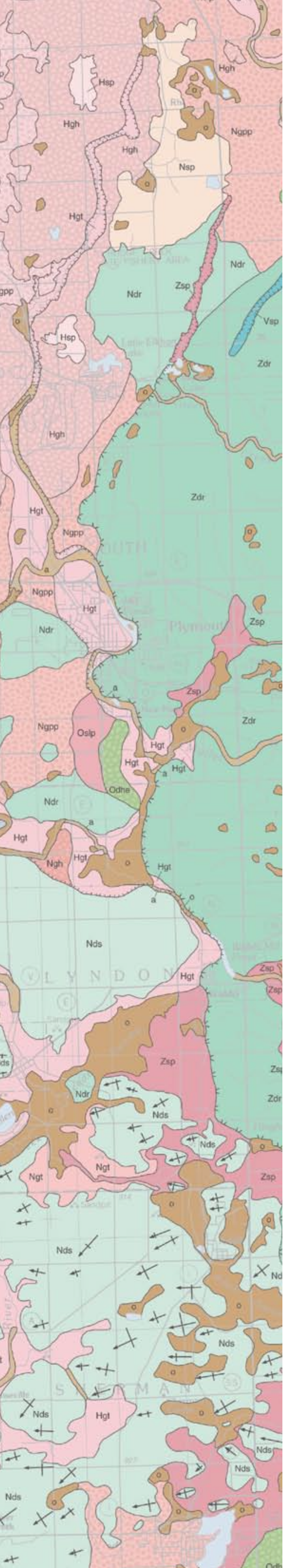

WISCONSIN GEOLOGICAL AND NATURAL HISTORY SURVEY

Quaternary Geology of Sheboygan County, Wisconsin

Bulletin 106 • 2011

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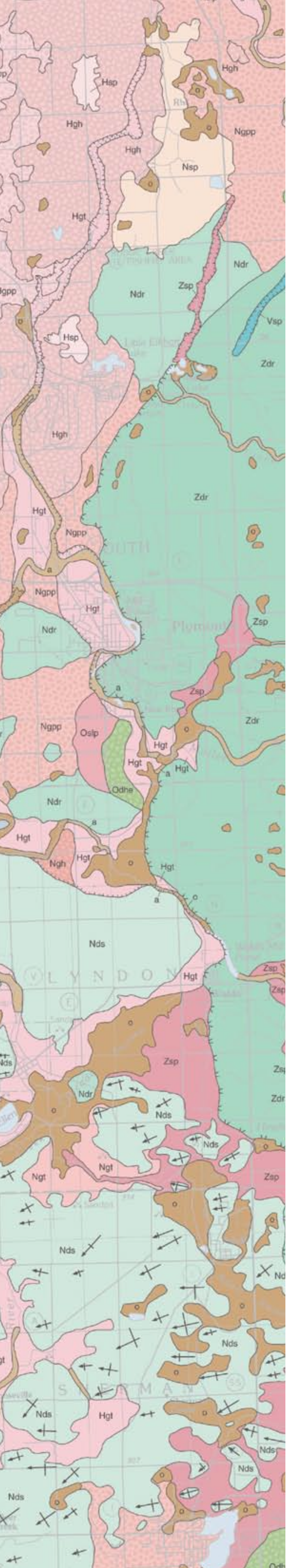
Cover photos

Front: White Kame at Kettle Moraine State Forest–Northern Unit, © Jackie S. Scharfenberg
Back: Erratic boulders in a kettle, © Robert E. Gantner



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Sand dunes at Kohler-Andrae State Park

cemillerphotography.photoshelter.com

Dennis Murphy

Abstract

Glacial ice repeatedly covered Sheboygan County during the late Wisconsin Glaciation, which lasted from about 30,000 to 10,000 years ago (ages are given in calendar years before present unless otherwise noted). Ice had covered the county before the last glaciation, but erosion by later ice advances and sediment deposited by the most recent advances obscure much of this record. The late Wisconsin deposits belong to the Holy Hill, Oak Creek, and Kewaunee Formations, all of which include till deposited directly by the glacier and outwash deposited by meltwater flowing away from the glacier.

Glaciers formed several different landscapes in Sheboygan County. The Kettle Moraine is a hummocky accumulation of sand and gravel deposited by meltwater that flowed on, under, and around ice between the Green Bay and Lake Michigan Lobes of the ice sheet. West of the Kettle Moraine, the Green Bay Lobe deposited brown, sandy till of the Horicon Member of the Holy Hill Formation in streamlined elongate hills called drumlins. Associated outwash fills depressions between drumlins. East of the Kettle Moraine, the Lake Michigan Lobe deposited brown, sandy till of the New Berlin Member of the Holy Hill Formation in drumlins. As ice retreated, meltwater was routed between the retreating ice lobe and the eastward sloping land surface, and thick sequences of sand and gravel were deposited. In a few places, meltwater incised this sediment, forming deep ice-marginal and proglacial channels now occupied by underfit streams. Ice also dammed eastward-flowing rivers, creating lakes that drained when the ice retreated. Subsequent readvances of the Lake Michigan Lobe deposited the silty, grayish-brown till of the Oak Creek Formation and the clayey, reddish-brown till of the Kewaunee Formation in low-relief plains and moraines. The fine-grained nature of these tills implies that ice retreated into the Lake Michigan Basin prior to these advances and incorporated lacustrine sediment during readvance. During the subsequent retreat, lakes formed from the ice damming of eastward flowing rivers, depositing lacustrine sediment over the till.

After the final retreat of ice from Sheboygan County, highstands of Lake Michigan deposited beaches and eroded shorelines into the glacial deposits and lake sediments. Postglacial streams deposited sand and gravel in former meltwater channels. Along Lake Michigan, wind modified former beach deposits into dune fields in southern Sheboygan County, while waves cut high bluffs in northern Sheboygan County.

Introduction

The landscape of Sheboygan County, like much of Wisconsin, was produced almost entirely by the deposition of sediment by glaciers and the rivers that flowed from them between about 30,000 and 12,000 years ago (figures 1 and 2). Since that time, rivers have downcut into this sediment, waves have eroded the Lake Michigan shoreline, and younger organic sediment has filled, or partly filled, lake basins, producing organic-sediment-filled wetlands. The nature of surface sediments greatly affects how we use the land: sand and gravel, and clay are important resources. Buildings and roads require large amounts of aggregate during construction, and most of it is mined locally in the county.

The nature of farming is also greatly influenced by what was left behind by the glacier. Clayey soil is common in the central and eastern part of the county. In the far west, the steep slopes and drought-prone gravel soils of the Kettle Moraine have made it difficult to farm without irrigation, but these same features make it a popular recreation area, with the extensive Kettle Moraine Sate Forest—Northern Unit and the world-class glacial landforms of the Ice Age National Scenic Trail.

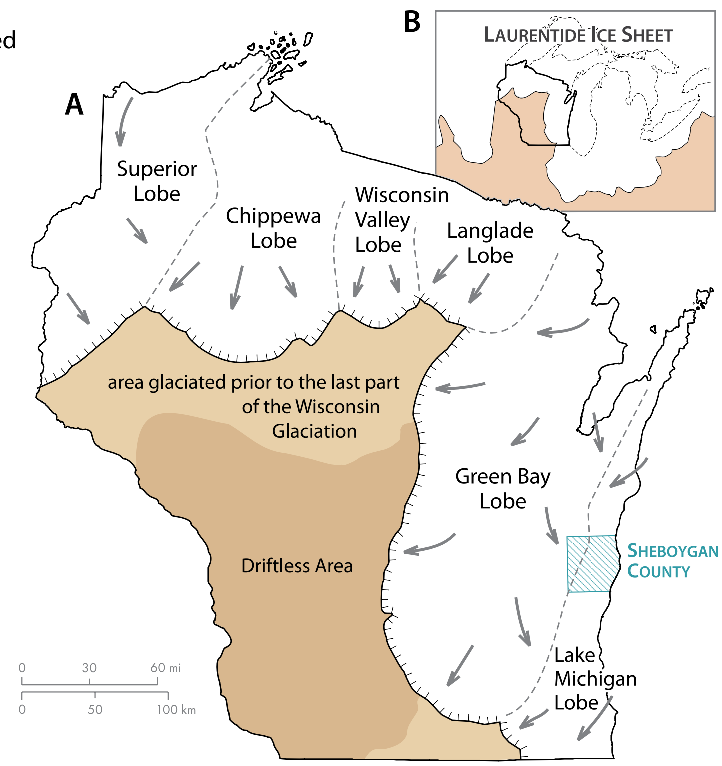
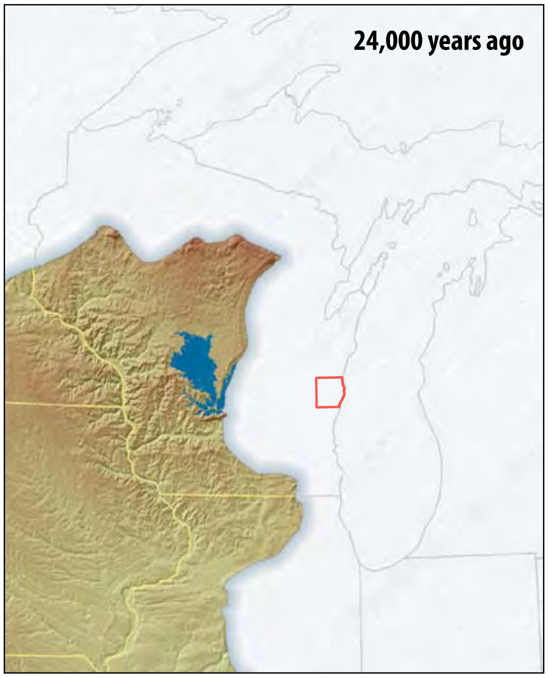
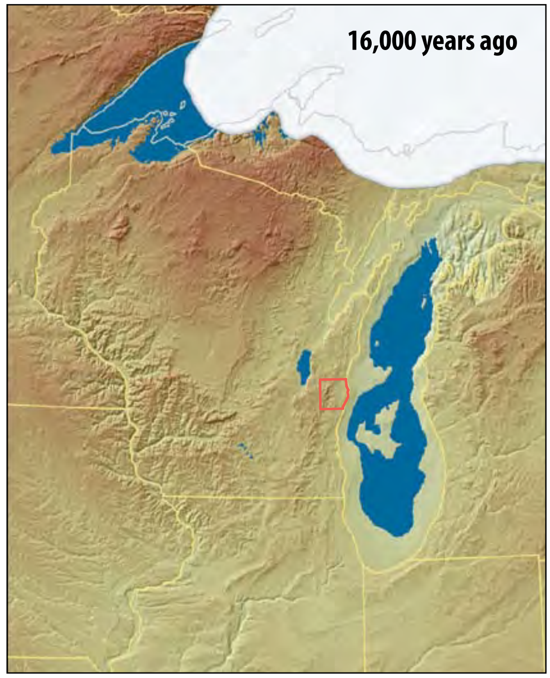


Figure 1. Location of Sheboygan County in Wisconsin (A) in relation to the Laurentide Ice Sheet (B) and its lobes during the most recent glaciation. Hachures indicate the edge of the ice sheet; arrows indicate direction of ice flow.

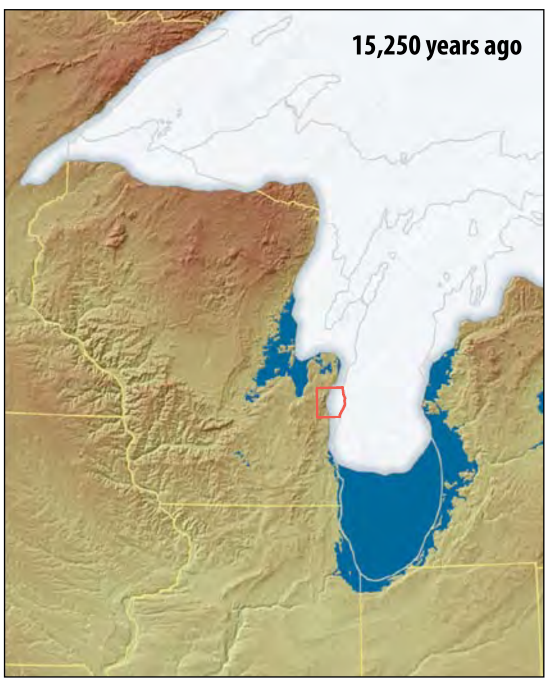
Figure 2. Extent of glaciers and large lakes at four times in the past (dates are approximate).



A. Ice at nearly its maximum extent about 24,000 years ago. Glacial Lake Wisconsin is dammed along the western edge of the Green Bay Lobe.



B. Estimated ice margin and Lake Michigan extent about 16,000 years ago between the Oak Creek and Kewaunee advances.



C. Maximum extent of glacier during the early Port Huron readvance, which deposited the Ozaukee till about 15,250 years ago. Glacial Lake Oshkosh is at its maximum.

D. Readvance of the glacier about 14,700 years ago depositing the Valders till. Glacial Lake Oshkosh reforms and Lake Michigan remains elevated.

Overview of glacial history

The late Wisconsin Laurentide Ice Sheet entered Wisconsin about 30,000 years ago, advancing southward through the Lake Michigan Basin and westward into what is now Sheboygan County. Earlier glacier advances occurred, but erosion and burial of their sedimentary deposits was so extensive that little is known about them. Prior to glaciation, the county probably had an overall slope toward the east as it does today (figure 3). This surface was incised by deep valleys that are now mostly filled with sediment. The distribution of sediment and landforms shows that the advancing Lake Michigan Lobe extended farther west than what is now the western edge of the county, then thickened as the Green Bay Lobe in the Green Bay–Lake Winnebago lowland resisted its flow to the west. Eventually, what is now the location of the Kettle Moraine became the place where ice of the two lobes merged and formed a broad southwestward-sloping trough on the ice surface. This joining of the two lobes was an important step in the development of the Kettle Moraine landscape.

Ice began to thin and melt more rapidly as climate warmed about 20,000 years ago, and the Lake Michigan and Green Bay Lobes began to separate. Large, fast-flowing rivers ran out of and off the glaciers, depositing broad plains of gravel in some places and cutting deep channels in others. Diamicton interpreted as till was deposited beneath the ice. This poorly sorted sediment with grain sizes ranging from clay to boulders was shaped into east–west trending hills called drumlins. In a few localities, diamicton was deposited as debris flows off the ice surface. The diamicton of this glacial advance is sandy and contains many cobbles and boulders. Shortly after 19,000 years ago, glacier ice probably had retreated from what is now Sheboygan County. Subsequent readvances of the glacier southward in the Lake Michigan Basin deposited gray clayey diamicton. Approximately 15,500 years ago, the glacier again advanced into this area, depositing clayey, reddish-brown diamicton. Thus, each major glacier advance deposited diamicton with distinguishing characteristics that allow the extent of each advance to be mapped. Gravel, sand, and finer particles carried by water are associated with each of these advances and mapped accordingly (plate 1).

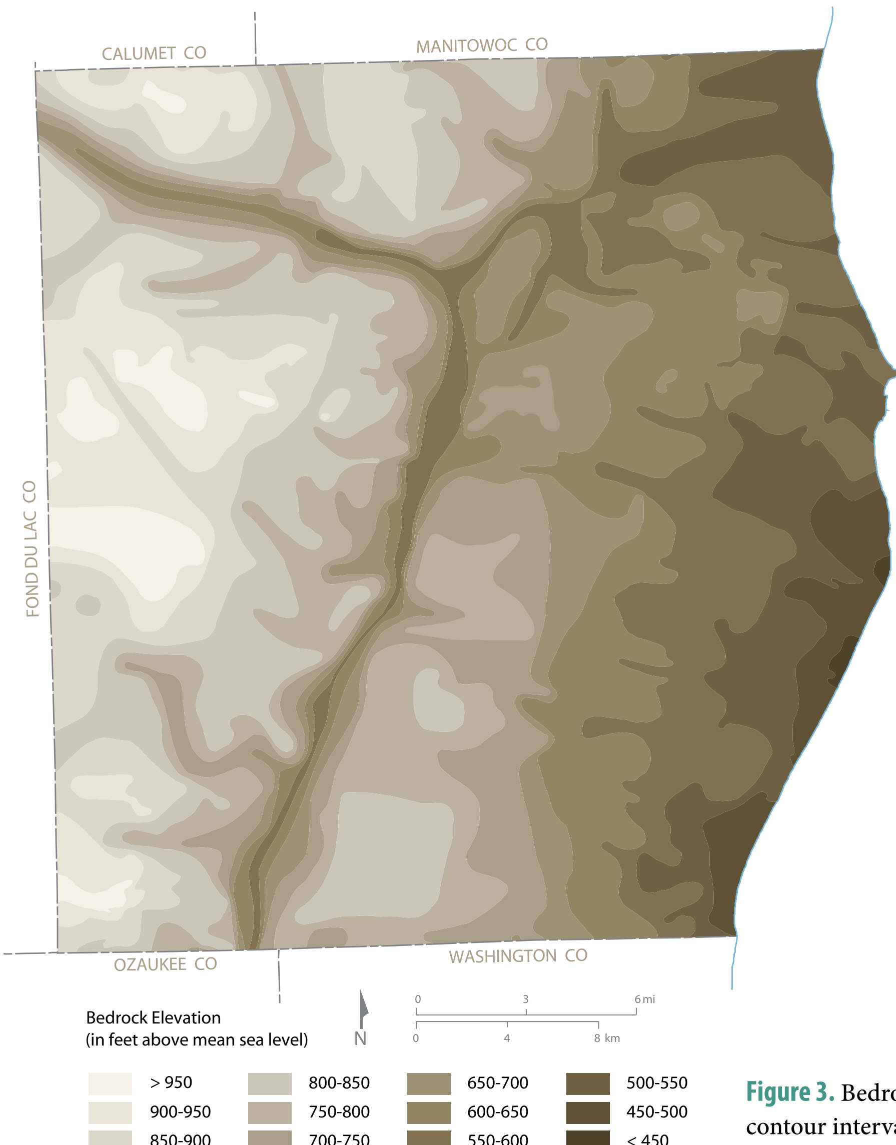


Figure 3. Bedrock topographic map of Sheboygan County, contour interval 100 ft (30 m). The bedrock surface slopes to the east with a deep valley cutting down the center.

The landscape continued to be modified after the ice retreated from this area for the final time. Rivers eroded sediment and carried it toward Lake Michigan. Although much of the sediment disappeared into the deep water of the lake, some of this sediment supplied the sand that is now on the beach and in dunes at Kohler-Andrae State Park. Wave erosion of the shoreline has continued since the last glacier left around 13,000 years ago, resulting in several miles of shoreline retreat.

In this report we detail the nature and development of the Sheboygan County landscape. We first describe the properties and distribution of the sediment, then characterize the physiographic regions and landforms therein. This is followed by a discussion of the Quaternary history of the county, focusing on the last 20,000 years. Readers not interested in the details of sediment characteristics may want to skip to the discussion of physiographic regions. A map of the distribution of deposits and landforms and cross sections schematically portraying deposits below the surface are shown on plates 1 and 2.

Methods

At the beginning of the project, air photographs, topographic maps, and the Soil Survey of Sheboygan County (Engel and others, 1978) were analyzed to produce a preliminary map of the Quaternary geology of Sheboygan County. Logs of wells and boreholes were used to construct a map of the bedrock topography, which later aided in determining drill sites. During the summers of 1998, 1999, and 2001, sediment samples were obtained where sediment was exposed in road cuts, stream cut-banks, gravel pits, quarries, and house foundations. Because few exposures exist, truck-mounted drill augering was necessary to construct cross sections and interpret lithostratigraphy.

Grain-size samples were analyzed in the Quaternary Research Laboratory of the University of Wisconsin–Madison, Department of Geoscience. Grain-size distribution, magnetic susceptibility, and carbonate content were determined following standard laboratory procedures. Dry sieving separated the sand fraction (> 0.0625 mm) from the fines. Hydrometer analysis was used to determine the silt (0.0625 mm–0.002 mm) and clay (< 0.002 mm) content. Chittick analysis provided the ratio between calcite and dolomite in the silt fraction.

Lithostratigraphic interpretations were used to revise and finalize contacts on the surficial map. The surficial map was then digitized and compiled at a 1:100,000 scale (plate 1). East–west cross sections were produced at 3-mile intervals (plate 2). More details are presented in Principato (1999) and Chapel (2000) and Carlson (2002).

Reliability of maps and cross sections

The reliability of information shown on plate 1 varies from place to place, depending largely on where exposures exist. All road cuts, gravel pits, shoreline bluffs, and other exposures were described and sampled. Well-construction reports, USDA Soil Survey maps (Engel and others, 1978), and other resources were also used to compile what is known of surficial deposits in the area. These were compiled on 1:24,000 maps and reduced to 1:100,000 for publication.

Limited resources prevent the collection of site-specific information from the subsurface except at a few places, so much interpretation has gone into the cross sections. In addition, geologic information has been projected into the line of the cross section from up to 1.5 mi (2.5 km) north and south. Thus, elevations of contacts in the cross sections are only schematic.

Thinly bedded ice-walled lake sediment

William N. Mode

Quaternary sediment

In this section, we describe the lithological and sedimentological properties of the Quaternary sediment in Sheboygan County. These deposits are classified into broad lithostratigraphic units called formations that are further subdivided into members. The members are composed of diamicton (poorly sorted sediment with clay to clast grain size), sand and gravel (commonly interpreted as outwash deposited by streams flowing away from the glacier or as ice-contact stratified deposits), and silt and clay (interpreted as lake sediment). Diamicton is further subdivided into till, which was deposited directly by overlying ice, and debris-flow deposits that flowed off the ice surface. These cannot always be distinguished, so we use diamicton as a general descriptive term and till when the diamicton is interpreted as deposited directly by the glacier.

The lithostratigraphic units described here are the Hayton, Holy Hill, Oak Creek, and Kewaunee Formations, as well as older sediment not yet classified (table 1). For a formal definition of classified units, see Syverson and others, 2011. Because parts of the map unit names on plate 1 describe landforms, these landforms are mentioned in the following section, but not discussed until later in the text.

Hayton Formation

In Sheboygan County, two or more diamicton units older than the Holy Hill Formation are preserved in depressions in the bedrock surface beneath younger deposits. Grayish brown, compact silty till is present at depth in both the central and southern parts of the county, but no evidence of this older till has been found in northern Sheboygan County (Principato, 1999). This diamicton has similar characteristics to silty gray diamicton, called the Hayton Member, which lies beneath the Holy Hill Formation at the Valders Lime and Stone Quarry in Manitowoc County (Syverson and others, 2011). Although previous studies mention an older gray diamicton at depth (Alden, 1918; Bleuer, 1971; Fricke, 1976; Nemchak, 1977; Battista, 1990), very little is known about its extent beneath the younger deposits (figure 4). Battista (1990) identified a gray, compact, silty till beneath the Horicon Member near Horicon Marsh that she informally named the Kekoskee till. It is not clear whether the Kekoskee till is the same as the grayish brown, compact silty till found in Sheboygan County or the Hayton till in Manitowoc County because it contains more clay and silt and considerably less sand (Battista, 1990), but Mickelson and Socha (in press) suggest that it is. If these older gray tills are correlative, then this pre–late Wisconsin Glaciation was extensive and possibly involved both the Green Bay and Lake Michigan Lobes.

In Sheboygan County, Hayton till has a mean grain-size distribution of 38 percent sand, 46 percent silt, and 16 percent clay (table 2). Magnetic susceptibility averages 0.0021 MKS units and ranges between 0.0017 and 0.0026 MKS units. The color varies between grayish brown (10YR 5/2) and very pale brown (10YR 7/4). The grayish brown till has no known surface exposure.

Table 1. Lake Michigan Lobe stratigraphic units, with approximate age and phases of the glacier and lake.

Time in years before present	Wisconsin lithostratigraphic units	Glacial phase	Lake phase
14,700–13,000	**Kewaunee Formation**		
13,200–13,000	Two Rivers Member	Greatlakean	Calumet
14,000–13,200	Two Creeks Forest Bed		Two Creeks low
14,700–14,000	Valders Member	Port Huron	Glenwood
15,500–14,800	Ozaukee Member	Port Huron	Glenwood
17,500–16,500	**Oak Creek Formation**	Crown Point	Glenwood
21,000–19,000	**Holy Hill Formation**		
	Waubeka Member	Woodstock	
	New Berlin Member	Putnam and Livingston	
32,000–22,000	**Zenda Formation**		
	Tiskilwa Member	Shelby and Marengo	

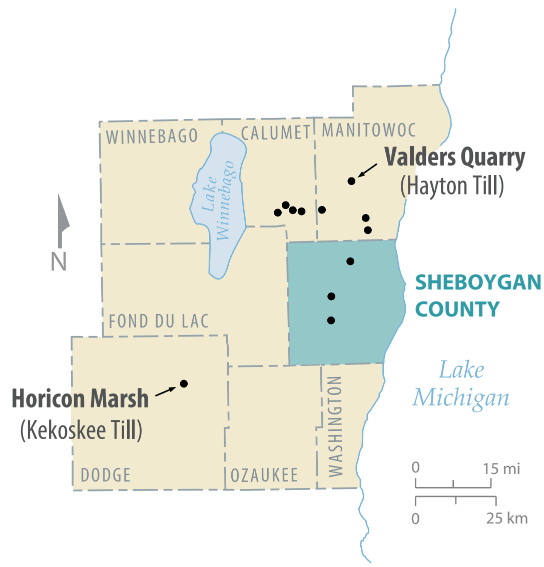


Figure 4. Possible correlative till units with the gray compact silty till.

Plymouth sediments

In the early spring of 1999, Earth Tech conducted a groundwater study of a contaminated landfill in the township of Plymouth (NW1/4, Section 36, T15N, R20E). Rotosonic drilling of four boreholes, with continuous sampling, was completed through Quaternary sediment down to bedrock within an approximately 1-mile radius of the landfill. The deepest borehole contained 325 ft (100 m) of glacial sediment.

A 1-mile east–west cross section of the stratigraphy from the boreholes can be broken into three units (figure 5). The top unit (Unit A) contains up to 215 ft (65 m) of sand and gravel interbedded with diamicton of the New Berlin Member of the Holy Hill Formation. The middle unit (Unit B) is composed of 50 ft (15 m) of lacustrine sand and silt. The bottom unit (Unit C) is composed of compact, reddish-gray diamicton units (interpreted as till) interbedded with lacustrine silt and sand, and outwash gravel, with a total thickness of about 80 ft (24 m). The reddish-gray diamicton beds of Unit C (hereafter referred to as the Plymouth diamicton units) are further subdivided into Bed 1, Bed 2, and Bed 3, which are separated from each other by silt, sand, and gravel. These may represent three different ice advances or an ice-marginal deposit from a single ice advance.

One sample from each diamicton unit was analyzed. Bed 1 contains 34 percent sand, 40 percent silt, and 26 percent clay and has a magnetic susceptibility of 0.0011 MKS units. Bed 2 is sandier, with 50 percent sand, 30 percent silt, and 20 percent clay and a magnetic susceptibility of 0.0015 MKS units. Bed 3 has more silt, with 39 percent sand, 46 percent silt, and 15 percent clay and a magnetic susceptibility of 0.0013 MKS units. All three diamicton beds are reddish gray (5YR 5/2) where unoxidized and pale brown (7.5YR 6/3) to very pale brown (10YR 7/4) where oxidized.

The ages of these diamicton layers are based on radiocarbon dates from these cores. Lacustrine sediment underlying Bed 1 of Unit C contains wood fragments, approximately 0.5 cm in length. The U.S. Forest Service Laboratory in Madison identified these fragments as a hardwood, possibly beech (*Fagus*), and yielded a radiocarbon age of 34,610±390 radiocarbon years before present (B.P.) (Beta Analytic Inc., Beta-129847; 39,530±410 calendar years B.P.). Smaller wood fragments (less than 0.5 cm in length) of an unknown species are present within the lacustrine sediment of Unit B; they yielded a radiocarbon age

Table 2. Percent grain size and magnetic susceptibility for the various members discussed in text, with 1 sigma standard deviation indicated.

Unit (No. samples)	Sand (%)	Silt (%)	Clay (%)	Magnetic susceptibility
Valders (15)	27.9	49.7	22.4	0.0016
1 sigma	6.0	3.6	5.0	0.0002
Ozaukee (269)	20.2	45.0	34.8	0.0013
1 sigma	4.3	5.2	6.0	0.0004
Oak Creek (13)	16.8	52.7	30.5	0.0017
1 sigma	3.1	8.5	9.8	0.0003
Waubeka (8)	32.8	50.4	16.9	0.0031
1 sigma	6.1	6.3	4.4	0.0005
New Berlin (12)	46.0	42.5	11.5	0.0021
1 sigma	7.8	8.6	5.7	0.0011
Horicon (5)	41.0	42.0	7.0	0.0017
1 sigma	4.4	3.2	3.1	0.0009
Hayton (16)	37.5	46.5	16.0	0.0021
1 sigma	6.8	7.0	4.9	0.0005

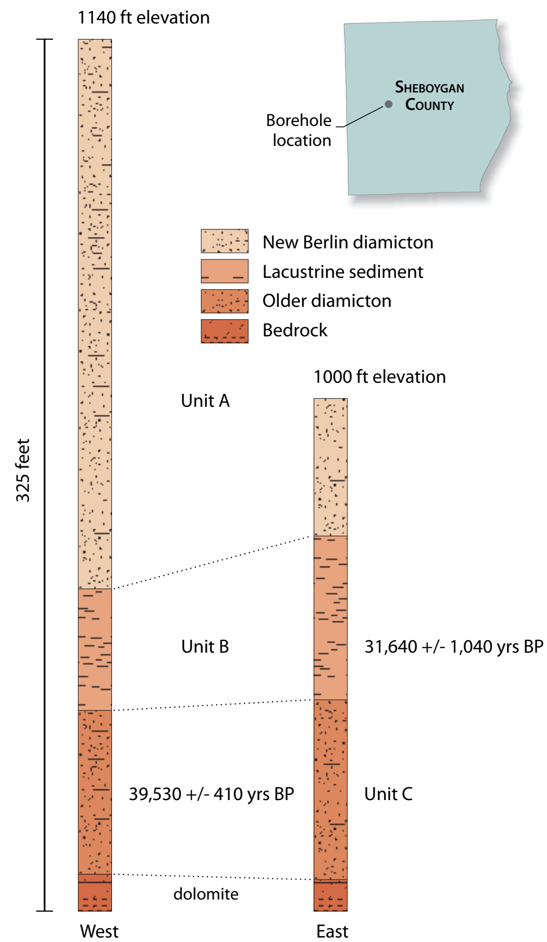


Figure 5. Stratigraphy of the two boreholes containing Plymouth diamicton. Location of radiocarbon dates noted.

of 26,400±920 radiocarbon years B.P. (National Ocean Sciences AMS Facility, OS-24520; 31,640±1,040 calendar years B.P.). The relationship between the underlying grayish brown, compact, silty till (see previous section) and Plymouth diamicton units is vague. Although grain-size distributions are somewhat similar, the Plymouth diamicton units are reddish-gray in their reduced form, while the compact, silty till is gray.

In the cross sections (plate 2), the Plymouth diamicton units and the grayish brown compact silty till are collectively shown as *Older diamicton units (Xd)* and associated *Older outwash (Xgs)*.

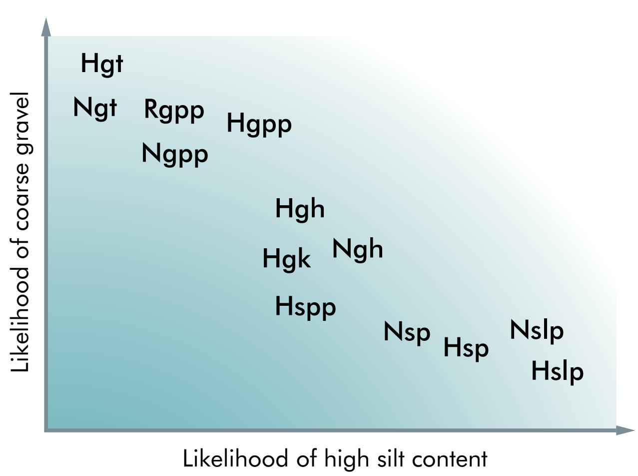
Holy Hill Formation

Holy Hill Formation sediment covers the western half of Sheboygan County and was deposited by both the Green Bay and Lake Michigan Lobes. The Green Bay Lobe advanced only far enough east to reach the west side of the Kettle Moraine, so Green Bay Lobe sediment is found only in northwestern Sheboygan County. This is mapped as the Horicon Member of the Holy Hill Formation (plate 1). The Lake Michigan Lobe deposited the New Berlin Member of the Holy Hill Formation to the east of the Kettle Moraine. Between the two lobes, meltwater deposited sand and gravel in the Kettle Moraine area, which is mapped as Undifferentiated Deposits of the Holy Hill Formation (plate 1). A minor readvance of the Lake Michigan Lobe during retreat deposited the siltier Waubeka Member of the Holy Hill Formation (Mickelson and Syverson, 1997).

Horicon Member

Deposits of the Horicon Member are at the surface in the northwestern part of Sheboygan County (plate 1). The diamicton, included in map units *Horicon diamicton rolling (Rdr)* and *Horicon diamicton streamlined (Rds)*, is light yellowish brown (10YR 6/4) and has an average magnetic susceptibility of 0.0017 MKS units. It has an average grain size of 41 percent sand, 52 percent silt, and 7 percent clay (table 2) and is generally interpreted as basal till. Sandy gravel is also contained in the Horicon Member, map unit *Horicon gravelly pitted plain (Rgpp)* (figure 6); it is interpreted as Green Bay Lobe outwash deposited as the ice retreated from its maximum position.

Figure 6. The likelihood of gravel aggregate relative to silt. Kewaunee Formation units are not included because these are poor sources of aggregate. (See plate 1 for unit descriptions.)



New Berlin Member

New Berlin diamicton occurs at the surface in parts of southern Sheboygan County, but is found at depth throughout much of the study area (plate 1). New Berlin till has a mean grain-size distribution of 46 percent sand, 43 percent silt, and 11 percent clay (table 2), which is siltier than the New Berlin till south of Sheboygan County (Mickelson and Syverson, 1997). Magnetic susceptibility averages 0.0021 MKS units, which falls in the wide range of values from previous studies (Mickelson and Syverson, 1997). The color of the New Berlin till varies from light brown (7.5YR 6/4) to very pale brown (10YR 7/4). *New Berlin diamicton on streamlined surfaces (Nds)* indicates drumlinized regions with a thin (6 to 33 ft, 2 to 10 m) mantle of till draped over sand and gravel (plate 1). *New Berlin diamicton in areas of rolling topography (Ndr)* has an irregular surface underlain by several meters of till over sorted sediment.

Stream-deposited stratified sand and combined sand and gravel cover much of central and western Sheboygan County (plate 1). The deposits display a wide variation in particle size as a result of fluctuations in stream discharge. Limited exposure and complex stratigraphy do not allow differentiation of stratified sediment units based on grain size and sorting. Approximately 75 percent of the mapped stratified deposits are moderately to well-sorted gravel. Another 20 percent are moderately to well-sorted sand. Silt comprises the remaining 5 percent of the glaciofluvial deposits. Geomorphic expression was also used as a mapping criterion on plate 1. *New Berlin gravel and sand in hummocky topography (Ngh)* generally has more sand and silt than *New Berlin gravel and sand in pitted outwash plains (Ngpp)*, which displays a greater degree of sorting (figure 6).

Ngh represents areas of high-relief hummocky topography, while *Ngpp* indicates sand and gravel plains containing isolated kettles. *New Berlin sandy plain (Nsp)* contains silty sand with little gravel. Incised stratified sediment with low relief is mapped as *New Berlin gravel and sand in terraces (Ngt)*, and this unit usually contains relatively little silt. These regions are usually poorly drained.

Undifferentiated deposits in the Kettle Moraine

Both the Green Bay and Lake Michigan Lobes acted as sources for the stratified sediment in the Kettle Moraine interlobate area. Distinction between the two sources is difficult because meltwater and sediment from each of these lobes mixed in a complex drainage system. Consequently, the deposits in the interlobate areas are not placed in a specific member and are mapped as undifferentiated (plate 1). *Undifferentiated Holy Hill gravel and sand in areas of hummocky topography (Hgh)* and *Undifferentiated Holy Hill gravel and sand in pitted outwash plains (Hgpp)* contain poorly to well-sorted gravel, with localized zones of well-sorted sand, bedded silt, and diamicton (figure 6). *Hgh* has more high-relief hummocky topography than *Hgpp*, which contains isolated kettles. *Undifferentiated silt and sand in lacustrine plain (Hslp)* has more silt than *Undifferentiated sand plain (Hsp)*. Both of these units contain little internal relief. Terraces associated with the Kettle Moraine sediment are mapped as *Undifferentiated gravel and sand in terraces (Hgt)*. *Undifferentiated diamicton in areas of rolling topography (Hdr)* represents regions in the Kettle Moraine with an irregular surface underlain by up to 10 ft (3 m) of diamicton.

Waubeka Member

A minor readvance of the Lake Michigan Lobe during retreat from its maximum position deposited the Waubeka Member of the Holy Hill Formation. The siltier till associated with the member indicates that ice had partially retreated into the lake basin before readvancing. It is exposed at the surface in Ozaukee County as a continuous till sheet (Mickelson and Syverson, 1997), but Waubeka sediment has a patchy distribution in Sheboygan County. It is present in drill cores, one exposure in the southern part of the county (Carlson, 2002), and bluffs in the northern part of the county (Principato, 1999).

Waubeka till in Sheboygan County has a grain-size distribution of 33 percent sand, 50 percent silt, and 17 percent clay (table 2). Mickelson and Syverson (1997) found a similar grain-size distribution as this study. Waubeka till varies in color from pinkish gray (7.5YR 6/2) to very pale brown (10YR 7/4) and has a magnetic susceptibility of 0.0031 MKS units. The Waubeka Member is not mapped on plate 1 because it is not exposed at the surface.

Oak Creek Formation

Oak Creek diamicton is exposed at the surface around the southern end of Lake Michigan, where it makes up much of the Valparaiso and Lake Border Morainic Systems (Schneider, 1983). In Sheboygan County, younger Kewaunee Formation diamicton buries the Oak Creek end moraine approximately 1 mi (1.6 km) north of the Ozaukee County line (plate 1). The Oak Creek diamicton also extends west of the Kewaunee Member boundary just south of the town of Plymouth (plate 1). The Oak Creek till has a sparse distribution in Sheboygan County, likely due to erosion by later readvances. The till exists at depth in the central and southern part of the county (Chapel, 2000; Carlson, 2002), but has yet to be found in the northern part of the county (Principato, 1999).

Oak Creek till in Sheboygan County has an average grain-size distribution of 17 percent sand, 53 percent silt, and 30 percent clay (table 2). Magnetic susceptibility averages 0.0017 MKS units. The till has an unweathered light brownish-gray (10YR 5/1 to 6/2) color and an oxidized color of pale brown to very pale brown (10YR 6/3 to 7/3). Two map units (plate 1) are associated with this formation: *Oak Creek diamicton in end moraines (Odhe)* has hummocky topography underlain by thick Oak Creek diamicton, while *Oak Creek silt and sand in lacustrine plains (Oslp)* is characterized by low-relief regions underlain by lake sediment. The Oak Creek Formation has no sand and gravel deposits.

Kewaunee Formation

The Kewaunee Formation contains reddish-brown clayey diamicton and associated stream deposits. Only Kewaunee till of the Lake Michigan Lobe was deposited in Sheboygan County. A succession of glacial readvances into and recessions out of the Lake Michigan Basin deposited several members of the Kewaunee Formation. The eastern two-thirds of the surface of Sheboygan County is covered by the Ozaukee and Valders Members of the Kewaunee Formation (plate 1).

The actual number of ice margin fluctuations and associated till units is unclear because minor readvances deposited very similar units. Based on a survey of deposits in the Lake Michigan bluffs in eastern Wisconsin, Acomb (1978) and Acomb and others (1982) recognized three pre–Two Creeks age Kewaunee till units older than 14,000 calendar years (the Ozaukee, Haven, and Valders). These units were deposited in a period of less than 1,000 years and record three readvances. In contrast, the records from the Green Bay Lobe (McCartney and Mickelson, 1982), Lake Michigan Basin (Lineback and others, 1972, 1974; Wickham and others, 1978), and eastern side of the Lake Michigan Lobe (Evenson and others, 1976; Eschman and Mickelson, 1986) provide evidence for only two pre–Two Creeks readvances.

There is a only a small difference in grain-size distribution between the reddish-brown till unit in Ozaukee County bluffs and the lower reddish-brown till in the northern Sheboygan County bluffs. There is no exposure of these units between northern Ozaukee County and north of Sheboygan, a distance of over 20 miles (32 km). Acomb (1978) and Acomb and others (1982) opted to call the reddish-brown till in northern Ozaukee County and the lower of two reddish-brown tills in northern Sheboygan County by different names—the Ozaukee and Haven Members, respectively. In this study, more samples were collected, including samples inland from the bluff. These samples do not have statistically significant differences in grain size. Another argument for them being the same unit is the fact that no more than two Kewaunee Formation till units have been identified in any exposure (Hadley and others, 1977a, 1977b; Acomb and others, 1977; Acomb, 1978; Acomb and others, 1982; Laabs, 1999). South of Sheboygan County, only one red till exists in the bluffs. There are no bluff exposures in southern Sheboygan County. In northern Sheboygan County, two till units exist, but these have been identified as either the Ozaukee or Haven till with the Valders till overlying them. Thus, there is no known exposure that contains till of both the Ozaukee and Haven Members.

Part of the difference in grain size between northern Sheboygan and Ozaukee Counties may have developed as the glacier moved southward and incorporated different material into the till. This is suggested by a compilation of all grain-size data collected within five miles of Lake Michigan from central Kewaunee County southward to the southern boundary of the Kewaunee Formation, which indicates a progressive increase in sand content and decrease in clay content southward (figure 7).

Because few exposures exist inland from Lake Michigan, much of our mapping of the Kewaunee Formation relied on drill holes from which relative differences in grain-size down core were interpreted as changes in stratigraphic unit (Principato, 1999; Chapel, 2000). However, based on high-resolution sampling (every 6 inches, 15 cm), these changes appear to be gradual rather than abrupt (Carlson, 2002). These units also have been differentiated based on the presence of intervening sand, gravel, and lacustrine layers in drill holes, but there is no significant change in grain size across the layers (Carlson, 2002). The relatively small thickness of these sorted layers (1 to 12 inches, 2.5 to 30 cm) and similarity to inclusions in exposed Kewaunee till suggest that they may be due to subglacial processes rather than ice retreat and readvance.

Because only two red till units are clearly documented in the bluffs of Lake Michigan, we suggest that the three pre–Two Creeks Forest Bed members previously recognized be considered two members, the Ozaukee and Valders. Thus, we consider the Haven till previously mapped in northern Sheboygan County to be Ozaukee till. To the northeast where Ozaukee and Valders tills were both deposited, we differentiate between the two tills based on stratigraphic location. Inside the Valders end moraine (plate 1), the upper red till is Valders, and the lower red till Ozaukee. Outside of the Valders end moraine, only one red till exists,

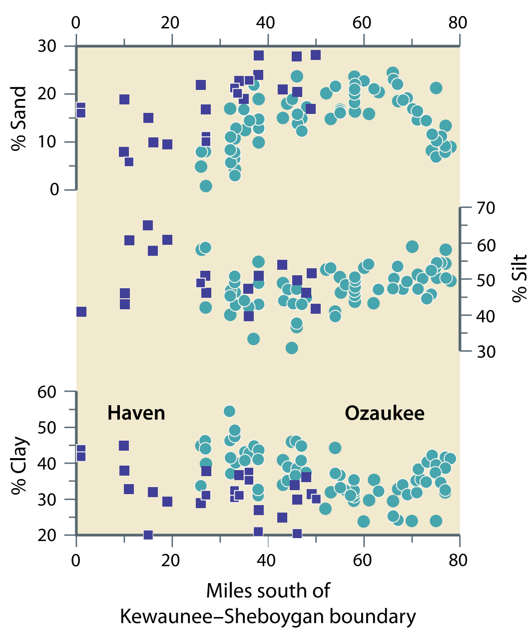


Figure 7. Change in sand, silt, and clay content of the Ozaukee and Haven Members of the Kewaunee Formation along an 80-mile stretch of Lake Michigan south from the Kewaunee–Sheboygan County border.

which is mapped as Ozaukee. Based on the locations of Ozaukee and Valders ice margins in Lake Michigan, the Ozaukee till likely corresponds with the Shorewood Till under Lake Michigan, while the Valders till correlates with the Manitowoc Till (Lineback and others, 1972, 1974).

Ozaukee Member

Ozaukee Member deposits cover the eastern half of southern Sheboygan County (plate 1). Till from this readvance is quite thin (< 6 ft, 2 m) near the terminal extent of the former ice, but thickens to over 100 ft (30 m) near Lake Michigan. The Ozaukee till has a mean grain size of 20 percent sand, 45 percent silt, and 35 percent clay (table 2). In Ozaukee County, Ozaukee till has less sand and more silt (Mickelson and Syverson, 1997). Magnetic susceptibility of Ozaukee till averages 0.0013 MKS units. Color ranges from reddish gray (5YR 5/2) to brown (7.5YR 5/4) where reduced and reddish brown (5YR 5/4) to reddish yellow (7.5YR 6/6) where oxidized.

Ozaukee diamicton in end moraines (Zdhe) has regions of hummocky topography, with thick diamicton (plate 1). This hummocky topography has much lower relief than the hummocky topography in the Kettle Moraine. *Ozaukee diamicton in areas of rolling topography (Zdr)* indicates areas of nondescript relief. *Ozaukee sand and gravel in outwash plains (Zsp)* denotes sand and gravel in nearly flat plains, most of this sand with small pebbles. Deposits have a lower concentration and smaller clast size than New Berlin sand and gravel. *Ozaukee silt and sand in lacustrine plains (Zslp)* are low, flat, poorly drained regions underlain by sand and silt.

Valders Member

The Valders Member is the youngest member of the Kewaunee Formation present in Sheboygan County and was deposited by the last advance of the Lake Michigan Lobe into this area. Deposits associated with the Valders Member are found in the central and northeastern part of the county (plate 1). The ice marginal position of the Valders Member is distinguished by a low rolling ridge of thin diamicton (10 ft, 3 m) overlying an Ozaukee end moraine, trending northwest–southeast and curving eastward into Lake Michigan just south of the Sheboygan River in the city of Sheboygan (plate 1). Valders diamicton is relatively thin (less than 10 ft, 3 m) compared to the underlying Ozaukee Member (up to 100 ft, 30 m).

Map unit *Valders diamicton rolling (Vdr)*, contains till with 28 percent sand, 50 percent silt, and 22 percent clay (table 2). Diamicton samples are similar in color to the Ozaukee diamicton—namely, light brown (7.5YR 6/4)—but the Valders diamicton is commonly redder in outcrop than the Ozaukee. Samples of the Valders till have a mean magnetic susceptibility of 0.0016 MKS units.

A low, rolling ridge is interpreted to be the recessional ice-margin position associated with the Valders Member. This ridge is oriented generally north–south, extends for at least 6 miles (9.7 km), and is approximately a quarter of a mile (0.4 km) wide; see plate 1, Mosel and Herman Townships (T16N, R23E and T16N, R22E). This ridge is interpreted as an end moraine composed of gravelly, silty, sandy diamicton, and is shown as map unit *Valders diamicton end moraine (Vdhe)* on plate 1. Diamicton samples of *Vdhe* are coarser than the diamicton found in the surrounding *Valders diamicton rolling (Vdr)*. Six diamicton samples of map unit *Vde* average 54 percent sand, 32 percent silt, and 14 percent clay, with a magnetic susceptibility of 0.0025 MKS units. The diamicton in the moraine (*Vdhe*) is interpreted as supraglacial sediment based on its higher sand content, angular clasts, and more abundant igneous and metamorphic lithologies than the diamicton found in the less hummocky till (*Vdr*).

Sand and gravel deposits in the Valders Member are mapped as *Valders sandy pitted plain (Vspp)* and *Valders sandy plain (Vsp)*, and they generally contain less than 5 ft (1.5 m) of gravelly, silty sand stratigraphically above diamicton. These units are less gravelly than Holy Hill Formation glaciofluvial deposits. *Vgh, Vspp,* and *Vsp* are interpreted as outwash deposits, and it is possible that *Vsp* sediments were deposited in proglacial lake basins associated with the Valders advance.

Post-glacial deposits

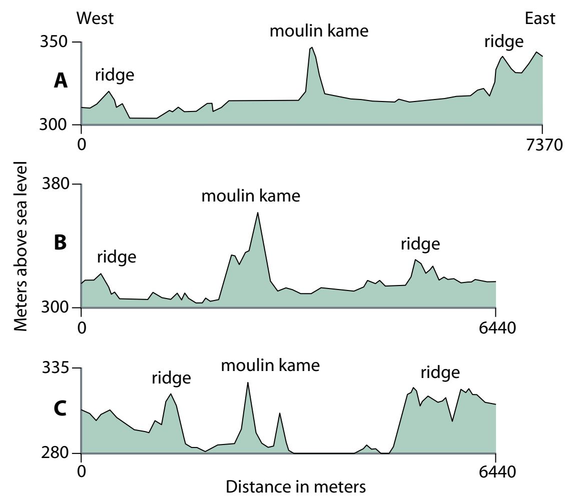
Post-glacial erosion of the landscape produced sediment that has been deposited in stream valleys, along the Lake Michigan shoreline, and in depressions in the landscape. Silt and fine sand deposited in flood plains of major streams are mapped as *alluvium* (*a*). The area covered by former high-water levels of Lake Michigan (most of the area east of Interstate 43) was reworked into now inactive sand dunes (map unit *s*) that extend parallel to the Lake Michigan shoreline in the southern part of the county (plate 1). The best-developed sand dunes occur in Kohler-Andrae State Park, but they are traceable northward to where the Black River discharges into Lake Michigan. Peat and muck that accumulated in wet depressions are mapped as *organic deposits* (*o*). Many of these depressions represent former lakes that have since filled with organic and mineral sediment.

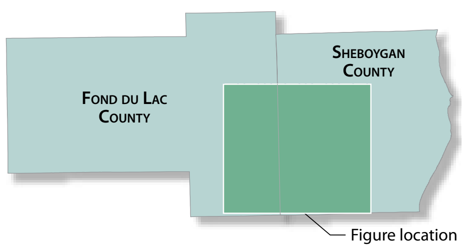
Physiographic regions and associated landforms

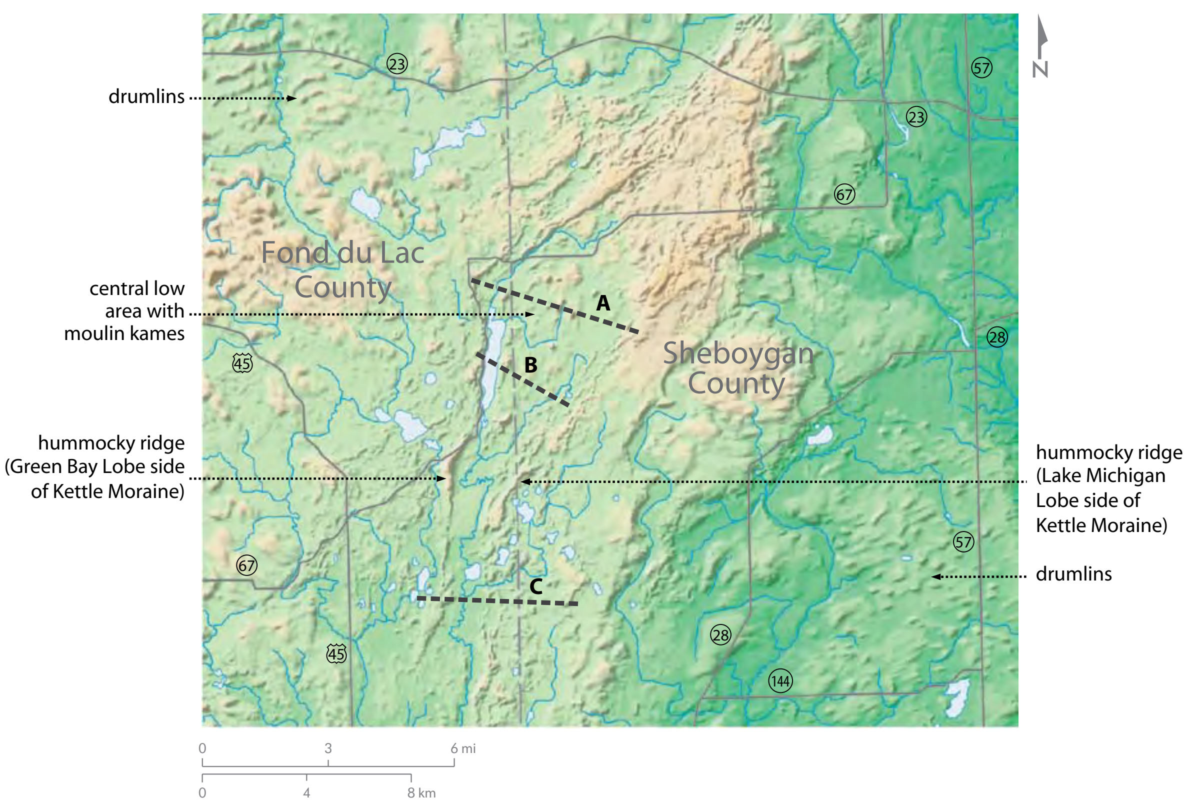
Glacial landforms contain an important record of glacial transport and deposition that relates to ice-sheet dynamics and ice-margin fluctuations. Examination of sediment characteristics, stratigraphy, structures, and sedimentary architecture within these landforms allows interpretation of glacial and glaciofluvial sedimentation processes, ice-margin positions, and ice behavior.

Sheboygan County contains three main physiographic regions, each representing a record of unique ice depositional and erosional processes (plate 1). First, the Kettle Moraine constitutes the most prominent landform complex in Sheboygan County. This region formed 20,000 to 19,000 years ago between the thinning Green Bay and Lake Michigan Lobes and is interpreted to have been a large braided river system on top of stagnant ice. Second, to the east and west of the Kettle Moraine lie regions of outwash and till. The primary glacial landforms of this region are drumlins, pitted outwash plains, large meltwater channels, and lake plains. Finally, farther east are low-relief end moraines and gently rolling, clayey till plains.

Figure 8. A 30 m digital elevation map of the Kettle Moraine with three cross sections. Dashed lines on map indicate locations of cross sections.



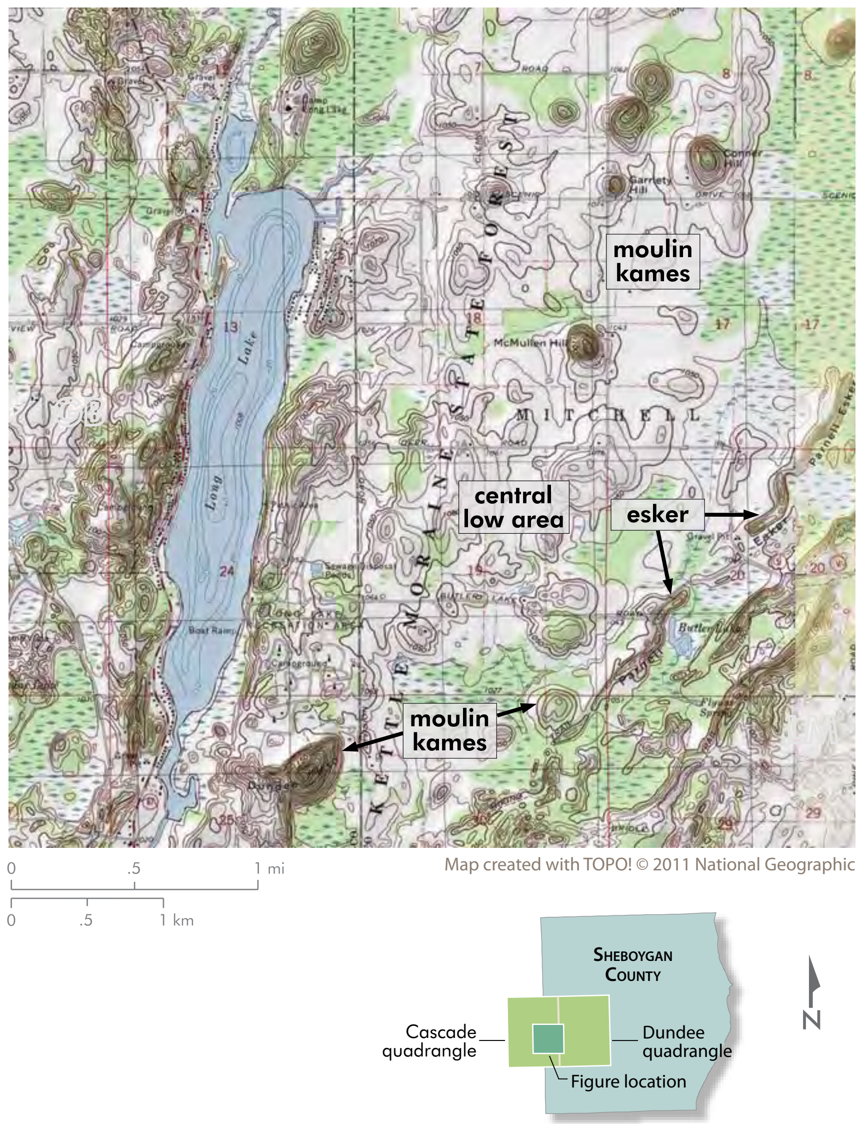




Kettle Moraine

The Kettle Moraine extends approximately 125 miles (200 km), from Walworth County in southern Wisconsin to Kewaunee County, at the southern end of the Door Peninsula. Chamberlin (1877, 1878) first named and described this feature, suggesting that it was formed by the accumulation of debris between the Lake Michigan and Green Bay Lobes as they retreated after the Last Glacial Maximum. However, this interlobate moraine does not fit the description of a true end moraine (Mickelson and others, 1983) because it is mainly composed of sand and gravel rather than thick diamicton. Opposing flow directions of the two lobes created upward, compressive ice flow that carried debris high into the ice (Chamberlin, 1878; Black, 1969). Meltwater from both lobes transported and deposited much of this sediment between the two lobes during retreat. In Walworth, Waukesha, and south Washington Counties, a single ridge characterizes the Kettle Moraine (Alden, 1918; Attig, 1986; Mickelson and Syverson, 1997; Clayton, 2001). However, from central Washington County to central Sheboygan County, the Kettle Moraine consists of two ridges separated by a central low area (figures 8 and 9) (Syverson, 1988; Mickelson and Syverson, 1997; Carlson and others, 2005). From northern Sheboygan County to Kewaunee County, the Kettle Moraine is a single ridge system.

Figure 9. Hummocky topography of the Kettle Moraine (parts of the Cascade and Dundee 7.5-minute quadrangles). Note the central low area and abrupt rise of the moulin kames and eskers.



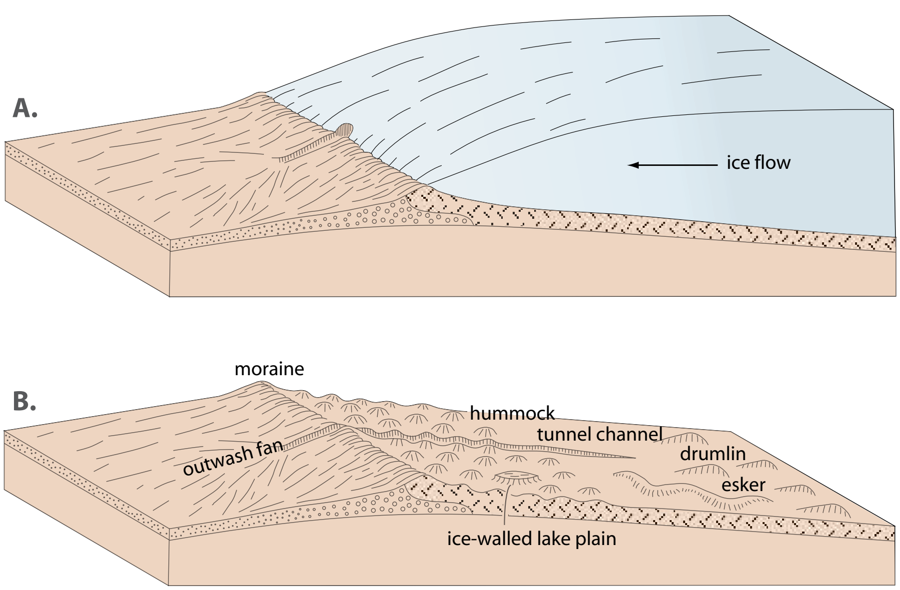
Much of the relief in the Kettle Moraine is due to the presence of hummocks and kettles (plate 1, map units *Hgh*, *Ngh,* and *Rgh*). These are formed when gravel or diamicton is deposited on the margin of a retreating glacier and the ice masses eventually melt out, creating depressions, or kettles, while the interkettle highs that were not on ice are hummocks (figures 10 and 11). This topography is called hummocky if most of the nearly flat depositional surface is collapsed, and pitted outwash if significant parts of the floodplain surface remain uncollapsed (figure 11). Kettles are usually deep depressions with steep-sided walls (30° to 35°). Some are circular and may resemble a cooking kettle, from which their name is derived (Chamberlin, 1878), while other kettles have irregular, elongate shapes.

Much of the central low area lacks this high-relief topography (figures 8 and 9). It is 65 to 165 ft (20 to 50 m) lower than the hummocky ridges on either side, and 0.5 to 1.5 miles (0.8 to 2.4 km) wide. It is underlain by rolling diamicton with 20 to 50 ft (6 to 15 m) of relief and relatively uncollapsed outwash, and it lacks the high-relief hummocky topography of the adjacent ridges. This low-relief central region also contains eskers and moulin kames. Eskers are ridges of subglacial stream sediment deposited in tunnels beneath or within the ice (figures 8 and 9). They are elongate and winding and can be traced for a considerable distance. The Parnell esker is an excellent example of these features in Sheboygan County. Eskers contain poorly to well-sorted sand and gravel, as well as particles exhibiting a high degree of rounding. Eskers are found in areas mapped as *Hgh* and *Ngh*, and they are marked with a specific symbol on plate 1.

Large conical moulin kames (Alden, 1918) rise 50 to 180 ft (15 to 55 m) above the central low area and rest directly on top of basal till (Carlson and others, 2005) (figures 8 and 9). Moulin kames are hills of sediment that accumulated at the base of vertical shafts in the ice, called moulins. The ones in Sheboygan County are very large, world-class examples of these features. These may have formed when moulins widened during melting or when the roof of a subglacial tunnel collapsed. Few moulin kames have exposures, but those that do contain a variety of sediment: diamicton, well-sorted to poorly sorted sand and gravel, and laminated silt with dropstones. The majority of sediment in these exposures is made up of steeply dipping, interbedded diamicton and poorly sorted sand and gravel. Maximum clast diameter is 3 ft (1 m), and clast lithology is predominantly dolomite (the local bedrock) with some far-traveled lithologies (igneous and metamorphic). Several of these hills have eskers (10 to 60 ft, 3 to 18 m, high) extending up to 1,300 ft (400 m) from their southern flanks, indicating the southward, subglacial drainage direction of meltwater that fell into the moulins.

Long, hummocky ridges border both sides of the central low area and rise steeply 65 to 165 ft (20 to 50 m) above the central low area (figures 8 and 9). Deep kettles abut the ridges on either side. The ridges generally contain well-sorted, well-rounded sand and gravel with a clast diameter of less than 3 ft (1 m). Dolomite is the prevailing clast lithology, and there are few far-traveled lithologies.

Figure 10. Landforms associated with ice sheet margins.



These marginal ridges grade eastward and westward into broad zones (up to 1 mile, 1.6 km, wide) of lower-relief (< 65 ft, 20 m) hummocky gravel and pitted outwash with kettles up to 1 square mile (2.6 sq km) in area (figures 8 and 9). Sediment in these areas ranges from well-sorted, well-stratified sand to poorly sorted, more massive sand and gravel, with diamicton near ice-contact facies. Most of the sediment is fairly well-sorted sand and gravel. Maximum clast size is between 2 and 3 ft (0.6 and 1.0 m). Most clasts are dolomite, with few far-traveled lithologies. Similar hummocky topography characterizes the single ridge Kettle Moraine in Washington and northern Sheboygan Counties.

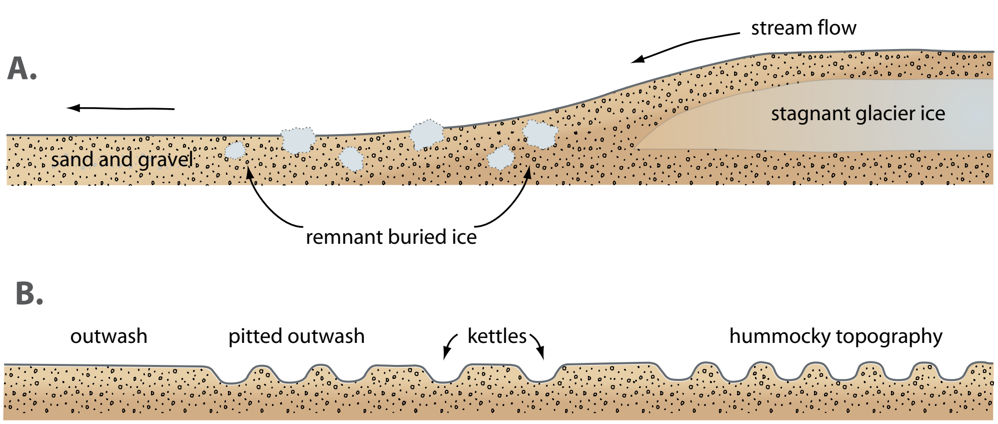
There are two contrasting landscape types in the Kettle Moraine. The central low area contains diamicton, which was likely deposited directly by overlying ice, and outwash that is finer grained than in the hummocky areas. Moulin kame deposits contain mainly diamicton and poorly sorted sand and gravel, and rocks are less rounded than gravel in the surrounding hummocky areas (table 3), which suggests transport in ice. Englacial transport is also indicated by the larger number of far-traveled clasts. The second landscape type is the hummocky marginal ridges and adjacent lower-relief hummocky and pitted outwash areas. The sediments in these features are more rounded and better sorted than sediment in the central low area, consistent with longer stream transport (table 3).

The meltwater depositing sediment on either side of the central low area flowed southeasterly on the western, Green Bay Lobe side of the axis and southwesterly on the eastern, Lake Michigan Lobe side (figure 8). In the single ridge north of the central low area, meltwater flowed south-southwest along the Kettle Moraine axis. Thus, most of the surface and subsurface water drained toward or at an angle to the central low area of the Kettle Moraine, but little of this sediment is found in the central low area. The coarse sediment in the moulin kames is distinctly different and underwent little fluvial transport. There is also a general lack of kettles in the central low area, where the only appreciable relief is the moulin kames and the abrupt rise of the marginal ridges from the central low area (figure 8). These observations suggest that there was still ice in the central area when gravel now in the hummocky ridges was deposited. The steep inner sides of the hummocky ridges also suggest sediment deposition in contact with ice. Moulin kame tops are generally higher in elevation than the adjacent marginal ridges, implying that during deglaciation, the ice surface in the central low area was higher than the ice surface where the hummocky ridges formed.

Table 3. Roundness data from the Kettle Moraine (0–1 scale measured on 100 clasts per site).

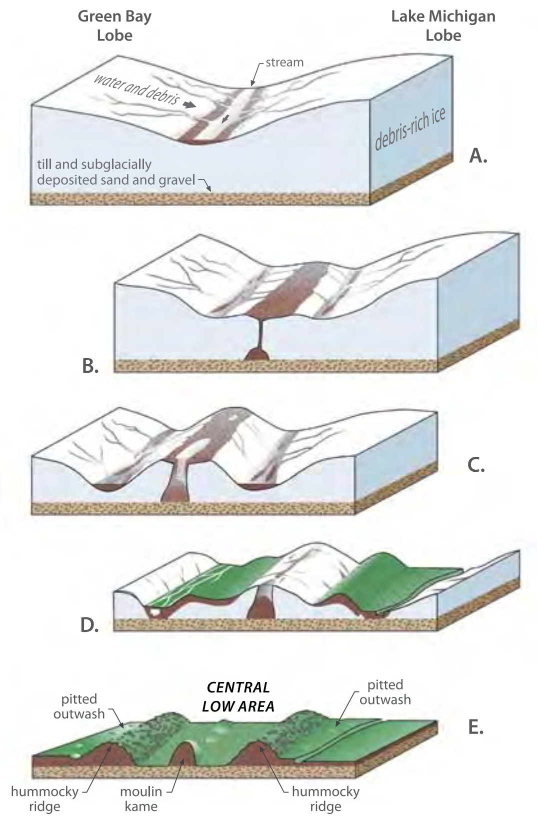
Sediment type (No. samples)	Average roundness (1 sigma)
Moulin kame (7)	0.55 (0.09)
Basal till (3)	0.64 (0.04)
Marginal ridge (3)	0.79 (0.02)
Hummocky zone (6)	0.79 (0.01)
Pitted outwash (3)	0.77 (0.03)
Transport path	**Modern roundness range**
Basal	0.5–0.8
Englacial	0.2–0.7
Glaciofluvial	> 0.7

Figure 11. Development of pitted outwash, kettles, and hummocky topography.



Carlson and others (2005) proposed a model for the formation of the northern Kettle Moraine that explains both its morphology and sedimentology. Initially, debris was concentrated along the Kettle Moraine axis as the Green Bay and Lake Michigan Lobes thinned (figure 12A). This protected the ice under the debris from melting. Cleaner ice adjacent to the debris-covered area melted more rapidly, forming channels (figures 12A and 12B), which limited further sedimentation along the axis. The double ridges of the northern Kettle Moraine contain gravel deposited in these large channels on top of ice as meltwater flowed southwestward on either side of the Kettle Moraine axis (figures 12C and 12D). Debris along the axis slid off into these channels or fell into holes and moulins in the ice, forming the moulin kames (figure 12D). The presence of these channels explains the distribution of rounded, stream sediment in marginal hummocky ridges on either side of a debris-poor low area along the axis that contains mainly angular moulin kame deposits. Where the Kettle Moraine is a single ridge, it appears that debris accumulated in a depression between the two ice lobes and the two ice marginal channels did not form. Eventually, all debris-covered ice in the Kettle Moraine melted, creating kettles and exposing moulin kames (figure 12E). Farther south in south-central Washington and Waukesha Counties, the opening of a broader area between the Lake Michigan and Green Bay Lobes did not allow the preservation of ice along the axis of the Kettle Moraine (Carlson and others, 2005). Thus the Kettle Moraine in these counties consists predominately of pitted outwash (Syverson, 1988; Mickelson and Syverson, 1997; Clayton, 2001).

Figure 12. Genesis of the Kettle Moraine (from Carlson and others, 2005).



Drumlins and outwash plains

A more regular and subdued surface extends east and west of the Kettle Moraine. Streamlined hills, called drumlins, rise above pitted outwash surfaces and lacustrine plains (figure 8). Meltwater from the Green Bay and Lake Michigan Lobes deposited sand, gravel, and ice blocks in this region, particularly between the higher drumlins. In a few places, water ponded in low areas or between stagnant blocks of ice, forming small lakes. Drumlins rose as islands above these lakes.

Drumlins

The northern edge of the Lake Michigan Lobe drumlin field and the eastern edge of the Green Bay Lobe drumlin field are in Sheboygan County. Drumlins are elongate hills that have long axes oriented parallel to the direction of ice flow (figure 10). Many of the hills are tear-drop shaped, with the steepest end commonly—though not always—on the up-ice-flow side. In Sheboygan County, many drumlins contain sand, gravel, and diamicton, and they are generally capped with a layer of diamicton.

The Green Bay Lobe drumlins are located in the northwestern part of Sheboygan County (plate 1, map unit *Rds*). These drumlins have length-to-width ratios of about 2:1 and range in height from 20 to 40 ft (6 to 12 m). They are oriented south–southeast, so ice flowed approximately perpendicular to the Kettle Moraine axis (figure 13) (Principato, 1999).

The Lake Michigan Lobe drumlins are located in the southwestern part of Sheboygan County (plate 1, map unit *Nds*). These drumlins vary in height from 20 to 120 ft (6 to 37 m). They have length-to-width ratios between 1.2:1.0 and 4.1:1.0. The drumlins become higher and more elongate toward the south. Their orientation shows that the Lake Michigan Lobe flowed westward in the central part of the county and southwestward in the southern part of the county (Carlson, 2002).

The cores of several drumlins in the Lake Michigan Lobe drumlin field are exposed. An exposure in the Michael's Manufacturing gravel pit (SW 1/4, Sec. 20, T13N, R21E) contains horizontally bedded gravel unconformably overlain by a layer of till. The Shaver gravel pit (NW 1/4, Sec. 13, T14N, R20E) contains folded sand, gravel, and till. The axes of these folds are both parallel and perpendicular to the ice-flow direction (figure 14). A sand diapir intrudes one of these folds. These exposures and ones similar farther south suggest that drumlins are formed by a combination of subglacial deposition, deformation, erosion, and folding of the sediment (Whittecar and Mickelson, 1979; Stanford and Mickelson, 1985).

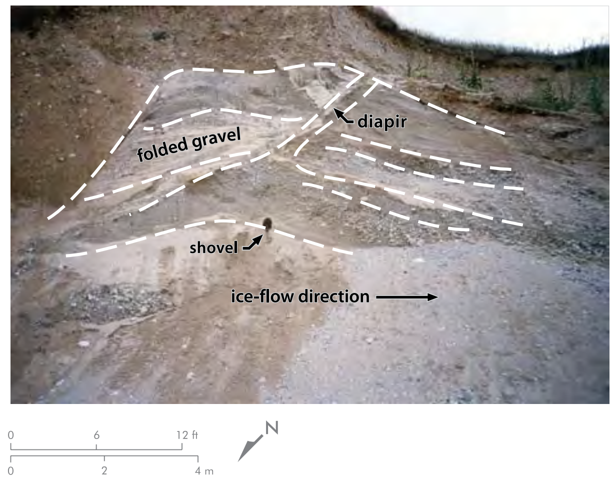


Figure 14. Folded gravel in the Shaver gravel pit (NW 1/4, Sec. 13, T14N, R20E) which cuts into a Lake Michigan Lobe drumlin (view towards the southeast). The sand diapir intrudes into the bedded sand and gravel (outlined).

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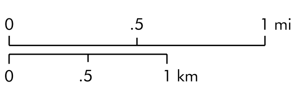
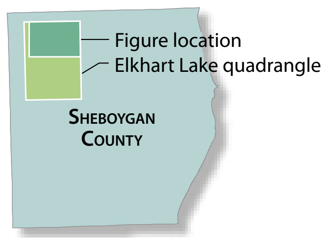


Figure 13. Green Bay Lobe drumlins (southwestern part of the Kiel 7.5-minute quadrangle), with crossed lines indicating width and length. Ice flow was toward the south-southeast.



Outwash plains and lake plains

Both the Green Bay and Lake Michigan Lobes deposited broad plains of outwash sand and gravel during retreat from the Kettle Moraine (plate 1, map units *Rgpp, Rsp*, *Ngpp,* and *Nsp*). On the Green Bay Lobe side, meltwater flowed toward the southeast, but was dammed between the Kettle Moraine and the ice margin, forming a large lake in the Sheboygan Marsh area (plate 1, map unit *Rslp*; figure 15). On the Lake Michigan Lobe side, the combination of the eastward-sloping land surface and the ice margin directed meltwater to the south. In places, meltwater incised channels into the outwash, forming terraces, which are former streambed surfaces abandoned after stream downcutting (plate 1, map units *Ngt* and *Hgt*; figure 16). Many of these are ice-marginal channels. They were occupied and then abandoned as ice retreat allowed lower channels to open along the ice margin. The channels are up to 70 ft (21 m) deep and 2,600 ft (800 m) wide. Several channels are up to 10 miles (16 km) long. Many of these channels, such as Mink Creek, North Branch of the Milwaukee River, Ben Nutt Creek, La Budde Creek, and parts of the Mullet River, now contain underfit streams (that is, streams with discharges too low to have eroded the channel) (Principato, 1999; Chapel, 2000; Carlson, 2002).

Figure 15. Proglacial lake that formed between the Green Bay Lobe and the Kettle Moraine (outlined in black). This area is now the Sheboygan Marsh (northern part of the Elkhart Lake 7.5-minute quadrangle).

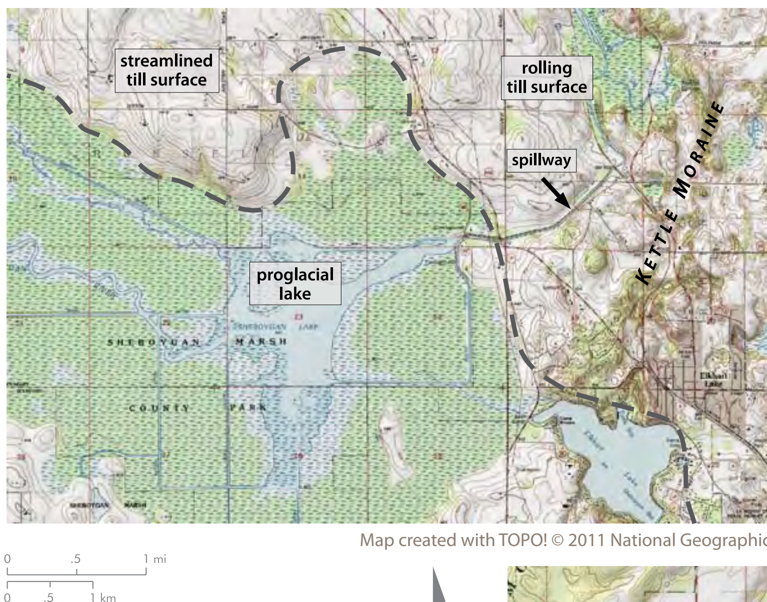
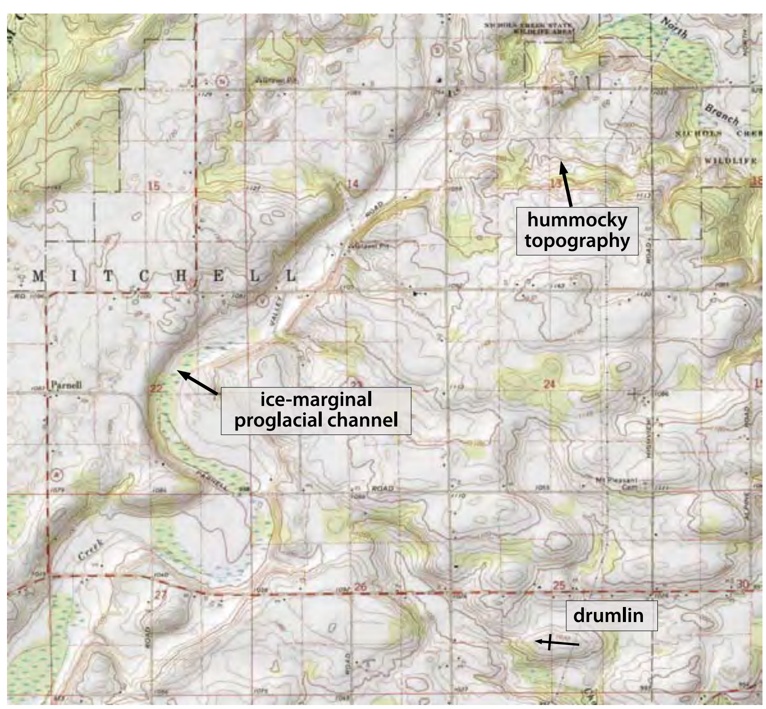


Figure 16. Ice-marginal proglacial channel (south-central part of the Cascade, WI 7.5-minute quadrangle).



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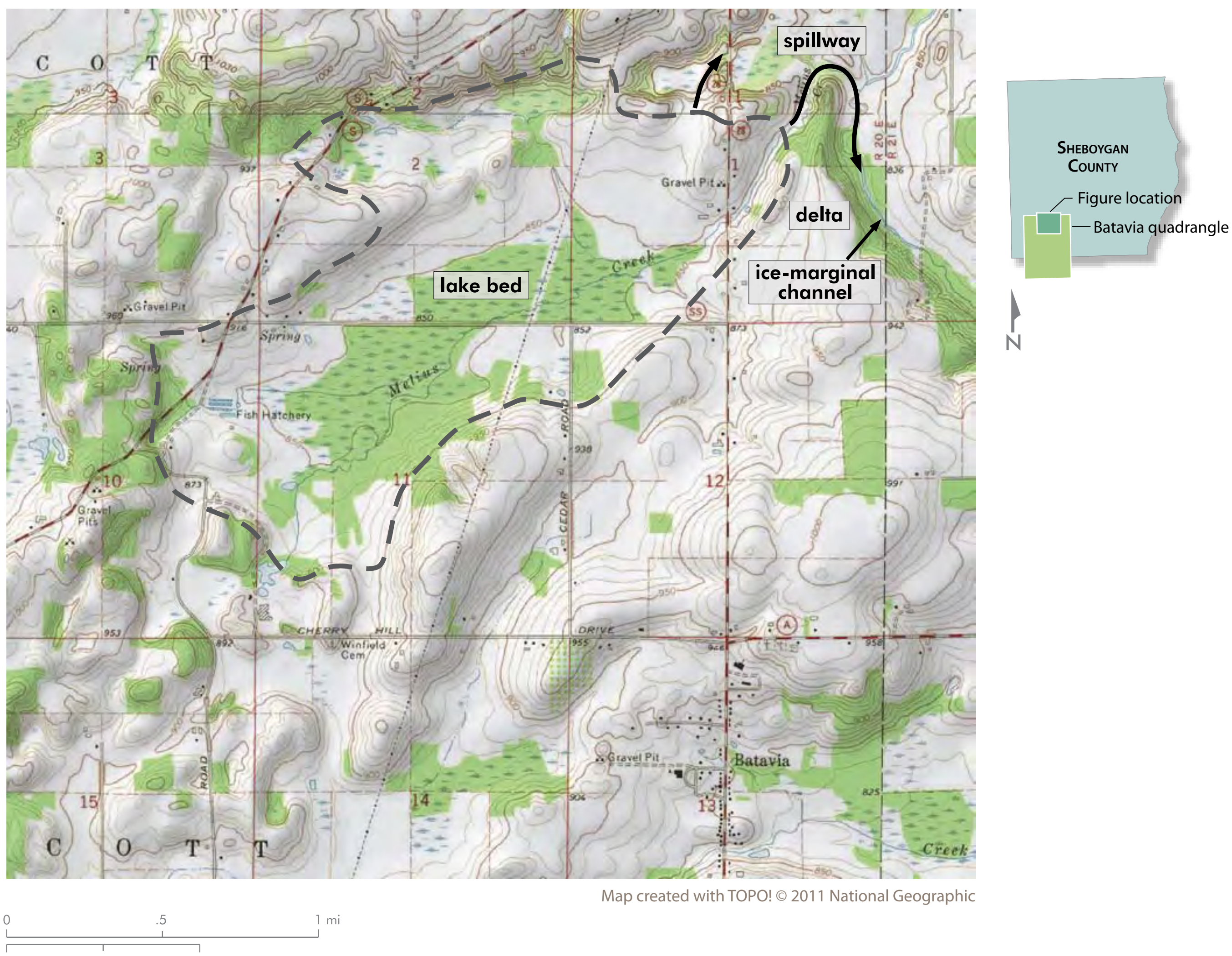
In a few places, stagnant ice blocks dammed meltwater drainage paths, and small lakes formed between the stagnant ice and the Lake Michigan Lobe terminus (plate 1, map unit *Hslp*). Melius Creek now occupies one such former lake bed (figure 17). The top surfaces of two deltas indicate that water filled this lake to 900 ft above sea level (275 m a.s.l.). Hummocky sand and gravel along the southern and western extents of the former lake show the location of the stagnant ice block that dammed drainage. Today, sandy silt underlies this flat, poorly drained area.

Figure 17. Melius Creek ice-dammed lake (outlined in black) (north-central part of the Batavia 7.5-minute quadrangle). Stagnant ice dammed this lake to a level of 900 ft a.s.l., as indicated by two delta surfaces. When the ice retreated, the lake drained to the east, incising the delta.



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Depressions in the till surface also collected meltwater, forming lakes (plate 1, map units *Hslp* and *o*). One such proglacial lake is formed in the Cascade Swamp lowland (figure 18). A delta surface indicates a former lake level elevation of 900 ft a.s.l. (275 m). This lake drained to the west through a channel now occupied by the North Branch of the Milwaukee River. As the water level dropped, the lake filled with silt, sand, and organic sediment, which resulted in the Cascade Swamp found today.

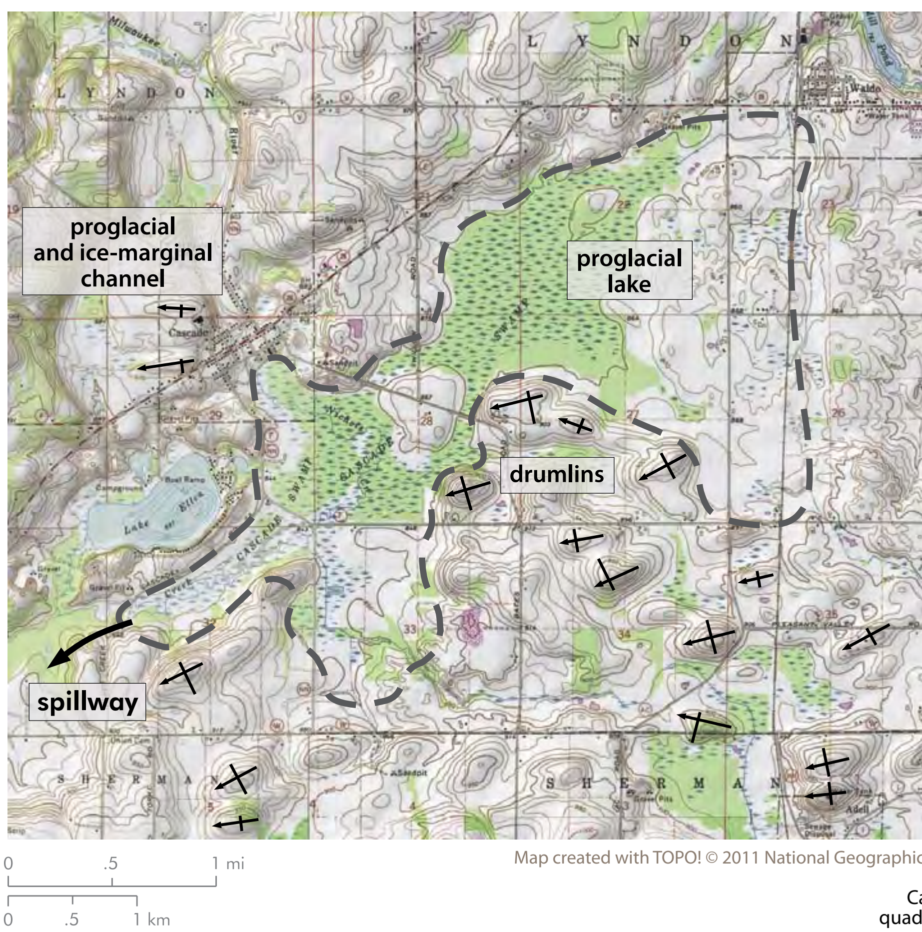
Holy Hill Formation till plain

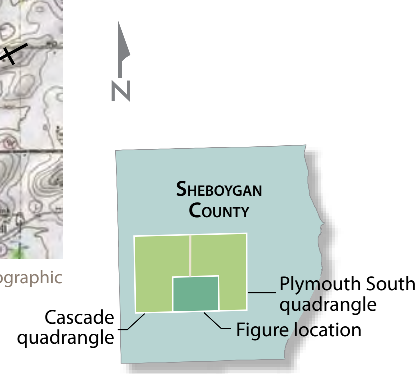
The Green Bay and Lake Michigan Lobes did not deposit true end moraines (discussed in next section) in Sheboygan County as they retreated from the Kettle Moraine. Instead, retreating ice left irregular, low-relief regions east and west of the Kettle Moraine and drumlin fields (plate 1, map units *Ndr* and *Rdr*). These regions are underlain by a thin layer of Holy Hill Formation till (less than 20 ft, 6 m) on pre-existing sediment. The absence of moraines containing Holy Hill Formation deposits suggests that ice retreated at a uniform rate or that the ice stagnated and had little debris.

Low-relief end moraines and rolling till plains

About midway between Lake Michigan and the Kettle Moraine, the landscape changes abruptly (plate 1). The drumlin fields and outwash plains of the New Berlin Member are covered by rolling diamicton and end moraines of the Kewaunee Formation and younger deposits. These north-south-oriented end moraines are traceable the length of the county (plate 1). Between these end moraines, there are low-relief surfaces (less than 20 ft, 6 m). These low rolling plains are underlain by basal till that increases in thickness toward Lake Michigan.

Figure 18. Proglacial lake extent (outlined in black) in Cascade Swamp area and Lake Michigan Lobe drumlins (parts of the Cascade and Plymouth South 7.5-minute quadrangles). A delta surface indicates that lake level rose to 900 ft a.s.l.



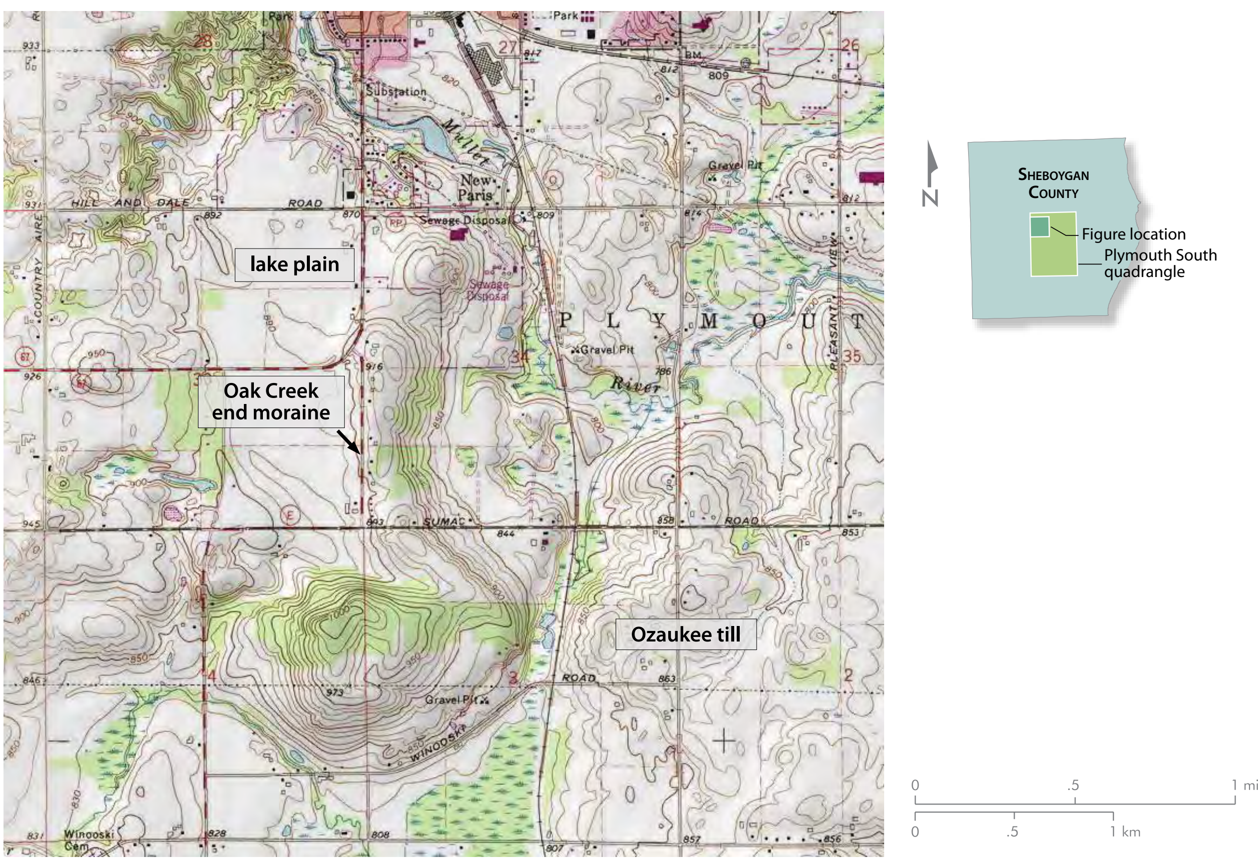


End moraines are ridges that form parallel to former glacier margins. A glacier delivers sediment to its terminus much as a conveyer belt does. Sediment is picked up behind the ice margin and carried forward until it is released by melting and deposited. As with a conveyer belt, two things determine the size of the sediment pile accumulated: the rate at which sediment is delivered to the ice margin and the length of time the ice margin remains stationary. If a glacier advances or retreats at a constant rate, it leaves a more or less constant thickness of till. If sediment is delivered at a constant rate and the ice-margin position remains more or less constant, thicker sediment accumulates to produce a moraine (figure 10). The outermost end moraine of an advance is called a terminal moraine. Moraines deposited behind the terminal moraine during ice margin retreat are called recessional moraines.

Advance of ice that deposited the Oak Creek Formation deposited a terminal moraine in Sheboygan County (plate 1, map unit *Ode*), which was covered by the younger Ozaukee advance. In central Sheboygan County, south of Plymouth, the moraine extends beyond the Ozaukee margin for approximately 1 mile (1.6 km) (W 1/2, Sec 34, T15N, R21E) (figure 19 and plate 1) (Chapel, 2000). In southern Sheboygan County, near the Ozaukee County line, the moraine extends beyond the Ozaukee Member deposits, and from there it can be traced southward into Ozaukee County (plate 1) (Mickelson and Syverson, 1997; Carlson, 2002). The Oak Creek moraine is approximately 30 ft (9 m) high and 1,000 ft (300 m) wide, with a fairly sharp crest.

The advance that deposited the Ozaukee Member did not construct a true terminal moraine while it occupied its maximum position even though a continuous ridge marks its location. Exposures and drill cores in this ridge reveal a thin layer of Ozaukee till (2.0 to 6.5 ft, 0.6 to 2.0 m) over a composite core of Oak Creek, Waubeka, and New Berlin gravel and diamicton.

Figure 19. Oak Creek end moraine (northwestern part of the Plymouth South 7.5-minute quadrangle) extending beyond the Ozaukee till.



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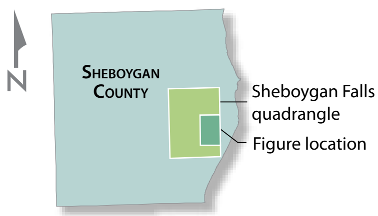
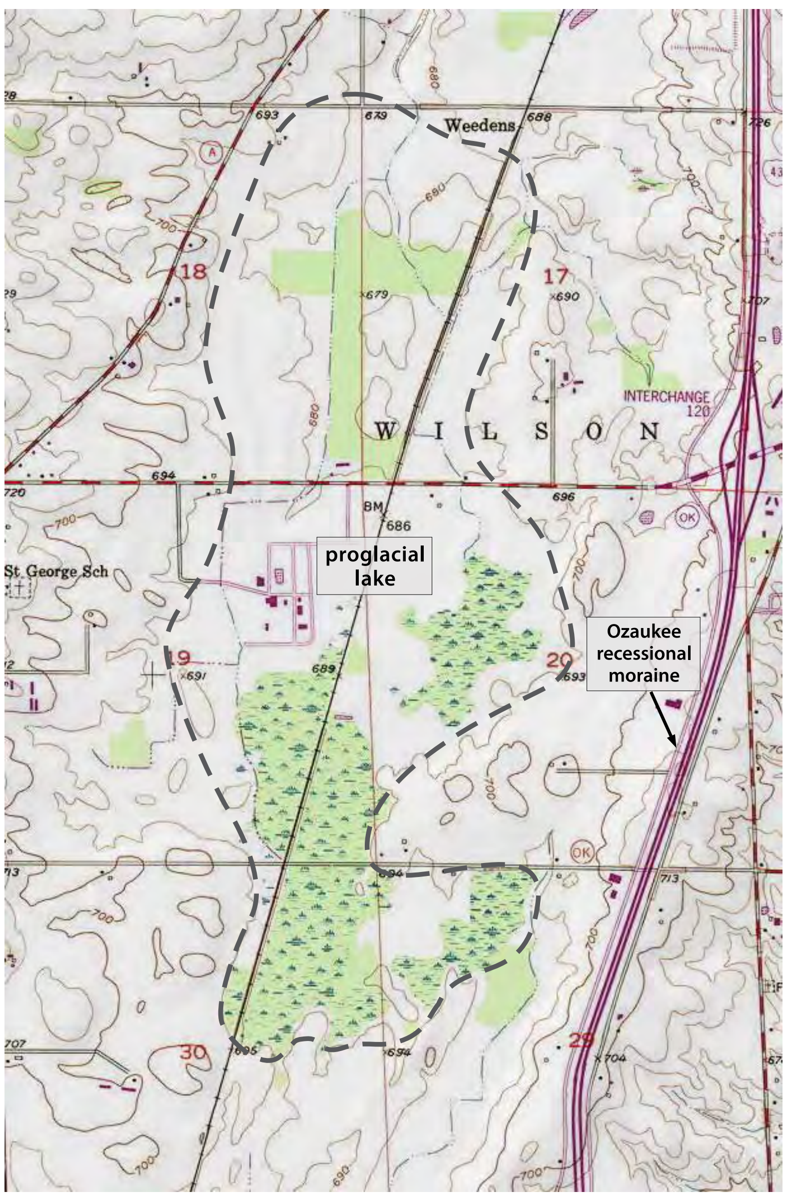


Figure 20. Ozaukee recessional moraine and proglacial lake (outlined in black) (east-central part of the Sheboygan Falls 7.5-minute quadrangle).



Ice wasting back from the maximum extent of the Ozaukee advance deposited several recessional moraines. These moraines have low-relief hummocky topography (figure 20). They rise 20 to 60 ft (6 to 18 m) above the till plain and are 1,000 to 3,000 ft (300 to 900 m) wide. Ozaukee recessional moraines (plate 1, map unit *Zdhe*) contain 12 to 55 ft (3.7 to 16.8 m) of clayey Ozaukee till (Carlson, 2002).

The later Valders readvance did not deposit a terminal end moraine, but did deposit a recessional moraine (plate 1, map unit *Vdhe*) over an older Ozaukee recessional moraine (Principato, 1999; Chapel, 2000). This moraine extends from the northern boundary of Sheboygan County to south of the town of Sheboygan, where it is covered by younger lake sediment (plate 1).

Outwash

Retreat of the ice lobe that deposited the Kewaunee Formation resulted in much less glaciofluvial sedimentation than the earlier ice retreats. Kewaunee Formation outwash is poor in gravel, containing mainly sand and silt. It lacks the cobbles and boulders of the outwash of the New Berlin Member (plate 1, map units *Vsp, Vspp, and Zsp*). In front of the outermost Kewaunee position, meltwater flowed southwestward in pre-existing drainage paths, eroding channels into older deposits. Behind the terminal position, moraines channeled meltwater southward into what are now the Sheboygan River, Pigeon River, Onion River, and Barr Creek Valleys (Principato, 1999; Chapel, 2000; Carlson, 2002). These channels are not deeply incised like those produced by meltwater from the ice that deposited the New Berlin Member, suggesting either less meltwater discharge or a shorter period of channel occupation. In places, water was dammed between the eastward-sloping land surface and the ice margin, forming lakes. These lake plains are now flat to slightly undulating and poorly drained (plate 1, map units *Vslp* and *Zslp*; figure 20).

Post-glacial deposits

Post-glacial erosion and deposition in Sheboygan County has had minimal effect on the landscape when compared to glacial sedimentation. Streams in glacial meltwater valleys eroded the glacial sediment and deposited sand, silt, and clay in terraces and flood plains (plate 1, map unit *a*). Similarly, fine sediment and organics accumulated in the kettles of the Kettle Moraine and pitted outwash plains, creating bogs (plate 1, map unit *o*). High lake levels of Lake Michigan deposited sand and silt over glacial deposits near Lake Michigan (plate 1, map units ending in *lp*) (Hansel and others, 1985; Hansel and Mickelson, 1988). Subsequent reworking of this sediment by wind created the dune fields of Kohler-Andrae State Park (plate 1, map unit *s*) in southern Sheboygan County. North of this dune field, wave action eroded the lacustrine and glacial sediment to produce steep lake bluffs in northern Sheboygan County. A more detailed history of Lake Michigan levels in eastern Wisconsin is given in Mickelson and Socha (in press).

Pleistocene and Holocene history

The glacial history of Sheboygan County is interpreted from mapping landforms and former ice margins, as well as characterizing lithostratigraphic units in boreholes, outcrops, and bluffs along Lake Michigan. From these data, the local glacial history is set in the context of the regional chronology (table 1 and figure 2). However, it is difficult to constrain the timing of glacial advances since the Last Glacial Maximum about 21,000 years ago, because there are few radiocarbon dates older than the Two Creeks Forest Bed, which formed 14,000–13,200 calendar years ago (Kaiser, 1994).

Pre-late Wisconsin Glaciation and drainage patterns

The oldest aspect of the landscape of Sheboygan County is a valley in the bedrock surface (figure 3). This valley is more than 200 ft (60 m) deep and mostly filled with glacial sediment. The north–south-trending part of the valley has an average width of 1.5 miles (2.4 km), while the east–west-trending part is about twice as wide. This valley is present southward into Washington County and through Waukesha and Jefferson Counties, where it joins the Rock Valley or Troy Valley in Walworth County (L. Clayton, oral commun., 1999). The pre-glacial drainage in this area was dominantly eastward, down the dip of the bedrock (Alden, 1918), toward the ancestral Michigan River, a name given to the river that flowed northward in the position of present day Lake Michigan. The orientation of this bedrock valley in Sheboygan County suggests it is part of the pre-glacial drainage system draining toward the Michigan River (Alden, 1918), which can be traced 10 miles (16 km) westward into Fond du Lac County, where the valley is expressed as an erosional low spot in the Niagara Escarpment.

Following the formation of this deep valley, one to several glacial advances in Sheboygan County deposited the three reddish-gray diamicton units found at depth in the Plymouth cores (see the Quaternary sediment section of this report and figure 5). Diamicton units older than the Holy Hill Formation with similar physical characteristics to these units have been found in southern Wisconsin and northern Illinois (Bleuer, 1970; Schneider, 1983; Fricke and Johnson, 1983; Mickelson and others, 1984; Mickelson and Syverson, 1997). These include the Tiskilwa and Capron Members of the Zenda Formation and the members of the Walworth Formation and its correlative, the Winnebago Formation of Illinois. The ages of these older diamicton units are not well constrained. The Tiskilwa is believed to have been deposited in northern Illinois between 31,000 and 22,000 years B.P. (Wickham and Johnson, 1981; Hansel and Johnson, 1992).There is no radiocarbon age control for the Capron Member (Eschman and Mickelson, 1986), but Johnson (1986) suggests this member was deposited between 28,000 and 75,000 years B.P. For a long time, the diamicton units of the Walworth and Winnebago Formations were thought to have been deposited approximately 40,000 years ago and to correlate with the Roxana Silt (Willman and Frye, 1970; Bleuer, 1970). However, paleosols, clay mineralogy, and accumulation of Beryllium-10 (^{10}Be) suggest an age of 125,000 to 300,000 years B.P. for these diamicton units (Kempton and others, 1985; Curry, 1989; Curry and Pavich, 1996).

Based on physical characteristics and radiocarbon age control, one interpretation is that Bed 1 correlates with the Capron Member of the Zenda Formation, is Middle Wisconsin in age, and may correlate with the reddish-colored Roxana Silt (27,000 to 55,000 years B.P.) (Leigh, 1994). Although the diamicton of Bed 1 is physically similar to the Tiskilwa Member, it is too old (older than ~31,000 years B.P.) to be correlative to the Tiskilwa Member. The Tiskilwa ice margin reached northern Illinois by 26,000 years B.P. and did not waste back from its maximum position until after 20,000 years B.P. (Hansel and Johnson, 1992; Clark and others, 2009).

Another pre-Late Wisconsin glacial event is interpreted from the gray, compact, silty Hayton diamicton encountered beneath the Kewaunee and Holy Hill Formations (figure 4). However, the relationship between this diamicton and the reddish-gray diamictons is unknown.

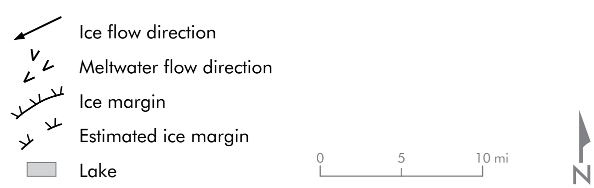
Last Glacial Maximum

It is not clear if significant retreat occurred before the Lake Michigan and Green Bay Lobes advanced and deposited the New Berlin and Horicon Members of the Holy Hill Formation. These lobes advanced as far south as Madison (Green Bay Lobe) and central Illinois (Lake Michigan Lobe). The ice advanced and retreated several times between 30,000 and 20,000 years B.P. (figures 1 and 2) (Mickelson and others, 1983; Hansel and Johnson, 1992, 1996; Clayton and Attig, 1997; Clark and others, 2009). The lithostratigraphic units associated with the Holy Hill Formation are primarily made up of sand and gravel, with thinner basal till than subsequent advances. In the study area, drumlin orientations indicate that the Green Bay Lobe flowed approximately southeastward, while the Lake Michigan Lobe flowed westward when ice occupied its maximum position.

Permafrost conditions existed in Wisconsin during this period (Cutler and others, 2000; Clayton and others, 2001), and this affected the landforms created by Holy Hill glacial ice. Drumlins that formed under both lobes may reflect the transition from a frozen bed at the ice margin to a wet bed further up the ice (Attig and others, 1989; Colgan and Mickelson, 1997).

At their maximum extent, the western margin of the Lake Michigan Lobe abutted the eastern margin of the Green Bay Lobe (figure 21A) (Chamberlin, 1878; Alden, 1918; Syverson, 1988). As the Green Bay Lobe retreated northwestward and the Lake Michigan Lobe eastward, large amounts of stagnant ice were buried by sediment in the interlobate zone, which is now the Kettle Moraine. Initially, meltwater from the Green Bay Lobe flowed toward the southeast and deposited outwash in a broad plain between the ice margin and the Kettle Moraine. West of the Kettle Moraine in

Figure 21. Progression of the Last Glacial Maximum.



A. Maximum Holy Hill ice margins.

B. Recessional margin and drainage paths.

C. Oak Creek (dashed lines) and Ozaukee (solid line) margins and drainage paths.

northern Sheboygan County, a large lake formed that is now Sheboygan Marsh (figure 21B). The level of this lake rose until it overtopped the Kettle Moraine to the east of the present marsh, and a narrow outlet was cut to bedrock. This water mixed with Lake Michigan Lobe meltwater and drained southward.

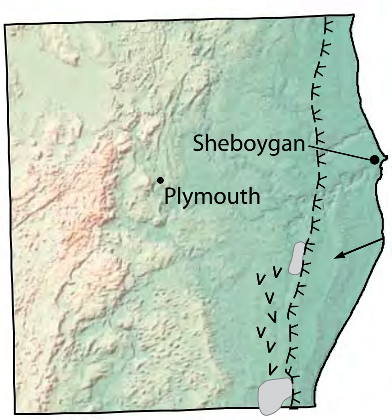
Meltwater from the Lake Michigan Lobe was routed southward between the eastward-sloping land surface and westward-sloping ice margin (figure 21B). Occasionally, these streams incised into their own deposits, forming ice-marginal and proglacial channels (figure 17). These channels coalesced in the broad outwash plain just north of the Sheboygan-Washington County border. Underfit streams, such as Mink Creek, Nichols Creek, and the North Branch Milwaukee River, now occupy these channels. Meltwater at times was trapped between the retreating Lake Michigan Lobe and stagnant ice, and proglacial lakes formed (figures 18 and 19).

Following the retreat of both lobes out of Sheboygan County, the Green Bay Lobe did not readvance into Sheboygan County, whereas the Lake Michigan Lobe readvanced approximately 19,000 years B.P. (Mickelson and Syverson, 1997). This advance reached as far south as Milwaukee County and deposited the Waubeka Member of the Holy Hill Formation (Mickelson and Syverson, 1997). The position of this former ice margin in Sheboygan County is now covered completely by younger Kewaunee Formation sediment, and its westward extent is unknown. Projections from Washington County into Sheboygan County (Mickelson and Syverson, 1997) suggest that the ice extended as far west as the Sheboygan River.

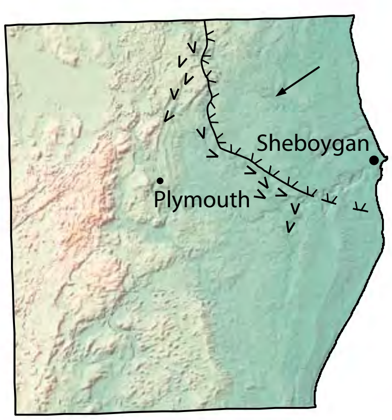
Oak Creek readvance

It is not known how far north the Green Bay and Lake Michigan Lobes retreated after the Waubeka readvance and before the next ice advance (Mickelson and others, 1983). The Lake Michigan Lobe must have retreated at least to the northern part of the Lake Michigan Basin, and a proglacial lake formed (Schneider, 1983; Hansel and others, 1985; Colman and others, 1994, 1995).

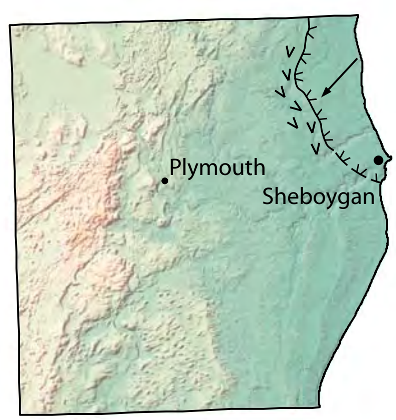
The Lake Michigan Lobe then rapidly readvanced approximately 17,500 years B.P., incorporated silty, clayey, lacustrine sediment that had accumulated in the basin, and deposited the Oak Creek Formation (Mickelson and others, 1984; Simpkins, 1989; Brown, 1990; Mickelson and Syverson, 1997). Short readvances and retreats are indicated by a series of end moraines parallel to the Lake Michigan shoreline in southeastern Wisconsin and northern Illinois and Indiana (Schneider, 1983; Hansel, 1983; Simpkins, 1989; Brown, 1990). Several of these moraines are traceable northward into Ozaukee County (Mickelson and Syverson, 1997), where they merge into one moraine. Just north of the Sheboygan-Ozaukee County line, this moraine is buried beneath younger deposits of the Ozaukee Member of the Kewaunee Formation (figure 21C). Meltwater associated with the Oak Creek readvance drained southward through channels previously formed during retreat from the Last Glacial Maximum ice extent.



D. Ozaukee recessional margins and drainage paths.



E. Valders maximum margin.



F. Valders recessional margin.

During deposition of the Oak Creek Formation, Lake Michigan stood at the Glenwood level (640 ft a.s.l., 195 m) (figure 22) (Hansel and others, 1985). Following the deposition of the Oak Creek Formation approximately 17,000 years B.P., the ice margin receded far enough north to allow eastward drainage through a lower outlet near the Straits of Mackinac. The lake level dropped several hundred feet (~50 to 100 m) below its present level, and water carrying reddish-brown silt and clay from the Superior Basin flowed into the Lake Michigan and Green Bay Basins (Hansel and others, 1985).

Kewaunee readvances

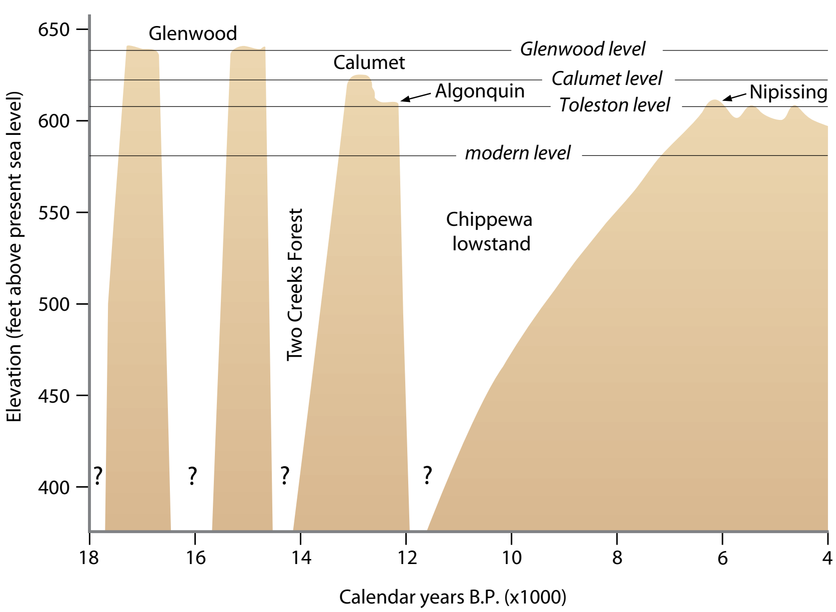
The Lake Michigan Lobe readvanced again approximately 15,500 years B.P. (Clayton and Moran, 1982; Hansel and Johnson, 1992; Mickelson and Syverson, 1997) and deposited the Kewaunee Formation. Much of this is reddish-brown clayey diamicton derived from lake sediment. The initial Kewaunee readvance terminated just south of Milwaukee (Alden, 1918; Acomb, 1978; Acomb and others, 1982; Mickelson and others, 1984) and deposited the Ozaukee Member. Later fluctuations of the Lake Michigan Lobe only advanced as far south as central Sheboygan County (Principato, 1999; Chapel, 2000; Carlson, 2002).

Ice of the Ozaukee readvance terminated at approximately the same location in Sheboygan County as the Oak Creek and Waubeka readvances (figure 21C). A gravel-cored ridge overlain by a thin (< 2 ft, 0.5 m) layer of till marks the ice margin. Pebble fabrics and striations indicate ice flow toward the northwest (Carlson, 2002). However, ice flow changed to a southwestward direction near Lake Michigan (Laabs, 1999; Carlson, 2002). While ice occupied its maximum position, meltwater drained southward in Otter Creek, Onion River, and part of the Sheboygan River (Principato, 1999; Chapel, 2000; Carlson, 2002). In southern Sheboygan County, meltwater accumulated between the eastward sloping land surface and the ice margin, forming a second proglacial lake in the area now occupied by Cascade Swamp (Carlson, 2002).

Two other proglacial lakes formed during retreat of this ice. The first developed south of the Onion River in front of the outermost recessional moraine in southern Sheboygan County (figure 21D). Meltwater flowing down the Onion River drained into this lake. A second lake formed when ice occupied the inner recessional moraine. This lake was located in the southeastern part of the county and drained down Barr Creek. As ice retreated further, lower drainage paths opened and each of these proglacial lakes drained.

After the Ozaukee readvance, ice retreated into Lake Michigan. It then readvanced approximately 14,700 years B.P. (Hansel and Johnson, 1992; Maher and Mickelson, 1996) and deposited the Valders Member. The Valders readvance terminated south of the city of Sheboygan approximately 10 miles (16 km) west of Lake Michigan (figure 21E), and meltwater drained down the Sheboygan River. The ice margin then retreated, but paused to form a recessional moraine approximately 3 miles (5 km) from Lake Michigan (figure 21F). Younger lacustrine sediment covers this moraine near the city of Sheboygan. Meltwater drained down the Pigeon River during deposition of the recessional moraine. The Valders readvance deposited a thin layer of till, suggesting that this advance was short lived and ice retreated rapidly (Principato, 1999; Chapel, 2000).

Figure 22. Lake Michigan water levels through time.



Ozaukee and Valders ice advances blocked the northern outlet of the Lake Michigan Basin. This caused the lake to rise to the Glenwood level during each readvance (approximately 640 ft a.s.l., 195 m) and drain out the Chicago outlet (Hansel and others, 1985; Hansel and Mickelson, 1988; Colman and others, 1994). A shoreline at this level is recognizable in Sheboygan County near Lake Michigan (figure 23).

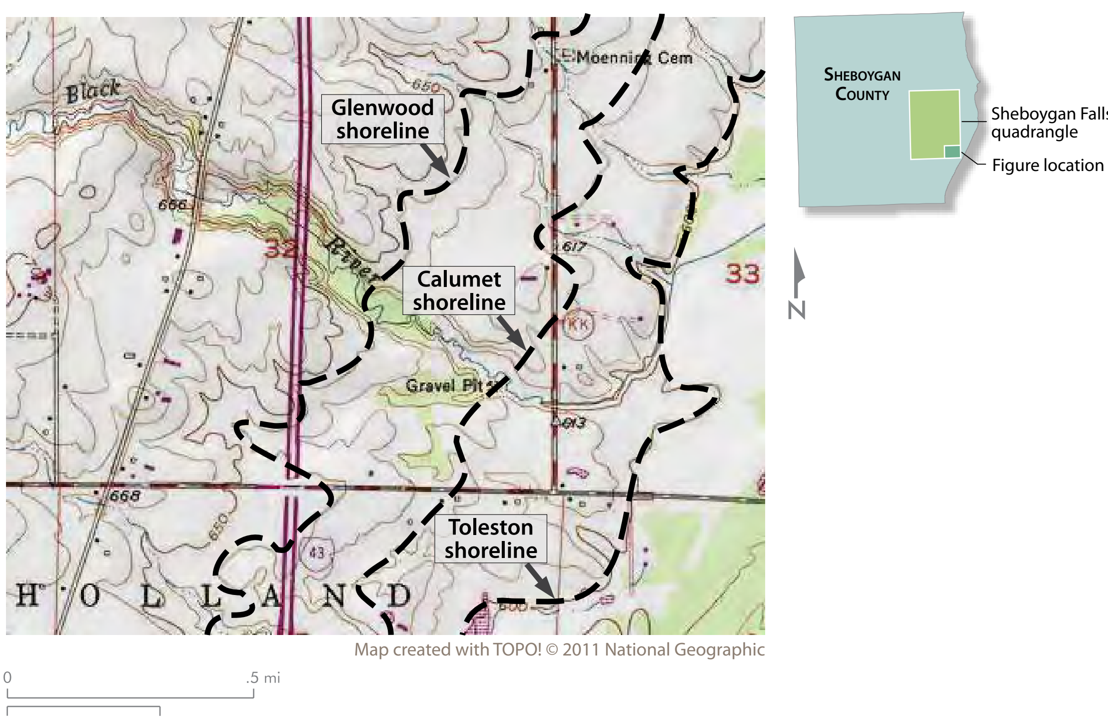
Climatic warming caused ice retreat and the end of permafrost conditions after deposition of the Valders till (Evenson and others, 1976; Acomb and others, 1979). The change from tundra vegetation to spruce-dominated boreal forest also occurred around the time of the retreat of Valders ice (Maher and Mickelson, 1996; Clayton and others, 2001).

Post-glacial fluctuations of Lake Michigan levels

Although the Lake Michigan Lobe never reentered Sheboygan County following the Valders advance, ice margin fluctuations north of the county caused variations in the level of Lake Michigan (figure 22). Three high levels are recognized from beach deposits. The highest lake level is the Glenwood stage at 640 ft a.s.l. (195 m), followed by the Calumet level at 620 ft a.s.l. (189 m) and the Toleston level at 605 ft a.s.l. (184 m). Present-day Lake Michigan is at about 590 ft (180 m). The chronology of the variation in the level of Lake Michigan is constrained by radiocarbon dates in the southern Lake Michigan area (Hansel and others, 1985; Hansel and Mickelson, 1988).

Despite clear evidence for lake-level fluctuations, explanations of when and why they took place have been subject to changes in interpretation (Bretz, 1951; Hansel and others, 1985; Hansel and Mickelson, 1988; Colman and others, 1994). Bretz (1951) proposed that downcutting of the Chicago outlet caused episodic fluctuations in the lake level through time (from the Glenwood level to the Calumet and then Toleston phases). However, radiocarbon dating indicates that the Chicago outlet was cut to bedrock during the Glenwood phase (Hansel and Mickelson, 1988). Thus, fluctuations of lake level were likely due to changes in the amount of glacial meltwater and precipitation entering the basin (Hansel and Mickelson, 1988).

Figure 23. Locations of the Lake Michigan shoreline during the Glenwood, Calumet, and Toleston stages (southeast part of Sheboygan Falls 7.5-minute quadrangle). Lake levels were at 640 ft (195 m), 620 ft (189 m), and 605 ft (184 m) above sea level, respectively; the present-day level is at about 590 ft (180 m).



Map created with TOPO! © 2011 National Geographic

After the Valders readvance, ice retreated north of the Straits of Mackinac, and Lake Michigan fell to a lowstand during the Two Creeks interval approximately 14,000 to 13,300 years B.P. (Colman and others, 1994; Kaiser, 1994). A spruce forest known as the Two Creeks Forest covered northeastern Wisconsin (Alden, 1918; Thwaites and Bertrand, 1957; Broecker and Farrand, 1963; Black, 1970; Evenson, 1973; Mickelson and Socha, in press). Subsequently, ice readvanced as far south as northern Manitowoc County and deposited the Two Rivers till after approximately 13,500 years B.P. (Hansel and Johnson, 1992). This readvance blocked the Straits of Mackinac again, and water rose to the Calumet stage. A wave-cut platform from this lake highstand is recognizable south of the city of Sheboygan, approximately 1 mile (1.6 km) west of Lake Michigan and can be traced into Ozaukee County (figure 23). This wave-cut platform grades northward into a large delta over 1 mile (1.6 km) wide where the city of Sheboygan is now located (Goldthwait, 1907; Evenson, 1973).

Ice retreated from the Lake Michigan Basin by 12,800 years B.P. The land north of Georgian Bay in Canada was much lower than today because the weight of the glacier had depressed the land surface beneath. Outlets opened and Lake Michigan dropped to the Chippewa low phase; the lake level was likely about 330 ft (100 m) lower than the present level. As the weight of the glacier was removed, the land rose. The northern outlets rose faster than areas farther south because ice had been thicker in the north. In response, the lake rose to the Toleston level. This occurred by approximately 5,000 years B.P. (Colman and others, 1994; Kiesel, 1998). A beach ridge and wave-cut bench from this level is present from south of the city of Sheboygan into Ozaukee County. From 5,000 years B.P. to present, beach dunes developed and stabilized on top of the Toleston bench in southern Sheboygan County (figure 23). This beach and dune complex is now part of Kohler-Andrae State Park. North of the city of Sheboygan, waves eroded these former shorelines and wave-cut benches, producing high, steep bluffs.

Kiesel (1998) conducted a detailed study of the sediments in the mouth of the Pigeon River, on the north side of the city of Sheboygan. The basal unit is diamicton and glaciolacustrine silt and clay. The river cut through these sediments prior to 6,500 years B.P., probably during the Chippewa lowstand of Lake Michigan, and stream deposition began between about 6,500 and 5,500 years B.P. Stream deposition indicates that the lake-level rose back up to the present level and continued rising to the Toleston level during the Nipissing phase from about 5,500 to 5,000 years B.P. Water of this high Nipissing phase, about 15 ft (5 m) higher than the current lake level, flooded into the valley. Subsequently, the lake level fell until about 2,000 years B.P., causing erosion of the valley. Since then, the floodplain has remained nearly at the same level as it is today, as the lake level stabilized or rose slightly to the modern level (Kiesel, 1998).

Post-glacial drainage

The present drainage of Sheboygan County developed during and after deglaciation. The four main rivers draining Sheboygan County today are the Onion, Mullet, Sheboygan, and Pigeon Rivers. Except for the Pigeon River, all originate near the flanks of the Kettle Moraine and follow their respective course eastward until they reach the city of Sheboygan Falls, where the Mullet and Onion join the Sheboygan within 1 mile (1.6 km) of each other. From there the Sheboygan River flows for about 5 miles (8 km) in a single, tightly meandering channel cut into bedrock before discharging into Lake Michigan at the city of Sheboygan.

The Onion River originates a few miles west of the city of Plymouth and flows for approximately 11 miles (18 km) southeastward before turning northward. From there, the Onion River flows northward for another 10 miles (16 km) before joining the Sheboygan River. The peculiar northward course of the Onion River is controlled by the 40 ft (12 m) high Ozaukee recessional moraine along its western margin. The southward and northward flowing portions of the Onion River were probably two separate rivers immediately after glaciation, but sometime during the Holocene, the headwaters of the northward-flowing channel eroded and captured the southward-flowing river near Cedar Grove in southern Sheboygan County.

Other rivers follow former ice-margin positions in the county. A stretch of the Mullet River near the city of Plymouth follows the former Ozaukee terminal ice margin. The Sheboygan River follows a section of the Valders terminal moraine in the central part of the county, while the Pigeon River parallels part of the Valders recessional ice-margin position north of the city of Sheboygan.

Summary

Ice covered Wisconsin and Sheboygan County numerous times after the onset of the Ice Age approximately 2.7 million years ago (Mix and others, 1995; Syverson and Colgan, 2004). However, only evidence of the most recent advances remain. The oldest advances in Sheboygan County are recorded by the gray, silty Hayton diamicton and the Plymouth diamicton units found in the subsurface, which predate the last glaciation.

Following these earlier advances, both the Lake Michigan and Green Bay Lobes advanced into Sheboygan County after about 32,000 B.P. Glacial ice covered the entire county, and the two lobes were sutured together at what is now the northern Kettle Moraine. These lobes deposited the sandy till of the Holy Hill Formation, which is streamlined into drumlins in the western part of the county. During retreat, perhaps about 20,000 years ago, the accumulation of supraglacial debris on stagnant ice between the two lobes and subsequent ablation created the Kettle Moraine. Large quantities of sand and gravel were deposited in outwash plains that cover much of the Holy Hill Formation till. A minor readvance of the Lake Michigan Lobe punctuated this retreat and deposited the siltier Waubeka Member in the eastern half of Sheboygan County.

Both lobes then retreated an unknown distance northward, and a proglacial lake formed in the Lake Michigan Basin. The Lake Michigan Lobe readvanced approximately 18,000 years B.P., incorporated lake sediment into its base, and deposited the silty till of the Oak Creek Formation. Ice of this advance covered the eastern half of Sheboygan County, but most of the surface expression left from this advance is buried by younger sediment. Little glaciofluvial sedimentation is associated with this advance.

Following this readvance, the Lake Michigan Lobe retreated north of the Straits of Mackinac, and reddish-brown lacustrine sediment from the Superior Basin drained into the Lake Michigan Basin. The Lake Michigan Lobe advanced again approximately 17,500 years B.P. and deposited the Kewaunee Formation, with its characteristic reddish-brown, clayey till. Ice covered the eastern half of Sheboygan County during the maximum ice extent, while a later readvance reached only the northeastern part of the county. Much of the meltwater from these advances drained down previously developed flow paths and deposited sandy outwash. During these advances and retreats, the level of Lake Michigan was about 640 ft a.s.l. (195 m), which is about 50 ft (15 m) higher than the modern lake level. Proglacial lakes also formed where water was dammed between the eastward-sloping land surface and the ice lobe. The Lake Michigan Lobe retreated approximately 14,000 years ago, and the Laurentide Ice Sheet never again entered Sheboygan County.

A later advance of the Lake Michigan Lobe blocked the northern end of the Lake Michigan Basin from about 14,000 to 13,000 years ago, and the level of the lake rose again, but only to about 620 ft a.s.l. (189 m). Within about 200 years, ice had again retreated out of the north end of the Lake Michigan Basin. Subsequent isostatic adjustment of northern outlets caused fluctuations in the water level of Lake Michigan. High levels of the lake created wave-cut platforms visible in the southeastern part of the county near Lake Michigan and deposited lake sediment over glacial sediment. Lowering of the lake level exposed these sediments to wind and water erosion. Dunes formed along Lake Michigan in southern Sheboygan County, while wave erosion along the northern coast created steep bluffs and caused several miles of shoreline retreat.


Greenbush Kettle

Robert E. Gantner

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Pocket contents:

Plate 1. Quaternary geologic map
Plate 2. Geologic cross sections

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