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Thomas S. Hooyer
William N. Mode

Wisconsin Geological and Natural History Survey
Bulletin 105 | 2008

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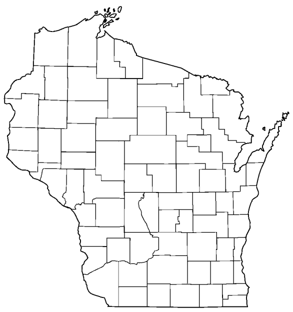

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PLATES (in back pocket)

Quaternary Geology of Winnebago County, Wisconsin

Thomas S. Hooyer

William N. Mode

ABSTRACT

Some of Wisconsin's largest lakes lie within Winnebago County. The presence of these lakes is the result of the most recent glaciation, which overran a large part of Wisconsin, including Winnebago County, approximately 24,000 cal yr BP. The county was covered with actively flowing ice of the Green Bay Lobe; the glacier scoured the landscape, eroding pre-existing valleys in the bedrock. In some areas, sediment from the base of the ice was plastered onto the bedrock surface, forming a sandy till (the Horicon Member of the Holy Hill Formation) that is widely recognized in the central and southern parts of the state. Upon recession of the ice sheet due to a warming climate, a large lake formed in front of the ice margin within the Fox River valley. The lake, called glacial Lake Oshkosh, began to form in low areas in front of the ice margin as the ice receded across east-central Wisconsin, approximately 19,000 cal yr BP. This lake drained through the Dekorra outlet, just south of the present location of the city of Portage. Sediment deposited in the lake filled preexisting bedrock valleys and other low-lying areas, eventually leveling the landscape.

The ice margin continued its northward recession; the lake level dropped as a series of progressively lower outlets was uncovered, which allowed flow eastward to the Lake Michigan basin. The glacial lake formed again when the Green Bay Lobe readvanced southwestward through the Fox River valley, blocked eastern outlets, and finally terminated in the southern part of Winnebago County, approximately 15,000 cal yr BP (12,700 ^{14}C yr BP). Material deposited by ice built the prominent Eureka moraine, which consists primarily of reworked lake sediment, indicating that the glacier was effective at eroding the lake sediment and redepositing it as till. This material is classified as the Kirby Lake Member of the Kewaunee Formation. Approximately 80 percent of the county is covered with fine-grained (clay and silt) sediment, much of which was initially deposited in glacial Lake Oshkosh.

The Green Bay Lobe receded once again, the lake drained, and the landscape became vegetated. Within a few hundred years, approximately 13,300 cal yr BP (11,500 ^{14}C yr BP), the Green Bay Lobe readvanced, but only to the northeast edge of the county. Glacial Lake Oshkosh refilled because ice blocked the eastern outlets. Just north and east of Winnebago County, the glacier overran a forest consisting primarily of spruce trees. Many of these trees and associated biota are preserved in a layer referred to as the Two Creeks Forest Bed, which lies beneath lake sediment and till of the Middle Inlet Member of the Kewaunee Formation. Radiocarbon dating of this organic material helped constrain the chronology of glacial events in Winnebago County.

With the final recession of the Green Bay Lobe from Wisconsin approximately 12,900 cal yr BP (11,000 ^{14}C yr BP), glacial Lake Oshkosh went through another series of lake-level drops as new outlets opened. It was at this time that the modern-day Lakes Poygan, Butte des Morts, and Winnebago began forming. Immediately following deglaciation of the region, sand deposited along the ancestral Wolf River was blown southward into northwestern Winnebago County. This sand coats the land surface and in some areas has accumulated against north-facing hill slopes.

Beneath the glacial sediment lie Cambrian and Ordovician sandstone and dolomite. The oldest unit, the Cambrian sandstone,

forms an aquifer used by many municipal and high-capacity industrial wells in the region. In many areas of the county, this sandstone is capped by dolomite of the Prairie du Chien Group, which extends northeast to southwest across the county. The St. Peter Formation of the Ancell Group, which overlies a large part of the Prairie du Chien, is used in places by residential wells. The youngest bedrock unit is dolomite of the Sinnipee Group; it is present in the eastern half of the county. This dolomite, where saturated, supplies residential wells, but wells open to this rock unit can also be contaminated with naturally occurring heavy metals.

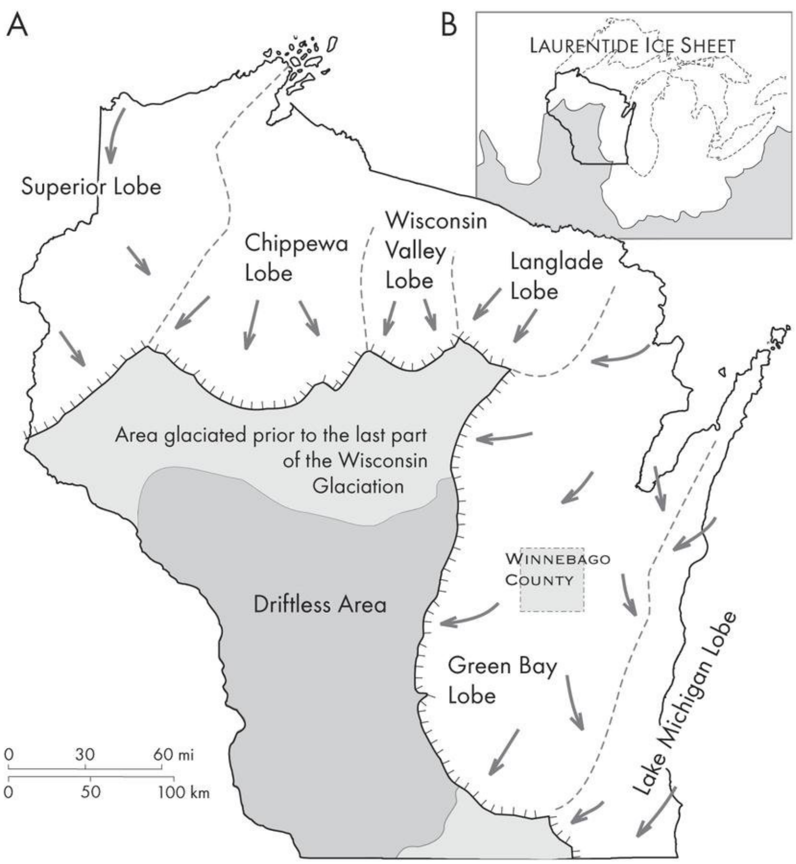

Figure 1. *Location of Winnebago County in Wisconsin (**A**) in relation to the Laurentide Ice Sheet and (**B**) its lobes during the most recent glaciation. Hachures indicate the edge of the ice sheet; arrows indicate direction of ice flow.*

INTRODUCTION

In this bulletin, we describe the glacial geology of Winnebago County, east-central Wisconsin (figs. 1–4). Winnebago County is in the Fox River valley, which extends over all or parts of 13 counties and occupies a triangular area that is roughly defined by the cities of Green Bay, Portage, and Fond du Lac. This region was occupied at various times by glacial Lake Oshkosh (fig. 5).

Study of the geology of Winnebago County and the Fox River valley began with the work of Whittlesey (1849). The first surficial map produced in the region was that of Warren (1876). Numerous observations relevant to the geology of the region were subsequently made by Chamberlin (1883), Upham (1903), and Weidman (1911). Alden (1918) published a general map of the surficial deposits of southeastern Wisconsin; this map includes the southern half of Winnebago County and the Fox River valley. The central and northern parts of the valley were mapped by Thwaites (1943) and Thwaites and Bertrand (1957). Their maps and accompanying manuscripts provided the foundation for understanding the Quaternary geology of east-central Wisconsin, but do not provide sufficient detail to understand the three-dimensional distribution of Pleistocene materials. Since the work of Thwaites (1943), no further surficial mapping of the valley has been done, with the exception of Brown County (Need, 1983). More recent work in the region has focused on understanding the glacial history (McCartney, 1979; McCartney and Mickelson, 1982) and the evolution of glacial Lake Oshkosh (Wielert, 1979, 1980).

The surficial deposits of Winnebago County consist of various types of sediment deposited by the glacier that most recently covered east-central Wisconsin approximately 24,000 cal yr BP (21,000 ^{14}C yr BP). This glacier, called the Green Bay Lobe, was part of the Laurentide Ice Sheet, which covered a large area of North America (fig. 1). This ice

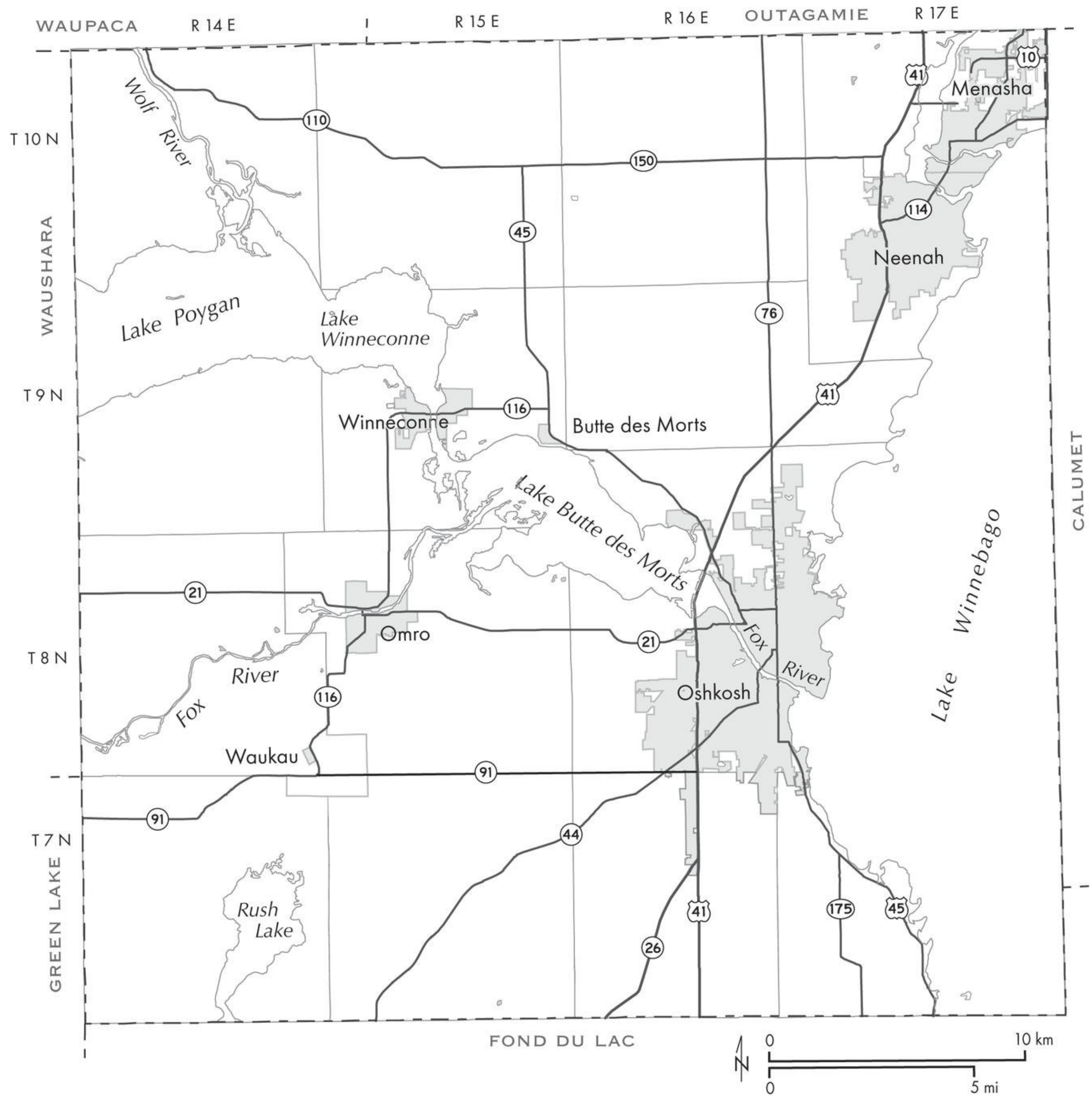

Figure 2. *Geographic features of Winnebago County, including major roadways and lakes.*

sheet was centered in east-central Canada and extended eastward to the Atlantic Ocean, west to the Rocky Mountains, north to the Arctic Ocean, and southward into the Great Lakes region. Six ice lobes extended over a large part of Wisconsin. The Green Bay Lobe covered the largest area of the state, including Winnebago County (fig. 1). The lobe, at its greatest extent, terminated in the south near the Wisconsin and Illinois border and to the west in an area commonly referred to as the Central Sand Plain. To the east, the lobe abutted the Silurian escarpment and the much larger Lake Michigan Lobe, which covered the Lake Michigan basin and extended southward into central Illinois. The Lake Michigan and Green Bay Lobes were part of the most recent glaciation, but older glacial deposits indicate that parts of Wisconsin were glaciated numerous times.

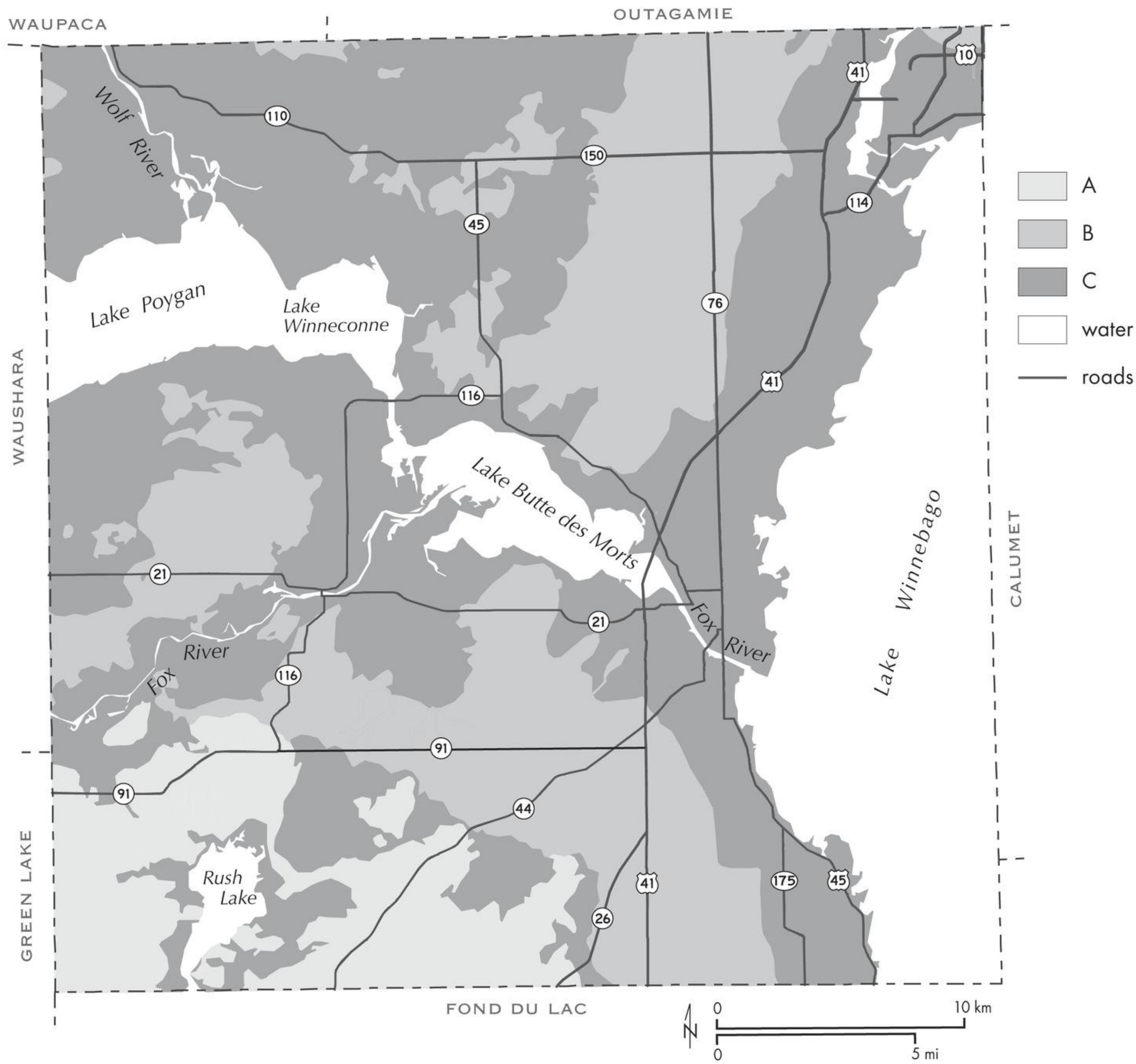

Figure 3. *Major landscape regions of Winnebago County.* **Area A** *is characterized by brown sandy till deposited by the Green Bay Lobe at its maximum extent during the most recent glaciation; ice-flow direction was to the southwest.* **Area B** *is similar to Area A, except the till is reddish brown, is very silt and clay rich, and was deposited by a readvance of the Green Bay Lobe.* **Area C** *is characterized primarily by lake sediment that in many areas underlies peat, fluvial, and windblown sediment. This lake sediment, deposited in glacial lakes that formed in front of the receding ice margin, has similar characteristics to the glacial till that covers Area B.*

METHODS

To understand and map the Quaternary geology of Winnebago County, we examined soils maps (Mitchell, 1980) and aerial photographs (1957) and conducted field studies during 2002 and 2003. We drove every road within the county and examined any available outcrop or exposure that could be used to determine the nature and distribution of surface materials. In places, we used a hand auger to examine the materials to a depth of 1.5 m. On the basis of this information,

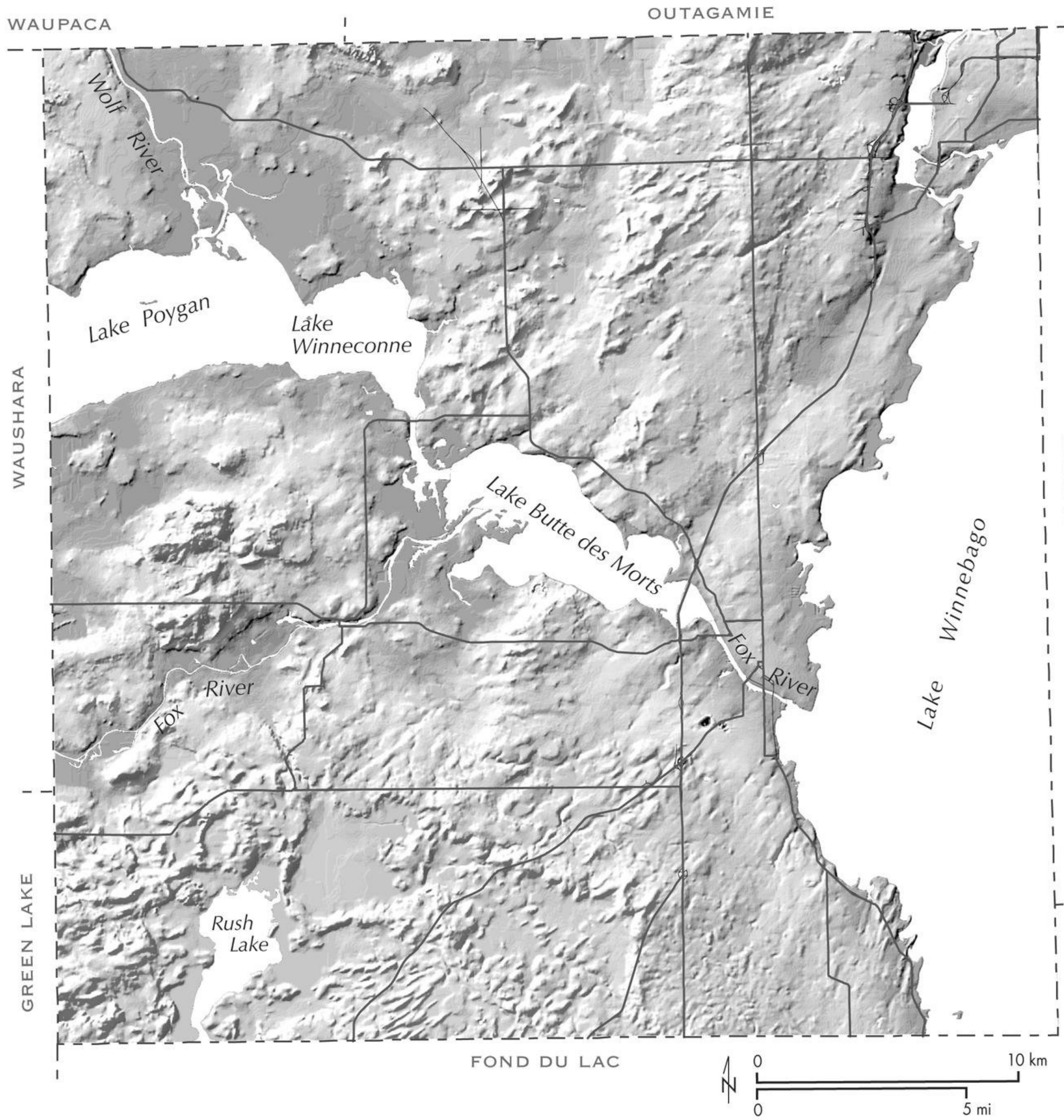

Figure 4. *Shaded-relief map of Winnebago County. Relief is from U.S. Geological Survey digital elevation model data (1998).*

we drew contacts between different geologic units on 12 U.S. Geological Survey quadrangle maps (7.5-minute series, topographic, scale 1:24,000); the contacts were digitized and generalized to a scale of 1:100,000 for plate 1, the Quaternary geologic map of Winnebago County. With the exception of some large rock quarries in the county, the surface materials shown on plate 1 represent what was present prior to the modern anthropogenic earth-moving activities that have modified parts of the landscape.

To examine the materials below the ground surface, truck-mounted drilling rigs were used to auger boreholes. Additional subsurface data were taken from geologic logs, Road Materials Investigation Reports, and Wisconsin Department of Natural Resources well construction reports on file at the Wisconsin Geological and Natural History Survey (WGNHS). On the basis of these subsurface data, four cross sections were

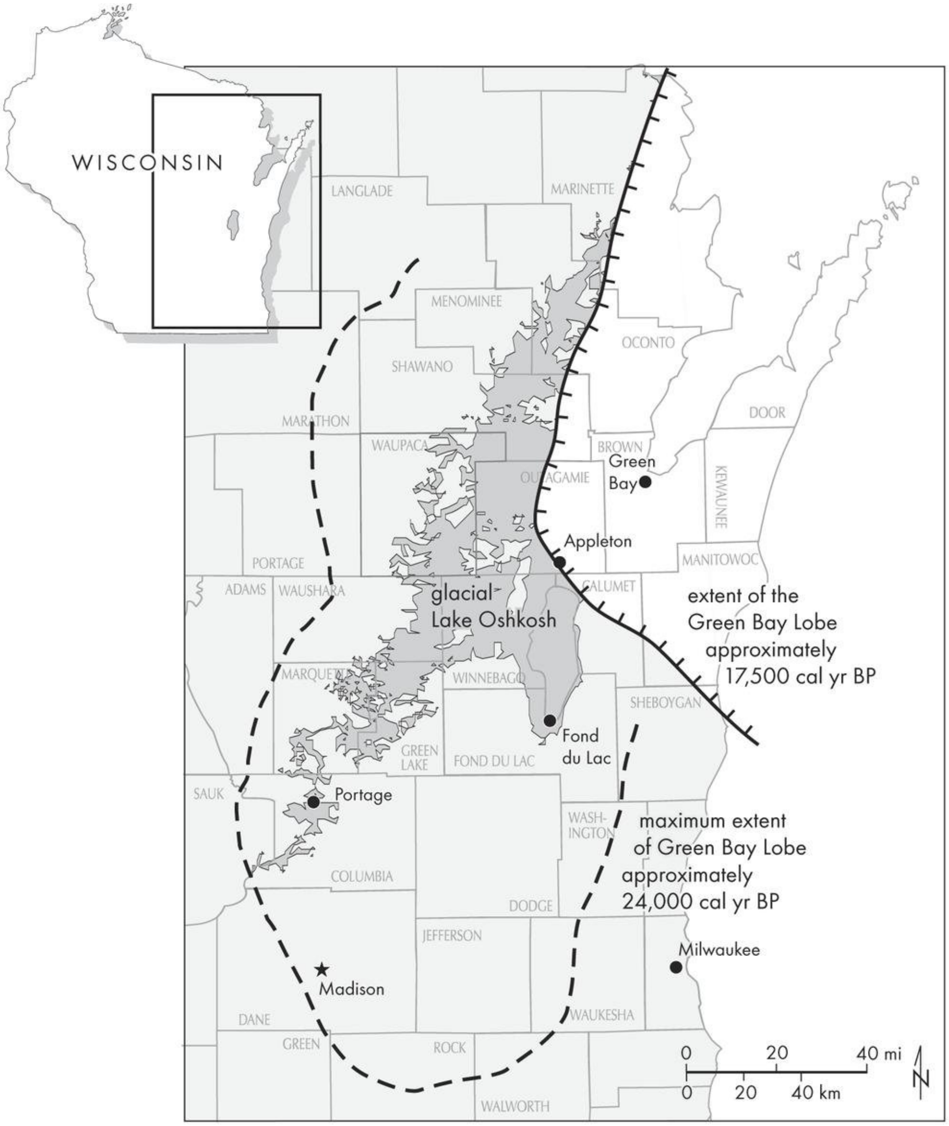

Figure 5. *Map of east-central Wisconsin, showing the margin of the Green Bay Lobe and the maximum extent of glacial Lake Oshkosh.*

constructed through representative parts of the county (plate 2). Selected borehole logs from which the cross sections were created are listed in appendix A1.

Throughout this bulletin, we provide dates that constrain the glacial geologic history of Winnebago County. These dates are based on samples from the Fox River lowland that were analyzed either for carbon-14 from wood, plant, and shell fragments, or by optically stimulated luminescence (OSL) of fine-grained lake sediment or windblown sand.

The chronology of events determined from these carbon-14 dates varies from previous work (Mickelson and others, 1984; Attig and others, 1988). As more dates and new test methods become available, the timing of the geologic events in the Fox River valley will continue to be refined.

All the carbon-14 dates presented in this bulletin have been calibrated from radiocarbon years (^{14}C yr BP) to calendar years before present (cal yr BP); "present" is taken by convention to be 1950 (Stuiver and others, 1998). This calibration is necessary to compare to other methods (such as OSL), the results of which are already in calendar years.

BEDROCK GEOLOGY

Cambrian and Ordovician sandstone and dolomite that formed 520 to 440 million years ago lie immediately beneath the unlithified sediment in Winnebago County (fig. 6). These layered rocks were deposited on Precambrian igneous and metamorphic rock as old as 1,750 million years. The Precambrian rock does not crop out at the land surface in Winnebago County, but exposures are present to the west in Waushara and Green Lake Counties.

The sedimentary rocks can be grouped into four major units, from oldest to youngest (fig. 6): Cambrian sandstone (which includes the Elk Mound, Tunnel City, and Trempealeau Groups), Prairie du Chien Group, Ancell Group, and Sinnipee Group. These rock units dip gently (about 3 m/km) to the east and extend under eastern Wisconsin and Lake Michigan. The map of the bedrock geology of

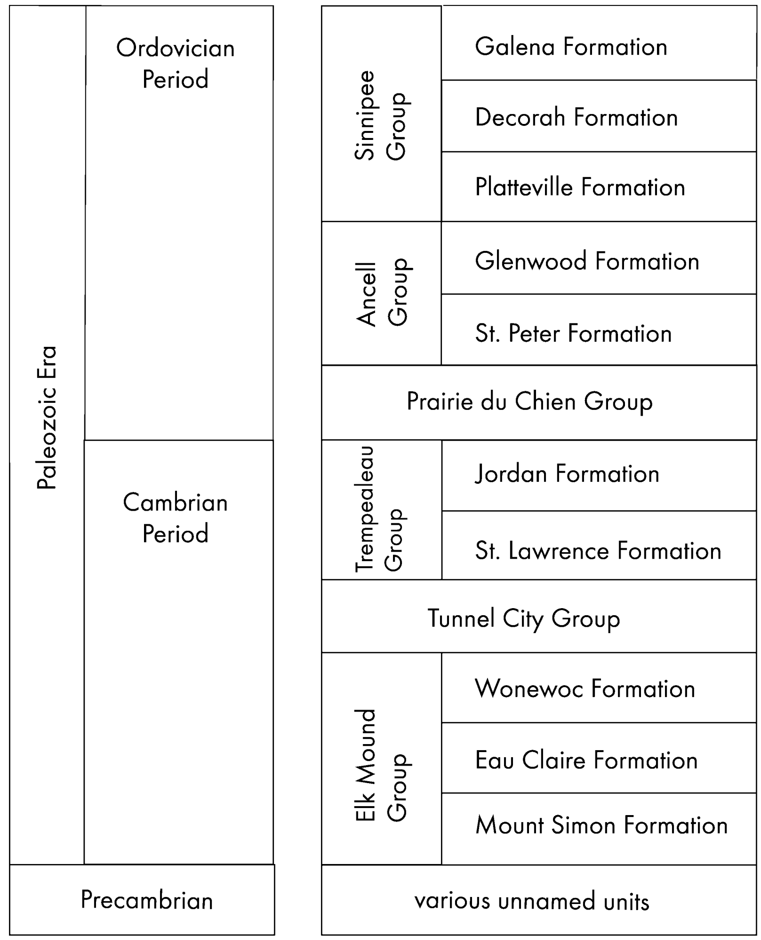

Figure 6. *Bedrock stratigraphic units in Winnebago County, showing relative position and age (modified from Batten and Bradbury, 1996).*

Winnebago County (fig. 1 on plate 2) shows that all four units are present at the bedrock surface (Brown, 2004).

The Cambrian sandstone (fig. 6) is known mostly from samples collected by well drillers and studied at the WGNHS. This rock is poorly exposed at the land surface, but forms the bedrock surface beneath the glacial deposits in the northwestern part of the county. The sandstone is commonly approximately 100 m thick. Saturated with water and permeable, it forms the most productive deep aquifer in Winnebago County; it is the source rock for most municipal and high-capacity industrial wells.

Immediately above the Cambrian sandstone lies the dolomite of the Prairie du Chien Group. It is exposed at the bedrock surface in a strip that extends from northeast to southwest across the central part of the county. In some places, this dolomite is at or near the land surface and crops out in a series of bluffs or escarpments. Rock from many of these exposures is quarried, crushed, and used as high-quality aggregate in the construction industry (fig. 7).

The Ancell Group consists mainly of sandstone of the St. Peter Formation. Where present, it usually overlies the Prairie du Chien dolomite. This sandstone is exposed at the bedrock surface in a narrow band that stretches from northeast to southwest across the county. A major geological break, or unconformity, between the Prairie du Chien dolomite and sandstone of the overlying Ancell Group is the result of a large river system that drained into an ancient sea and eroded deep channels into the Prairie du Chien dolomite, which later filled with sand. Some of these channels were so deep that in places the Prairie du Chien dolomite may have been completely eroded, resulting in the Ancell Group sandstone of the St. Peter Formation directly overlying the older Cambrian sandstone. In other places, however, minimal erosion of the Prairie du Chien dolomite occurred, so no sand was deposited. As a result, there are areas where the Ancell Group sandstone is absent and younger rocks lie directly on top of the Prairie du Chien. The irregular presence of Ancell Group sandstone across the county is poorly known because of the lack of good subsurface geologic information.

The St. Peter Formation, which historically has been an important aquifer for rural and suburban residential wells in the eastern part of the county, in places contains naturally occurring sulfide cement that includes metals, such as arsenic (Schreiber and others, 2000, 2003; Thornburg and Sahai, 2004). In high concentrations, arsenic in well water can pose health hazards; its occurrence in well water is difficult to predict and can vary widely over short distances.

The youngest bedrock unit in Winnebago County is the Sinnipee Group, which consists primarily of dolomite and is the uppermost

Figure 7. *Photograph of the Ben Carrie Quarry in Neenah, Wisconsin, showing the Platteville Formation of the Sinnipee Group overlying a sandy zone of the Prairie du Chien Group (NW¼ NE¼ sec. 29, T20N, R17E). The contact between the two groups is at the level of the person's head.*

bedrock unit in the eastern half of the county. The Sinnipee overlies either Ancell Group sandstone or the Prairie du Chien dolomite. Dolomite of the Platteville and Galena Formations of the Sinnipee Group is the primary source of aggregate in the county. Its strength and durability make it ideal aggregate material for asphalt and concrete.

Like the Ancell sandstone, dolomite of the Sinnipee Group may contain metallic minerals along joints or in dissolution pockets. Many residential water wells finished in the Sinnipee are subject to elevated levels of heavy metals, including arsenic.

PLEISTOCENE GEOLOGY

Thickness of unlithified sediment

The depth to the bedrock surface in Winnebago County is highly variable. That surface is the result of millions of years of erosion before glaciation. Prior to the most recent Ice Age, the landscape was probably similar to what we observe today in the Driftless Area of southwest Wisconsin: high, broad plateaus or ridges dissected by deep, continuous valleys that can be more than 150 m deep. Evaluation of well construction reports revealed a set of deeply incised bedrock valleys cutting across Winnebago County (fig. 1 on plate 2). The deepest parts of these valleys coincide with the axes of the Fox and Wolf Rivers and Lakes Poygan, Winneconne, and Butte des Morts. Because the topographic relief of the ground surface is relatively slight, especially compared to that of the underlying bedrock surface, the bedrock topography is the primary control on the thickness of surficial sediment. Deep, buried bedrock channels, such as the one beneath Lake Butte des Morts, have been filled with a substantial thickness of sediment (more than 100 m in places); bedrock high points usually have only a thin cover of sediment (no more than a few meters).

Unlithified sediment that overlies the bedrock in Winnebago County was deposited primarily during the Pleistocene Epoch (1.8 million to 10,000 years ago), although some sediment, such as peat, was deposited during the Holocene Epoch (the past 10,000 years) (fig. 8).

Stratigraphy

Pleistocene sediment in Winnebago County consists of part of the Holy Hill Formation (Mickelson and Syverson, 1997) and the younger Kewaunee Formation (Mickelson and others, 1984), which were deposited during the late Pleistocene, approximately 30,000 to 13,000 yr BP (fig. 8). There is little evidence of older Pleistocene sediment, although it could be present in places in buried bedrock valleys. In the southwestern corner of the county, only the Holy Hill Formation is at the land surface (plate 1; cross-section D–D′, plate 2). Elsewhere in the county, the Kewaunee Formation is at the land surface and overlies the Holy Hill Formation or bedrock, if the Holy Hill Formation is absent.

In Winnebago County, the Holy Hill Formation consists of one member, the Horicon Member, which is mainly till and some associated stream and lake sediment. The Kewaunee Formation includes two members on the west side of the Fox River, the Kirby Lake and Middle Inlet Members, and two equivalent members on the east side (in the northeastern corner of the county), the Chilton and Glenmore Members. The buried Two Creeks Forest Bed (Maher and Mickelson, 1996), if present, lies beneath the Middle Inlet and Glenmore Members and above the Kirby Lake and Chilton Members. The Two Creeks Forest Bed is a distinct buried soil horizon in the Fox River valley and contains a variety of fossils, such as beetles, mollusks, and trees (trunks, branches, needles, and cones), all of which serve as excellent material for radiocarbon dating. As a result, the Two Creeks interval is a well dated period, 14,000 to 13,300 cal yr BP (12,000 to 11,500 ^{14}C yr BP), that occurred late in deglaciation. Three radiocarbon dates for Winnebago County were acquired for this study (table 1). Two of these dates, from WGNHS samples 24 (collection site shown in fig. 9) and 26, are from the Two Creeks buried soil. A third date, from WGNHS sample 23, represents an older buried soil related to an earlier readvance of the Green Bay Lobe.

Elsewhere in east-central Wisconsin, the Kewaunee Formation is known to include other members underlying the Kirby Lake and Chilton Members (McCartney and Mickelson, 1982; Clayton and others, 2006). Because of limited exposures and lack of concise information in drilling records, it is not certain whether any of these members of the Kewaunee Formation are present in Winnebago County.

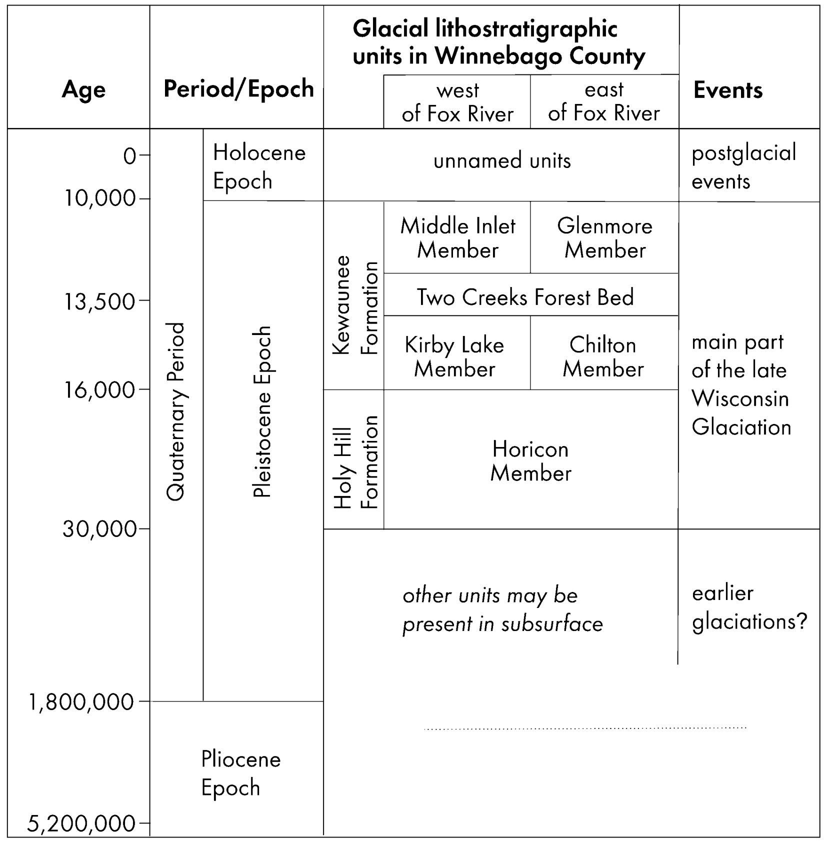

Figure 8. *General chronology of Pleistocene materials and events in Winnebago County.*

Properties of unlithified sediment

During the course of mapping the Quaternary geology of Winnebago County, we collected samples of several types of sediment and analyzed them to characterize their physical properties, including grain size, hydraulic conductivity, plasticity, and shear strength. The results of the grain-size analyses were used to distinguish different types of sediment in the field during mapping. The remaining physical properties are important to geologists and engineers who are concerned with groundwater supply and infrastructure development, including road and building construction. Because these physical proper-

Table 1. *Summary of radiocarbon analyses for wood samples collected in 2003 in Winnebago County.*

WGNHS sample number	Sample site	Location	Sediment	Measured radiocarbon age (^{14}C yr BP)	Calibrated radiocarbon age (cal yr BP)	Laboratory
23	Highway 116/45 overpass	NW¼NE¼ sec. 24 T19N, R15E	silty sand	13,650–13,110	16,460–15,694	Geochron Laboratories
24	Wellhouse pit	SW¼SE¼ sec. 6 T19N, R17E	lake sediment	11,920–11,800	14,090–13,570	Beta Analytical
26	Ames Construction borrow pit	NW¼NW¼ sec. 17 T20N, R15E	lake sediment	12,250–11,810	15,066–14,827 14,295–13,817	Geochron Laboratories

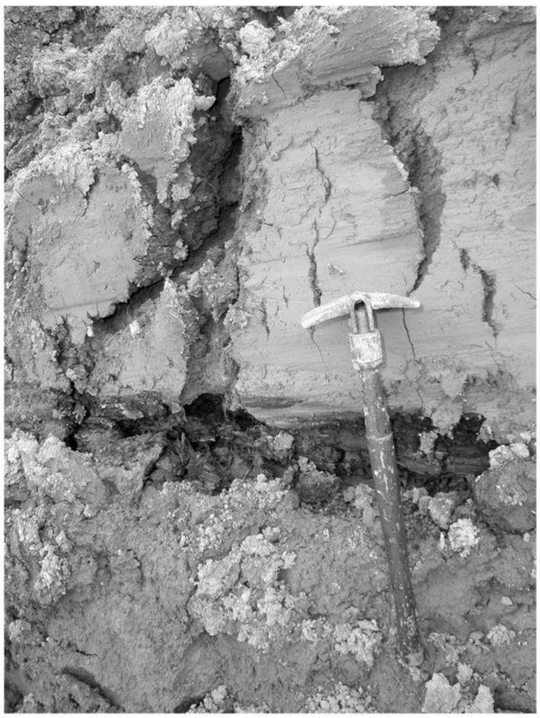

Figure 9. *Photograph of the buried soil of the Two Creeks Forest Bed. The soil, 0.01 m thick, is sandwiched between lake sediment of glacial Lake Oshkosh (SW¼SE¼ sec. 6, T19N, R17E). A piece of wood collected from this location (sample 24, table 1) was used for radiocarbon analysis.*

ties were not used to directly construct the geological map (plate 1) and associated cross sections (plate 2), the results and interpretation are presented in appendix B.

Grain size and color

Analyses showed that till of the Horicon Member of the Holy Hill Formation is usually brown to yellowish brown (7.5YR hues) and sandy. On the basis of 28 samples, its average sand, silt, and clay percentages are 65, 27, and 8 percent, respectively (table 2; fig. 10).

In a few locations, usually at the bottom of deep boreholes in Outagamie County, some till deposited before the most recent glaciation has grain sizes similar to that of the Horicon till. Fourteen samples from this older till indicated a grain size of 58, 26, and 16 percent of sand, silt, and clay, respectively.

The two till units of the Kewaunee Formation are much finer grained (more silt and clay) and redder (5YR hues) than the Horicon till. The sand, silt, and clay grain-size distribution for till of the Middle Inlet Member is 32, 45, and 23 percent; for the Kirby Lake Member, 24, 42, and 34 percent (table 2; fig. 10). The higher content of silt and clay in these two tills is the result of the readvancing Green Bay Lobe eroding and incorporating fine-grained sediment previously deposited in glacial Lake Oshkosh. Because the grain-size distributions of the Middle Inlet and Kirby Lake Members are similar, it is difficult to distinguish them in the Fox River valley except by stratigraphic position in drillholes.

Table 2 shows our findings in relation to those of McCartney and Mickelson (1982), Need (1983), and Rodenbeck (1988).

Glacial sediment and landforms

Glacial sediment and landforms of Winnebago County derived largely, if not completely, from the last part of the Wisconsin Glaciation, approximately 24,000 to 12,900 cal yr BP (21,000 to 11,000 ^{14}C yr BP), when the county was covered, and eventually uncovered, by the Green Bay Lobe of the Laurentide Ice Sheet. At its maximum extent, approximately 24,000 cal yr BP (21,000 ^{14}C yr BP), the Green Bay Lobe terminated near the present locations of the villages of Plainfield and

Table 2. *Summary of grain-size distribution of the less-than 2 mm fraction for samples collected from the Kewaunee, Holy Hill, and pre-late Wisconsin tills in east-central Wisconsin. Size ranges: sand, 0.063–2 mm; silt, 0.002–0.063 mm; clay, less than 0.0002 mm; SD = standard deviation.*

Unit	Source	Sediment	Number of samples	Percentage sand (SD)	Percentage silt (SD)	Percentage clay (SD)
Kewaunee Formation						
Middle Inlet Member	this study	till	15	32 (±12)	45 (±6)	23 (±13)
	McCartney and Mickelson (1982)	till	54	64 (±9)	28 (±8)	8 (±3)
	Need (1983)	till	119	39 (±9)	42 (±8)	19 (±5)
	Rodenbeck (1988)	till	18	18 (±11)	47 (±11)	35 (±19)
Kirby Lake Member	this study	till	54	24 (±13)	42 (±8)	34 (±11)
	McCartney and Mickelson (1982)	till	33	36 (±14)	47 (±10)	17 (±9)
	Need (1983)	till	44	32 (±12)	45 (±8)	23 (±10)
	Rodenbeck (1988)	till	73	28 (±16)	44 (±11)	29 (±19)
undifferentiated	this study	lake sediment	14	3 (±7)	61 (±26)	36 (±27)
Holy Hill Formation						
Horicon Member	this study	till	28	65 (±19)	27 (±17)	8 (±5)
Pre-late Wisconsin	this study	till	17	58 (±18)	26 (±16)	16 (±5)

Coloma in Waushara County, west of Winnebago County, and southward, near the cities of Madison and Janesville.

Moraines

At the edge of the Green Bay Lobe, sediment that melted out of basal ice commonly forms curvilinear ridges called moraines. Because moraines develop in a complex depositional environment, they can contain considerable amounts of meltwater-stream, hillslope, and lake sediment.

A series of moraines extends north–south and northwest–southeast through Waushara and Winnebago Counties and records recessions and readvances of the ice margin until approximately 12,900 cal yr BP (11,000 ^{14}C yr BP), when the county was free of glacial ice. These moraines are commonly discontinuous, but can be linked together to decipher former ice-margin positions.

Numerous moraine segments exist in Winnebago County (fig. 11; plate 1). The oldest of these moraines, the Rush Lake moraine, is in the southwestern corner of the county (Alden, 1918). It consists of a series of disconnected segments that trend north–northwestward and pass just west and south of Rush Lake (Colgan, 2002). On the east side of Rush Lake is another moraine, the St. Anna moraine (Alden, 1918; Mountain–St. Anna moraine of Thwaites, 1943). It, too, consists of a series of disconnected segments, but this moraine is easier to distinguish than the Rush Lake moraine. Both moraines are composed primarily of silty sand with dispersed gravel that we interpreted to be Horicon till (map units **gh** and **ghd** on plate 1). The crests of moraine segments are shown on plate 1.

The largest and most continuous moraine in the county extends northwest, along Highway 41 near the Fond du Lac County line west–northwestward to the Waushara County line about 3 km south of Highway 21. Neither Alden (1918) nor Thwaites (1943) named this moraine; they simply called it the outer limit of reddish-brown glacial sediment because they believed that the red till simply veneered an older, buried moraine. This is probably the case in some places, but in many places in the county, well construction reports indicate a considerable thickness of reddish-brown till. For example, a well drilled in the moraine just west of Highway

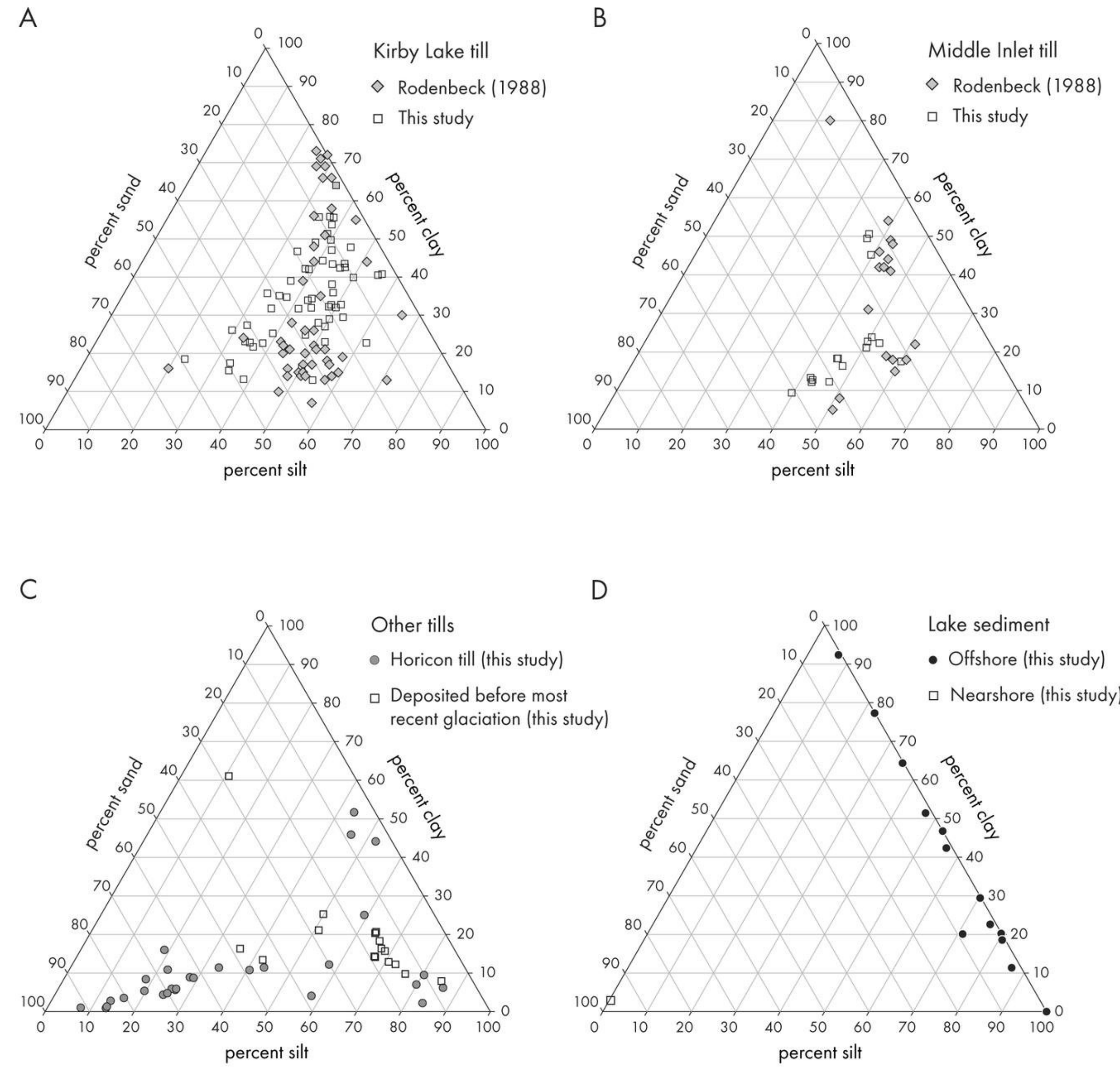

Figure 10. *Grain-size distributions of (**A**) till of the Kirby Lake Member, (**B**) till of the Middle Inlet Member, (**C**) till of the Horicon Member and pre-late Wisconsin tills, and (**D**) lake sediment.*

41 in sec. 21, T17N, R16E contains more than 25 m of red till, indicating that this ridge is a moraine. We call this the Eureka moraine (first use of this name), after the locality in west-central Winnebago County where the moraine is cut by the Fox River. This moraine consists primarily of red, clayey silt with some gravel that we interpreted as Kirby Lake till (map unit **gk**, plate 1). Other short moraine segments composed of Kirby Lake till also are found in north-central Winnebago County, where they are partly covered with windblown sand (map unit **gkw**, plate 1).

Another relatively continuous moraine extends southward along Highway 76 from the Outagamie County line to approximately 5 km north of Highway 41 (figs. 5 and 11). This unnamed moraine consists of Kirby Lake till and represents a standstill of the margin of the Green Bay Lobe as it receded northward from the Eureka moraine. In the northeast corner of the county, another unnamed moraine extends northward into Outagamie County and eastward into Calumet County. This

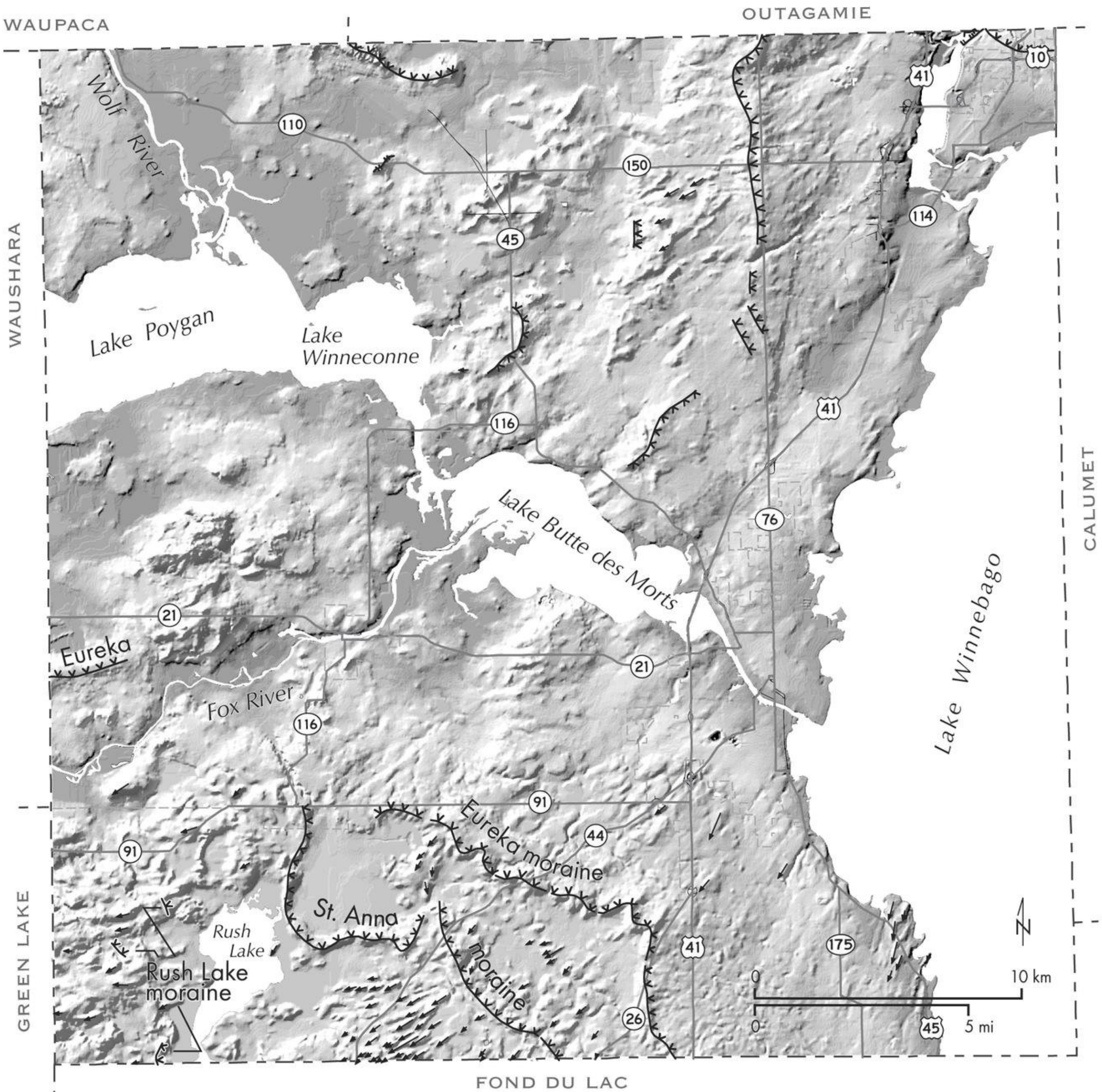

Figure 11. *Map showing moraines in Winnebago County. The Eureka moraine represents the southern edge of the Kirby Lake Member of the Kewaunee Formation. Arrows represent length and orientation of drumlins.*

moraine is thought to represent the western extent of the Glenmore and Middle Inlet tills deposited during the Denmark Phase (map unit **gg**, plate 1) (McCartney and Mickelson, 1982; Clayton and others, 2006).

Drumlins

Drumlins are subglacially molded, elongate ridges of various sizes, usually composed of till, but sometimes of meltwater-stream sediment. These features are key indicators of ice-movement direction and reflect sliding of the glacier over an unfrozen substrate. Each arrow on figure 11 and plate 1 indicates a drumlin.

Most drumlins are in the southwestern corner of the county that is underlain by the Horicon Member. The areas containing numerous drumlins are mapped as unit **ghs** on plate 1. A group of much smaller drumlins is found near Fahrney Point, south of the city of Oshkosh near the shoreline of Lake Winnebago. Bathymetric maps also indicate several drumlins (not shown on plate 1) on the floor of Lake Winnebago adjacent to this area. Onshore, these drumlins are in an area mapped as red, clayey Kirby Lake till covered with thin patches of lake sediment (map unit **gkl**, plate 1). These drumlins are not as well defined as their counterparts to the southwest, probably because they are relict or palimpsest features that have been buried by either lake sediment or thin Kewaunee till.

Smaller drumlins of low relief exist, but do not usually appear on 7.5-minute topographic maps because the contour interval of 3 m (10 ft) provides insufficient resolution. Therefore, these drumlins are not shown on plate 1. Higher-resolution data available in a digital-elevation model (DEM) used to make the relief map (figs. 2 and 11) show many of these drumlins southeast of Fahrney Point.

Rolling glacial topography

Low- to moderate-relief rolling topography that has up to 15 m of local relief is evident in the southwestern corner of the county where sandy till of the Horicon Member of the Holy Hill Formation (map unit **gh**, plate 1) is at the surface. The surface is undulating, and the area may contain drumlins. In most places, the till is at least 3 m thick. The topography most likely reflects the form of older, buried glacial deposits and possibly the bedrock surface (map unit **ghd**, plate 1).

Nondescript glacial topography

Areas lacking rolling topography and large numbers of drumlins are classified here as having nondescript glacial topography. Undrained depressions are found in some parts of this area. Nondescript glacial topography is most common in Winnebago County in areas where the surficial material is till of the Kirby Lake Member of the Kewaunee Formation. Local relief in these areas is typically low, usually less than 7 m. Although the till is usually more than 3 m thick, in many places it is not thick enough to mask the underlying topography, which is probably controlled by older glacial deposits and the bedrock surface. The till merely drapes pre-existing topography (map unit **gk**, plate 1).

Higher-relief (up to 25 m locally) areas of nondescript glacial topography are present in the southwestern part of the county where till of the Horicon Member of the Holy Hill Formation drapes older glacial deposits and possibly the bedrock surface (map unit **ghd**, plate 1).

Lake sediment and landforms

Pleistocene lakes

Glacial Lake Oshkosh is one of the two largest Pleistocene lakes identified in the state of Wisconsin, with the exception of the glacial lakes that occupied the basins of Lakes Michigan and Superior. Much of Winnebago County is dominated by the nearly flat, low-lying plains that we interpreted as the bed of glacial Lake Oshkosh, which formed in front of the Green Bay Lobe (fig. 5). Many of these plains are underlain with lake sediment (map unit **l**, plate 1), consisting of sand and silt deposited near the shoreline and silt and clay deposited in deeper water. In the northwest part of the county, large areas of lake sediment are covered with patches of windblown sand (map unit **lw,** plate 1). This sand is relatively thin (less than 2 m) and was most likely deposited shortly after the draining of glacial Lake Oshkosh, before vegetation could grow and when strong winds blew southward from the ice margin. Many areas of lake sediment are also covered with peat (map unit **pl,** plate 1) because lake sediment tends to limit surface-water infiltration; as a result, many low-lying areas are perennially wet and form abundant wetlands in which organic material accumulates.

Field evidence

Extensive field evidence records the former existence of glacial Lake Oshkosh. Examina-

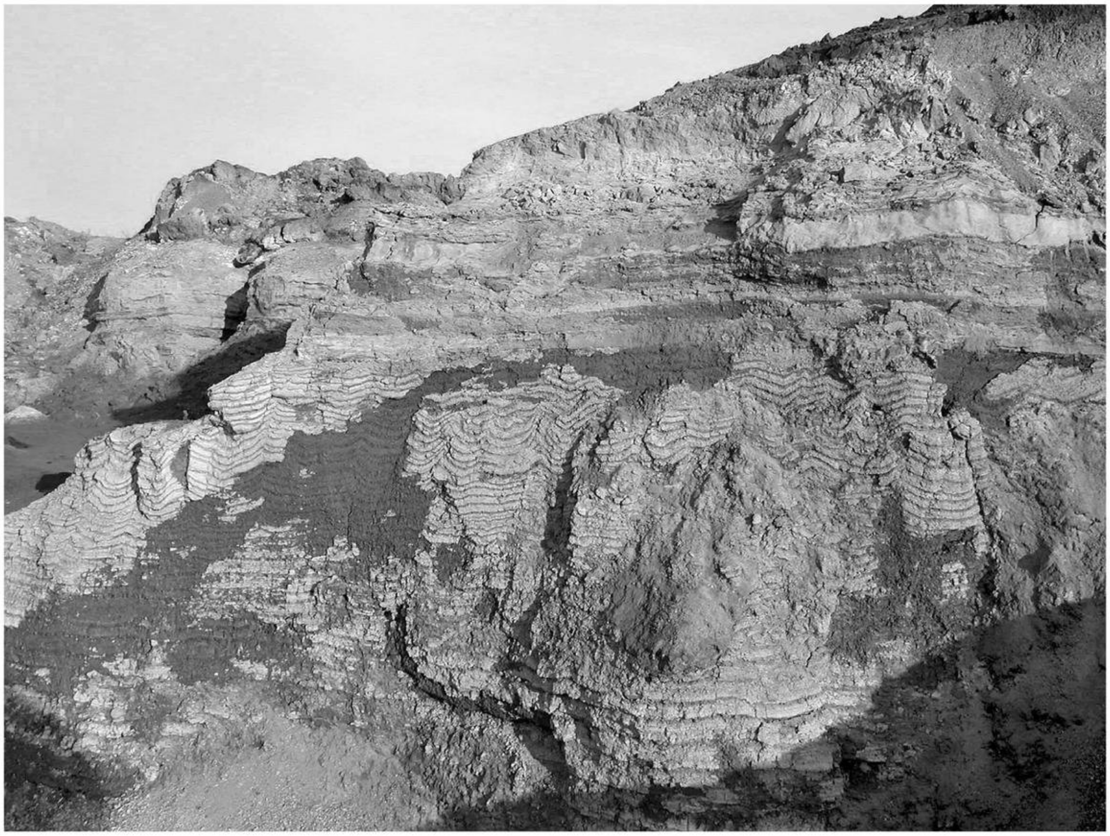

Figure 12. *Photograph of glacial Lake Oshkosh sediment in the Ames Construction Borrow pit (SW¼ SE¼ sec. 11, T20N, R15E). The exposure, approximately 5 m high, shows laminated clay and silt grading upward to sand. Such a coarsening-upward sequence is typical of a falling lake level that was probably due to the opening of a lower outlet across the Silurian escarpment to the Lake Michigan basin.*

tion of samples from hand-auger holes drilled to a depth of 1.5 m combined with the examination of material exposed in quarries, foundation excavations, and gravel and borrow pits documented the presence of lake sediment. One such example is a borrow pit (fig. 12) excavated for Highway 10, 2 km north of the rural locality of Winchester (SW¼ SE¼ sec. 11, T20N, R15E). This borrow pit is a good example of fine-grained laminated silt and clay lake sediment (fig. 10D), which is commonly overlain by lake sand. The increase in grain size from clay and silt to sand, known as a coarsening-upward sequence, is typical of many exposures in which the laminated sediment, deposited in an offshore environment, is capped by sand deposited in a higher-energy, near-shore environment, probably as lake level fell with the opening of lower outlets.

Field evidence also includes sediment cores collected from 18 rotosonic boreholes drilled in five counties in the Fox River valley. One of these boreholes, RS-13, was drilled in Winnebago County. The borehole, drilled just north of Oshkosh, encountered 40 m of fine-grained sediment. Examination of the core revealed 8 m of laminated lake sediment sandwiched between two till layers interpreted as Horicon till (bottom layer) and the Kirby Lake till (upper layer) (fig. 13). The Middle Inlet till is not present because the borehole is beyond the margin of the latest ice readvance.

A more complete rotosonic core, RS-3, representing the history of the lake basin, was drilled to the north in Outagamie County (NE¼ SW¼ sec. 24, T23N, R16E). This borehole was drilled on the edge of a marsh (elevation 235 m [771 ft]) well below the maximum level of glacial Lake Oshkosh (fig. 14). The core includes three lake sediment sequences—the three main phases of glacial Lake Oshkosh. A downhole geophysical log of natural gamma radiation of this borehole is consistent with the lithologic log. Both show the various advances and recessions of the Green Bay Lobe as glacial Lake Oshkosh filled and emptied.

We found little evidence of well developed beaches in Winnebago County, even though the lake had numerous phases. This may be explained by fluctuating lake levels caused by small changes in the elevation of the outlet. Even a small elevation change can cause the shoreline to migrate a great distance laterally across the landscape in flat lake basins. In addition, in the northern and central parts of the basin, sufficient sand to develop beaches might not have been present because the landscape was covered predominantly in silt and clay. It is more difficult to explain the lack of well developed beaches in the southern part of the basin, where wave action was directly reworking the sandy Horicon till. Despite the lack of beaches, numerous washed till surfaces are evident at an elevation of approximately 241 m (790 ft). These till surfaces are easily recognized by the presence of an abnormally large number of boulders (fig. 15). It is apparent that wave action along the shoreline effectively eroded and transported the silt, clay, and sand, but left the larger boulders to form a lag.

Holocene lakes

Once the Green Bay Lobe receded from Wisconsin and glacial Lake Oshkosh drained for the last time, standing water remained in the low-lying areas to form Lakes Winnebago, Butte des Morts, Winneconne, and Poygan. These lakes have always been fed by the Wolf and Fox Rivers to the north and southwest of Winnebago County, respectively. Two cores collected in Lake Winnebago in 1995 contain a record of lake sediment deposited during the Holocene (Smith, 1997). Several radiocarbon dates from organic material collected from various intervals of the core indicated that the lake existed at various times during this period. However, from these data it is difficult to determine the size and volume of Lake Winnebago and whether it existed continuously since the most recent glaciation. The levels of all the lakes

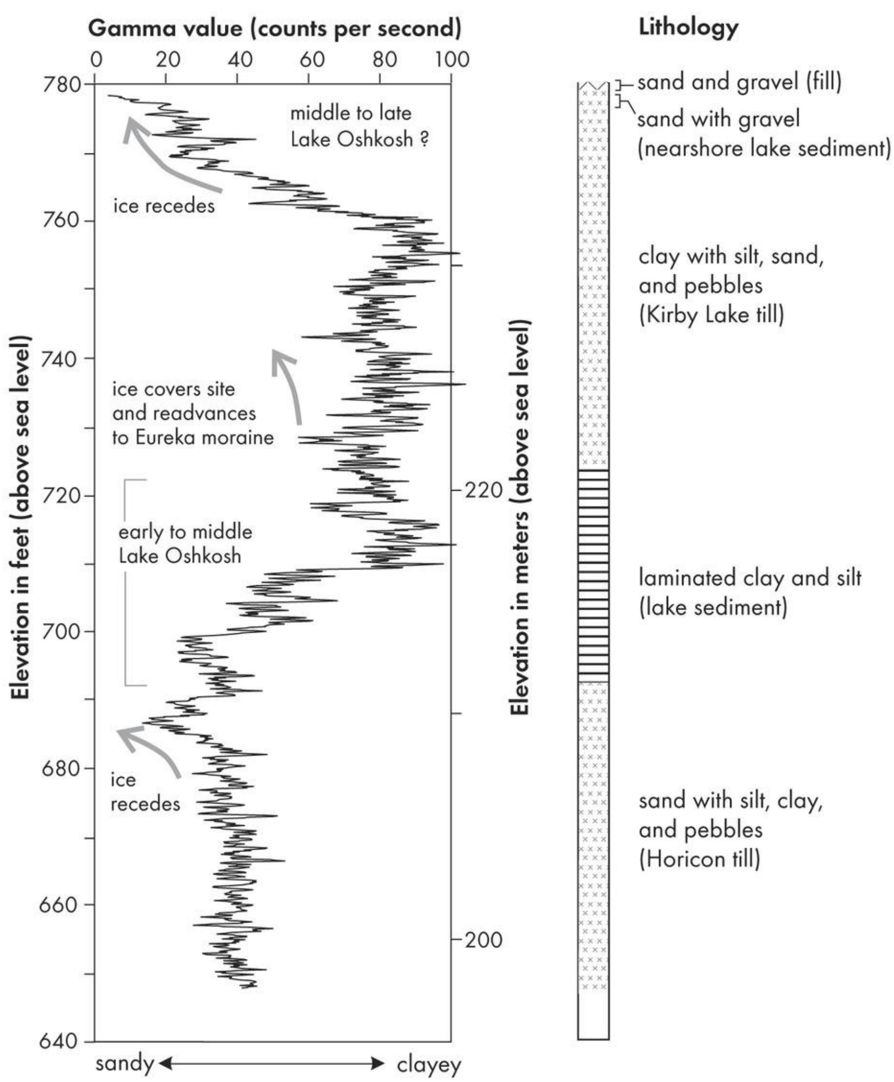

Figure 13. *Downhole geophysical log of natural gamma radiation and associated lithologic log for rotosonic borehole RS-13, Winnebago County. The gamma radiation is measured in counts per second; low counts represent sandy sediment and high counts represent a greater amount of silt and clay. The lithologic log shows 8 m of laminated lake sediment sandwiched between layers of till of the Horicon and Kirby Lake Members.*

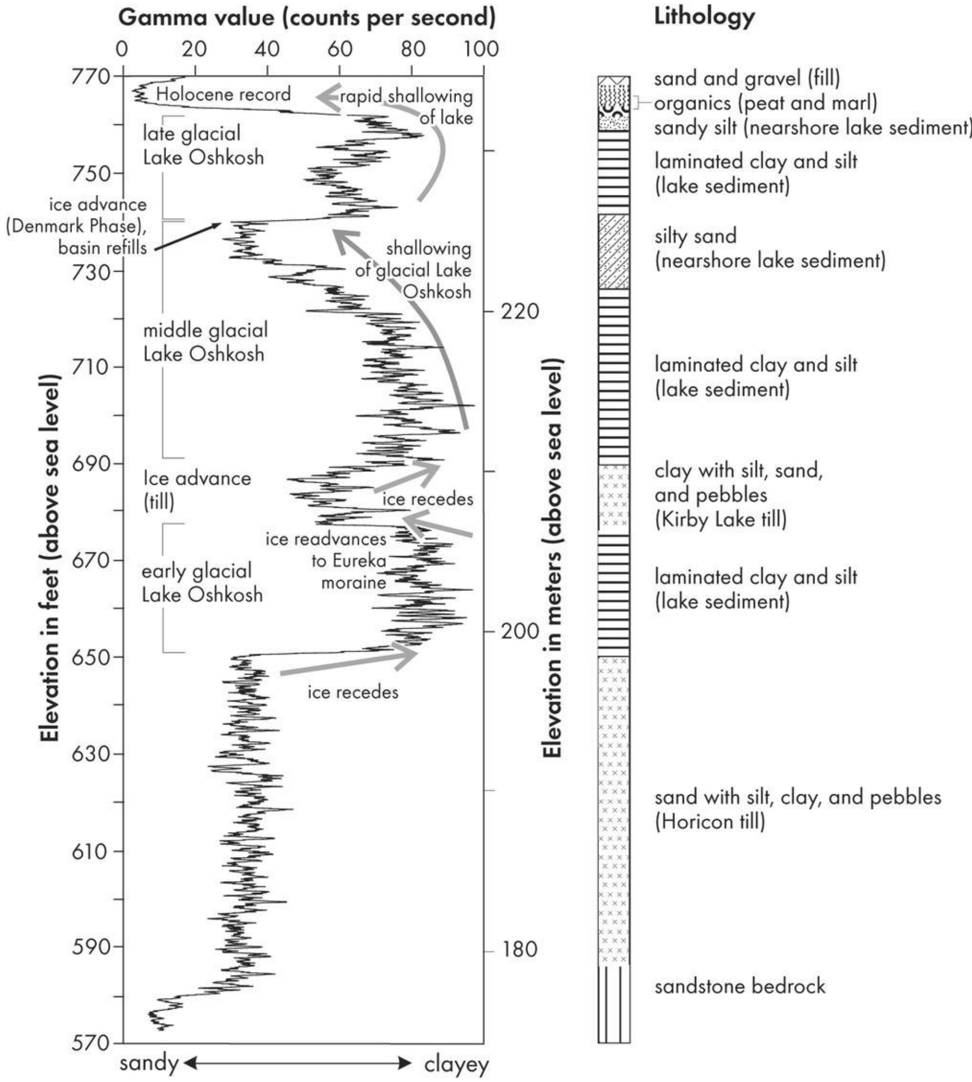

Figure 14. *Downhole geophysical log of natural gamma radiation and associated lithologic log for rotosonic borehole RS-3, Outagamie County. The gamma radiation is measured in counts per second; low counts represent sandy sediment and high counts represent a greater amount of silt and clay. This log and that in figure 13 show several lake sediment sequences that can be attributed to the draining and refilling of glacial Lake Oshkosh.*

have been artificially managed in historic times with locks and dams at the head of the lower Fox River in the cities of Neenah and Menasha. Although these structures were built to control water levels, it appears that the present lakes have existed in some form in essentially the same locations since the most recent glaciation.

Rush Lake, in the southwest part of the county, was once part of glacial Lake Gleason, which formed in front of the Eureka ice margin (fig. 16). The present lake is surrounded by peat-covered lake sediment, which indicates the former size of glacial Lake Gleason (map unit **pl,** plate 1). Given that Rush Lake sits in a naturally low-lying basin, it also has probably existed in some form since the most recent glaciation. Rush Lake is now shallow (less than 3 m), and its level is controlled by a dam at its outlet.

Figure 15. *Photograph of a shoreline boulder lag at an elevation of approximately 790 ft (241 m). Such boulder lags are common along some of the former shorelines of glacial Lake Oshkosh.*

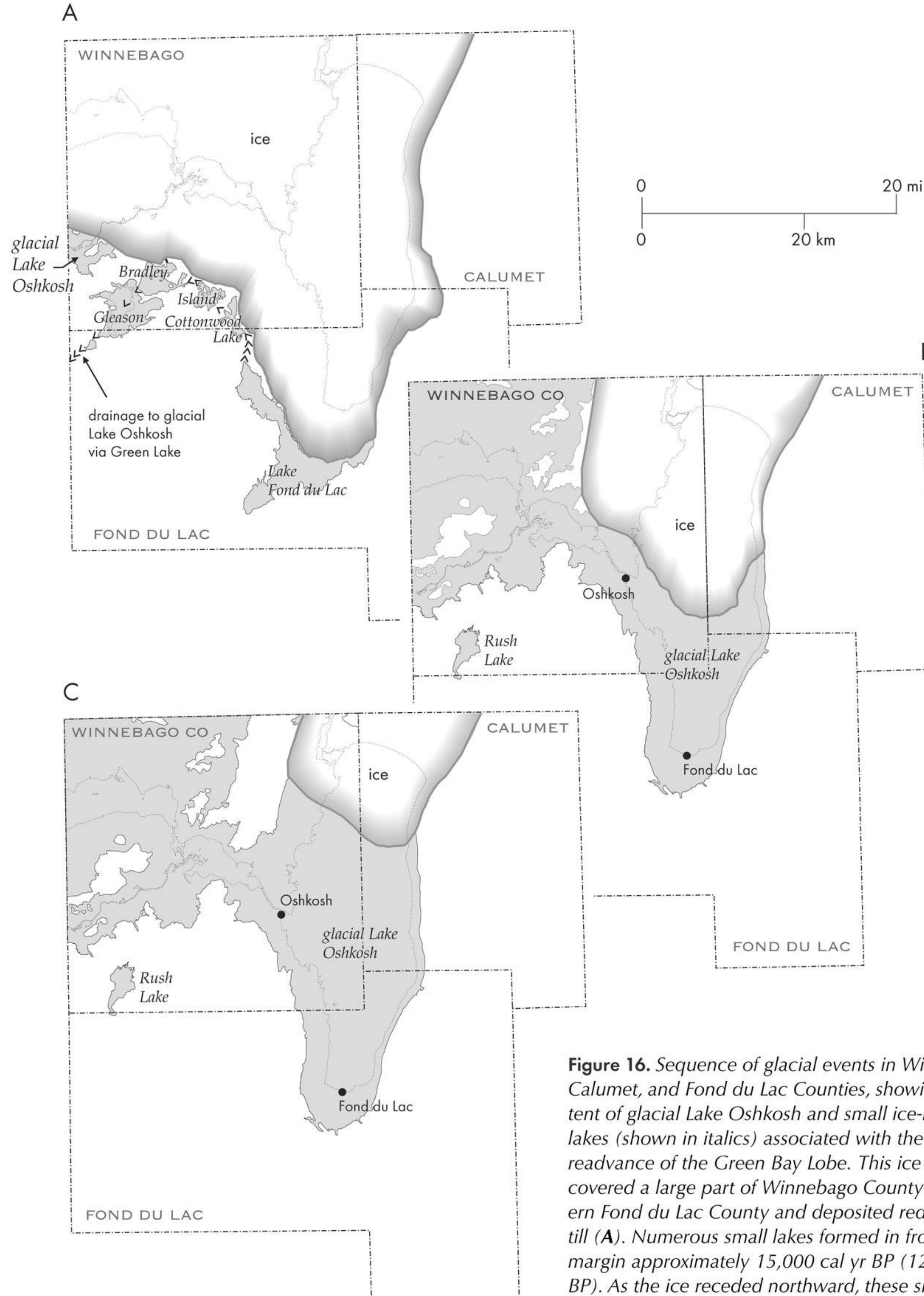

Figure 16. *Sequence of glacial events in Winnebago, Calumet, and Fond du Lac Counties, showing the extent of glacial Lake Oshkosh and small ice-marginal lakes (shown in italics) associated with the first major readvance of the Green Bay Lobe. This ice readvance covered a large part of Winnebago County and northern Fond du Lac County and deposited reddish-brown till (**A**). Numerous small lakes formed in front of the ice margin approximately 15,000 cal yr BP (12,700 ^{14}C yr BP). As the ice receded northward, these small lakes drained into glacial Lake Oshkosh (**B**). Continued recession of the ice northward resulted in the expansion of glacial Lake Oshkosh (**C**).*

Hillslope sediment and landforms

Hillslope sediment (map unit **h,** plate 1), defined as sand, silt, and clay that has moved down slope from upland areas, is limited in Winnebago County because of the low-relief landscape. Most of this sediment is in swales and along small ephemeral streams; much of it was probably deposited immediately following deglaciation, when the landscape was devoid of vegetation. This would have allowed runoff from storm events to transport the sediment to low-lying areas. Much of this sediment probably has filled parts of the modern lakes, explaining their generally shallow depths.

In addition to this postglacial erosion of hillslopes, human occupation of Winnebago County has increased the amount of sediment runoff to existing streams, rivers, and lakes. This runoff is primarily the result of farming and construction practices that modified or removed the vegetative cover. Some part of the area mapped as hillslope sediment on plate 1 probably was partly eroded in the post-settlement era.

Stream sediment and landforms

Stream sediment and associated landforms consisting of sand and gravel are relatively uncommon in Winnebago County. This is partly because glacial Lake Oshkosh covered much of the landscape when the ice receded and buried preexisting sand and gravel deposits beneath silt- and clay-rich lake sediment. Where stream sediment is at the surface, it is shown as meltwater-stream sediment (map units **sa**, **su**, and **se,** plate 1) and postglacial stream sediment (map units **s** and **sp,** plate 1), which is usually found along modern streams and rivers.

Meltwater-stream sediment

The meltwater-stream sediment in Winnebago County is highly variable and can range in grain size from fine sand to gravel and small cobbles. Distribution of this sediment was dependent upon the distance to the source of the meltwater. The coarser materials, including gravel and cobbles, were deposited immediately adjacent to the ice margin, where there was a high-energy environment. As the meltwater flowed away from the ice margin and the river gradient decreased, even smaller-sized grains were not transported effectively and accumulated on the bed of the river. Because the position of an ice margin can fluctuate, it is common to have layers of coarser sediment interspersed with layers of finer sediment.

Most meltwater-stream sediment in Winnebago County is in alluvial fans or small deltas that formed in front of former ice margins. At various locations along these margins, rivers carrying abundant sediment emerged from beneath the ice (fig. 17). Coarse sediment, such as gravel and cobbles, was deposited near the mouth of the emerging river. According to Road Materials Investigation Reports, more than 85 percent of this coarse material consists of dolomite subglacially eroded from the local bedrock. Finer sediment, such as sand and silt, was deposited farther away from the ice margin. Significant accumulation of these sediments occurred where the ice margin remained at one location for many years (fig. 18).

The most prominent ice-margin positions in Winnebago County are associated with alluvial fans (map unit **sa**, plate 1). Most of these fans are in the southern part of the county and are adjacent to parts of the St. Anna and the Eureka moraines. The meltwater-stream sediment in front of the St. Anna moraine is limited in area because the receding margin of the Green Bay Lobe probably did not stabilize at this position for a long time. As a result, sand and gravel carried by the meltwater streams did not have sufficient time to accumulate. By comparison, the meltwater-stream sediment in front of the Eureka moraine is more extensive, indicating that the ice margin stabilized at this location for a longer period of time or that water pro-

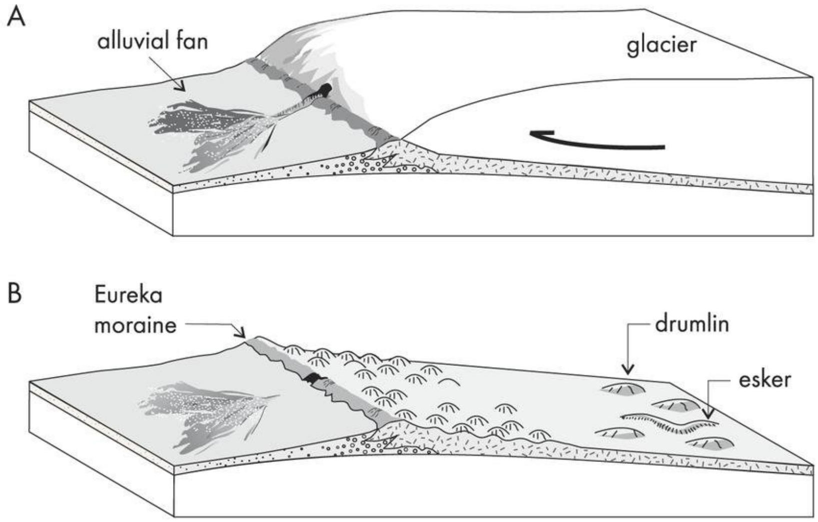

Figure 17. *Schematic showing the margin of the Green Bay Lobe forming a moraine and associated proglacial alluvial fan (**A**). Many features, such as drumlins and eskers that formed on the bed of the glacier (**B**), have been buried beneath lake sediment in Winnebago County. (Modified from Attig and others, 1989.)*

duction was higher due to a warming climate.

In many areas, a veneer of lake sediment has covered the meltwater-stream sediment. Road Materials Investigation Reports and well construction reports for Winnebago County showed that although this sediment is present in the subsurface, mainly in buried bedrock valleys, it appears to be relatively discontinuous. As a result, its distribution in the subsurface is difficult to predict.

Sand and gravel resources

Sand and gravel is a limited resource in Winnebago County because most of the county is covered by either fine-grained lake sediment or glacial till. Historically, the largest

Figure 18. *Photograph of sand and gravel in a proglacial alluvial fan (SW¼ NW¼ sec. 4, T20N, R15E). Such fans commonly exist in front of moraines in Winnebago County. The exposure has a height of approximately 15 m.*

sand and gravel pits have been located in meltwater alluvial fan deposits in front of moraines. A review of topographic maps and aerial photographs revealed that many old pits were located along the Eureka moraine in the southern part of the county. Many of these pits are now ponds. Although areas along the moraine have been mined over the past 80 years, significant reserves still exist; several pits are currently in operation.

The only other significant known sand and gravel deposit is the narrow band of meltwater-stream sediment (map unit **su**, plate 1) in the village of Clayton and the city of Menasha in the northeast part of the county. Review of topographic maps and Road Material Investigations Reports revealed that this narrow zone has many abandoned sand and gravel pits. Given past mining activities, the area would have limited resources for future development of sand and gravel.

Road Materials Investigation Reports and well construction reports of Winnebago County showed that sand and gravel is present at various depths in the subsurface, mainly in buried valleys. Because these deposits are overlain by lake sediment and appear to be relatively discontinuous, their distribution in the subsurface is difficult to predict or map.

Modern stream sediment

Modern postglacial stream sediment (map units **s** and **sp**, plate 1), consisting of silt and clay, underlies floodplains adjacent to most rivers and streams in Winnebago County. Most of this fine-grained sediment probably originated from nearby upland areas that are easily erodable when disturbed by farming, road construction, and urban development. Much of the sediment within the floodplain has accumulated since the most recent glaciation because of the relatively flat topography, which results in low river gradients. This accumulation of sediment indicates that rates of upland erosion are greater than the rate of sediment transport through most river systems to Lake Winnebago. Many rivers in Winnebago County have not incised the landscape. Instead, they have aggraded and created relatively wide floodplains. Many of these floodplains are overlain by peat (map unit **sp**, plate 1).

In addition, where the Fox and Wolf Rivers flow into Lakes Butte des Morts and Poygan, respectively, modern stream sediment has accumulated in prograding deltas. These deltas consist primarily of sand, silt, and clay that accumulated since the most recent glaciation. Large parts of these deltas are currently covered by peat (map unit **sp**, plate 1).

Windblown sediment and landforms

Windblown sediment in Winnebago County is composed of sand and silt. Deposition of most of this sediment probably occurred during and shortly after deglaciation and final drainage of glacial Lake Oshkosh, but was strongly influenced by local wind and weather patterns. At that time, the freshly deglaciated landscape had little vegetative cover to resist wind action and hold sediment in place. In addition, a center of high atmospheric pressure existed over the Laurentide Ice Sheet (Kutzbach, 1987), which caused windy conditions in areas peripheral to the ice sheet. Strong surface winds (katabatic winds) blew outward from the center of the ice sheet and off the ice margin, and most storms (low-pressure cells) tracked eastward across North America along the ice-sheet margin (Busacca and others, 2004).

The most prominent accumulation of windblown sediment consists of sand dunes (now vegetated) that are up to 3 m in height and contain more than 2 m of sand (map unit **w**, plate 1); these dunes are found only in the northern part of the county. The dunes extend northward and westward into adjacent counties, where they are larger and more numerous (Thwaites, 1943). In Winnebago County, dunes are smaller and less widespread southward, giving way to thinner, patchy sand deposits (map units **wg**, **wl**, **lw**, and **gkw**, plate 1) south of Lakes Poygan and Butte des Morts.

In the southwest quarter of the county, windblown sediment is present in small, nondescript dunes and thin, patchy, discontinuous sheet sands. Thus, it was difficult to map, especially where it rests on till of the sandy Horicon Member (map units **ghd** and **ghs**, plate 1) and in places on meltwater-stream sediment (map units **sa**, **su**, and **se**, plate 1).

Disturbed land

Many areas in Winnebago County that originally were marsh or had wet soil have been drained and/or filled to make them suitable for construction of roads, streets, railways, and buildings, particularly in cities. In addition, landfills, quarries (included in map unit **r,** plate 1), and gravel pits represent other areas of human disturbance. However, on plate 1, we have inferred the type of material that was present in most of these areas prior to disturbance during historical times. For example, in the case of much of the filled land in the city of Oshkosh, the surficial material was till of the Kirby Lake Member of the Kewaunee Formation, overlain by patches of lake sediment (map unit **gkl**, plate 1) and perhaps thin accumulations of peat. Areas with peat at the surface were only mapped as peat (map unit **p,** plate 1) if the peat was at least 1 m thick.

PLEISTOCENE HISTORY

Summary of events during the Wisconsin Glaciation

Winnebago County was entirely covered by the Green Bay Lobe during the last part of the Wisconsin Glaciation (fig. 1). Apparently, most unlithified materials that existed in the county prior to the most recent glaciation were eroded by the ice. In addition, the bedrock surface was also probably eroded, presumably enhancing the stream-eroded pre-glacial topography. Striae (scratches that result from subglacial processes) are commonly observed on the bedrock surface exposed by quarrying operations (fig. 19); they indicate that the ice moved southwestward at this time. This ice-flow direction is confirmed by the long-axis orientation of drumlins. Although till of the Horicon Member and associated waterlaid sediments were deposited in places by the ice at this time, most sediment was deposited in the county as the Green Bay Lobe receded from its outermost end moraine, beginning after 21,000 cal yr BP.

Early glacial Lake Oshkosh

During recession of the ice, which began approximately 20,000 cal yr BP (16,900 ^{14}C yr BP), glacial Lake Oshkosh formed; it eventually covered more than 60 percent of Winnebago County (fig. 5) and initially drained southward through the Dekorra outlet near the present location of the city of Portage (fig. 20); this area now has an elevation of approximately 241 m (790 ft). As the margin of the Green Bay Lobe receded toward the northeast across the county, it experienced brief stillstands or minor readvances that formed the Rush Lake and St. Anna moraines (fig. 11) in the southwestern corner of the county. Approximately 17,500 cal yr BP, the Green Bay Lobe had receded north of Winnebago County. As the ice margin receded out of the Fox River valley and later into the Green Bay lowland, it exposed a succession of progressively lower outlets for glacial Lake Oshkosh across the Silurian escarpment (fig. 20). These outlets, which drained eastward to the Lake Michigan basin, were probably reoccupied and modified by glacial erosion each time the Green Bay Lobe advanced into and receded from the Fox River valley. At least two such readvances occurred after 16,000 cal yr BP; it is uncertain whether all the outlets were used when the Green Bay Lobe initially receded northward.

As the Green Bay Lobe continued to recede northeastward across the Fox River

Figure 19. *Photograph of bedrock striae on top of the Sinnipee Group in the Gruska pit (SE¼SE¼ sec. 8, T20N, R17E). The striae trend to the southwest, indicating the ice-flow direction of the Green Bay Lobe.*

valley, the Dekorra outlet was abandoned and a series of lower outlets, none of them in Winnebago County, opened eastward into the Lake Michigan basin (fig. 20). The elevation and use of these outlets during the initial recession of the ice lobe are not well known because subsequent readvances may have modified them. However, given the large drainage channels that were cut downstream of each outlet, we assumed that their modern-day elevations reflect the sequence of lake drainage during the initial recession of the Green Bay Lobe.

The Manitowoc outlet was the first of four eastern outlets to open through a low area on the northern edge of the village of Sherwood, Calumet County (not shown). Although this low area is at a present-day elevation of 253 m (830 ft), it must have been lower than the Dekorra outlet at the time as a result of depression from the loading of the Earth's surface with the Green Bay Lobe (see section entitled *Isostatic adjustment of east-central Wisconsin*). The outlet used a channel that now is occupied by the North Branch of the Manitowoc River. Glacial Lake Oshkosh must have drained through this channel and into a lake that once occupied the low areas of the Brillion, Killsnake, and Collins State Wildlife Areas. The lake that occupied these low areas must have drained through a bedrock-floored outlet now known as Cato Falls, which has an elevation of 241 m (790 ft) (Mickelson and Socha, in press).

With the continued recession of the Green Bay Lobe, a lower outlet just east of the city of Green Bay opened through the Neshota and West Twin River valley system. The base of this outlet is now at an elevation of 233 m (765 ft), approximately 20 m lower than the Manitowoc outlet; drainage through this outlet should have caused a dramatic fall of the lake level in glacial Lake Oshkosh.

It was not until the opening of the third eastern outlet, along the Kewaunee River valley, that glacial Lake Oshkosh decreased sig-

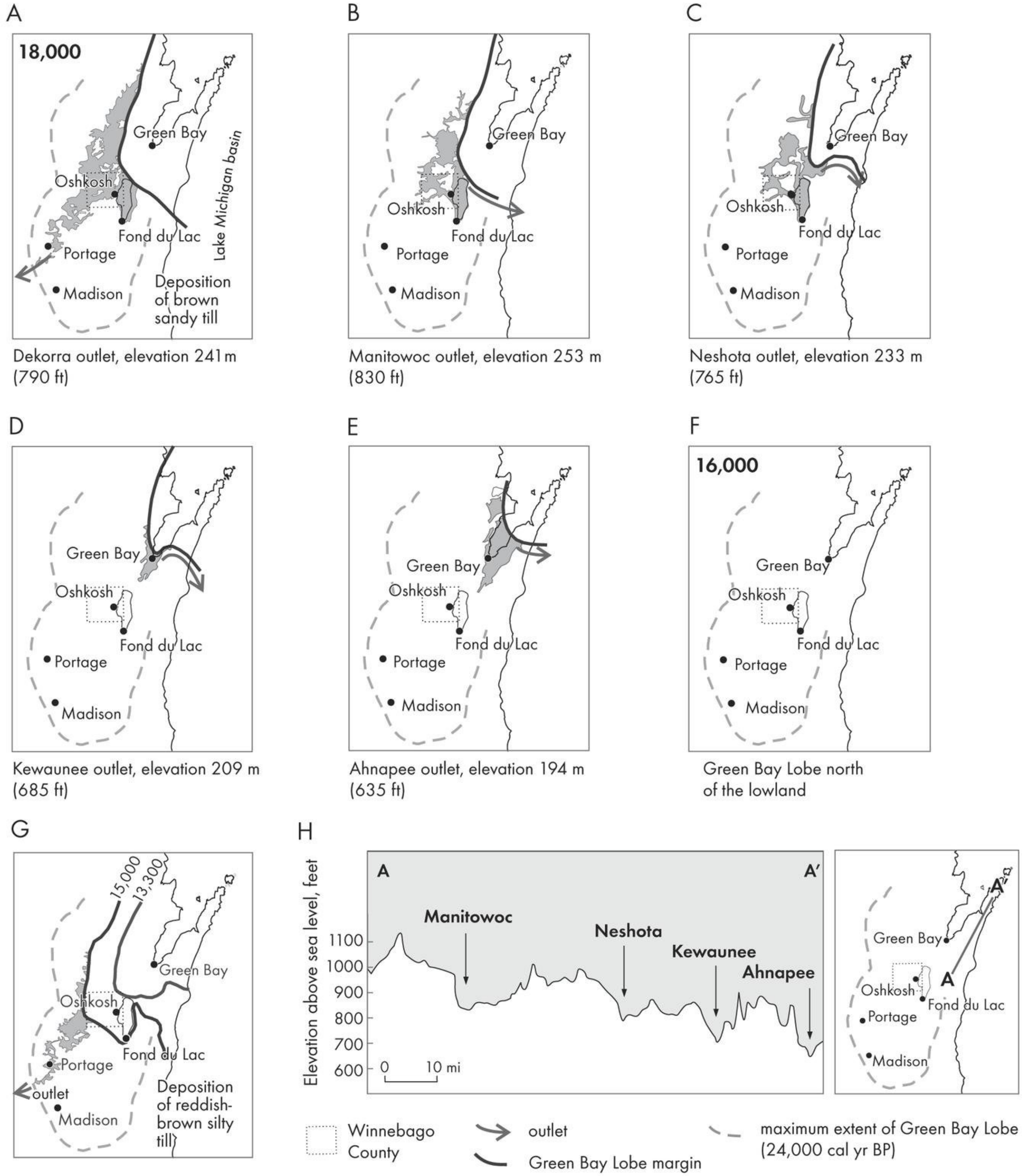

Figure 20. *Stages of glacial Lake Oshkosh. Approximately 18,000 cal yr BP (15,000 ^{14}C yr BP), the Green Bay Lobe began to recede, opening a sequence of progressively lower outlets to glacial Lake Oshkosh (**A–E**). By approximately 16,000 cal yr BP (13,400 ^{14}C yr BP), the lake drained completely **(F).** The lobe readvanced to the central part of the valley at least twice, about 15,000 and 13,300 cal yr BP (12,700 and 11,500 ^{14}C yr BP), reactivating glacial Lake Oshkosh (**G**). A profile of the land-surface elevation along the Silurian escarpment shows a cross section of the four river valleys in which water drained from glacial Lake Oshkosh (**H**).*

nificantly in size. The base of the outlet, 3 km northwest of the village of Frog Station (not shown), is at an elevation of 209 m (685 ft). This represents a 24 m drop in lake level from the Neshota and West Twin River outlet and a 44 m drop from the Manitowoc outlet. Such a drop must have been caused by glacial Lake Oshkosh draining quickly through the valley now occupied by the Kewaunee River. This outburst resulted in the relatively flat, isolated basins of ancestral Lakes Rush, Poygan, Butte des Morts and Winnebago being filled with water.

With the continued recession of the Green Bay Lobe northward, a fourth and final outlet eastward to the Lake Michigan basin opened, and drainage decreased the level of glacial Lake Oshkosh to an elevation of 194 m (635 ft). This outlet, 3 km south of Little Sturgeon Bay in the Gardner Swamp State Wildlife Area, lowered the level of glacial Lake Oshkosh another 15 m. Water from the lake discharged down the valley now occupied by the Ahnapee River. This decrease in lake level had no effect upon Winnebago County because most of the land elevation of the county was already above this elevation (approximately 225 m [738 ft]). However, there was probably a lake similar in size to the existing Lake Winnebago that drained northward to the ancestral lower Fox River. This lake probably drained through a bedrock-controlled outlet near the city of Appleton.

The Green Bay Lobe ultimately receded north of Wisconsin, opening the drainageway of the Fox River to the existing Glenwood level of ancestral Lake Michigan (glacial Lake Chicago) in Green Bay (Hansel and others, 1985). This lake then dropped to well below its present level during the Mackinaw Interstadial (Hansel and Mickelson, 1988).

Middle glacial Lake Oshkosh

Eventually, the Green Bay Lobe started to readvance approximately 15,500 cal yr BP, reforming glacial Lake Oshkosh as the ice blocked the eastern outlets to the Lake Michigan basin. The lake level rose once again, and large parts of Winnebago County were again inundated with water. The lobe continued to readvance through the lake onto an upland area, ultimately terminating at the Eureka moraine in southern Winnebago County. As the ice advanced across the county, it eroded and redeposited lake sediment (the Kirby Lake Member of the Kewaunee Formation) across the landscape. In several places, the Green Bay Lobe buried organic material that dates to approximately 16,000 cal yr BP (13,400 ^{14}C yr BP). One of these sites is located in Winnebago County (table 1, sample 23).

Five small glacial lakes formed along the ice margin in front of the Eureka moraine (fig. 16), well above the level of glacial Lake Oshkosh, at an elevation of 265 m (870 ft). These lakes occupied small basins that were enclosed and isolated by upland areas to the east, south, and west. The largest of these lakes, glacial Lake Fond du Lac, drained northward through several smaller lakes in southern Winnebago County. These smaller glacial lakes, called Cottonwood, Island, Bradley, and Gleason, drained to the west near Green Lake (not shown) to glacial Lake Oshkosh. When the Green Bay Lobe started to recede, an outlet was cut northward through a low spot in the Eureka moraine near the community of Waukau (not shown). The water drained down a small valley, now occupied by Rush Creek (not shown), to glacial Lake Oshkosh, which was draining southward to the reoccupied Dekorra outlet. All five lakes, with the exception of Lake Gleason, drained completely after glaciation. Lake Gleason was apparently deeper than the rest of the proglacial lakes and sat in a low-lying area, which is now occupied by Rush Lake.

As the Green Bay Lobe continued to recede from the Eureka moraine, glacial Lake Oshkosh still covered Winnebago County. As the ice receded north of the county line, the eastern outlets opened once again to drain the lake. The outlets must have opened relatively quickly because a large part of eastern Winnebago County that is below projected lake level consists of Kewaunee till covered only by thin patches of lake sediment (map unit **gkl,** plate 1). Either the lake was short lived or it was so shallow that only a small amount of fine-grained sediment accumulated.

Late glacial Lake Oshkosh

Immediately after the ice receded, large upland areas of east-central Wisconsin, including parts of Winnebago County, were covered with tundra and eventually a boreal forest. In low-lying areas, extensive wetland vegetation covered the landscape.

Shortly thereafter, at approximately 14,000 cal yr BP (12,000 ^{14}C yr BP), the Green Bay Lobe readvanced (Denmark Phase) one last time into Wisconsin, stopping at a position on the northern edge of Winnebago County near the present location of the city of Appleton. Glacial Lake Oshkosh again formed as the eastern outlets were blocked by the advancing ice margin. The rising water and the readvancing ice buried a boreal forest that was growing on the landscape. This forest, called the Two Creeks Forest Bed, is known to have grown around 14,000 to 13,300 cal yr BP (12,000 to 11,500 ^{14}C yr BP). In Winnebago County, many of the wetlands surrounding the basins now occupied by Lakes Winnebago, Poygan, and Butte des Morts were buried beneath lake sediment after glacial Lake Oshkosh reformed. As the ice receded, glacial Lake Oshkosh drained for the last time to the Michigan basin though the series of four eastern outlets. The existing outlet elevations reflect this final draining.

Isostatic adjustment of east-central Wisconsin

The weight of the ice sheet on the Earth's surface during the most recent glaciation caused vertical motion (deformation) of the land across Wisconsin. As the ice advanced across the state, most of the deformation was downward, depressing the land surface. When the ice sheet started to recede northward, the land started to rebound upward because of the unloading of the overlying ice. The effects of this loading and unloading are still measurable today as vertical motion continues at different rates across the state. This differential isostatic adjustment of the Earth has been known to be an important factor in changing lake levels (Clark and others, 1990). This is probably not the case in the Oshkosh basin because the opening of lower outlets resulting from recession of the ice margin occurred at a much faster rate than isostatic rebound. This is not to say that isostatic adjustment of the Oshkosh basin is not important over a longer time span. Isostatic rebound resulting from glacial loading has had a long-term effect on the Oshkosh basin and is important to understanding the history of the region (Clark and others, 2008).

Isostatic adjustment of Wisconsin caused changes in land elevation, including the elevations of the outlets that controlled the levels of glacial Lake Oshkosh. The extent of the lake at any stage varied as a function of time, depending on the amount of adjustment. For example, at any given outlet, such as Kewaunee, the extent of glacial Lake Oshkosh differed between phases simply because the elevation of the outlet and land surface varied over time.

To help understand the glacial-isostatic adjustment of the Earth's surface in east-central Wisconsin, Clark and others (2008) used a numerical ice-sheet model. Two important parameters of this model are the viscoelastic properties of the Earth's mantle and the thickness history of the Late Wisconsin ice sheets. Details of the model can be found elsewhere (Clark and others, 1990; Clark and others, 2008).

Initial runs of the ice-sheet model resulted in calculations of tilt of east-central Wisconsin three times greater than that observed across the Oshkosh basin. To address this poor fit, the thickness of the ice sheet in the model needed to be reduced over the Great Lakes region (Clark and others, 2008). After several attempts, it became apparent that only 40 percent of the ice thickness was required to fit the observed tilt in the basin. Therefore, the model used the original ice-sheet configuration everywhere except over the Great Lakes region, where the thickness is 40 percent of its initial value. This reduction in ice thickness results in the Green Bay Lobe at its maximum extent being approximately 300 m thick over east-central Wisconsin. This is similar to the ice-sheet reconstruction of Clark (1992), but thinner than that proposed by Colgan (1999).

With the ice-sheet model reasonably well calibrated, deformation of the Oshkosh basin was calculated for the past 30,000 years. High resolution digital elevation models (DEMs), lake bathymetry, and deformation calculations of glacial-isostatic adjustment were used to reconstruct glacial Lake Oshkosh. No assumptions about outlet locations or shoreline positions were needed for the calculation. We used the calculated deformations, relative to the present geoid, to warp the present DEM through time. We constructed a series of paleo-DEMs for east-central Wisconsin, giving the topography at 1,000-year intervals for the past 30,000 years.

Paleo-DEMs and an estimated location of the ice-sheet margin were incorporated in a geographic information system to determine the extent of glacial Lake Oshkosh at the various stages (Clark and others, 2008). Figure 21 shows the calculated deformation isobases (lines of equal tilt) relative to the present geoid for 13,600 cal yr BP. It appears there is approximately 50 m of differential uplift between the southern and northern parts of glacial Lake Oshkosh. Figure 22 shows isobases and calculated lakes over the entire Great Lakes region at a coarser resolution.

The model results revealed that the Oshkosh basin is dynamic. Figure 23 displays the amount of deformation calculated along a transect through the various outlets of glacial Lake Oshkosh as a function of time. It is clear that the amount of tilt and the absolute elevation of the transect points (outlets) varied during the glacial advance over the region (30,000 to 18,000 cal yr BP) and the subsequent recession. Maximum tilt (approximately 0.2 m/km) occurred at 18,000 cal yr BP. Calculations of deformation for the known outlets of glacial Lake Oshkosh indicated that the area of the outlets initially subsided during the ice advance and recession. However, most of the region has been rebounding throughout the Holocene (see Clark and others, 2008). Approximately 100 m of vertical movement has affected the region.

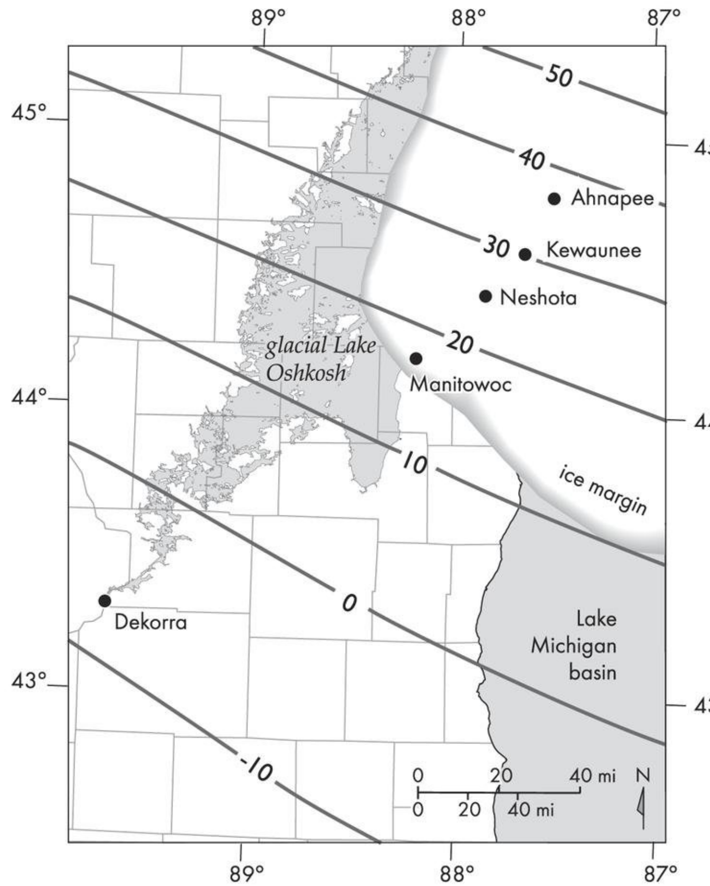

Figure 21. *Isobases (in meters) of deformation in relation to present geoid calculated for the Oshkosh and Michigan basins for 13,600 cal yr BP. Shorelines of glacial Lake Oshkosh formed at that time would be tilted upward 50 m, toward the northeast between the southern and northern limits of the lake. The circles represent outlet locations. Modified from Clark and others (2008).*

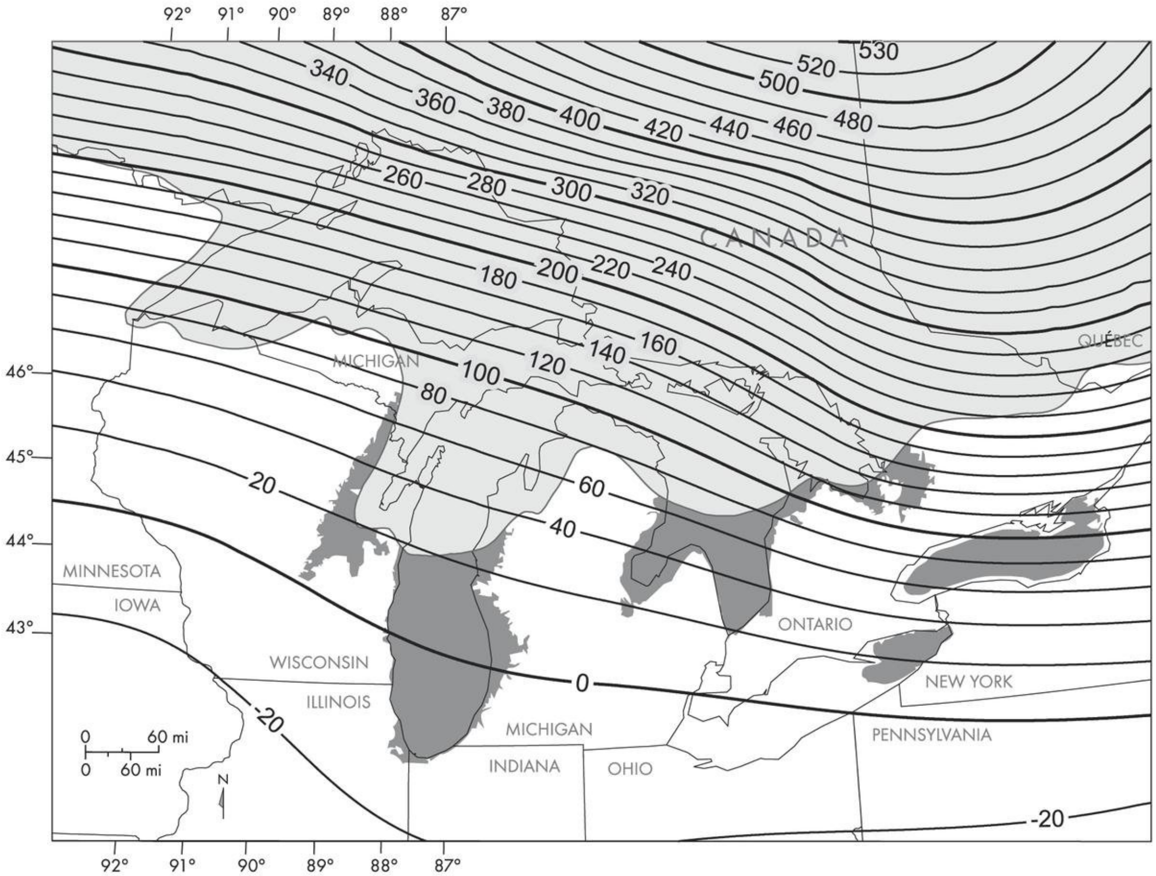

Figure 22. *Isobases (in meters) of deformation in relation to present geoid calculated for the Upper Midwest for 13,600 cal yr BP. Modified from Clark and others (2008).*

GROUNDWATER SYSTEM

Knowing the type of rock and sediment layers beneath the land surface is critical for understanding water-supply issues in Winnebago County. Because of the importance of groundwater withdrawal for municipal and private wells, several investigations (Conlon, 1997; Batten and Bradbury, 1996; Krohelski, 1986; Olcott, 1966) have addressed, in varying detail, the hydrogeology of the Winnebago County area. The following discussion summarizes these studies.

Aquifers

Early research (Olcott, 1966) combined the entire sequence of Cambrian and Ordovician sandstone and dolomite (fig. 6) underlying Winnebago County into one unit called the sandstone aquifer. More recently, Conlon (1997), in modeling the groundwater system in several counties, including Winnebago County, considered the lower part of the Sinnipee Group (fig. 6) a confining unit in the eastern part of the county. The underlying units were then lumped into a single aquifer. In nearby Brown County, Krohelski (1986) treated the St. Lawrence Formation of the Trempealeau Group and the Tunnel City Group as a second confining unit, thus defining two sandstone aquifers: the upper aquifer, comprising the Ancell and Prairie du Chien Groups and the Jordan Formation, and the lower aquifer, including the Cambrian sandstone units that underlie the Tunnel City Group and overlie the Precambrian basement. The top of the Precambrian igneous and metamorphic rock is usually considered the bottom of the groundwater flow system because little is known about groundwater movement below this depth.

The combined thickness of the sandstone and dolomite that make up the sandstone aquifer increases from the northwest to southeast; it is absent in a small area along the western edge of the county just north of Lake

Poygan, but thickens to approximately 200 m to 215 m at the city of Oshkosh. This range in thickness is the result of two factors. First, the underlying Precambrian surface slopes from a high of more than 150 m (500 ft) above sea level where Precambrian igneous and metamorphic rocks subcrop just north of Lake Poygan to an elevation less than 30 m (100 ft) above sea level along Lake Winnebago (Olcott, 1966, plate 3). Older Cambrian sandstone pinches out along the Precambrian high, but thickens to the east. Second, all Ordovician rock and uppermost Cambrian rock have been completely eroded in the northwestern part of the county (fig. 1 on plate 2). The resulting bedrock surface in this area of the county, prior to the deposition of glacial deposits, comprises several west–southwest trending valleys that joined a larger regional drainage network (Olcott, 1966). These ancestral bedrock valleys underlie topographic low areas, such as Lake Poygan, Rush Lake, and the Fox River, and are filled in many places with more than 60 m of glacial deposits, much of it glacial lake sediment.

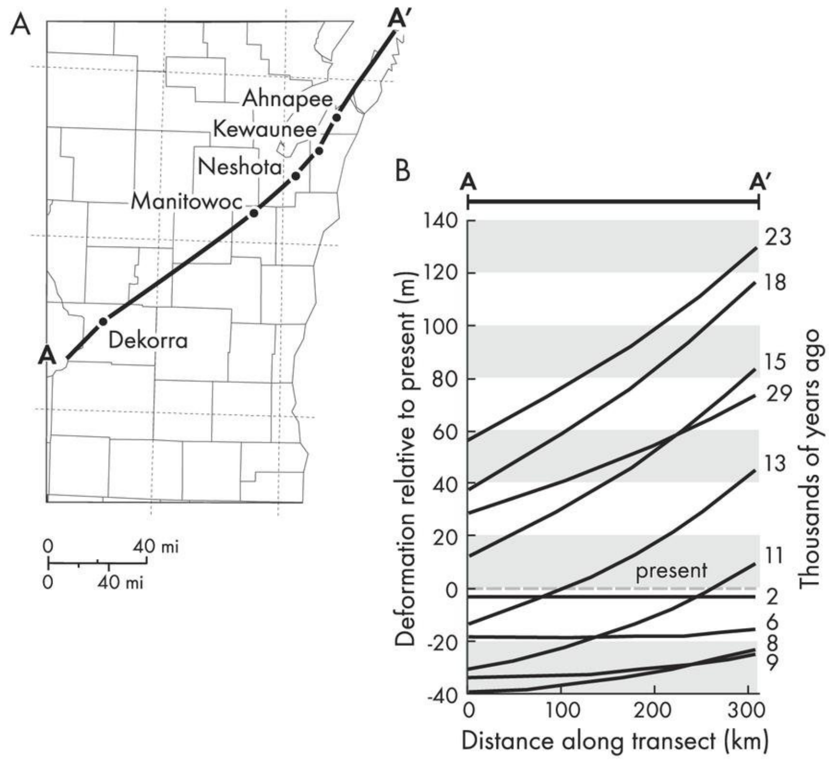

Figure 23. *Deformation between 29,000 and 2,000 cal yr BP in relation to present along a transect (**A**; transect A–A') that intersects the outlets of glacial Lake Oshkosh. These deformations, when subtracted from the present land surface, give the elevations relative to present sea level (**B**). The amount of tilt and the magnitude of deformation differs at the indicated times. Modified from Clark and others (2008).*

Well yield

The rate that water can be pumped from a well is determined by the physical properties of the aquifer that is open to the well and how a well is constructed. Well-construction factors include total well depth, casing depth, and borehole diameter. Well yield is the rate of water pumped from a well in liters per minute (L/min). In Winnebago County, rural private domestic wells that require only occasional short periods of pumping at 20 to 40 L/min during the day are typically 0.15 m in diameter, and their total depths range from about 30 to 75 m. These wells are generally finished in bedrock aquifers, such as the St. Peter sandstone (fig. 6) in the central part of the county, and the fractured upper parts of the Sinnipee Group dolomite and/or St. Peter sandstone in the eastern part of the county. Where the Sinnipee Group and the St. Peter Formation are absent in the western and central parts of Winnebago County (fig. 1 on plate 2), rural domestic bedrock wells typically extract water from whichever Cambrian sandstone unit is encountered. Many rural domestic wells in these areas are also finished with well screens in buried glacial sand and gravel deposits at various depths in the bedrock valleys. Large-capacity municipal and industrial wells in urban areas, such as Oshkosh, Neenah, and Omro, are typically 0.30 to 0.6 m in diameter and are drilled to Cambrian sandstone, to total depths of 150 to 215 m. Properly constructed wells in these bedrock units are typically capable of sustained pumping rates from 800 to 2,000 L/min.

Groundwater flow

Groundwater recharge in Winnebago County is similar to most places in that a percentage of precipitation and snowmelt infiltrates the land surface and moves vertically until it reaches the water table. From there, much of the water begins to move laterally from upland areas to nearby lowland areas, such as wetlands, streams, and lakes, where it discharges to these surface-water bodies as groundwater seepage. This flow regime is referred to as the shallow groundwater system. In the shallow system, the length of the flow path from the recharge to the discharge area is usually less than 2 km and in many cases less than 1 km. Part of the water reaching the aquifer will continue to move vertically downward into deeper aquifer units, such as the Cambrian sandstone in Winnebago County. At depth, this water will also begin to flow laterally, sometimes traveling kilometers before discharging to larger bodies of water. Groundwater flowing at these greater depths and distances is referred to as the deep or regional groundwater system.

The groundwater system in Winnebago County is reasonably complex as a result of the combination of aquifers and confining units that underlie the county (Batten and Bradbury, 1996). For example, the lower part of the Sinnipee Group, a confining unit, restricts downward flow of groundwater into the underlying sandstone units in the eastern third of the county. Here, most groundwater recharge infiltrates and remains in the shallow flow system. In the western two-thirds of the county, small upland areas underlain by Prairie du Chien Group dolomite (fig. 1 on plate 2) may be the only areas of recharge to either the shallow or the deep groundwater. The fine-grained glacial lake sediment that covers most of the broad lowlands in the county somewhat confines the aquifers that underlie it and also restricts groundwater recharge and discharge to shallow and regional systems. This is best exemplified by the large number of flowing wells finished at all depths along the shores of Lake Poygan, Lake Butte des Morts, Rush Lake, and all along the shoreline of the Fox and Wolf Rivers in the western half of the county.

Although the direction of flow in the shallow groundwater system can be determined for this part of the county, it is unclear in what direction and how far groundwater flows in the deeper sandstone units underlying the western part of the county. Conlon's (1997) groundwater flow model simulated a divide in the deep sandstone aquifer units. This divide ran essentially north–south through the middle of the county, with groundwater discharging to the Fox River and Lake Poygan in the western half of the county and groundwater moving east and discharging to Lake Winnebago and pumping wells in the Neenah area on the eastern side of the county. However, there are very few water-level measurements in deep sandstone wells in the western half of the county with which to calibrate the model.

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REFERENCES

Alden, W.C., 1918, Quaternary geology of southeastern Wisconsin: U.S. Geological Survey Professional Paper 106, 356 p.

Attig, J.W., Clayton, Lee, and Mickelson, D.M., eds., 1988, Pleistocene stratigraphic units of Wisconsin 1984–87: Wisconsin Geological and Natural History Survey Information Circular 62, 61p.

Attig, J.W., Mickelson, D.M., and Clayton, Lee, 1989, Late Wisconsin landform distribution and glacier-bed conditions in Wisconsin: *Sedimentary Geology,* v. 62, p. 399–405.

Batten, W.G., and Bradbury, K.R., 1996, Regional groundwater flow system between the Wolf and Fox Rivers near Green Bay, Wisconsin: Wisconsin Geological and Natural History Survey Information Circular 75, 28 p.

Bradbury, K.R., and Muldoon, M.A., 1990, Hydraulic conductivity determinations in unlithified glacial and fluvial materials, *in* Nielson, D.M., and Johnson, A.I., eds., *Ground Water and Vadose Zone Monitoring:* ASTM Special Technical Publication 1053, p. 138–151.

Brown, B.A., 2004, Preliminary bedrock geologic map of Winnebago County, Wisconsin: Wisconsin Geological and Natural History Survey Open File Report 2004-24, scale 1:100,000.

Busacca, A.J., Begét, J.E., Markewich, H.W., Muhs, D.R., Lancaster, N., and Sweeney, M.R., 2004, Eolian sediments, *in* Gillespie, A.R., Porter, S.C., and Atwater, B.F., eds., *The Quaternary Period in the United States:* Amsterdam, Elsevier, Developments in Quaternary Science, no. 1, p. 275–309.

Chamberlin, T.C., 1883, *Geology of Wisconsin—Survey of 1873-1879,* v. 1: Milwaukee, Commissioners of Public Printing, 725 p.

Clark, J.A., Befus, K., Hooyer, T.S., Stewart, P., Shipman, T., Gregory, C., and Zylstra, D., 2008, Numerical simulation of the paleohydrology of glacial Lake Oshkosh, eastern Wisconsin: *Quaternary Research,* v. 68, p. 117–129.

Clark, J.A., Pranger, H.S., Walsh, J.K., and Primus, J.A., 1990, Numerical model of glacial isostasy in the Lake Michigan basin, *in* Schneider, A.F., and Fraser, G.S., eds., Late Quaternary History of the Lake Michigan Basin: Geological Society of America Special Paper 251, p. 111–123.

Clark, P.U., 1992, Surface form of the southern Laurentide Ice Sheet and its implications to ice-sheet dynamics: *Geological Society of America Bulletin,* v. 104, no. 5, p. 595–605.

Clayton, Lee, Attig, J.W., Mickelson, D.M., Johnson, M.D., and Syverson, K.M., 2006, Glaciation of Wisconsin (third edition): Wisconsin Geological and Natural History Survey Educational Series 36, 4 p.

Colgan, P.M., 1999, Reconstruction of the Green Bay Lobe, Wisconsin, United States, from 26,000 to 13,000 radiocarbon years B.P., *in* Mickelson, D.M., and Attig, J.W., eds., Glacial Processes Past and Present: Geological Society of America Special Paper 337, p. 137–150.

Colgan, P.M., 2002, Glacial landforms of the southern Green Bay Lobe, southeastern Wisconsin: Wisconsin Geological and Natural History Survey Miscellaneous Map 52, scale 1:250,000.

Conlon, T.D., 1997, Hydrogeology and simulation of ground-water flow in the sandstone aquifer, northeastern Wisconsin: U.S. Geological Survey Water-Resources Investigations Report 97-4096, 60 p.

Das, B.M., 1994, *Principles of geotechnical engineering,* third edition: PWS Publishing Company, Boston, Massachusetts, 672 p.

Edil, T.B., and Mickelson, D.M., 1995, Overconsolidated glacial tills in eastern Wisconsin: *Transportation Research Record* 1479, p. 99–106.

Hansel, A.K., and Mickelson, D.M., 1988, A reevaluation of the timing and causes of high lake phases in the Lake Michigan Basin, *Quaternary Research,* v. 29, p. 113-128.

Hansel, A.K., Mickelson, D.M., Schneider, A.F., and Larsen, C.E., 1985, Late Wisconsinian and Holocene history of the Lake Michigan basin, *in* Karrow, P., and Calkin, P.E., eds., Quaternary evolution of the Great Lakes: Geological Association of Canada Special Paper 30, p. 40–53.

Krohelski, J.T., 1986, Hydrogeology and groundwater use and quality, Brown County, Wisconsin: Wisconsin Geological and Natural History Survey Information Circular 57, 42 p.

Kutzbach, J.E., 1987, Model simulations of the climatic patterns during deglaciation of North America, *in* Ruddiman, W.F., and Wright, H.E., Jr., eds., North America and adjacent oceans during the last deglaciation, *The Geology of North America,* v. K-3: Geological Society of America, p. 425–446.

Maher, L.J., Jr., and Mickelson, D.M., 1996, Palynological and radiocarbon evidence for deglaciation events in the Green Bay Lobe, Wisconsin: *Quaternary Research,* v. 46, p. 251–259.

McCartney, M.C., 1979, Stratigraphy and compositional variability of till sheets in part of northeastern Wisconsin: Ph.D. thesis, University of Wisconsin, Madison, 147 p.

McCartney, M.C., and Mickelson, D.M., 1982, Late Woodfordian and Greatlakean history of the Green Bay Lobe, Wisconsin: *Geological Society of American Bulletin,* v. 93, no. 4, p. 297–302.

Mickelson, D.M., Clayton, Lee, Baker, R.W., Mode, W.N., and Schneider, A.F., 1984, Pleistocene stratigraphic units of Wisconsin: Wisconsin Geological and Natural History Survey Miscellaneous Paper 84-1, 15 p plus appendixes.

Mickelson, D.M., and Socha, B.J., in press, Quaternary geology of Calumet and Manitowoc Counties: Wisconsin Geological and Natural History Survey Bulletin.

Mickelson, D.M., and Syverson, K.M., 1997, Quaternary geology of Ozaukee and Washington Counties, Wisconsin: Wisconsin Geological and Natural History Survey Bulletin 91, 56 p.

Mitchell, M.J., 1980, Soil survey of Winnebago County, Wisconsin: United States Department of Agriculture, 182 p.

Need, E.A., 1983, Pleistocene geology of Brown County, Wisconsin: Wisconsin Geological and Natural History Survey Information Circular 48, 19 p.

Olcott, P.G., 1966, Geology and water resources of Winnebago County, Wisconsin: U.S. Geological Survey Water-Supply Paper 1814, 61 p.

Rodenbeck, S.A., 1988, Merging Pleistocene lithostratigraphy with geotechnical and hydrogelogic data—Examples from eastern Wisconsin: Wisconsin Geological and Natural History Survey Open-File Report 88-9, 303 p.

Schreiber, M.E., Gotkowitz, M.B., Simo, J.A., and Freiberg, P.G., 2003, Mechanisms of arsenic release to ground water from naturally occurring sources, eastern Wisconsin, *in* Welch, A.H., and Stollenwerk, K.G., eds., *Arsenic in Ground Water: Geochemistry and Occurrence:* Kluwer Academic Publishers, p. 259–280.

Schreiber, M.E., Simo, J.A. and Freiberg, P.G., 2000, Stratigraphic and geochemical controls on naturally occurring arsenic in groundwater, eastern Wisconsin, USA: *Hydrogeology Journal,* v. 8, no. 2, 161–176.

Smith, G.L., 1997, Late Quaternary climates and limnology of the Lake Winnebago basin, Wisconsin, based on ostracodes: *Journal of Paleolimnology,* v. 18, no. 3, p. 249–260.

Stuiver, M., Reimer, P.J., Bard, E., Beck, J.W., Burr, G.S., Hughen, K.A., Kromer, B., McCormac, G., van der Plicht, J., and Spurk, M., 1998, IINTCAL 98 radiocarbon age calibration, 24,000-0 cal BP; *Radiocarbon,* v. 40, no. 3. p. 1041–1083.

Thornburg, K. and Sahai, N., 2004, Arsenic occurrence, mobility, and retardation in sandstone and dolomite formations of the Fox River valley, eastern Wisconsin: *Environmental Science and Technology,* v. 38, no. 19, p. 5087-5094.

Thwaites, F.T., 1943, Pleistocene of part of northeastern Wisconsin: *Geological Society of America Bulletin,* v. 54, p. 87–144.

Thwaites, F.T., and Bertrand, K., 1957, Pleistocene geology of the Door Peninsula, Wisconsin: *Geological Society of America Bulletin,* v. 68, no. 7, p. 831–880.

Upham, W., 1903, Glacial Lake Jean Nicolet: *The American Geologist,* v. 32, p. 330–331.

Warren, G.K., 1876, Report on the transportation route along the Wisconsin and Fox Rivers: U.S. Engineers, Washington.

Weidman, Samuel, 1911, The glacial lake of the Fox River Valley and Green Bay and its outlet: *Science,* v. 33, no. 847, p. 467.

Whittlesey, C., 1849, Geological report on that portion of Wisconsin bordering on the south shore of Lake Superior, *in* Owen, D.D., 1852, *Report of a Geological Survey on Wisconsin, Iowa, and Minnesota:* Lippincott, Grambo & Co., p. 425–480.

Wielert, J.S., 1979, The late Wisconsinan glacial lakes of the Fox River watershed, Wisconsin: Ed.S. thesis, University of Wisconsin–Superior, 42 p.

Wielert, J.S., 1980, The late Wisconsinian glacial lakes of the Fox River watershed: *Wisconsin Academy of Science, Arts and Letters,* v. 68, p. 188–201.

APPENDIX A

LISTING OF SELECTED GEOLOGIC LOGS AND WELL CONSTRUCTION REPORTS USED TO CREATE CROSS SECTIONS

Cross sections are shown on plate 2. The records for all logs and well construction reports are available from the Wisconsin Geological and Natural History Survey.

Cross section A–A′

Wisconsin unique well number	Total depth (ft)	Location (WTM-easting)	Location (WTM-northing)
MX187	307	611306	419396
IB614	280	611999	418509
NU108	310	612781	416754
HM035	350	613212	415986
IK188	150	617291	412354
MR723	340	617571	411761
EP904	140	618232	411075
CX506	210	618829	409977
FP821	102	620706	406822
AF730	122	621275	406012
QS817	142	623422	406333
RN033	142	624018	405998
DS723	120	624489	405106
AA766	180	625575	404510
AK698	145	625970	404144
KN894	140	627146	404349
LK310	130	627664	404120
FW931	255	628082	403759
MO739	120	630074	402069
FU312	230	630438	401622
MC779	80	631074	401784
CJ174	145	631914	401191
HO965	85	631446	400659
GI768	238	631523	400080
AH729	160	633173	399108
FV404	245	634787	398358
AH687	124	638467	394315

Cross section B–B′

Wisconsin unique well number	Total depth (ft)	Location (WTM-easting)	Location (WTM-northing)
MR609	150	609157	417508
FP590	170	609665	417749
DT233	73	610586	417482
GL237	180	611715	417864
NK839	234	613017	417391
MR795	163	614797	417399
LC080	56	617750	417868
GL076	240	619907	418702
FL982	440	621973	418518
EK561	210	623387	418746
MZ361	164	624361	418545
LX936	107	627014	417870
HL116	100	628052	417859
OD040	120	630830	418022
AJ087	198	632421	418058
DO423	200	633102	417950
OP493	142	634195	417981
LI073	183	634884	418334
ND789	240	635966	418736
KL381	183	637958	419271
FJ292	160	639175	419406
NK852	140	639313	418491
HK515	160	640706	419242
NQ885	215	642166	419241
DS920	100	642954	419354
AX115	180	644649	419832
OI138	48	647152	419552

Cross section C–C′

Wisconsin unique well number	Total depth (ft)	Location (WTM-easting)	Location (WTM-northing)
DC175	164	609609	392443
OF671	156	611847	393240
KK589	94	613410	393550
NP389	202	615697	394419
CZ566	342	615954	395113
CY290	144	619156	397367
ND740	230	619842	398435
IL657	160	620766	401061
LV731	125	622860	401083
DC775	144	624651	399548
DD319	147	626281	398287
HJ891	185	627083	398484
OL600	121	628498	398892
MO723	198	629436	398433
AH659	111	629822	398130
AF734	115	630562	397818
RX212	123	631783	397681
AH729	160	633173	399108
OD282	182	633668	399680
FW945	265	634444	400410
QW551	62	633938	402109
AJ810	300	635585	402298
CW474	245	636294	403467
ID533	131	636531	404152
MR979	298	636520	404367
FP824	200	636546	406022
QL053	220	638121	407856
HW812	122	638952	408632
GH402	217	641748	409846
MC803	220	642842	410744
QT059	422	643785	415349
OB304	180	644365	418637
AX115	180	644649	419832

Cross section D–D′

Wisconsin unique well number	Total depth (ft)	Location (WTM-easting)	Location (WTM-northing)
RJ814	165	611053	384901
QS838	102	611616	384880
EO482	119	612060	384912
OE082	148	613428	384911
MY108	145	613875	384518
ME891	139	614678	384323
NU790	103	615525	384144
OP799	143	617064	383515
KZ854	90	617347	383560
HT053	200	620116	383767
HL720	122	621969	383631
OD650	162	623473	383433
FT499	145	624955	384043
DC757	145	626442	383387
KY835	125	627476	383504
QJ127	182	627965	383719
LV556	155	629624	383338
QV227	173	631819	383578
IG935	162	633538	384776
NQ092	182	635064	384228
QQ382	130	636906	384627
QL003	181	638325	384248
RW667	177	640090	384386
MT141	203	640509	384394
CW436	105	641434	384376
LV536	105	642309	384430
GH801	125	642704	385015

APPENDIX B

HYDRAULIC CONDUCTIVITY, PLASTICITY, AND SHEAR STRENGTH OF UNLITHIFIED SEDIMENT

Hydraulic conductivity

Hydraulic conductivity is a measure of the capability of rock or sediment to transmit water. Although hydraulic conductivity was not directly measured in this study, it has been determined for various till units by Rodenbeck (1988) and Edil and Mickelson (1995). In both studies, hydraulic conductivity data were compiled from solid-waste, hazardous-waste, and sewer-line reports submitted to the Wisconsin Department of Natural Resources. To determine hydraulic conductivity, field and laboratory measurements were made on Kewaunee Formation tills, including the Kirby Lake and Middle Inlet Members and their counterparts in the Lake Michigan basin, the Valders and Two Rivers Members (table B1). For the Kirby Lake, Valders, and Middle Inlet tills, the mean field hydraulic conductivity values (10^{-7} m/s) were at least two orders of magnitude greater than the mean laboratory values (10^{-9}–10^{-10} m/s). The disparity likely resulted from different test methods used in the field and in the laboratory as well as the scale and disturbance of samples (Bradbury and Muldoon, 1990). Regardless of this difference, the mean values of hydraulic conductivity determined in the field were similar between the tills (10^{-7} m/s). This is not the case for the mean laboratory hydraulic conductivity values, which ranged over two orders of magnitude (10^{-9}–10^{-10} m/s), probably because the effects of fractures in the clay-rich tills were not taken into account in laboratory studies.

Plasticity

Various index tests have been devised by geotechnical engineers to classify cohesive sediment such as glacial till. One series of tests, the Atterberg limits, relates the water content of sediment to its response to an applied stress. For example, when cohesive sediment is dry, it acts as a solid. However, as water is added, it may act like a plastic or liquid. With an increasing amount of water, cohesive sediment will deform more readily due to an applied stress.

In Atterberg limits testing, the plastic limit is reached when the sediment contains a specific amount of water and begins to behave like plastic. The plastic limit is defined as the water content (%) at which sediment begins to crumble when rolled into threads of a specified thickness (3.2 mm). If more water

Table B1. *Field and laboratory values of hydraulic conductivity for till members of the Kewaunee Formation.*

Unit	Source	Sediment	Mean field hydraulic conductivity (ms^{-1})	Number of field tests	Mean laboratory hydraulic conductivity (ms^{-1})	Number of laboratory tests
Kewaunee Formation						
Kirby Lake Member	Rodenbeck (1988)	till	7.19×10^{-7}	44	9.46×10^{-10}	26
Valders Member	Edil and Mickelson (1995)	till	3.2×10^{-7}	12	4.0×10^{-9}	19
Middle Inlet Member	Rodenbeck (1988)	till	6.97×10^{-7}	21	1.16×10^{-9}	10
Two Rivers Member	Edil and Mickelson (1995)	till	—	—	4.0×10^{-10}	11

Table B2. *Atterberg limits for Kewaunee Formation sediment (till of the Kirby Lake Member and undifferentiated glacial Lake Oshkosh sediment) in Winnebago County.*

Unit	Sediment	Number of samples	Plastic limit (%)	Liquid limit (%)	Plasticity index	Activity
Kewaunee Formation						
Kirby Lake Member	till	3	17	41	24	0.7
undifferentiated	lake sediment	3	32	91	59	1.6

is added to the sediment, the liquid limit is reached when the sediment has sufficient water to deform after being jarred in a specified manner. In other words, the sediment would not be able to sustain an applied stress at this water content or higher. The plasticity index *(PI)* is the difference between the plastic and the liquid limit. With this parameter, activity *(A)* can be calculated by dividing the PI by the percentage of clay determined from grain-size analyses *(A = PI/clay %)*. Activity values for sediment less than 0.75, between 0.75 and 1.25, and greater than 1.25 are classified as inactive, normal, and active, respectively. Sediment classified as active is usually not preferred for engineering projects, such as liners and caps for landfills, because it can shrink or swell, which reduces its structural integrity.

We measured Atterberg limits on three samples each of the Kirby Lake till and glacial Lake Oshkosh sediment (table B2). For the Kirby Lake till, the plasticity index was 24 and the activity 0.7, indicating that it is inactive. These values are similar to those determined for previous analyses of Kirby Lake till. For example, the results for 67 Kirby Lake till samples showed that 97 percent were inactive or normal (Rodenbeck, 1988).

The Atterberg limits of the fine-grained glacial Lake Oshkosh sediment had a plasticity index of 59 and an activity of 1.6 (table B2), indicating active sediment. Both values are high and are somewhat typical of sediment that has a relatively high water-holding capacity and that will likely experience an unusual amount of compaction under a load. In addition, such sediment can have a high cation exchange capacity, a low resistance to shear, and a low permeability. Sediment that has these properties would not be suitable for engineering applications, such as road construction and landfill liners and caps.

Shear strength

The shear strength *(τ)* of sediment is a critical factor in the engineering of structures, such as buildings and bridges. Engineering designs must be modified to accommodate the strength of underlying materials. Numerous field and laboratory tests can be conducted to determine the internal resistance per unit area that sediment can offer to resist failure and sliding along a given plane (Das, 1994). The direct shear test is one such laboratory method.

To determine the shear strength of remolded Kirby Lake and Horicon tills, we used a direct shear test: We sheared a small volume of sediment (2×10^{-4} m^3) between two horizontal plates under a known axial stress. The tests were strain controlled and the sediment fully saturated with water. During the experiment, water flowed freely in and out of the sediment pores as the sample contracted or expanded (that is, drained conditions) during shearing. As a result, the applied stress was equivalent to the effective normal stress *(P_e)*. For each till unit, the shear strength was measured under several different normal stresses to establish a linear relationship. From this relationship, two strength param-

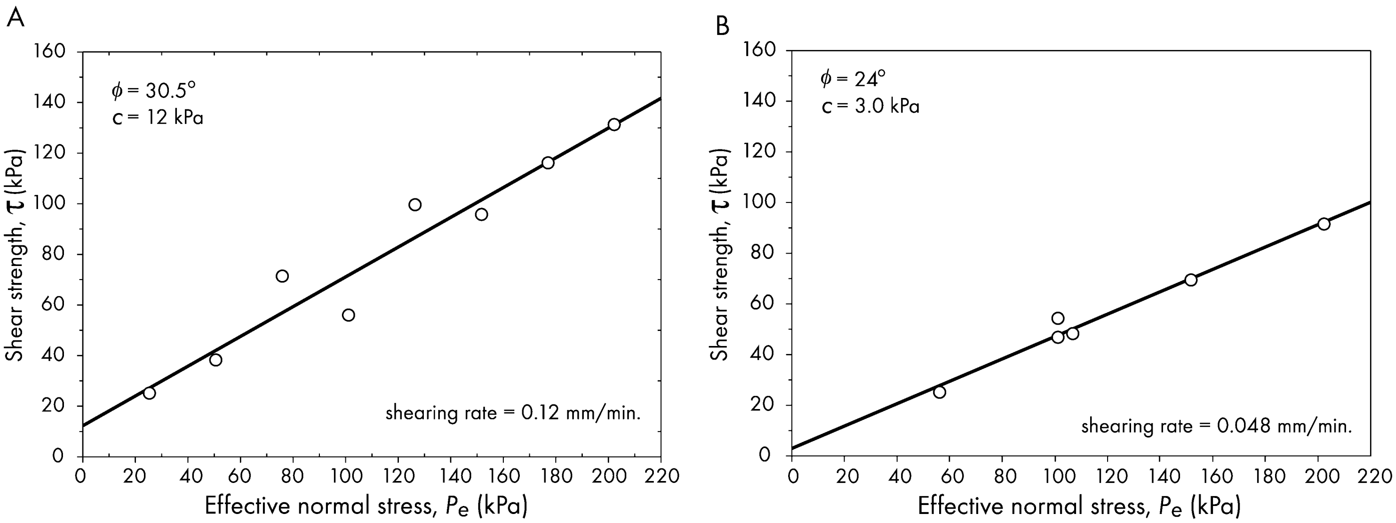
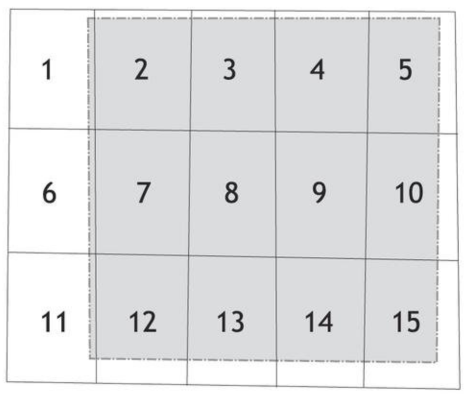


Figure B1. *Steady-state shear strength of the (**A**) till of the Horicon Member of the Holy Hill Formation, and (**B**) till of the Kirby Lake Member of the Kewaunee Formation.*

eters, angle of internal friction *(ϕ)* and cohesion *(c),* were determined.

The results of the direct shear tests for the Horicon and Kirby Lake tills indicated angles of internal friction values of 30.5° and 24° and cohesion values of 12 kilopascal (kPa) and 3 kPa, respectively (fig. B1). The lower angle of internal friction value for the Kirby Lake till is not surprising because it consists of a greater percentage of silt and clay-sized particles. This value is only about 5° less than angle of internal friction values determined for the Valders till, the Kirby Lake equivalent, which is present in several counties along Lake Michigan (Edil and Mickelson, 1995). Because the Horicon till is sandier than the Kirby Lake till, it is not surprising that it has a higher angle of internal friction.

Index to 1:24,000 maps



1 Poy Sippi–1961
2 Lake Poygan–1961 (75 PR)
3 Oshkosh NW–1961 (75 PR)
4 Oshkosh NE–1961 (75 PR)
5 Neenah–1955 (75)
6 Auroraville–1961
7 Eureka–1961 (75 PR)
8 Omro–1961 (75 PR)
9 Oshkosh–1961 (75 PR)
10 Indian Point–1974
11 Berlin–1980
12 Rush Lake–1980
13 Picket–1980
14 Van Dyne–1980
15 Fahrney Point–1974

PR Photorevised

Bulletin 105

Quaternary Geology of Winnebago County, Wisconsin

2008

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COVER: *Glacial Lake Oshkosh sediment in the Ames Construction Borrow pit. (Photograph by T.S. Hooyer.)*

Wisconsin Geological and Natural History Survey
Bulletin 105
Quaternary Geology of Winnebago County, Wisconsin
Plate 1

Thomas S. Hooyer
William N. Mode

2008

Figure 1. Shaded-relief map of Winnebago County.

Explanation

p, pl, pg — **Peat.** Unit **p:** peat on low-lying, flat to low-relief surfaces; typically between 1 and 3 m thick. Unit **pl:** peat over lake sediment. Unit **pg:** peat overlying sandy till of the Horicon Member of the Holy Hill Formation or clayey and silty till of the Kirby Lake Member of the Kewaunee Formation.

s, sp — **Postglacial stream sediment.** Commonly consists of silty, clayey sediment and some channel sand and silt; typically between 1 and 15 m thick. Unit **s:** deposited in floodplains adjacent to postglacial streams. Unit **sp:** similar to unit **s**, but commonly overlain by peat less than 1 m thick.

h — **Hillslope sediment.** Primarily sand, silt, and clay eroded from adjacent upland areas (those areas mapped as unit **gk**); usually between 1 to 2 m thick.

w, wg, wl — **Windblown sand.** Unit **w:** between 2 and 7 m thick, dunes generally no more than 5 m high; most sand deposited immediately following deglaciation. Unit **wg:** overlies red, clayey, silty till of the Kirby Lake Member of the Kewaunee Formation. Unit **wl:** overlies lake sediment.

l, lw — **Lake sediment of the Kewaunee Formation, undifferentiated.** Sediment of glacial Lake Oshkosh. Unit **l:** largely sand near the shoreline, grading to silt and clay where deposited in deeper water; typically between 1 and tens of meters thick. Unit **lw:** lake sediment covered with thin patches of windblown sand; generally less than 2 m thick.

sa, su, se — **Meltwater-stream sediment.** Silty sand and gravel deposited directly by streams originating from the margin of the Green Bay Lobe; commonly between 1 m and several tens of meters thick. Unit **sa:** meltwater-stream sediment deposited in an alluvial fan or delta immediately adjacent to a moraine. Unit **su:** meltwater-stream sediment deposited in proglacial river channels or in tunnel channels beneath the margin of the Green Bay Lobe. Unit **se:** eroded meltwater-stream sediment; postglacial erosion resulted in gullied topography.

gg — **Till of the Middle Inlet Member of the Kewaunee Formation.** Red, clayey silt with some gravel deposited by the Green Bay Lobe; generally at least 3 m thick.

gk, gkw, gkl — **Till of the Kirby Lake Member of the Kewaunee Formation.** Red, clayey silt; contains some gravel deposited by the Green Bay Lobe; generally at least 3 m thick. Unit **gk:** low-relief, nondescript topography; generally draped over pre-existing topography; till in places less than 3 m thick. Unit **gkw:** similar to unit **gk**, but covered with thin (less than 2 m thick) patches of windblown sand. Unit **gkl:** similar to unit **gk**, but covered with thin (generally less than 2 m thick) patches of lake sediment.

gh, ghw, ghs, ghd — **Till of the Horicon Member of the Holy Hill Formation.** Yellow-brown to reddish-brown, gravelly, clayey, silty sand deposited by the Green Bay Lobe; generally at least 3 m thick. Unit **gh:** areas of rolling topography and no drumlins. Unit **ghw:** similar to unit **gh**, but covered with thin (generally less than 2 m thick) patches of windblown sand. Unit **ghs:** areas of rolling topography with drumlins. Unit **ghd:** areas of low-relief, nondescript topography; till is generally draped over pre-existing topography.

r — **Bedrock.** Ordovician dolomite and sandstone and Cambrian sandstone. Many of these areas contain quarries that once were covered with less than 1 m of glacial sediment.

Symbols

Contact
Moraine crest
Ice-margin limit
Meltwater channel
Drumlin crest
Steep slope

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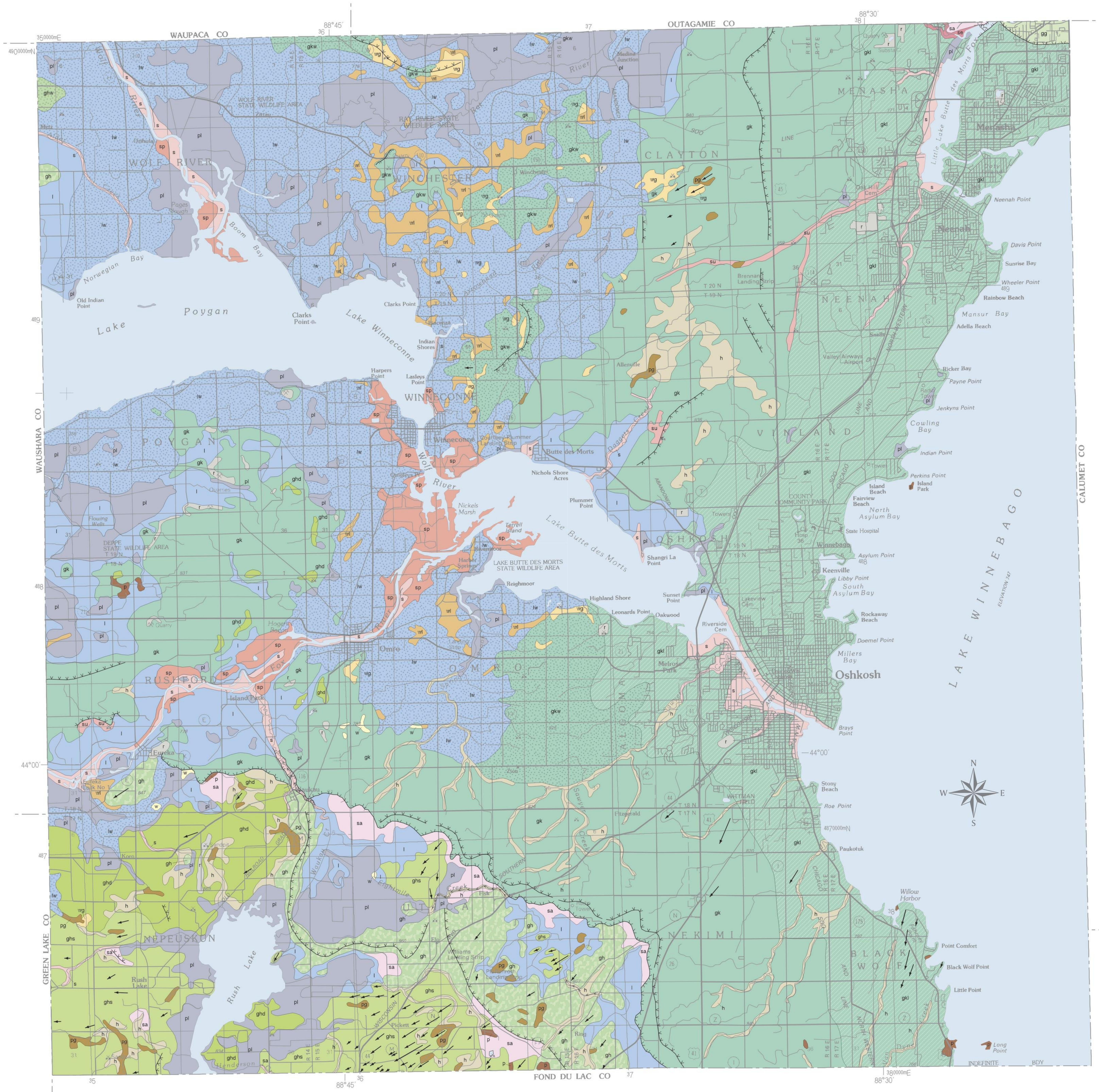
Cartography by D.L. Patterson.



Wisconsin Transverse Mercator Projection
1991 adjustment to the North American Datum of 1983 (NAD 83/91)

The base map was constructed from U.S. Geological Survey digital line graph files (1990, scale 1:100,000) and modified by the Wisconsin Department of Natural Resources (1992) and the Wisconsin Geological and Natural History Survey (2004).

Scale 1:100,000
1 0 1 2 3 4 5 6 7 8 9 10 KILOMETERS
1 0 1 2 3 4 5 MILES

This map is an interpretation of the data available at the time of preparation. Every reasonable effort has been made to ensure that this interpretation conforms to sound scientific and cartographic principles; however, the map should not be used to guide site-specific decisions without verification. Proper use of the map is the sole responsibility of the user.

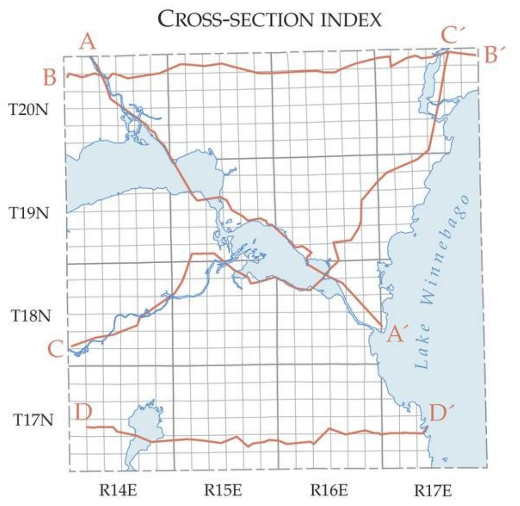
Plate 1. Quaternary geologic map of Winnebago County, Wisconsin.

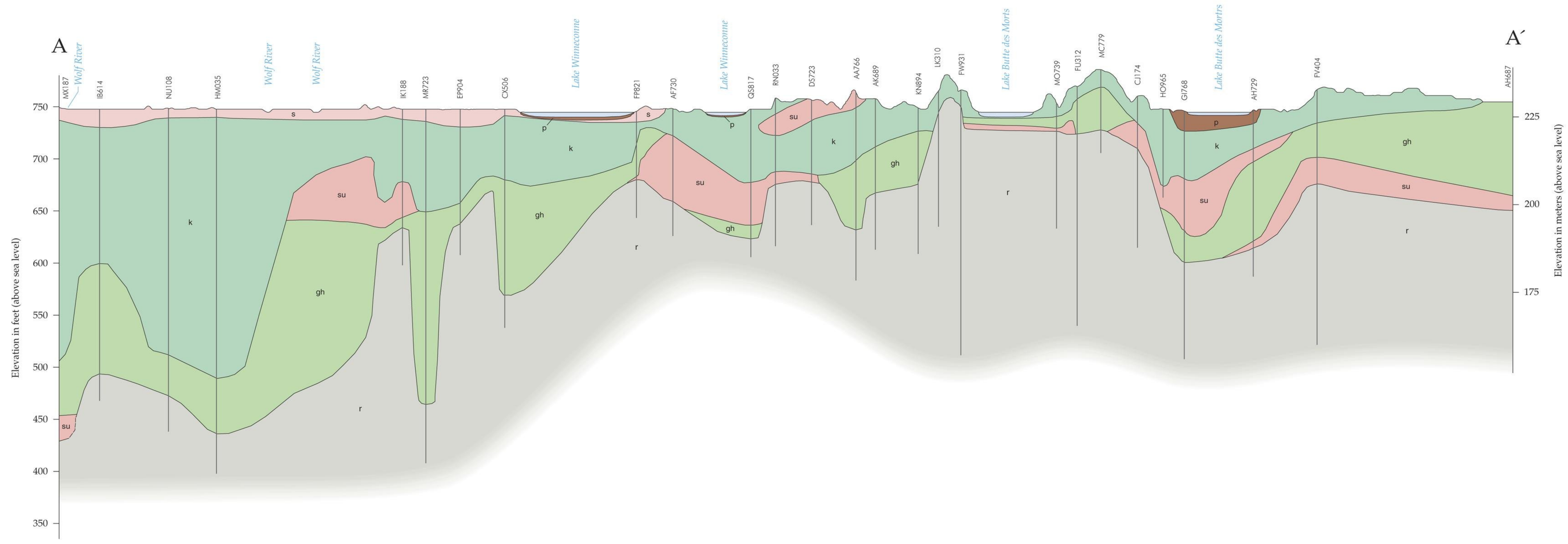
Wisconsin Geological and Natural History Survey
Bulletin 105
Quaternary Geology of Winnebago County, Wisconsin
Plate 2

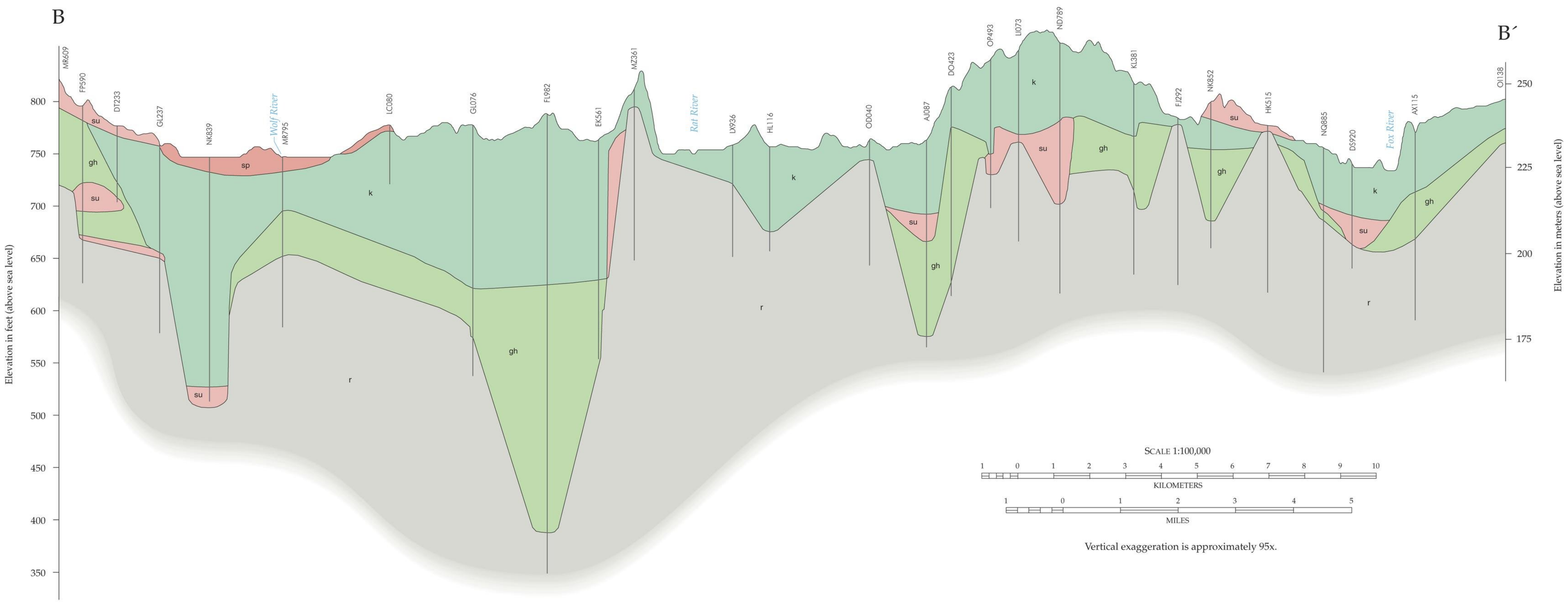
Thomas S. Hooyer
William N. Mode

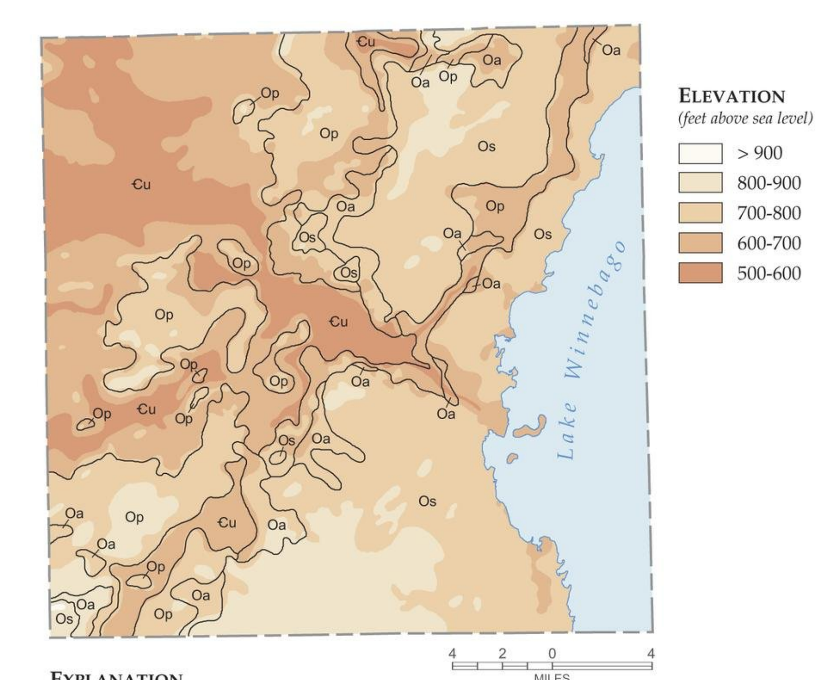
2008

Cross-section index









Explanation

- Os Dolomite of the Sinnipee Group, Ordovician
- Oa Sandstone of the St. Peter Formation of the Ancell Group, Ordovician
- Op Dolomite of the Prairie du Chien Group, lower Ordovician
- Cu Sandstone of the upper Cambrian

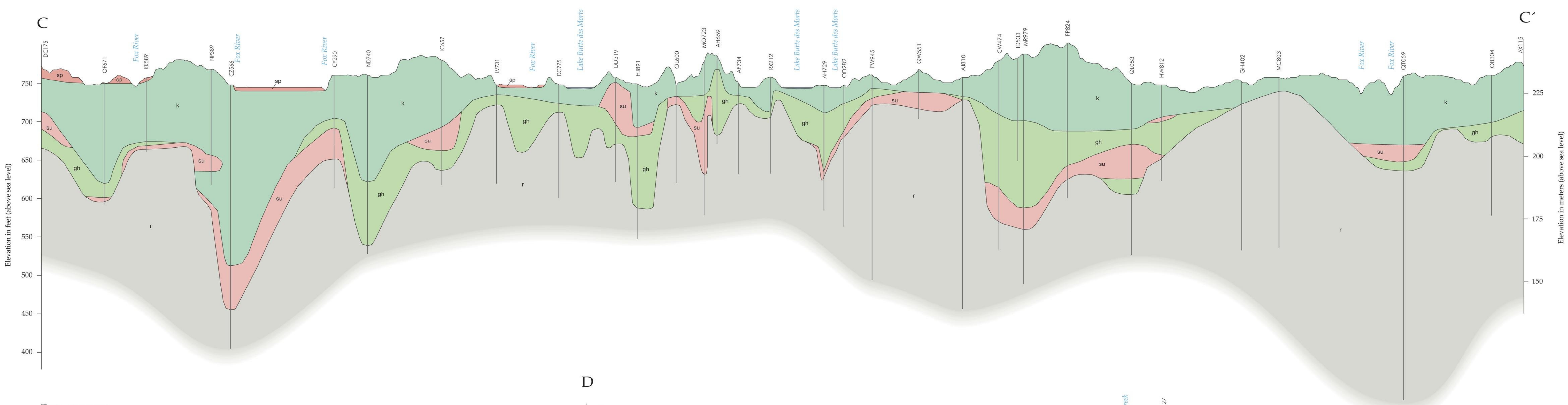
Figure 1. *Preliminary geology and elevation of the bedrock surface (modified from Brown, B.A., 2004, Preliminary bedrock geologic map of Winnebago County, Wisconsin: Wisconsin Geological and Natural History Survey Open-File Report 2004-24, scale 1:100,000).*

Scale 1:100,000

Kilometers

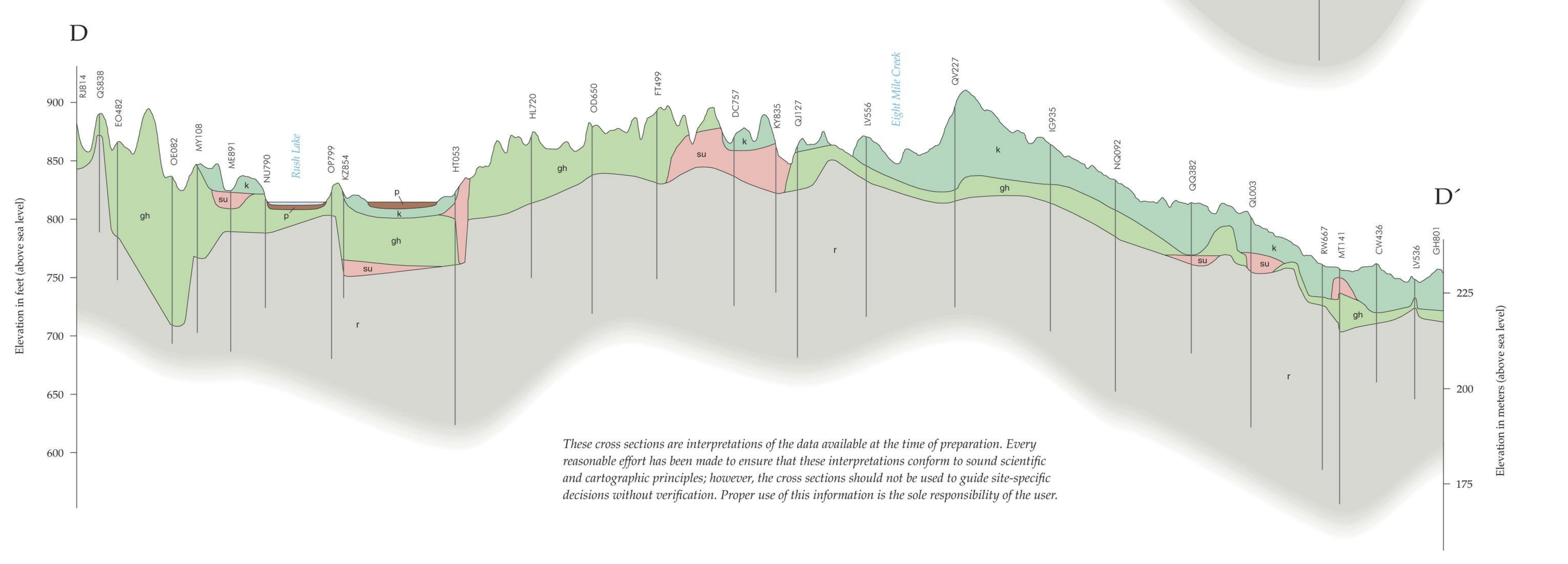
Miles

Vertical exaggeration is approximately 95x.



Explanation

- p — Peat and/or Holocene lake sediment
- s — Stream sediment in Holocene floodplains
- sp — Stream sediment in Holocene floodplains, overlain by peat
- su — Meltwater stream sediment
- k — Till and lake sediment of the Kewaunee Formation
- gh — Till of the Holy Hill Formation
- r — Ordovician sandstone and dolomite and Cambrian sandstone
- Well location
- *MR723* Wisconsin unique well number



These cross sections are interpretations of the data available at the time of preparation. Every reasonable effort has been made to ensure that these interpretations conform to sound scientific and cartographic principles; however, the cross sections should not be used to guide site-specific decisions without verification. Proper use of this information is the sole responsibility of the user.

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Data capture by S. Kostka. Cartography by D.L. Patterson.

Plate 2. Geologic cross sections of Winnebago County, Wisconsin.