lack the abundant gravel that is found in meltwater-stream sediment. Streams such as the Fond du Lac River that drain areas of silty and clayey lake sediment have silt- and clay-rich flood-plain deposits. By contrast, because the upper Sheboygan River drains areas of sandy till of the Horicon Member, its flood-plain sediment is sandier. Significant areas within the flood plains contain peat deposits (map unit **ps** on plate 1) that overlie and are interbedded with detrital stream sediment.

Peat

Peat deposits are found throughout Fond du Lac County where standing water in wetlands reduces decomposition of dead plant litter, enabling the partly decomposed plant litter to accumulate as peat (fig. 12C). Large wetlands include Eldorado Marsh, Gallagher Marsh, and Horicon Marsh in the western part of the county. In the east, large wetlands include McCoullough Marsh, Mullet Marsh, and large parts of the upper Sheboygan River and Manitowoc River drainage basins. The thickness of the mapped peat ranges from 1 to 3 m. Where the material underlying the peat is unknown, the map unit is simply peat (**p**) on plate 1. Also on plate 1, map unit **pg** represents peat overlying till; **po** represents peat overlying glacial Lake Oshkosh sediment; and **ps** represents peat overlying stream sediment. Additionally, there are many areas, such as in flood plains, where peat is less than 1 m thick. In these areas, the underlying unit is shown on the map instead (plate 1).

Fill

Although humans extensively modified the landscape of the county, our mapping attempted to show the Quaternary deposits as they existed before human settlement. For example, we do not map the artificial fill that underlies Interstate Highway 41; we map the sediment that underlies the fill. However, there is one area along the southern shore of Lake Winnebago, in the city of Fond du Lac, where the artificial fill is sufficiently extensive to be shown at the scale of plate 1 (1:100,000) as map unit **f**. This area of filled wetland became part of Lakeside Park.

Pleistocene history

Syverson and Colgan (2011) provide a summary of the glacial record of Wisconsin, including the relatively scant record of early and middle Pleistocene events (2.6 million to 120,000 yr BP). The first part of the Wisconsin glaciation began approximately 80,000 yr BP, and the last part of the Wisconsin glaciation began about 35,000 yr BP and ended 11,700 yr BP. In Fond du Lac County we found no evidence of glaciation older than that of the last part of the Wisconsin glaciation. Nevertheless, the county was doubtless glaciated a number of times during this interval, but subsequent postglacial and glacial erosion removed deposits of those events. During the late Wisconsin, the Laurentide Ice Sheet had advanced into the state by about 32,000 yr BP and reached its maximum extent prior to 26,000 yr BP (Carson and others, 2012). The ice's recession from the glacial maximum began at 23,000 yrs BP (Attig and others, 2011; Carson and others, 2012; Ullman and others, 2015) and progressed slowly until the ice margin reached the Green Lake moraine at 18,400 yr BP. Thereafter, the recession accelerated, and the Green Bay Lobe and glacial Lake Oshkosh formed in front of it. The state was probably ice free by 16,000 yr BP (Mickelson and Attig, 2016).

During the interval between 26,000 and 16,000 yr BP, the Holy Hill Formation was deposited in Fond du Lac County. As the ice's recession progressed, the area in eastern Fond du Lac County where the Green Bay and Lake Michigan Lobes met became the focus of much meltwater-stream deposition by runoff from both ice lobes. The glacial readvance that deposited the Eureka moraine at the southern end of Lake Winnebago occurred at 15,500 yr BP; glacial Lake Fond du Lac formed at this time. As the ice receded from the Eureka moraine, glacial Lake Fond du Lac drained and glacial Lake Oshkosh formed once again. The ice margin again receded from eastern Wisconsin completely only to readvance one last time at 13,100 yr BP (Panyushkina and others, 2017), once again impounding glacial Lake Oshkosh. This final readvance did not reach Fond du Lac County, but glacial Lake Oshkosh rose to an elevation of 263 m and deposited lake sediment in the county up to that level. Soon after 13,000 yr BP, the Green Bay Lobe receded from eastern Wisconsin and did not readvance into the state. Sediment deposited between 15,500 and 13,000 yr BP is represented by members of the Kewaunee Formation. Postglacial Pleistocene deposits—including hillslope sediment and peat—were deposited until 11,700 yr BP, when the Holocene Epoch began (fig. 6). Holocene deposition of hillslope sediment, peat, and stream sediment occurred thereafter.

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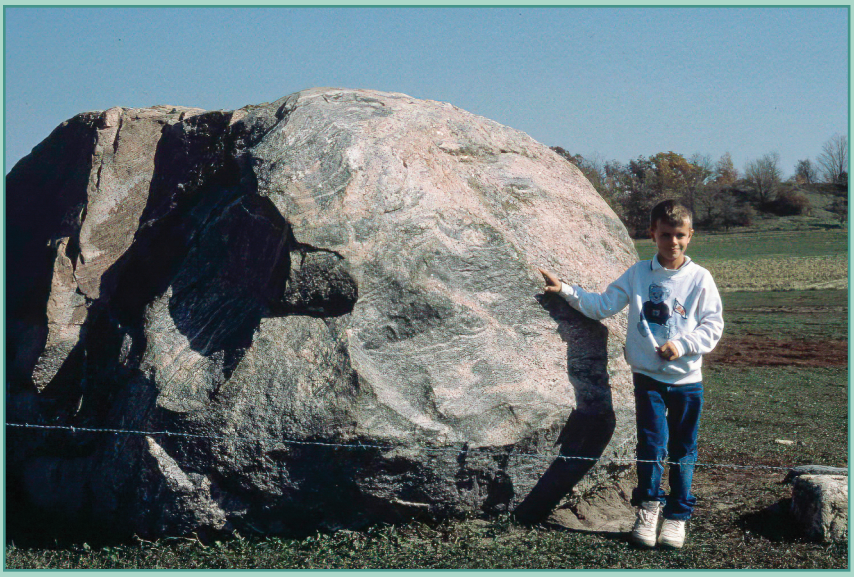

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