Quaternary Geology of Ozaukee and Washington Counties, Wisconsin

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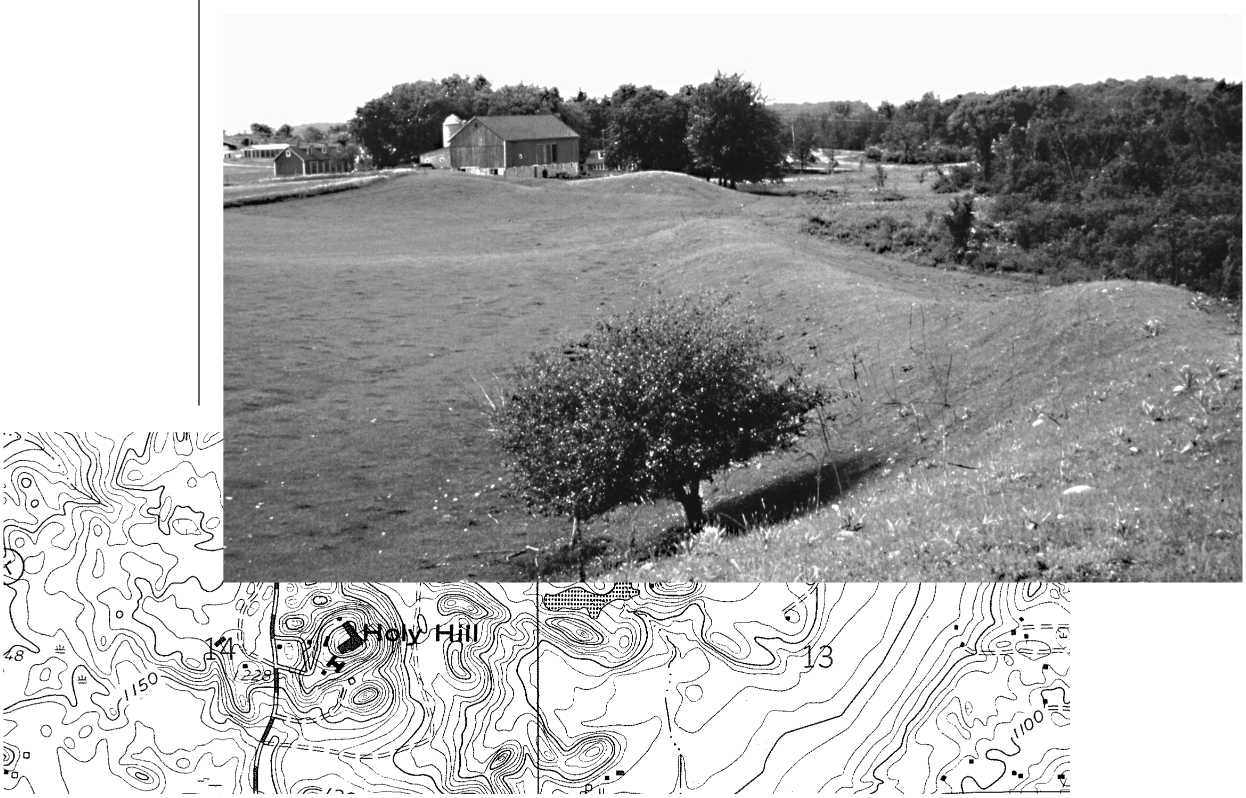

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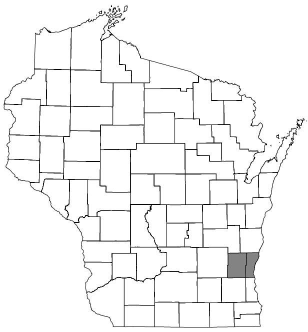

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FIGURES

TABLE

PLATES (inside back pocket)

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ABSTRACT

Glacial ice covered Ozaukee and Washington Counties between about 25,000 and 13,000 years ago. Glacial and related stream and lake sediment, included in the Zenda, Holy Hill, Oak Creek, and Kewaunee Formations, consists of coarse gravelly sediment in some places and silty clay in others.

The ice sheet left several geologically and topographically distinct areas. The Kettle Moraine is a hummocky ridge trending north–south through central Washington County. Much stratified sand and gravel was deposited on stagnant ice by southerly flowing meltwater streams in this interlobate region between the Green Bay and Lake Michigan Lobes; as buried ice melted, the hummocky Kettle Moraine formed. The region west of the Kettle Moraine has a rolling topography dominated by large northwest–southeast-trending drumlins composed of sandy till that formed beneath the Green Bay Lobe.

The sediment east of the Kettle Moraine was deposited by the Lake Michigan Lobe and its glacial meltwater. The region immediately east of the Kettle Moraine, in eastern Washington and western Ozaukee Counties, has flat to rolling topography and east–west-trending drumlins. Ice-dammed lakes formed as the ice margin retreated down the regional slope of the land, damming drainage in the Milwaukee and other river valleys. Lacustrine sand and silt plains remain from these former lakes. Successively younger advances of the Lake Michigan Lobe deposited the Oak Creek and Kewaunee Formations, which are silty and clayey, indicating that the ice margin retreated into, and later advanced out of, the Lake Michigan basin several times during general deglaciation of the area. Fine-grained lacustrine (lake) sediment was incorporated into the till, producing the silty and clayey sediment that is present in eastern Ozaukee County. High stands of Lake Michigan cut shorelines into these deposits, leaving beaches above the modern one. Postglacial streams have cut channels through the glacial deposits and deposited floodplain sediment along their banks.

INTRODUCTION

Scope of this report

Glacial features dominate the landscape in Ozaukee and Washington Counties. Road names such as Kettle Moraine Drive, Kettle View Road, and Clay Ridge Road are colorful reminders of the glacial features that have contributed to the heritage of the area. Except for a few isolated spots where bedrock is exposed, or along streams or beaches, the entire area is covered with glacial deposits. Glaciers produced the lakes that abound in many areas, formed the prominent hills of the Kettle Moraine, produced the rich agricultural land in both counties, and left behind sand and gravel—major commodities in this rapidly developing area.

Although many communities and some residences obtain their water supply from aquifers in the underlying sandstone and dolomite bedrock, many domestic wells derive water from Pleistocene deposits above the bedrock. These deposits will be important to the future water supply and water quality in these two counties. Knowledge of the deposits is crucial for understanding the groundwater system and for protecting it from degradation: Decisions about the siting of landfills, application of pesticides and herbicides, and reaction to spills of chemical contaminants should be made with an understanding of Quaternary deposits and how contaminants move in them.

In this report we

- provide a map (plate 1) that shows the distribution of glacial and related deposits in the two-county area and cross sections (plate 2) from west to east across the two counties that show the vertical distribution of these deposits;
- describe these materials in terms of their physical characteristics, engineering properties, and their ability to transmit groundwater;
- provide a detailed description of sediment exposed in the eroding coastal bluffs along the Lake Michigan shoreline of Ozaukee County; and
- describe the landforms that residents and visitors can readily see in the two-county area and discuss the history of glaciation in the counties.

Pre-Quaternary history

All the deposits we discuss in detail were formed during the Quarternary Period, which began about 1.6 million years ago and continues today (see figs. 1 and 2). However, the geologic history of Washington and Ozaukee Counties extends back several hundred million years. (More detailed discussions of the earlier geologic history are found in LaBerge, 1994.)

By about 570 million years ago, Precambrian rock had been severely eroded and deeply weathered. At that time, the vast global sea advanced into Wisconsin from the south and west and covered all the state. Since that time, the elevation of central Wisconsin has remained high in relation to the neighboring states of Michigan and Illinois, where basins collected deeper-water marine sediment and slowly settled over time. The cross section in figure 3 shows rock that was deposited during the *Paleozoic Era* (250–570 million years ago: see fig. 1) as oceans alternately deepened and shallowed in the region. The type of sedimentary rock deposited reflects a different depth of water or different sediment supply to this part of the ocean basin. *Sandstone* formed as sand was deposited in a relatively shallow sea and at times even as sand dunes above sea level. Sand was transported to the shallow sea by rivers flowing off the land mass to the north and west. At other times, deposition in the shallow sea was dominated by the accumulation of limestone ($CaCO_3$), which was later converted to dolomite [$CaMg(CO_3)_2$].

By the *Silurian Period* (410–440 million years ago; fig. 1) large coral reefs had developed in much of eastern Wisconsin; the remains of these coral reefs can be seen today in quarries throughout much of the eastern part of the state. *Shale* layers (mud deposited in deep water) are relatively thin in Wisconsin, although the Maquoketa Formation, which contains shale, is widespread beneath the Silurian dolomite underlying Ozaukee and Washington Counties (fig. 3). Thick accumulations of shale and evaporites were deposited in increasingly deep basins to the east under the southern peninsula of Michigan, and to the south beneath central and southern Illinois. The subsiding basin in Michigan produced a gentle tilting (dip) of all these rock layers toward the east in Washington and Ozaukee Counties (fig. 3).

The youngest marine rock in the state lies along the Lake Michigan shore in

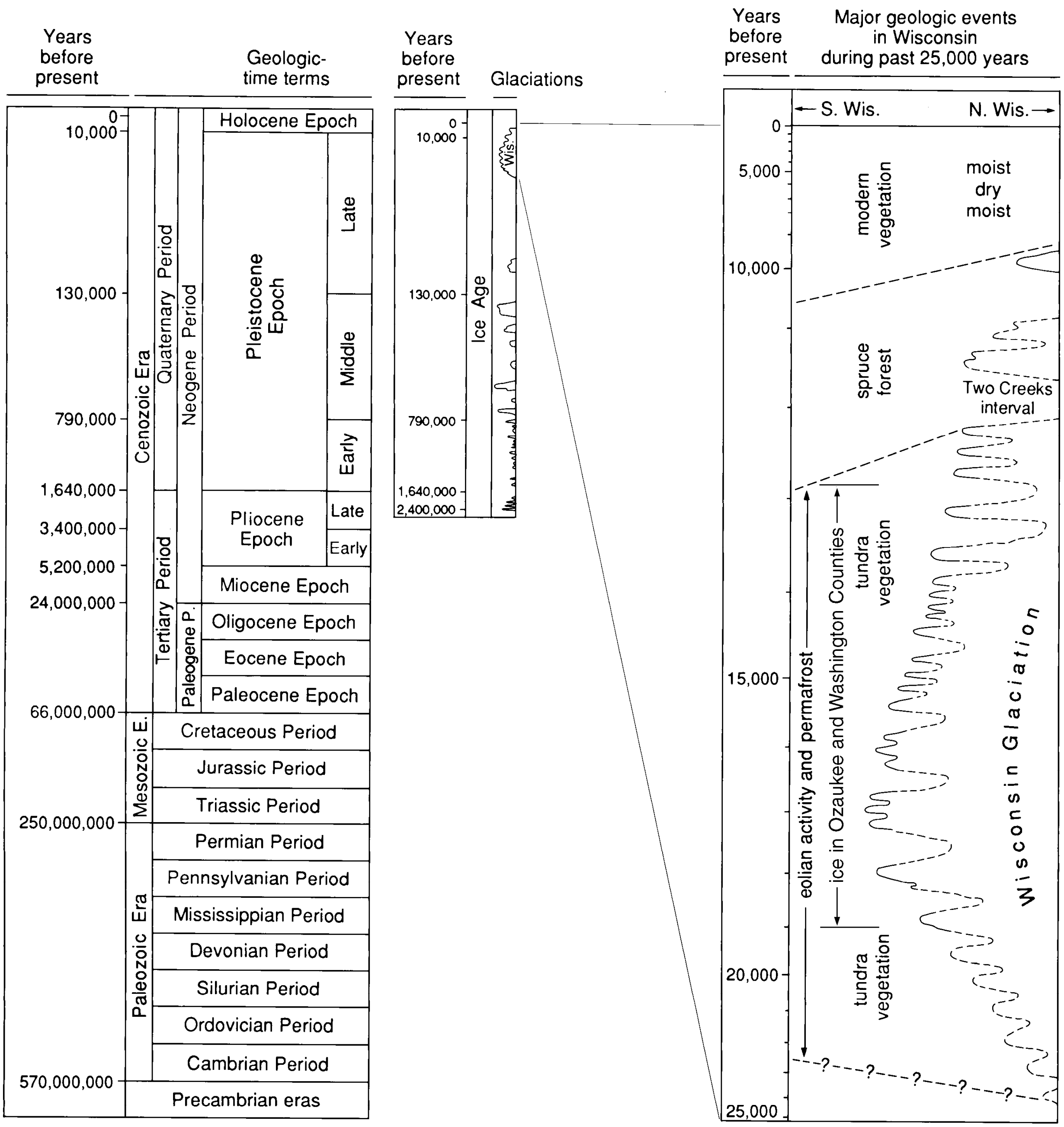


Figure 1. *Geologic time scale (modified from Clayton and others, 1992). Geologic time terms are given in the left part of the diagram. The center column shows times of major glaciations during the last 2.5 million years based on oxygen isotopes in deep sea sediment. Some of the less extensive glaciations may not have reached Wisconsin. The past 25,000 years is expanded in the right column, which shows the phases of the Wisconsin Glaciation and the conditions south of the glacier. The horizontal axis represents the approximate distance from southern to northern Wisconsin, and the curves represent the ice-margin position at any given time (dashed where uncertain). The time of ice cover in Ozaukee and Washington Counties during the Wisconsin Glaciation is indicated.*

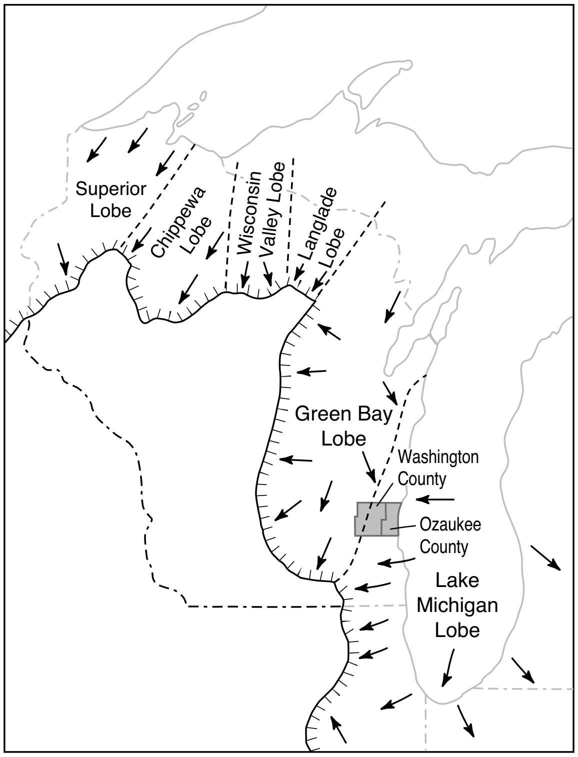


Figure 2. *Glacial lobes in Wisconsin. Shaded area indicates location of Ozaukee and Washington Counties.*

Ozaukee County. It is *Devonian* (about 370 million years old) (fig. 1). After several hundred million years of high sea levels, interrupted by short periods of retreat of the sea and subaerial erosion, the sea retreated to the east into the Michigan Basin and southward to the Illinois Basin. The area of Ozaukee and Washington Counties became a land mass that may never again have been submerged beneath the sea. Although younger rock probably was deposited in this area, it has since been removed by stream or glacial erosion. Thus, the geologic record is missing for the period from Devonian to late Pleistocene (about 25,000 years ago). Glacial sediments were deposited directly on Silurian and Devonian bedrock that is 370 to 440 million years old.

Large river valleys developed in the Great Lakes area before glaciation. Glaciers have greatly modified some of these valleys, and it is impossible to reconstruct the drainage pattern before the most recent ice advances. However, a large buried valley that is probably a remnant of the preglacial stream system extends through central Washington County (fig. 4). It appears to connect with deep valleys in other parts of the state, but because sediments in the valleys are much younger than the valleys themselves, it is impossible to determine whether the valleys are all the same or vastly different in age. It is also not known how long before the early glacial periods these valleys were eroded.

Summary of glacial events

The Laurentide Ice Sheet covered much of Wisconsin several times during the last 1.6 million years, during the *Quaternary Period* (fig. 1). When temperatures fell low enough for an ice sheet to form in central and eastern Canada, the Laurentide Ice Sheet advanced southward, sometimes reaching what is now the United States. Valleys strongly influenced ice flow, so the Laurentide Ice Sheet separated into distinct lobes. Figure 2 shows the ice lobes that advanced into Wisconsin during the Pleistocene Epoch, which ended 10,000 years ago. During the past 10,000 years of the Holocene Epoch, these deposits have become vegetated and smoothed by erosion. Glaciers reached as far south as Nebraska well before two million years ago (Boellstorff, 1978), and it seems likely that glaciers also flowed down the valley now occupied by the Lake Michigan basin at about the same time.

All the glacial features we see in Ozaukee and Washington Counties, however, were formed during the last major phase of glacier expansion, which is called the *Wisconsin Glaciation*. On the basis of radiocarbon dates in Illinois (Johnson, 1986), we believe this glacier advanced into what are now Washington and Ozaukee Counties about 24,000 years ago. The Lake Michigan and Green Bay Lobes must have advanced at more or less the same time, and they joined near the present position of the Kettle Moraine. Although there were small advances and retreats during the advance phase, the ice probably thickened fairly rapidly, reaching its maximum thickness by about 23,000 to 20,000 years ago. This was followed by a retreat of the Lake Michigan Lobe and its later advance to rejoin the Green Bay Lobe in the Kettle Moraine region about 18,000 years ago.

The two lobes remained together until about 15,000 years ago in Washington and Ozaukee Counties, although by that time the ice may have been thinning slowly for several thousand years. As the ice margin retreated between 15,000 and 13,000 years ago, a corridor developed between the two lobes in the southern part of Washington County and grew northward at a fairly rapid rate. Meltwater flowed southward beneath and above the ice in this interlobate corridor, depositing large quantities of sand and gravel in the Kettle Moraine area. The ice then readvanced several times into Ozaukee County from the Lake Michigan basin before finally disappearing from the county about 12,400 years ago.

SURFICIAL MATERIALS

Classification of sediment

Sediment consists of mineral and rock particles and dissolved components transported and deposited by agents such as water, wind, or glaciers. Much sediment is classified on the basis of its grain size. The term *gravel* is used in this report for grains coarser than 2 mm. *Sand* ranges in diameter from 0.0625 mm to 2 mm; *silt*, from 0.002 mm to 0.0625 mm; *clay*, finer than 0.002 mm. These grains are mixed or *sorted* in various proportions by the different transporting agents. For instance, wind typically transports silt considerable distances from the source, sorting the grains

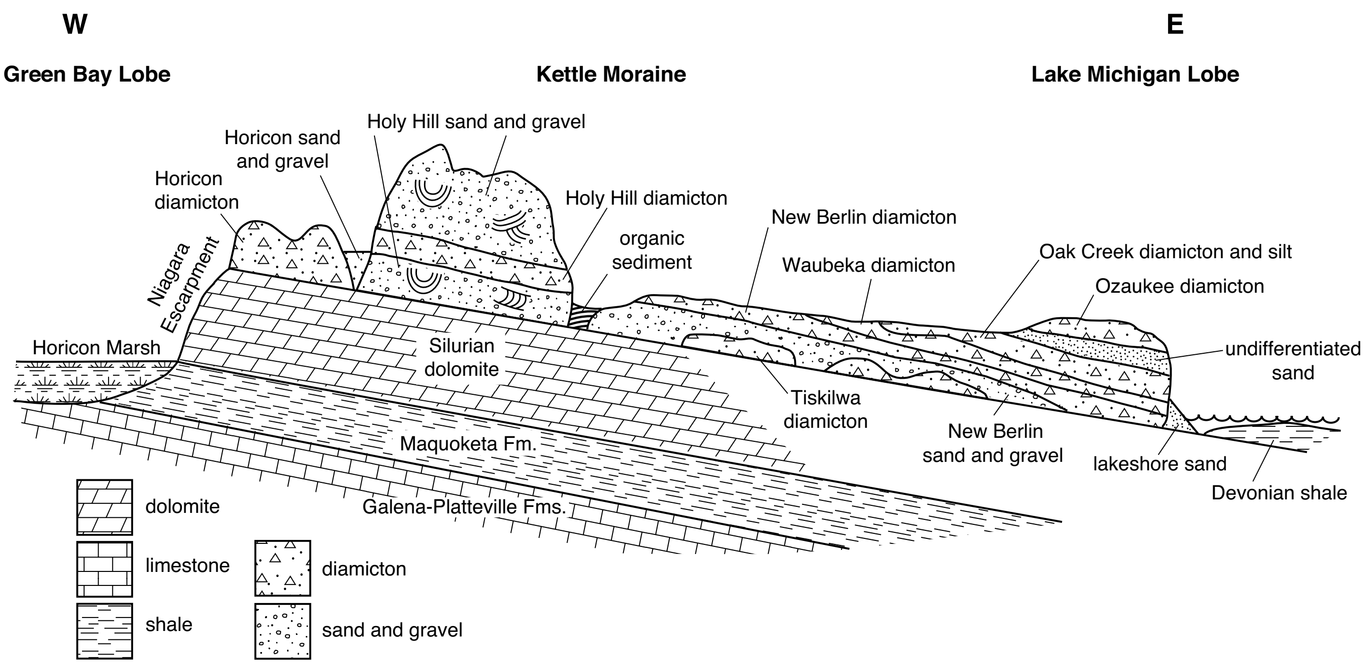


Figure 3. *Diagrammatic cross section of glacial deposits and underlying bedrock in Ozaukee and Washington Counties. Not to scale.*

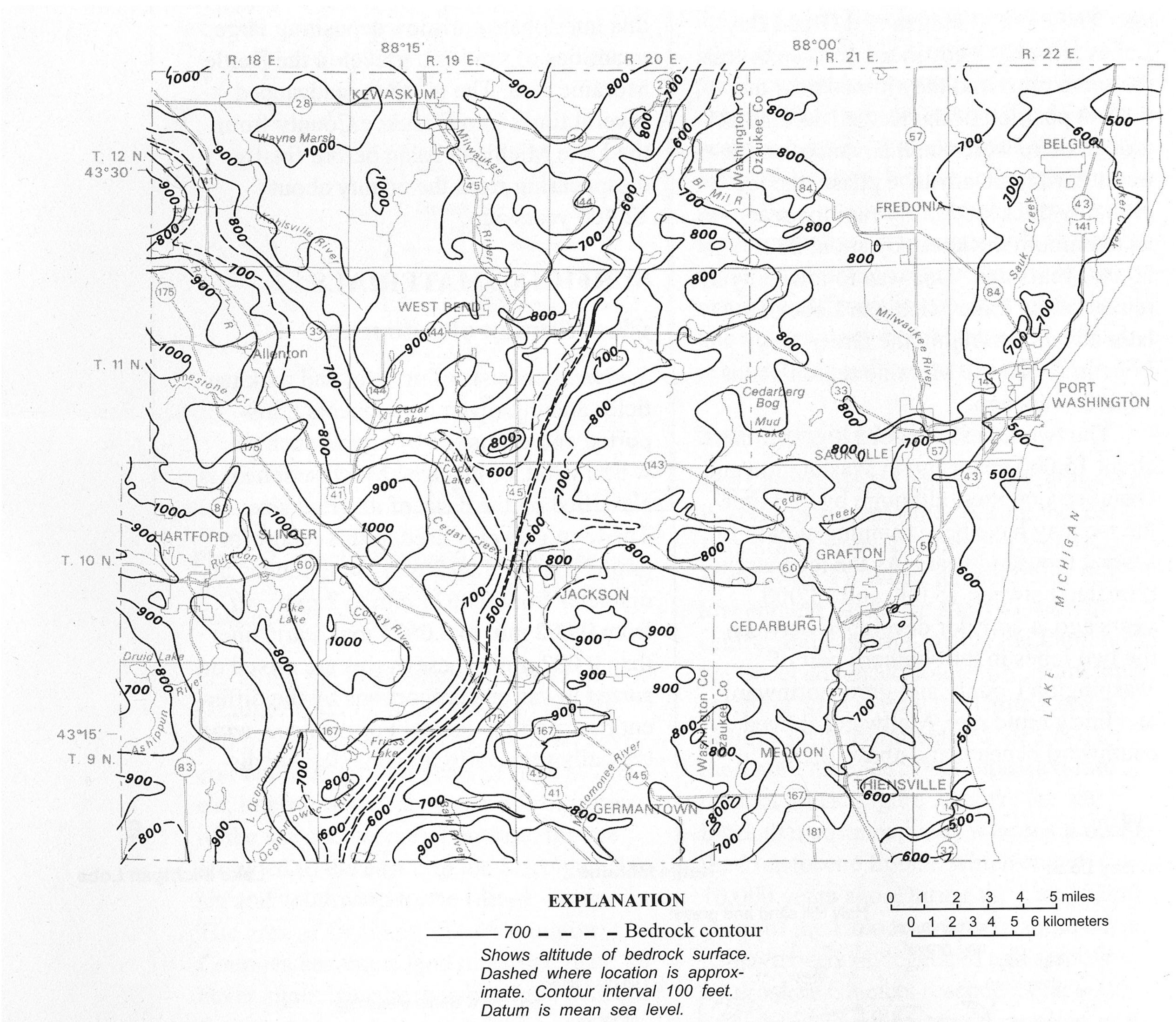


Figure 4. *Bedrock topography map of Ozaukee and Washington Counties (from Young and Batten, 1980).*

before deposition takes place, forming a homogeneous material called *loess*. Grains deposited closer to the source, in dunes, are sand size. Rivers transport all sizes, but normally there is some sorting of these grains by size as the sediment settles. Thus, a stream in one place may deposit sand layers; in another, coarse gravel layers. Sediment deposited in lakes and streams is generally sorted more thoroughly than sediment left by glaciers.

Most of the landscape in Ozaukee and Washington Counties is underlain by sediment directly associated with glaciation. The descriptive term *diamicton* is used to describe nonsorted or poorly sorted sediment that has a wide range of grain size and a fine-grained matrix that may have been deposited in one of several ways.

Diamicton can be deposited directly beneath the ice (subglacially) or on ice margins by mudflows, landslides, and collapse off ice or surrounding slopes. These origins are difficult to determine without detailed study, so the term diamicton is used on plates 1 and 2 without further indication of genesis. We did interpret the genesis of diamicton in places where we collected samples. The most common type of diamicton in this area is called *till,* and it is generally deposited at the base of the glacier as *basal till*. Till is deposited directly by ice without subsequent transport by streams or downslope movement. References in the text to till, basal till, or supraglacial sediment are based on genetic interpretation.

Sediment that has characteristics similar to till accumulates at the edges of many glaciers as debris melts out at the ice surface. This material is called *supraglacial sediment*. It settles onto the ground with some sliding and flowing off the ice, and this may lead to some sorting. Poorly sorted supraglacial sediment is included with basal till in the diamicton units on plates 1 and 2. Supraglacial sediment units are usually thin, and unless good exposures of the sediment are studied in detail, they cannot be distinguished from till. Other sediment released on the ice surface is transported by streams; this sediment is somewhat stratified and sorted and we mapped it as sand and gravel.

Each glacial advance deposited till with a characteristic set of physical properties. Much of the "red clay" found in eastern Ozaukee County is till deposited by readvances of ice out of the Lake Michigan basin. Till here is more clayey than it is farther west because the glacier incorporated lake sediment that was rich in silt and clay during its advance; till in western Ozaukee County and all of Washington County contains more sand and gravel particles because it was derived from the underlying dolomite bedrock or older sand and gravel deposits.

Lithostratigraphic units

Explanation of units

The diamicton deposited during an individual glacial advance is generally somewhat distinct from that deposited during earlier or later advances. This allows us to look at the distribution of diamicton layers that have different characteristics and to reconstruct the sequence of glacial events. Sand and gravel deposits and silt and clay deposits of glacial lakes can also be associated with a particular glacial advance. To provide a framework for classifying these major groups of deposits, geologists define lithostratigraphic units called formations, which are subdivided into members. These units cover areas of at least several square kilometers, have more or less consistent characteristics, and are recognizable by field or laboratory investigation of their physical or chemical characteristics. Formations are easily distinguishable in the field in most of eastern Wisconsin. In some places successive readvances of ice deposited materials that are so similar that they cannot be distinguished from each other in the field, but require laboratory tests to differentiate them; these lithostratigraphic units are termed members of a formation.

Deposits of four formations are present in the two-county area, and all but one of these are present at the surface (figs. 3 and 5; plates 1 and 2). The oldest of these, the Zenda Formation (fig. 3), consists of one member called the Tiskilwa Member and contains reddish-brown silty diamicton (Mickelson and others, 1984). The Zenda is not present at the surface any-

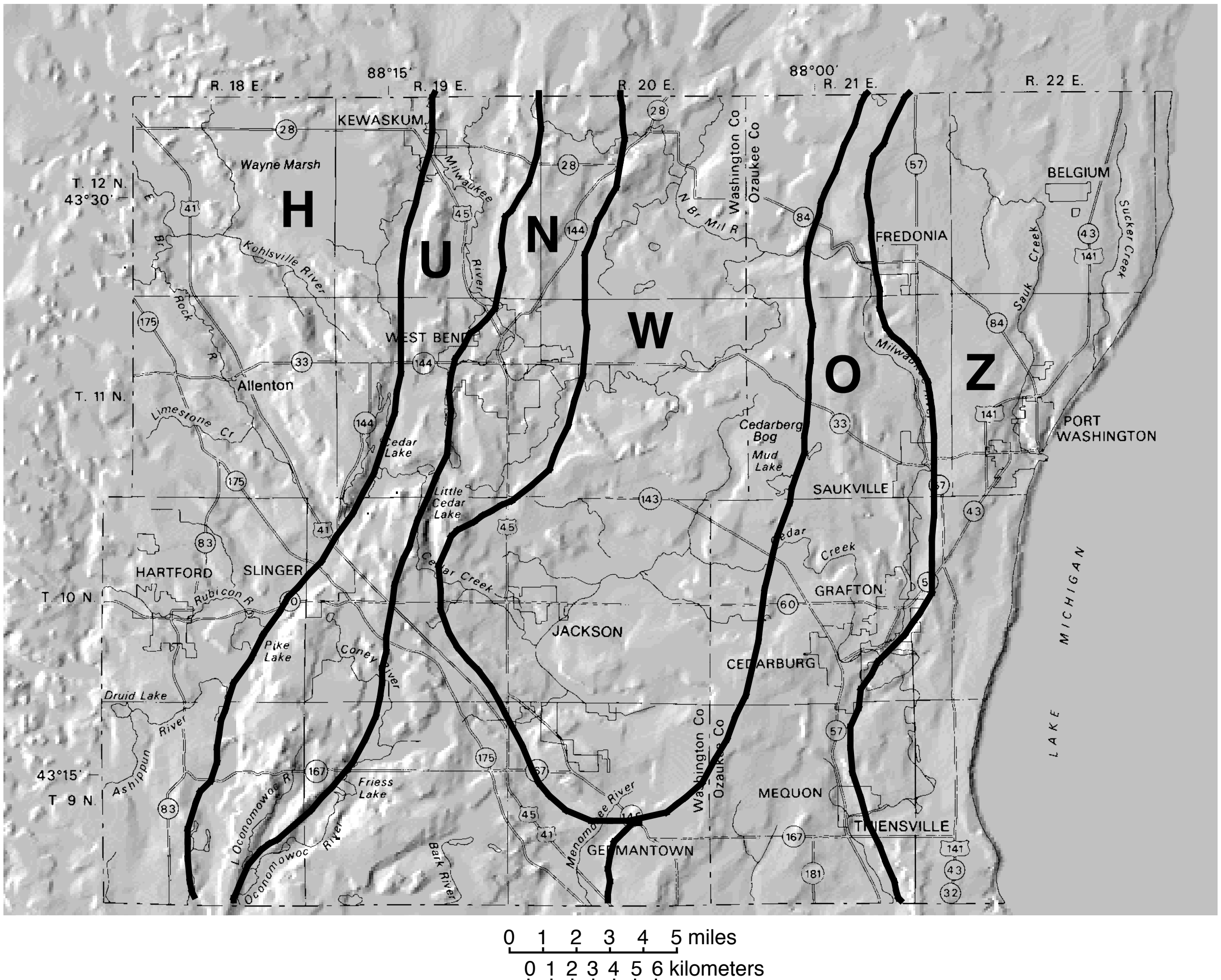


Figure 5. *Physiographic regions of Ozaukee and Washington Counties.*
Z—Ozaukee Member of the Kewaunee Formation
O—Oak Creek Formation
W—Waubeka Member of the Holy Hill Formation
N—New Berlin Member of the Holy Hill Formation
H—Horicon Member of the Holy Hill Formation
U—Holy Hill Formation (undifferentiated New Berlin and Horicon Members in the Kettle Moraine region)

where in the two counties, but has been found in a few places in the subsurface. It is generally thin.

Stratigraphically above (and therefore younger than) the Zenda is the Holy Hill Formation (figs. 3 and 5). This name is used here for the first time, and it is formally defined in the appendix. The sediment in the Holy Hill Formation was deposited at about the same time by ice and water of the Green Bay Lobe (Horicon Member, map-unit identifiers starting with **H** on plate 1, defined by Mickelson and others, 1984) and the Lake Michigan Lobe (New Berlin Member, map-unit identifiers starting with **N** on plate 1, defined by Mickelson and others, 1984) when these lobes were at their maximum extent. The Holy Hill Formation and its members contain sandy, stony diamicton, and most of the large sand and gravel pits in western Ozaukee and Washington Counties are located in the sand and gravel of these units. The strip of undifferentiated Holy Hill Formation sand and gravel, found in the Kettle Moraine between the Horicon and New Berlin Members (figs. 3 and 5; map-unit identifiers starting with **U**, plate 1), is a mixture of sediment from both ice lobes, thus preventing differentiation of the sand and gravel into the two named members. Diamicton in this area is part of either the Horicon or New Berlin Members. However, these members cannot be differentiated strictly on the basis of lithology; therefore, these units in the Kettle Moraine region (map units **Utr** and **Uth**, plates 1 and 2) are shown as undifferentiated Holy Hill diamicton.

Stratigraphically above the New Berlin Member is the Waubeka Member of the Holy Hill Formation (figs. 3 and 5; map-unit identifiers starting with **W** on plate 1; plate 2). This is the first usage of the term Waubeka Member, and it is defined in the appendix. The Waubeka Member contains diamicton (intermediate in grain size) deposited by the Lake Michigan Lobe between diamicton of the New Berlin Member to the west and more clayey surficial diamicton units to the east. Ice of subsequent readvances from the Lake Michigan basin deposited the younger diamicton of the Oak Creek Formation. The gray clayey diamicton extends from Ozaukee County southward around the Lake Michigan basin into the state of Michigan. Ice from the latest advance into Ozaukee County deposited the Ozaukee Member of the Kewaunee Formation (defined by Mickelson and others, 1984) (figs. 3 and 5; map-unit identifiers starting with **Z** on plate 1). The diamicton of the Ozaukee Member is distinctly reddish brown and clayey. It covers a zone several kilometers wide along the Ozaukee County shoreline.

Water was produced by melting at the ice surface and bed throughout the time glaciers covered Ozaukee and Washington Counties. Water flowed off the glacier, out from beneath the glacier, and away from the ice. This meltwater transported sand and gravel that had been picked up beneath the ice or along the ice margin. It transported sediment southward into the area of Waukesha County, or southward and then eastward into Lake Michigan. Many valleys in the two-county area are filled with sand and gravel deposits, called *outwash,* left by glacial meltwater streams. Outwash is more thoroughly sorted and stratified and lacks a fine-grained matrix. This material is commonly mined for sand and gravel. Outwash has hydraulic conductivity values ranging from 10^{-1} to 10^{-6} ms^{-1} (a function of sediment permeability) and is a source of usable groundwater in eastern Wisconsin.

Streams carried silt and clay particles farther than they carried sand and gravel. Silt and clay were normally deposited only in standing bodies of water such as Lake Michigan and other glacial lakes in Ozaukee and Washington Counties. Stratified and sorted sand, silt, and clay are present in areas once covered by lakes (plate 1). All the stratified gravel, sand, silt, and clay deposits are included in a formation or member along with the diamicton with which they are associated.

Methods

Samples collected from surface exposures and power-auger holes during the 1986, 1987, and 1988 field seasons were analyzed in the Quaternary Laboratory of the University of Wisconsin–Madison (Mickelson and Syverson, 1996). Sand:silt:clay ratios were calculated for the less-than-2-mm fraction using wet sieving, dry sieving, and hydrometer methods described by Muldoon (1987). Reported means are arithmetic means. The magnetic susceptibility was calculated using methods described by Muldoon (1987) and DonLevy (1987). All values are reported in MKS units. Munsell colors were measured on moist till samples under field conditions and in Quaternary Laboratory water suspensions. Clay mineralogy was determined using the X-ray diffractometer at the University of Wisconsin–Madison. Clay-mineral percentages were calculated using the semi-quantitative peak ratio method of Guccione (1985), unless otherwise indicated. Mechanical analysis fractions 0.25 to 0.1 mm, 2 to 1 mm, and greater than 2 mm in diameter are on file in the Quaternary Laboratory, Department of Geology and Geophysics, University of Wisconsin–Madison. Drillhole records are on file at the Wisconsin Geological and Natural History Survey (WN-941–WN-969 and OZ-535–OZ-541).

Zenda Formation

Tiskilwa Member. In a few places in the two-county area diamicton and stratified sand and gravel of this formation lie between the bedrock and the overlying Holy Hill Formation. Only four samples of what we believe to be Tiskilwa diamicton were collected (WN-52-87, WN-118-87, WN-37-88, WN-38-88). The diamicton is a gravelly, clayey, silty sand that is light reddish brown (5YR 6/4) to pink (7.5YR 7/4) where it has been oxidized. Samples from below the water table are generally grayer. Analyses of the samples interpreted to be till resulted in an average sand:silt:clay ratio of 44:37:18 (table 1; fig. 6), similar to the mean ratio of 42:35:25 reported by Mickelson and others (1984) for the unit in southeastern Wisconsin. Syverson (1988) reported one sample that had an expandable clay:illite:kaolinite plus chlorite ratio of 20:60:20, fairly similar to the 18:67:15 ratio reported by Mickelson and others (1984). Magnetic susceptibility ranges

Table 1. *Properties of till deposits in Washington and Ozaukee Counties. Only samples interpreted as basal till are included in the database for this table. (For statistics and individual sample data, see Mickelson and Syverson, 1996.)*

Unit	Sand:silt:clay	Color	Magnetic susceptibility (MKS units)
Ozaukee Member	17:50:33	5YR 5/4	1.2×10^{-3}–7.9×10^{-4}
Oak Creek Formation	13:58:29	10YR 5/1	1.3×10^{-3}–9.8×10^{-4}
Waubeka Member	33:52:14	10YR 6/4	1.3×10^{-3}–2.1×10^{-3}
New Berlin Member	54:35:11	10YR 6/4	3.0×10^{-3}–9.7×10^{-4}
Horicon Member	55:33:12	10YR 6/4	1.4×10^{-3}–8.0×10^{-3}
Undifferentiated till of the Holy Hill Formation (Kettle Moraine region)	46:39:15	10YR 6/4	1.4×10^{-3}–5.7×10^{-3}
Tiskilwa Member	40:38:22	5YR–7.5YR 6/4	1.8×10^{-3}–8.6×10^{-4}

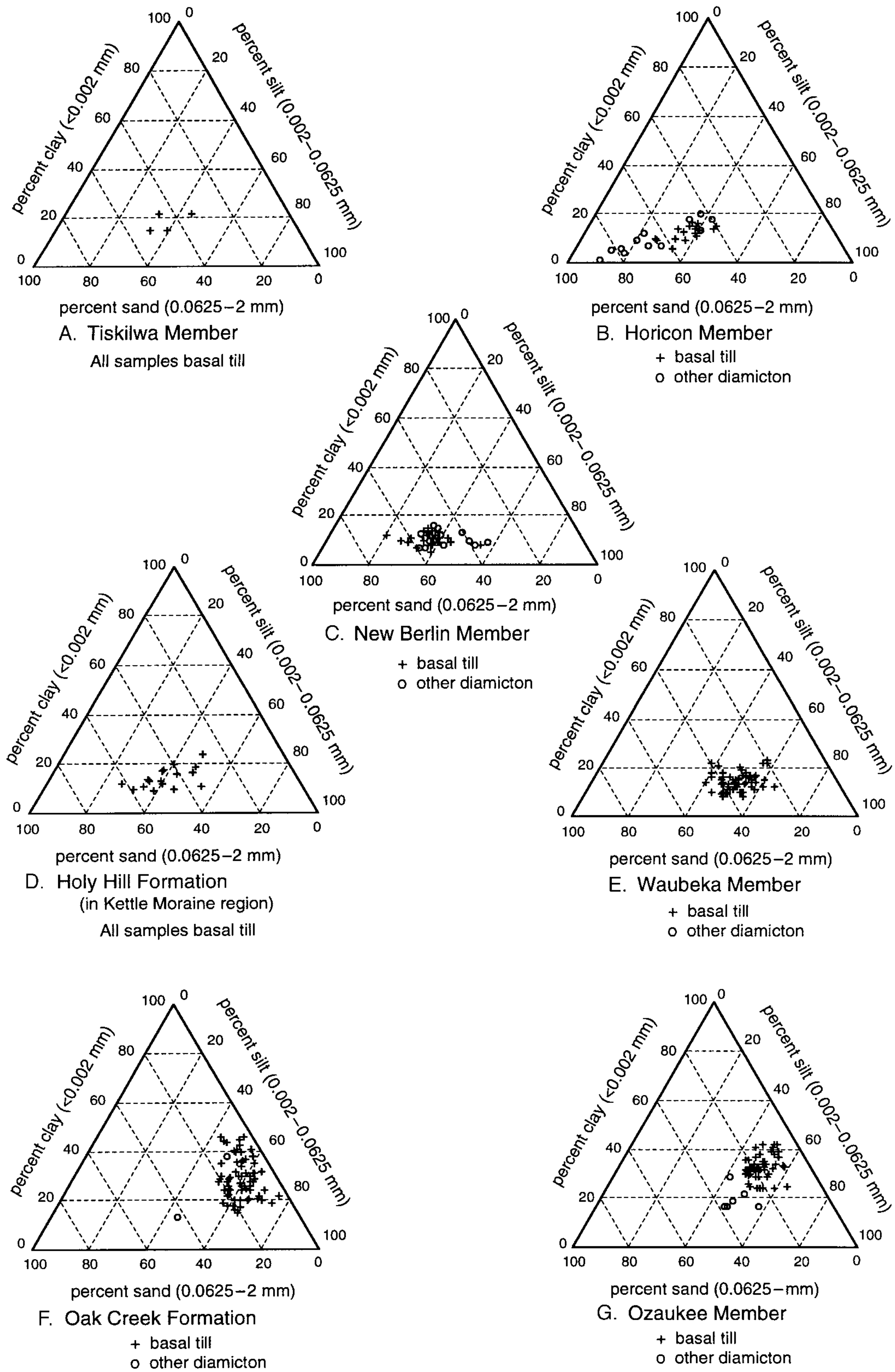


Figure 6. *Triangular diagrams showing distribution of sand, silt, and clay for till and other diamicton.*

from 1.8 x 10^{-3} to 8.6 x 10^{-4} (MKS units), not significantly different from other lithostratigraphic units. The unit is thin and only identified in the subsurface, so no values of hydraulic conductivity or engineering properties could be measured. Correlation is tenuous because of the long distance between Washington and Ozaukee Counties and the type section in Illinois.

Holy Hill Formation

Horicon Member. Deposits of the Horicon Member cover most of western Washington County (fig. 5; map-unit identifiers starting with **H** on plate 1; plate 2). Horicon sediment was deposited by ice and meltwater of the Green Bay Lobe as ice flowed into the county from the northwest. The diamicton (map unit **Hts**, plate 1) is gravelly, clayey, silty sand. The field color is light yellowish brown (10YR 6/4). Analyses of 20 samples interpreted to be till resulted in a mean sand:silt:clay ratio of 51:36:12 (table 1; fig. 6). The till is sandier close to the Kettle Moraine than it is along the western edge of Washington County. Other properties are tabulated in table 1.

Although the hydraulic conductivity of this unit was not measured as part of this study, measurements of nearby Horicon Member sites in Dodge County have field conductivity values of 10^{-4} and 10^{-8} ms^{-1} (Rodenbeck, 1988). This wide range in values probably indicates that some measurements were made in diamicton and some in better-sorted sediment.

Stratified sand and gravel of the Horicon Member is variable, ranging from bouldery gravel to fine sand. The distribution of stratified sand and gravel and diamicton is shown on plates 1 and 2. Syverson (1988) offered a more detailed discussion of properties of the Horicon Member in Washington County.

New Berlin Member. At the time that ice and meltwater from the Green Bay Lobe were depositing Horicon Member diamicton and stratified sand and gravel west of the Kettle Moraine, the Lake Michigan Lobe and its streams were depositing diamicton and stratified sand and gravel of the New Berlin Member east of the Kettle Moraine (fig. 5). This diamicton (map units **Ntr**, **Nts**, and **Nth** on plate 1; plate 2) is gravelly, clayey, silty sand, and is similar to Horicon Member diamicton. Samples interpreted to be till have a mean sand:silt:clay ratio of 54:36:11 (table 1; fig. 6). Sand and gravel of the Horicon and New Berlin Members is rich in dolomite (80–95%). No compositional differences between the sand and gravel in the New Berlin Member and that in the Horicon Member were determined, although Alden (1918) stated that they could be distinguished on the basis of color between westerly derived Ordovician dolomite and easterly derived Silurian dolomite. Rodenbeck (1988) reported a value of between 10^{-5} and 10^{-6} ms^{-1} for a field hydraulic conductivity test on diamicton at one site in Washington County. The actual range of hydraulic conductivity values is probably similar to that of the Horicon Member.

Undifferentiated sediment in the Kettle Moraine area. Coarse, stratified sand and gravel derived from the Green Bay and Lake Michigan Lobes dominates the sediment of the Kettle Moraine (fig. 5; map-unit identifiers starting with **U** on plate 1). The sediment from the two lobes is indistinguishable in this area because of similar lithologies. Properties of the sediment are provided in figure 6 and table 1. In places on rolling uplands where diamicton is at the surface, sand and gravel is at relatively shallow depths beneath the diamicton. The diamicton is interbedded with well sorted sand and gravel in several areas; this probably is the result of mudflows coming off the ice margins into the interlobate trough. Other diamicton units may represent minor ice-margin advances over stream sediment previously deposited in the interlobate zone.

Waubeka Member. Ice evidently retreated from the Kettle Moraine into the Lake Michigan basin after deposition of diamicton of the New Berlin Member and the associated sand and gravel. When the Kettle Moraine was being formed, ice flow was approximately from east to west in western Ozaukee and eastern Washington Counties. A subsequent readvance out of the Lake Michigan basin came from the northeast to an ice margin that was oriented northwest–southeast in southern Washington County (fig. 5; plate 1). Compared to the underlying New Berlin till, the diamicton we interpreted as till deposited by this advance (map units **Wtsp** and **Wtr**, plate 1) contains more silt and clay and has a mean sand:silt:clay ratio of 35:32:14 (fig. 6; table 1). The field color of this unit is generally yellowish brown to brown (10YR–7.5YR hues). This previously unnamed unit (formally defined in the appendix) has been recognized along the shoreline of Lake Michigan in Ozaukee and Milwaukee Counties and is probably the same unit as till 1B described by Mickelson and others (1977). The diamicton (map unit **Wtsp**, plate 1; plate 2) is relatively thin (normally less than 2 or 3 m thick) and blankets east–west trending drumlins of the slightly older New Berlin Member. It is present along the base of the Lake Michigan bluff (plate 1) in several places, indicating that ice retreated at least that far into the Lake Michigan basin before readvancing and depositing this diamicton as a separate unit. No engineering properties or hydraulic conductivity values are available for this unit. It is above the water table and relatively thin where observed in the field, so determinations of engineering properties and hydraulic conductivity have been difficult.

Oak Creek Formation

After deposition of the diamicton of the Waubeka Member, the ice margin retreated into the Lake Michigan basin and may have retreated far to the north. Diamicton (map units **Oth** and **Othe**, plate 1; plate 2) and associated stream sediment of the Oak Creek Formation were deposited when the ice readvanced. The diamicton interpreted to be till is silty clay that has relatively few gravel-size particles. The mean sand:silt:clay ratio is 13:58:29 in Ozaukee and southwestern Washington Counties (fig. 6; table 1). The field color of this unit is generally gray (10YR 5/1) where unoxidized and light yellowish brown (10YR 6/4) where oxidized. The glacier flow direction was different from that of the ice that deposited diamicton of the Waubeka Member: It appears that the diamicton of the Oak Creek Formation was deposited by ice flowing out of the Lake Michigan basin almost directly toward the west. The ice may have flowed slightly toward the northwest in parts of southern Ozaukee County. Diamicton, till, and outwash of the Oak Creek Formation contain a large amount of black shale compared to that found in the New Berlin Member. This suggests that much of the diamicton and stream sediment were derived from lake sediment and shale beneath present-day Lake Michigan.

Rodenbeck (1988) summarized numerous measurements of engineering and hydrologic properties at Omega Hills landfill in the southeastern corner of Washington County. Values of field hydraulic conductivity for what was described as till ranged from 10^{-6} to 10^{-8} ms^{-1}. These values from the southeasternmost corner of Washington County and adjacent Waukesha County are the only ones available for till of the Oak Creek Formation in the two-county area. However, numerous field measurements of hydraulic conductivity by Simpkins (1989) for diamicton in southern Milwaukee and northern Racine Counties ranged from 10^{-6} to 10^{-8} ms^{-1}. Further discussion of correlation of deposits across Milwaukee County is included in the final section of this report.

Kewaunee Formation

Ozaukee Member. After several minor readvances of the ice deposited layers of diamicton of the Oak Creek Formation (only one or two of which are recognizable in Washington and Ozaukee Counties), the ice retreated to the north end of the Lake Michigan basin. This retreat of the ice front allowed water and large amounts of reddish-brown sediment to enter the Lake Michigan basin from the Lake Superior basin. The subsequent ice advance deposited reddish-brown, silty, clayey diamicton of the Ozaukee Member of the Kewaunee Formation (map units **Ztdb, Zth, Zthe,** and **Ztsp,** plate 1). The mean sand:silt:clay ratio for diamicton interpreted to be till in Ozaukee County is 17:50:33 (fig. 6; table 1). Its deep reddish-brown color (5YR 5/4), where oxidized, makes it easily distinguishable from older units. Diamicton of the Ozaukee Member is richer in dolomite fragments and has fewer shale fragments than the underlying diamicton of the Oak Creek Formation, suggesting that the shale beneath Lake Michigan was covered by a thick blanket of sediment when this ice advance took place. No measurements of hydraulic conductivity were done for this study, but two values were compiled from Wisconsin Department of Natural Resources files by Rodenbeck (1988) for diamicton in northern Ozaukee County. These field hydraulic conductivity values are about 10^{-7} ms^{-1}. If more samples were available, a wider range of values would be present.

Postglacial sediment

A thin layer of *loess* (wind-blown silt) was deposited on much of the land surface after the retreat of the glacier, but this material is generally less than 0.3 m thick and is not shown on plates 1 or 2. The landscape has been modified by streams and downslope movement since the ice melted and throughout the Holocene. Erosion has taken place on hillslopes and in small channels, and deposition of this sediment has taken place in larger stream valleys (map unit **a**, plate 1). Mass-wasting deposits and deposits in small streams are not shown on plate 1 because they cover too small an area.

The Lake Michigan shoreline of Ozaukee County has eroded considerably. Shoreline erosion observed during the last 100 years is probably typical of what has taken place during much of the last 5,000 years. The amount of erosion is linked to fluctuating lake level, which is briefly discussed later in this report. The beach sand along Lake Michigan is not wide enough to be shown on plates 1 or 2, except where older beach sand is preserved on a wave-eroded terrace.

Finally, peat and muck have accumulated in lowlands throughout the county. Generally, they are shown as organic deposits (map unit **o**, plate 1) but are too thin to be shown on plate 2. Many areas that once contained a considerable thickness of peat have been drained and farmed so long that much of the peat has been destroyed by oxidation of the organic matter.

LANDFORM REGIONS

The Laurentide Ice Sheet in Ozaukee and Washington Counties formed unique glacial features between 25,000 and 12,000 years ago (fig. 7). Most of these landforms can be found on plate 1 by reading the unit descriptions or line symbols.

Origin of glacial landforms

Moraines

End moraines, often simply called moraines, are ridges formed perpendicular to ice-flow direction at the end or outermost edge of a glacier. They are composed mostly of till and supraglacial diamicton, although hummocky stream-deposited sand and gravel is commonly present. Although they probably form during brief periods of stability during ice-margin advance as well as during ice-margin retreat, those formed during retreat are commonly the only ones clearly preserved. A glacier acts like a conveyor belt, carrying boulders, sand, silt, and clay from

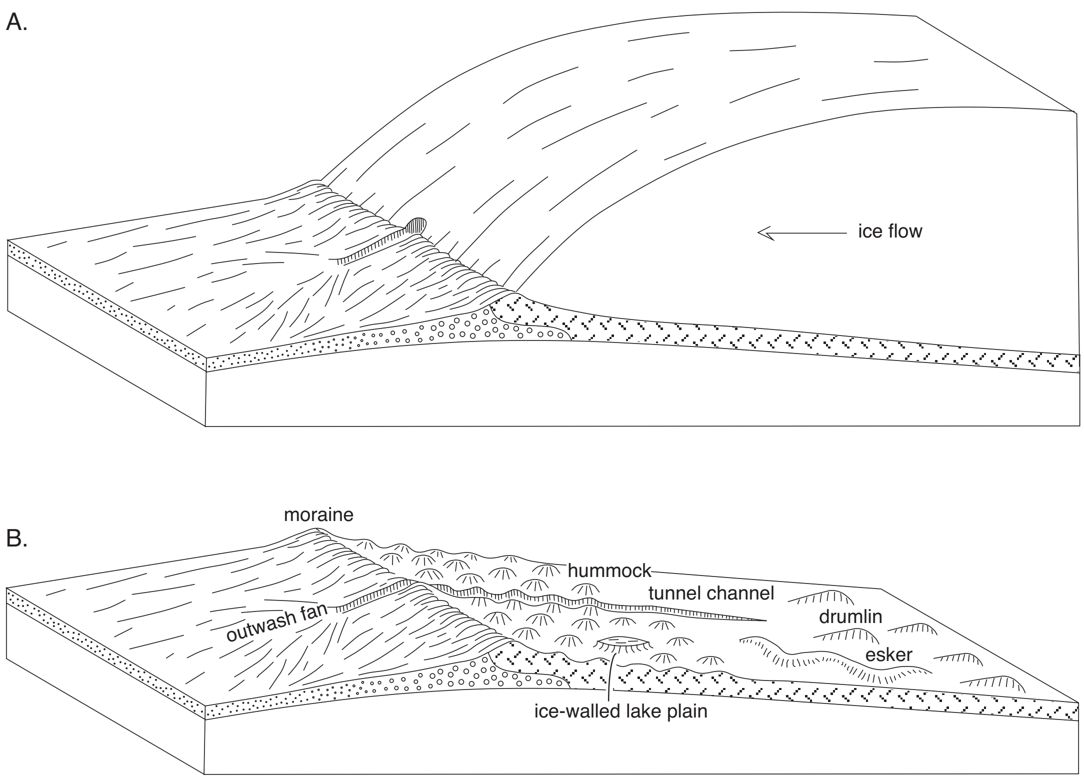


Figure 7. *Sketch of (A) ice sheet at maximum extent and (B) the distribution of landforms left after ice retreat (modified from Attig and others, 1989). Distance across diagram approximately 10–20 km.*

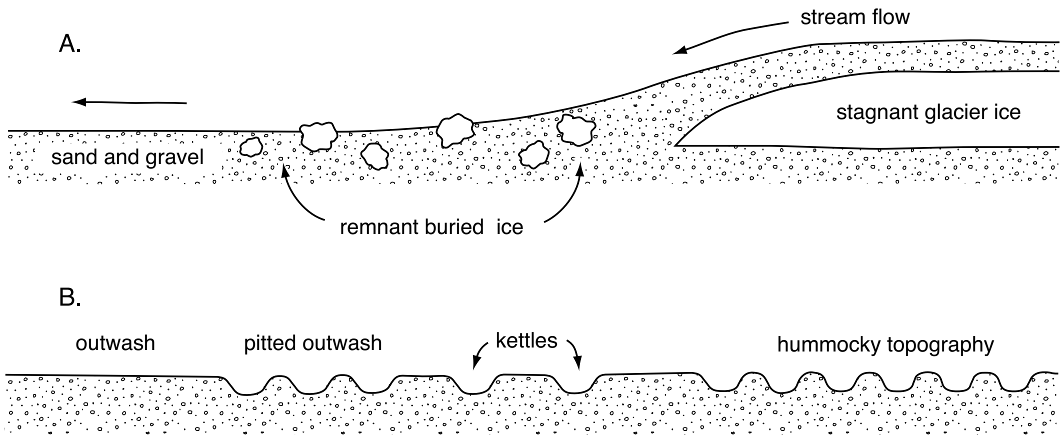


Figure 8. *Formation of outwash plain, pitted outwash plain, and hummocky topography. A. Water from melting ice deposits sediment and buries residual ice. B. Water flow stops and residual ice melts to produce final topography.*

beneath the ice to its terminus; as the ice melts, end moraines are formed. The sediment accumulates to produce a moraine during times when the glacier margin remains stationary. If the glacier advances or retreats at a uniform rate, in all likelihood no moraines would be produced. Rather, a thin layer of diamicton would be distributed evenly across the landscape.

Kettles

At the edge of glaciers, sediment is often carried upward in the ice; it accumulates on the ice surface as the ice melts. (The outermost kilometer or so of the ice in Wisconsin was likely covered with at least 1 m of sediment that had melted out of the ice.) The sediment cover, in turn, slows the melting of ice below. This allows the formation of *kettle holes* or *kettles* (fig. 8). These depressions, formed by melting of buried ice blocks followed by the collapse of the overlying sediment, often produce *hummocky topography* (many small, irregular hills and depressions) that develops as sediment is slowly let down over hundreds or thousands of years. End moraines normally have hummocky topography with many kettles that often contain ponds, lakes, or bogs.

Outwash plains and pitted outwash plains

Outwash is sand and gravel deposited by streams flowing away from the glacial margin. Where streams deposit outwash on solid ground, no collapse takes place and the former stream bed is preserved in a gently sloping outwash plain (fig. 8; plate 1). Where glacial meltwater exits from tunnels beneath the ice or flows off the ice at the ice margin, sand and gravel is sometimes deposited on ice. When this happens, the buried ice slowly melts to produce kettles. In some places, hummocky sand and gravel is produced because the buried ice was extensive and the whole surface of the gravel ultimately collapsed (fig. 8). Only isolated blocks of ice were covered by stream-deposited sand and gravel in other places; in these places, part of the former stream bed was preserved after collapse and is only interrupted here and there by kettle holes. We mapped this type of surface as a *pitted outwash plain* (fig. 8; plate 1).

Ice-walled-lake plains

Ice-walled lakes are common features where a thick sediment cover is present on the ice. These lakes are confined on all sides by debris-covered ice. Sediment flows and slides into the lake, where it is deposited. After the surrounding ice melts, the lake deposits often stand higher than the surrounding landscape and are called *ice-walled-lake plains* (fig. 7; map unit **Uipi,** plate 1).

Interlobate moraines

When two lobes of glacial ice flow together, as they did in Washington County, a large ridge or set of ridges is deposited between the two lobes. This is called an *interlobate moraine*. The Kettle Moraine, which runs through Washington County (fig. 5; plate 1), is an interlobate moraine, and it does not contain as much till as most end moraines. Here, ice flow carried sediment up to the ice surface where it accumulated to form supraglacial sediment (fig. 9). A fairly thick debris cover must have formed at the junction of the two lobes when the ice was at its maximum extent. As the ice started to melt down and retreat, this supraglacial sediment, much of it deposited by supraglacial streams in the low area between the two lobes, settled onto the land surface as a complex set of smaller landforms. Most of the Kettle Moraine consists of hummocky sand and gravel formed in this way. In places along the Kettle Moraine, these deposits form a double ridge, each ridge built by one lobe.

Moulin kames

An impressive landform in the Kettle Moraine is the *moulin kame* (sometimes called a *sinkhole kame)*. These high, conical hills are unusual in other environments, but are abundant throughout the Kettle Moraine area. Researchers have conflicting hypotheses about their mode of formation. Alden (1918, p. 308) believed that these conical hills formed at the base of vertical shafts in the ice (moulins) as meltwater carried debris into the shaft and dropped vertically down the moulin. Black (1969, 1970, 1974) also advocated this mechanism of formation.

Alternative mechanisms have been proposed by several authors (Cook, 1946; Holmes, 1947; Mickelson and others, 1989). In some cases it is likely that these hills formed in places where the roofs of subglacial tunnels collapsed (*glacier sinkholes*), allowing water and sediment to pour into a tunnel from above (fig. 10). Many subglacial tunnels were located in the interlobate region during the formation of the Kettle Moraine. When parts of these collapsed, probably at the location of moulins, water and sediment from the surface of the ice poured into these glacier sinkholes. The water flowed away and a mound of sand and gravel accumulated and remained after the surrounding ice melted away. We have observed small moulin kames forming beneath moulins as well as glacier sinkholes associated with the collapse of parts of subglacial tunnels in Alaska. Many of the highest hills in Washington County, including Holy Hill (which can be seen from many kilometers away), are sinkhole kames or moulin kames.

Drumlins

Some glacial features in the area formed beneath the glacier. One of the most striking is the *drumlin*, a streamlined hill with its long axis oriented parallel to the ice-flow direction (fig. 7; plate 1). These hills, often shaped like inverted spoons, are composed of diamicton and sorted sand and gravel and were shaped by flowing glacial ice.

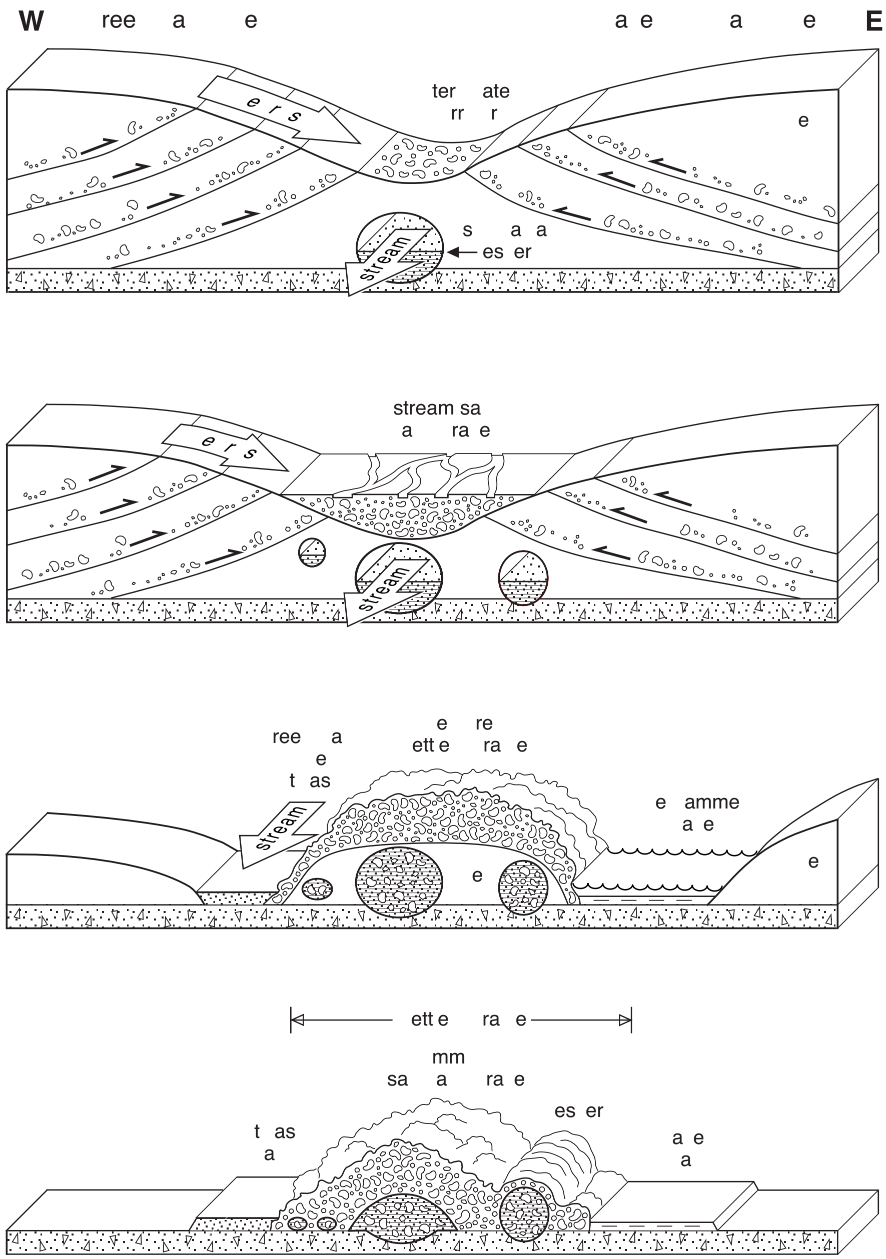


Figure 9. *Formation of Kettle Moraine. A. Green Bay and Lake Michigan Lobes meet in the interlobate region. Lake Michigan Lobe flows up the regional slope of the land surface. Compression brings debris from the base of the ice up to the surface. Subglacial stream flowing in tunnel deposits sand and gravel. B. Ice thins. Meltwater streams at the surface transport and deposit sand and gravel in the interlobate corridor. More subglacial tunnels form in the interlobate region. C. Glacier lobes separate from the interlobate region. Thick layer of debris insulates underlying ice. Material starts to slump into low areas. Meltwater streams deposit outwash parallel to the western margin of the Kettle Moraine. Ice-dammed lakes form in front of the Lake Michigan Lobe as the ice margin retreats down the easterly sloping land surface. D. Hummocky sand and gravel is lowered as underlying ice melts, thus forming most of the high areas in the Kettle Moraine of Washington County. Eskers remain as prominent ridges in segments of the Kettle Moraine.*

Tunnel channels

Water produced by melting at the glacier's surface or base generally moves along the bottom of the ice toward the ice margin. A major landform produced by this subglacial water is the *tunnel channel,* a large channel cut by subglacial water flowing toward the margin (fig. 7). These channels, cut into rock or glacial sediment, are typically about 1 km wide and longer than 10 km, and are especially common in areas covered by the Green Bay Lobe. They probably formed in Wisconsin when the ice was quite thick and cold enough to prevent the melting of tunnels up into the ice.

Eskers

Another major landform produced by subglacial water is the *esker*, a ridge of sand and gravel deposited by streams flowing beneath the ice (fig. 7). Eskers presumably form when the ice temperature is at the melting point, so a tunnel can form more easily in the ice than it can below the ice, just the opposite of the tunnel channel. Eskers are commonly located in tunnel channels, demonstrating that they formed later than the tunnel channel (perhaps after the ice had warmed to the pressure melting point). Eskers are common in the Kettle Moraine, and in places make up most of the interlobate ridge.

Meltwater channels

Erosional features are also formed by meltwater near the edge of the glacier. One type of channel, a *proglacial channel*, forms as water flows away from the ice margin. Another type, an *ice-marginal channel,* is cut by water flowing along the ice margin. It is found where the land slopes toward the glacier so that water is prevented from flowing directly away from the ice margin.

Glacial lake plains

Water derived from the ice is commonly ponded in depressions against the ice margin (where river drainages are dammed by ice). These proglacial lakes collect sand, silt, and clay to form relatively flat plains. These *lacustrine plains* or *lake plains* are common in Washington and Ozaukee Counties.

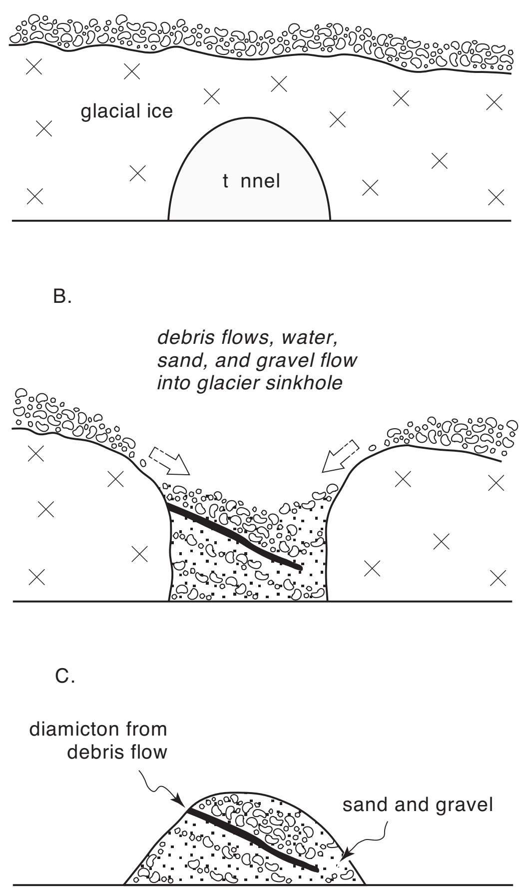


Figure 10. *Model of moulin kame or sinkhole kame formation (modified from Brodzikowski and van Loon, 1991). A. Subglacial tunnel forms. Debris is present at the ice surface. B. Glacier sinkhole develops as roof of tunnel collapses. Water and debris from the ice surface flow into the depression. Sediment accumulates in depression as water flows out through a tunnel. C. Conical hill remains after ice melts away.*

Landforms associated with Horicon Member

The western one-third to one-half of Washington County was most recently covered by ice of the Green Bay Lobe (fig. 5). This lobe abutted ice of the Lake Michigan Lobe at what is now the Kettle Moraine. All glacial and related deposits in this area are part of the Horicon Member.

The dominant glacial landform in western Washington County is the drumlin. Subglacially streamlined hills (fig. 11) are common features throughout this area (Alden, 1918; Borowiecka and Erickson, 1985) and are oriented northwest–southeast, indicating that ice was flowing toward the Kettle Moraine. The drumlins in Washington County are part of the Campbellsport drumlin field described by Black (1974). They are among the highest in the state, but in Washington County the relief is more subdued than it is to the north in Fond du Lac County.

Although the scientific community generally agrees that drumlins are subglacial features, the details of their formation are still debated. Whittecar (1976), Whittecar and Mickelson (1977, 1979), and Stanford and Mickelson (1985) studied drumlins in Waukesha County and concluded that, for the most part, they consist of deposits that predate the last glaciation. The drumlin-forming ice advance carved the drumlins out of preexisting deposits across the landscape. Almost all drumlins have at least a surface layer of till that was deposited during the retreat of the most recent glacier. Very few exposures in drumlins exist to test hypotheses of drumlin formation in western Washington County.

Syverson (1988) found that the drumlins in Washington County typically have length-to-width ratios of about 1.8:1 or less in the area west of Kewaskum, and greater than 2:1 west of Cedar Lake. This increasing elongation of drumlins is unexplained. Borowiecka and Erickson (1985) point out that drumlins "are smaller, more round, and more closely spaced on uplands (than in the lowlands)," and this appears to be the case in Washington County. They are found in some places where glacial deposits are very thick (120 m); in other places, in areas of shallow bedrock.

The drumlins do not extend eastward to the Kettle Moraine; instead, there is a drumlin-free area of outwash plains and gently rolling till surfaces. The conditions necessary for drumlin formation presumably did not exist under ice that was near the present-day position of the Kettle Moraine. It is also possible that small drumlins on the till surface have been buried by sand and gravel.

Two major valleys west of Cedar Lake are interpreted to be tunnel channels (Syverson, 1988). These tunnel channels are cut into till and bedrock for lengths of 3 km or more and trend in a northwest–southeast direction. One, shown in figure 12 (and on plate 1 as cutbank symbols about 5 km west of West Bend), is as much as 35 m deep, 500 m wide, and more than 3 km long. Several eskers up to 10 m high are present in the bottom of the channel (figs. 12 and 13). Like many tunnel channels that formed beneath the Green Bay Lobe, the floor of the channel slopes downward to the northwest, opposite the ice-flow direction. Water in the channel flowed uphill to the southeast and out from beneath the ice sheet. This characteristic, along with the presence of eskers on the valley floor, is a sign that this is a subglacial channel and not a channel formed by streams flowing away from the glacial margin.

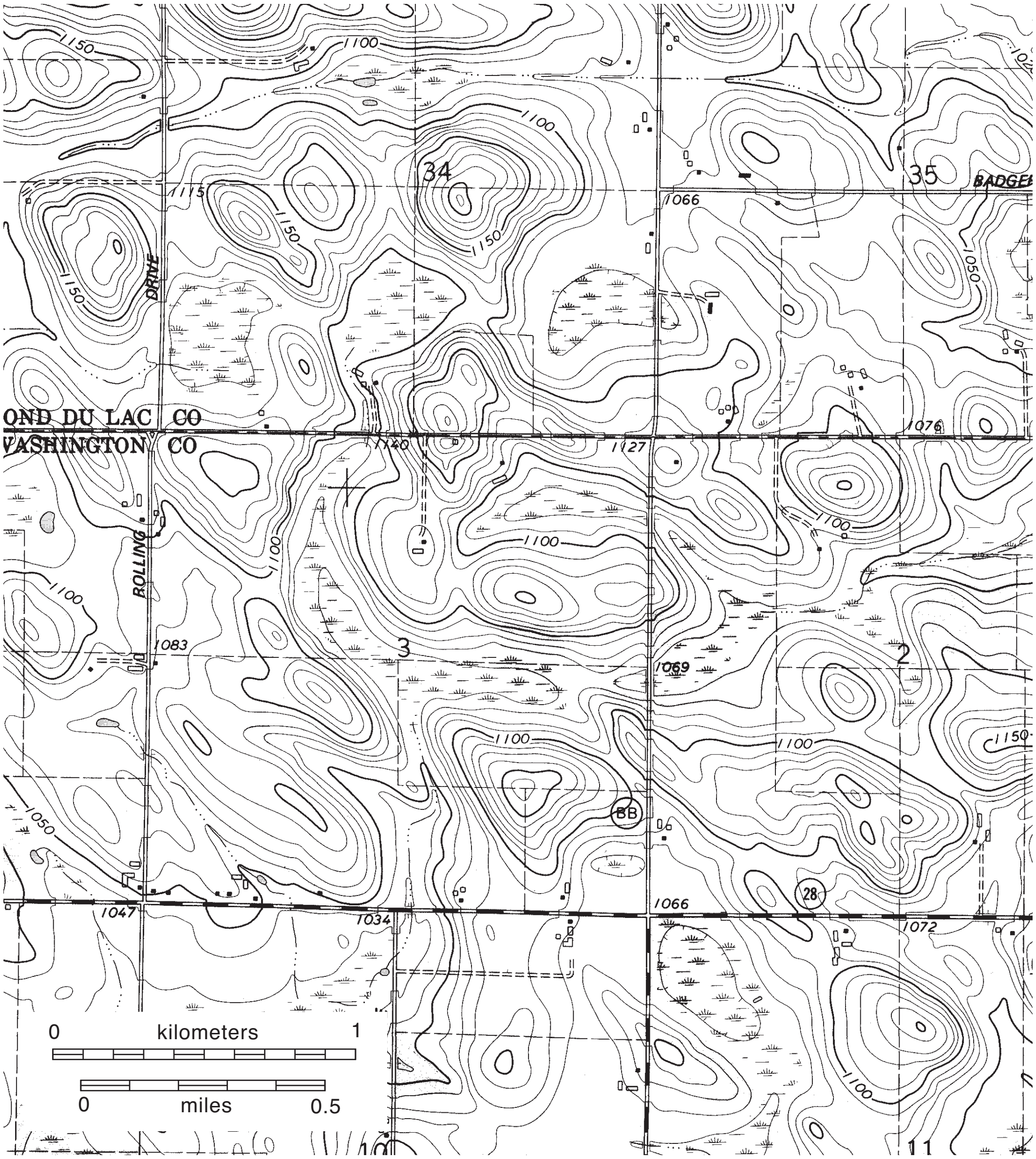


Figure 11. *Part of Campbellsport Quadrangle, Wisconsin (U.S. Geological Survey, 7.5-minute series, topographic, 1974), showing closely spaced drumlins that lack pronounced elongation (T12 and 13N, R18E).*

Another tunnel channel is present 3.5 km northwest of Slinger. This channel is about 25 m deep, 500 m wide, and is traceable for 3.2 km to a large swamp in secs. 22 and 27, T11N, R18E. After the tunnel channel formed, ice filled the depression. Water drained southeastward along the edge of the partly buried ice block as the ice wasted away, forming a well developed terrace underlain by gravel in secs. 22, 26, and 36. An outwash fan at the mouth of this channel is graded to the outwash surface between Cedar and Pike Lakes.

As the glacier began to retreat from the Kettle Moraine, streams flowing away from the ice deposited sand and gravel in gently sloping outwash plains. An extensive outwash plain lies in southwestern Washington County (map units

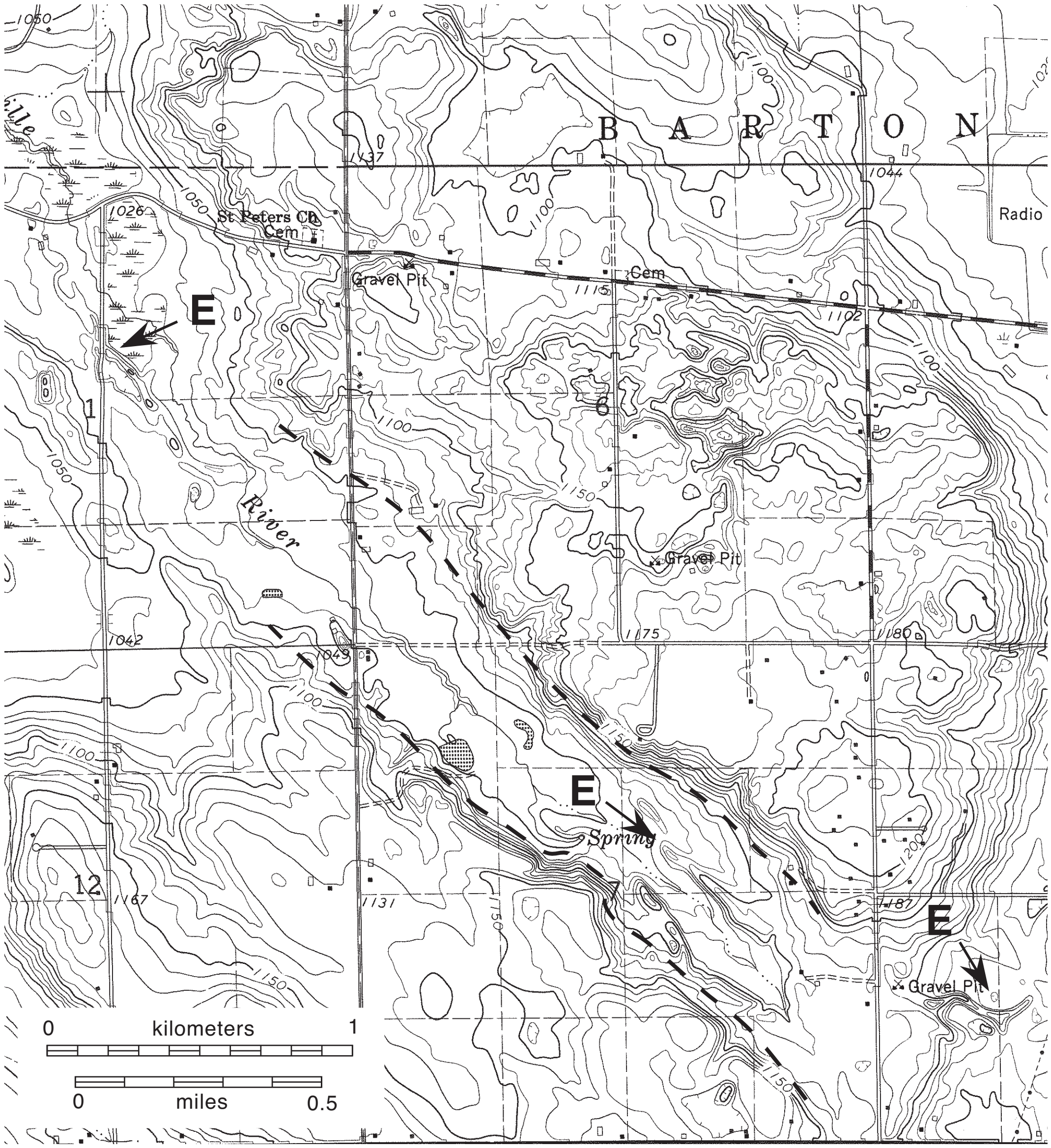


Figure 12. *Part of Allenton Quadrangle, Wisconsin (U.S. Geological Survey, 7.5-minute series, topographic, 1971), showing tunnel channel (banks marked with dashed lines) and associated eskers (E), T11N, R18 and 19E. Water flowed to the southeast.*

Hgp and **Hgpp**, plate 1). The plain slopes south–southwestward from a hummocky, collapsed area with an elevation of 320 to 323 m, located 3 to 5 km southwest of Pike Lake. The density of kettles gradually decreases to the south. The hummocky, collapsed upstream end of the outwash plain is an ice-contact face that marks an ice-marginal position of the Green Bay Lobe. The Ashippun River flows west–southwestward, parallel to the ice-contact face of the outwash plain. This river valley developed as an ice-marginal channel during retreat of the glacier, after the outwash plain had formed.

Sand and gravel outwash of the Horicon Member forms another smooth, gently sloping plain abutting the western face of the Kettle Moraine from Cedar Lake to a point 2 km south of Pike Lake (map units **Hgp** and **Hgpp**, plate 1). This plain formed as meltwater from the wast-

Figure 13. *Photograph of esker in tunnel channel (NE1/4 NW1/4 sec. 1, T11N, R18E; seen on topographic map in fig. 12).*

ing Green Bay Lobe was deflected toward the southwest by the high, ice-cored Kettle Moraine ridge. Large blocks of ice buried by this outwash east of Hartford and north of Slinger later melted to form kettles now occupied by Pike and Cedar Lakes.

Large, flat areas containing thick deposits of peat, silt, and sand are present at Wayne Marsh (fig. 14; map units **o**, **Hip**, and **Hsp**, plate 1) and the area to the southeast. An early ice-margin position is marked by the hummocky sand and gravel deposits south of Wayne Marsh (fig. 14; map unit **Hgpp**, plate 1). As the ice wasted to the north across the local drainage divide, the drainage basins that now drain westward into the Rock River and northward into the west branch of the Milwaukee River were dammed by stagnant ice. This created proglacial Lake Wayne, first named by Syverson (1988), with beach deposits at an elevation of 323 to 326 m and an outlet north of Cedar Lake into the Ashippun River drainage. When Lake Wayne was at this level, several drumlins rose as islands above the lake surface. Wells in the area penetrate as much as 15 m of silt. Presumably, Lake Wayne drained as the northern outlet was deglaciated, so the lake was short-lived.

Landforms associated with undifferentiated Horicon and New Berlin Members (Kettle Moraine)

The hummocky topography, numerous lakes, and forests have made the Kettle Moraine a popular recreational area. To protect this unique area, the state of Wisconsin established the Kettle Moraine State Forest in 1936. In 1971, the Kettle Moraine was included in the Ice Age National Scientific Reserve to preserve its glacial features.

The Kettle Moraine forms a conspicuous hummocky ridge or series of ridges that bisect Washington County from north to south (fig. 5; map-unit identifiers starting with **U**, plate 1). The numerous hills in the Kettle Moraine rise up to 150 m above the surrounding low, rolling till surfaces on either side. The entire Kettle Moraine is a high area that extends approxi-

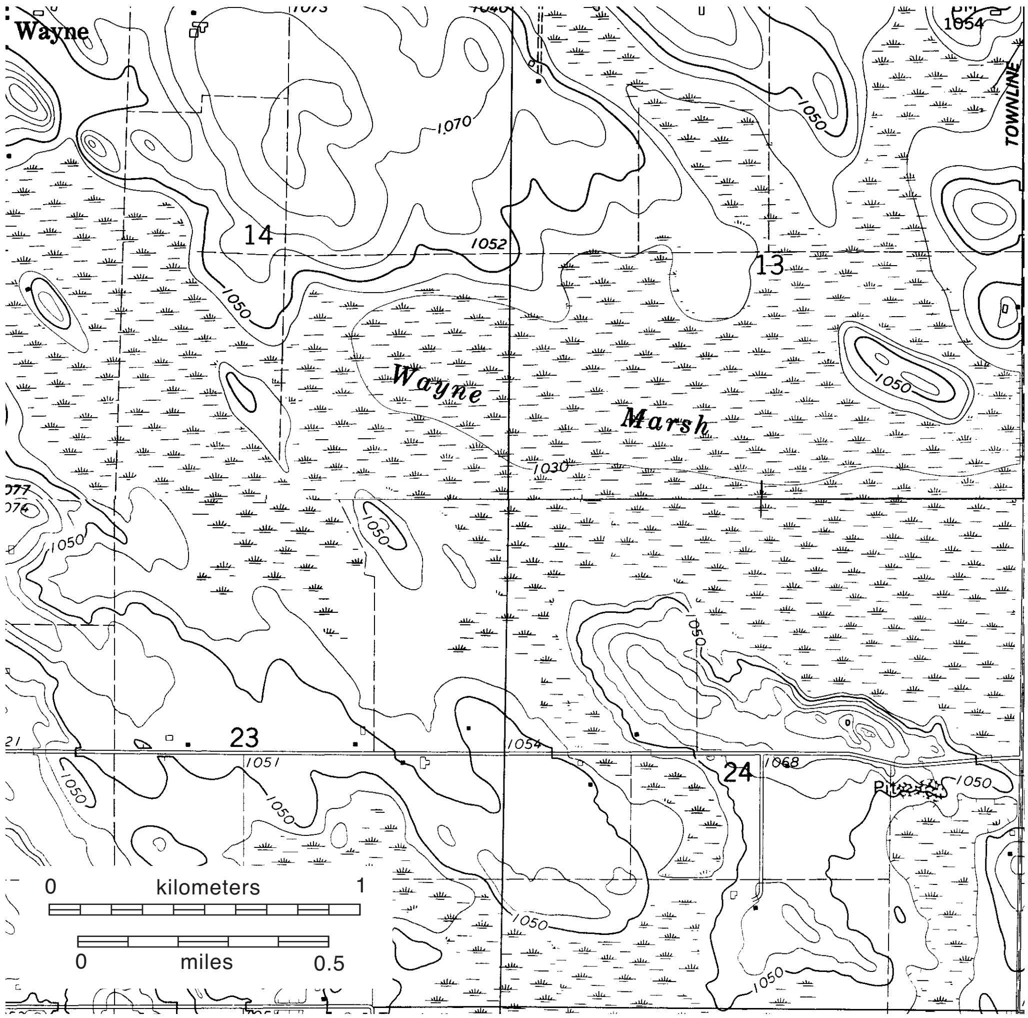


Figure 14. *Part of Campbellsport and Allenton Quadrangles, Wisconsin (U.S. Geological Survey, 7.5-minute series, topographic, 1974 and 1971, respectively), showing extensive lake plain at Wayne Marsh, T12N, R18E. Standline was 317 to 326 m above sea level, so drumlins formed islands.*

mately 175 km from Walworth County to Kewaunee County in eastern Wisconsin.

The Kettle Moraine contains mainly stratified sand and gravel deposited by meltwater streams flowing between the Green Bay and Lake Michigan Lobes. As shown in figure 2, ice from both lobes was flowing toward the interlobate region (Chamberlin, 1883). Because glacial ice always slopes downward in the direction of ice flow, a low trough must have existed on the ice surface at the junction between the two lobes (fig. 9). In addition, the flow of meltwater within and beneath the glacier is controlled mainly by the slope of the ice surface (Shreve, 1985; Syverson and others, 1994). For these reasons, a large river system developed in the southwesterly sloping trough as the climate warmed, and the Kettle Moraine began to form.

The rivers picked up sediment that was accumulating on the ice surface and transported the sediment in braided streams toward the southwest. This sediment, much of it coarse grained, was deposited on, under, and adjacent to the ice. The irregular topography of the Kettle

Moraine formed as the underlying ice melted and the sediment collapsed, and water carried sediment through tunnels in the ice. Because most of the Kettle Moraine contains sorted sand and gravel (and little diamicton), the Kettle Moraine is not typical of most moraines (Syverson, 1988). Similar interlobate moraines containing abundant stream sediment have been described in Ireland by Warren and Ashley (1994). Most of the diamicton in the Kettle Moraine underlies rolling surfaces at intermediate heights within the landscape. The diamicton may have been deposited by mud flowing off the ice margins or as basal till of minor ice advances over sediment deposited in the interlobate zone.

T.C. Chamberlin was one of the early glacial geologists in North America. At a time when the idea of continental glaciation was still quite new, he published an article (1878) on the origin of the outermost moraine of Wisconsin's last glaciation, which he called the Kettle Moraine. This name, derived from the abundance of kettles in the end moraine, gradually became restricted to the physiographic region containing the interlobate ridge found in eastern Wisconsin. (Clayton, in press, provided a detailed discussion about how the Kettle Moraine was named.) The Kettle Moraine has attracted the attention of many geologists since Chamberlin's first article. Chamberlin (1883), Alden (1918), Black (1969, 1970, 1974), Stoelting (1970), Attig (1986), Syverson (1988), and Clayton (in press) have all described aspects of this feature. The Kettle Moraine contains impressive landforms resulting from the most recent glaciation.

Some of the unique landforms found in the Kettle Moraine are moulin kames (indicated by a symbol on plate 1). Several of these conical hills are present at Slinger and in the Holy Hill area of southern Washington County (fig. 15). These hills are 10 to 50 m high and their round contour lines on topographic maps resemble bull's-eyes (fig. 15). Large boulders are common on the steep hillsides.

Many eskers are present in the Kettle Moraine and all suggest that water was flowing toward the southwest (parallel to the axis of the Kettle Moraine) when they formed. In fact, north of Kewaskum, much of the hummocky sand and gravel in the Kettle Moraine probably was deposited in a subglacial or englacial (within the glacier) tunnel environment. The sediment collapsed as underlying or adjacent ice melted. Warren and Ashley (1994) suggested that ridges formed by subglacial streams flowing parallel to the ice margins in an interlobate zone should not be called eskers. However, in this discussion we call all ice-tunnel deposits eskers.

Two Kettle Moraine eskers are especially prominent. An esker south of Pike Lake (secs. 34 and 35, T10N, R18E; secs. 3 and 10, T9N, R18E) is up to 27 m high and can be traced as a discontinuous ridge 11 km south to the Waukesha County line (fig. 16; map unit **Ug**, plate 1), where the subglacial stream emerged from its tunnel and deposited sand and gravel in an outwash fan on stagnant ice (map unit **Ugpp**, plate 1, secs. 9 and 10, T9N, R18E).

Another esker, up to 23 m high and 3 km long, is west of West Bend (fig. 17; plate 1). A large gravel pit owned by West Bend Sand and Stone is in this esker just north of Highway 33.

Thick deposits of silt are found high in the Kettle Moraine landscape. They are small, circular, and sometimes have raised rims surrounding a flat, silty plain (fig. 17, map unit **Uipi**, plate 1). These are ice-walled-lake plains, remnants of

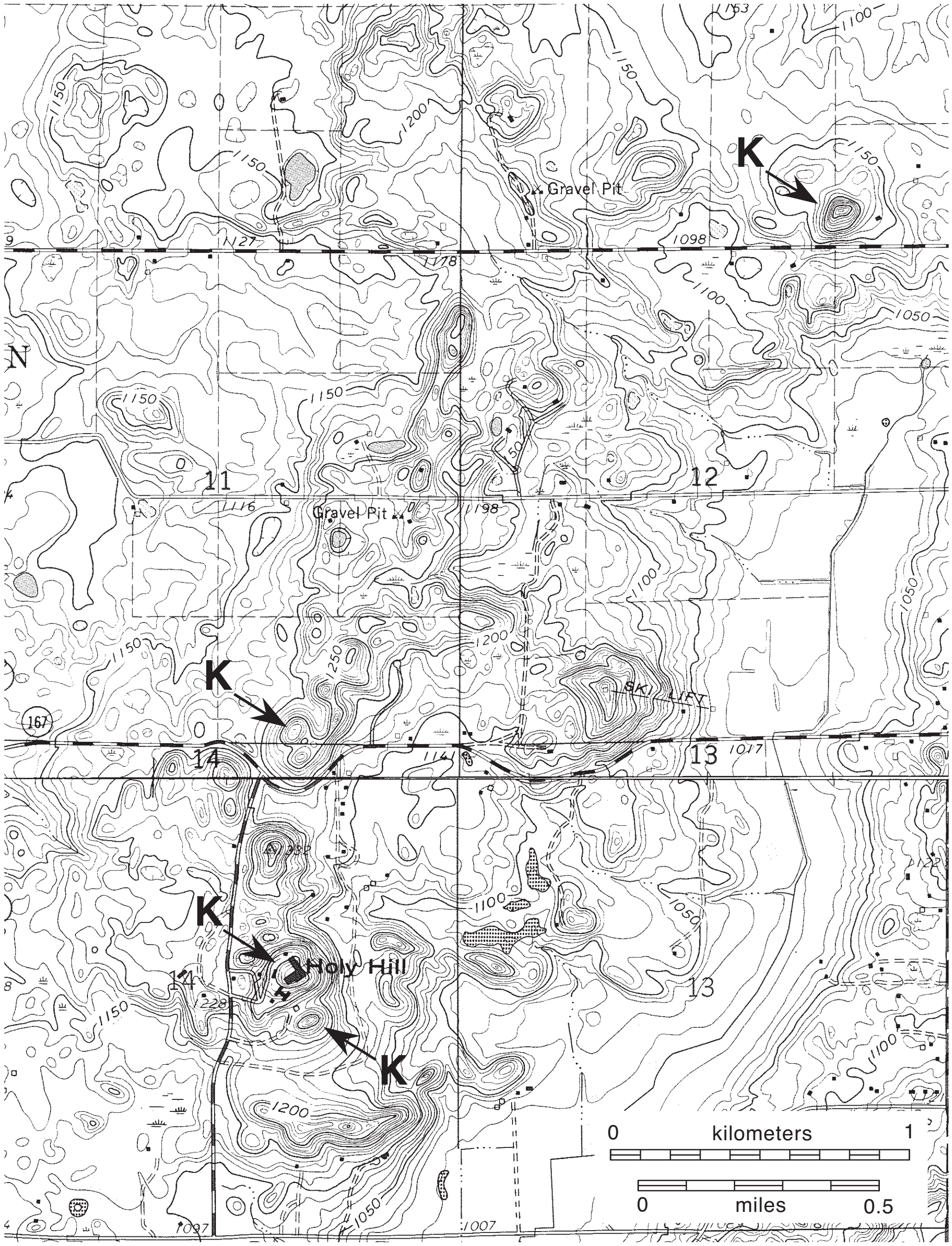


Figure 15. *Part of Hartford East and Merton Quadrangles, Wisconsin (U.S. Geological Survey, 7.5-minute series, topographic, 1976 and 1974, respectively), showing Holy Hill moulin kame complex. Notice the high relief moulin kames (K) and numerous kettles (T9N, R18E).*

lakes that were present at that location while stagnant ice was sufficiently thick and continuous to hold water in the basin. Syverson (1988) reported silt interbedded with fine-grained sand in several of these features in Washington County. Because the disappearance of the stagnant ice surrounding the lake created a low, hummocky landscape, the ice-walled-lake plains now stand above the surrounding topography.

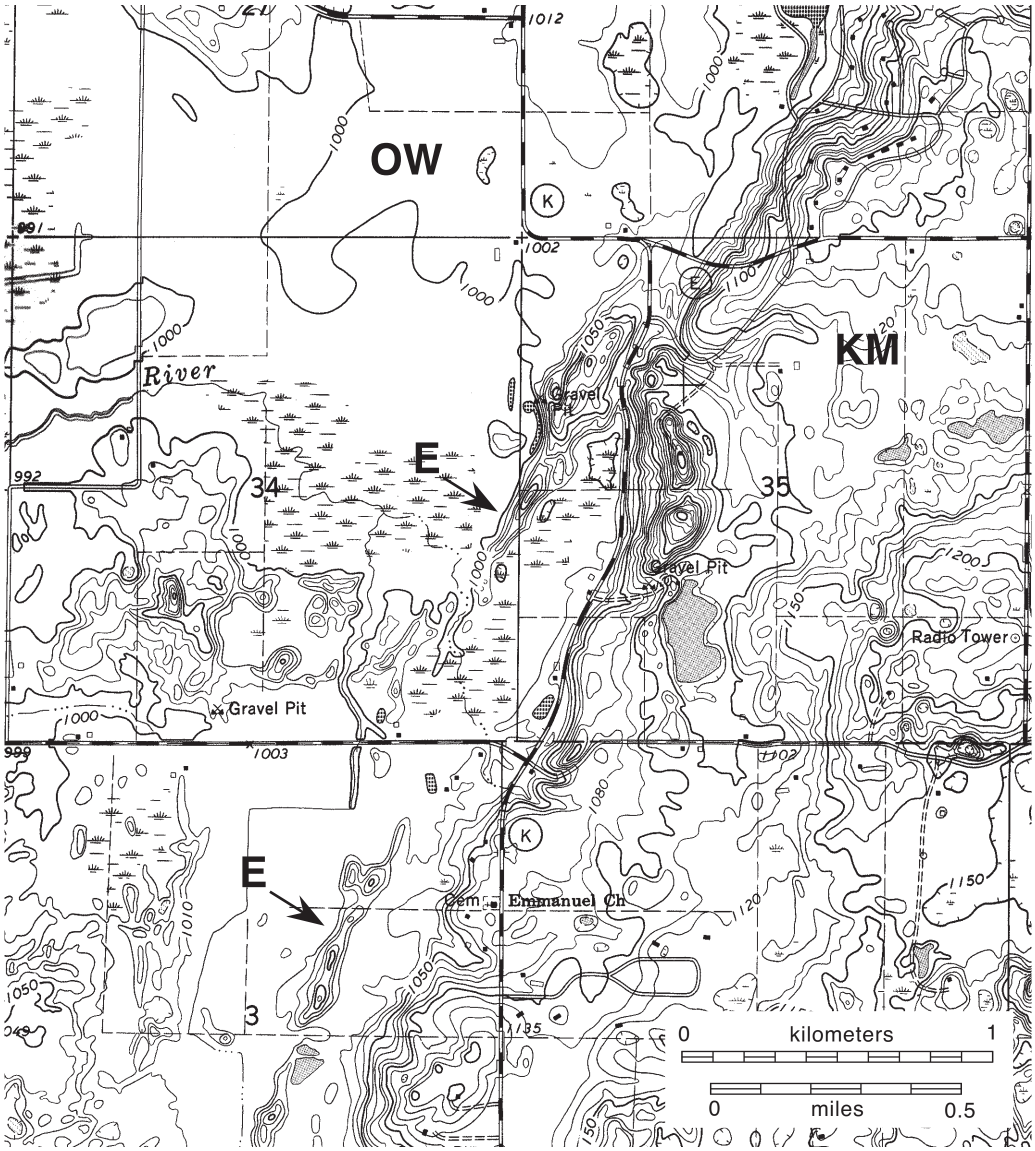


Figure 16. *Part of Hartford East Quadrangle, Wisconsin (U.S. Geological Survey, 7.5-minute series, topographic, 1976), showing the steep western front of the Kettle Moraine (KM). Esker (E) crosses outwash plain (OW), T9 and 10N, R19E.*

The most prevalent landscape type in the Kettle Moraine is hummocky sand and gravel (map unit **Ugh**, plate 1). This stream sediment was deposited on nearly continuous masses of stagnant ice. As the underlying ice melted, the sediment collapsed and completely destroyed the original depositional surface. Many of the highest parts of the Kettle Moraine are made up of sand and gravel hummocks.

Pitted outwash plains, flat to gently rolling surfaces interrupted by numerous kettles, also are common in the Kettle Moraine (map unit **Ugpp**, plate 1). They were deposited in the narrow corridor between the Green Bay and Lake Michigan Lobes. Many meltwater streams flowed through the interlobate trough close to or over stagnant ice. This ice was buried by sand and gravel, which

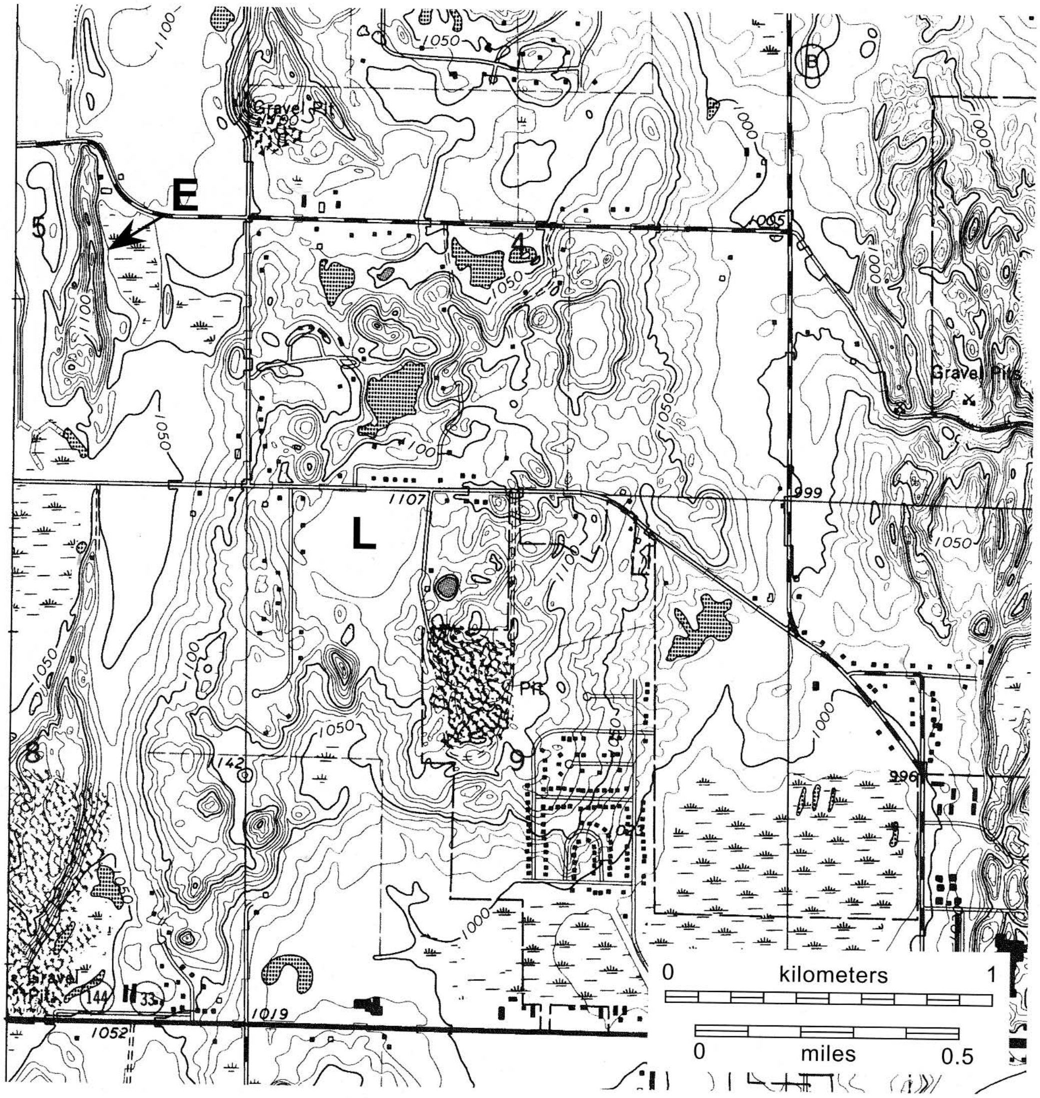


Figure 17. *Part of West Bend Quadrangle, Wisconsin (U.S. Geological Survey, 7.5-minute series, topographic, 1974), showing esker (E) and ice-walled-lake plain (L).*

later collapsed, but parts of the original depositional surface were preserved. Relatively uncollapsed outwash surfaces are present in places on either side of the Kettle Moraine, but they are uncommon in the Kettle Moraine itself, except for farther south in Waukesha and Walworth Counties (Clayton, in press).

Syverson (1988) suggested that the changes in Kettle Moraine landforms from south to north are a function of where and how long meltwater flowed through the interlobate corridor. Because ice flow was converging toward the interlobate zone from the east and west, meltwater also moved toward the interlobate zone. Apparently, water was confined in the interlobate corridor to the south (Walworth and southern Waukesha Counties) for a long time, but it did not flow over much stagnant ice. Instead, outwash with relatively few kettles filled much of the interlobate area. This outwash buried most of the eskers and other subglacial landforms deposited earlier.

During deglaciation of the northern Kettle Moraine region (Fond du Lac, Sheboygan, and northern Washington

Counties), meltwater also deposited stratified sand and gravel in the interlobate region. However, lower pathways for water flow quickly became available on either side of the Kettle Moraine, and thick outwash did not accumulate in the interlobate zone. Eskers deposited beneath the ice were not obscured by outwash deposited at the ice surface as the ice melted. The result: Eskers, moulin kames, and hummocks are more common features in the northern Kettle Moraine landscape than they are farther south.

Landforms associated with New Berlin Member

When the margin of the glacier was retreating from the Kettle Moraine, diamicton was being deposited by westerly flowing ice in the area between the Lake Michigan basin and the edge of the present-day Kettle Moraine. The landforms in this area are the same age as, and quite similar to, landforms in the area covered by the Horicon Member west of the Kettle Moraine. The New Berlin deposits are covered by younger deposits in all of Ozaukee County and much of eastern Washington County (figs. 3 and 5; map-unit identifiers starting with **W**, **O**, and **Z**, plates 1 and 2).

Drumlins are common features in this area (fig. 5). They are oriented east–west, and in some places, somewhat east–southeast to west–northwest. Most of the drumlins underlying younger deposits to the east were probably formed by the New Berlin advance and simply overridden by younger ice advances (map-unit identifiers starting with **W**, **O**, and **Z**, plates 1 and 2). Drumlins containing sediment of the New Berlin Member are located in the northeastern part of Washington County and northwestern part of Ozaukee County in the area mapped as diamicton of the Waubeka Member. In many places, diamicton of the Waubeka Member was not deposited or was eroded so that New Berlin till is at the surface.

Exposures in the drumlins are few, but one excellent exposure in Newburg shows sand and gravel of the New Berlin Member composing most of the core of the drumlin (fig. 18). Some sand and gravel in this drumlin has been cemented by groundwater moving through the sediment and precipitating calcium carbonate. Gravel probably is common in the cores of many other drumlins as well because it is farther south in western Milwaukee and eastern Waukesha Counties. Many Lake Michigan Lobe drumlins have a thin layer of till over the gravel (for example, the drumlin at Newburg). Sand and gravel in some drumlin cores is a potential aggregate resource that could be tapped in addition to the obvious gravel in outwash plains.

The glacier that deposited diamicton of the New Berlin Member in southern Washington County also appears to have overridden an extensive outwash plain. In several large gravel pits, sand and gravel is exposed beneath diamicton of the New Berlin Member. Drumlins were cut into this surface, and intrusions of the older diamicton of the Tiskilwa Member extend upward into the sand and gravel as they do in drumlins in Waukesha County, described by Whittecar (1976), Whittecar and Mickelson (1977, 1979), and Stanford and Mickelson (1985). Syverson (1988) described similar sediment-deformation structures at the Jacklin Construction Company pit in Hubertus. It is possible that these structures represent an early stage in the formation of a drumlin.

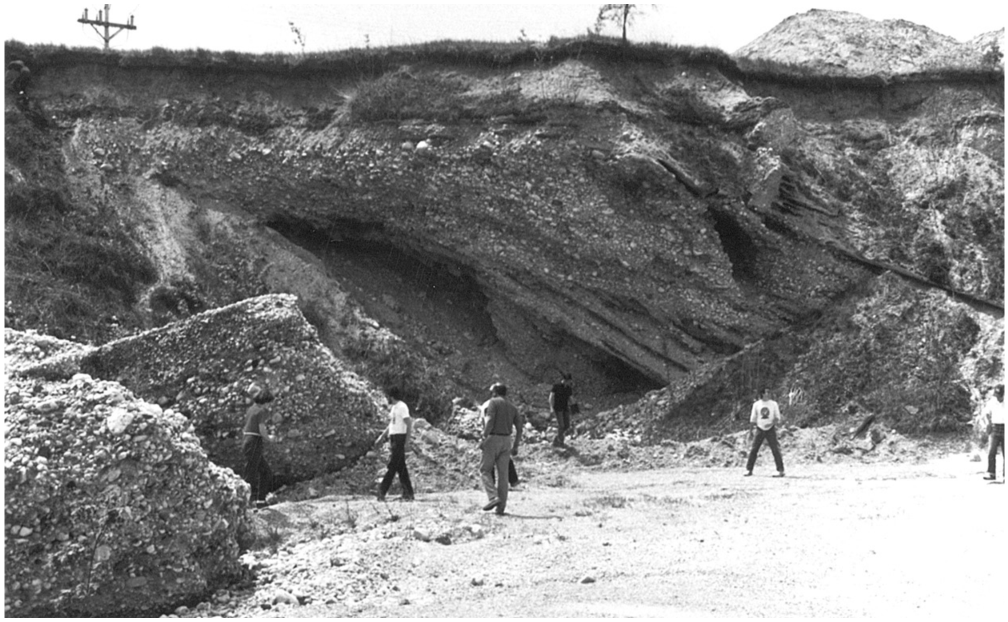


Figure 18. *Photograph of cemented (far left) and uncemented New Berlin gravel in drumlin core beneath till of the Waubeka Member near Newburg, Washington County, NW1/4 SW1/4 SE1/4 sec. 12, T11N, R20E.*

Flowing water played an important role in landscape development as the glacier margin retreated. Hummocky, pitted, and unpitted meltwater-stream sediment is widespread between Germantown and the Kettle Moraine (map units **Ngp**, **Ngpp**, and **Ngh**, plate 1). Two large channels, the Friess channel (fig. 19) and the Bark channel (fig. 20), carried water toward the southwest across the diamicton and gravel surfaces of southern Washington County. Syverson (1988) and Syverson and Mickelson (1989) considered several possibilities for the formation of these large channels. The channels may have formed initially as proglacial channels during ice advance, but it is also possible that they formed subglacially as tunnel channels. Clearly, ice was still buried beneath parts of the channels when they were last occupied by water because hummocky sand and gravel lies in the bottoms of both channels.

The Friess channel may have formed as the outlet of one of the phases of glacial Lake Farmington. As ice retreated, drainage was blocked between the retreating ice edge and the Kettle Moraine to the west. A large lake, glacial Lake Farmington, formed as soon as ice pulled away from the Kettle Moraine west of Jackson. As ice continued to retreat, glacial Lake Farmington expanded, probably eastward to the vicinity of Newburg and northward into Sheboygan County. Because nearly all of this area was covered by a later phase of glacial Lake Farmington and by ice of the Waubeka advance, no details of the extent and history of this early lake are known. It appears that the Bark channel is too high in elevation to have been cut by meltwater from this or later advances unless the Menomonee River was blocked, which seems unlikely.

Landforms associated with Waubeka Member

After the ice margin retreated along and away from the Kettle Moraine in northern Washington County, the Washington–

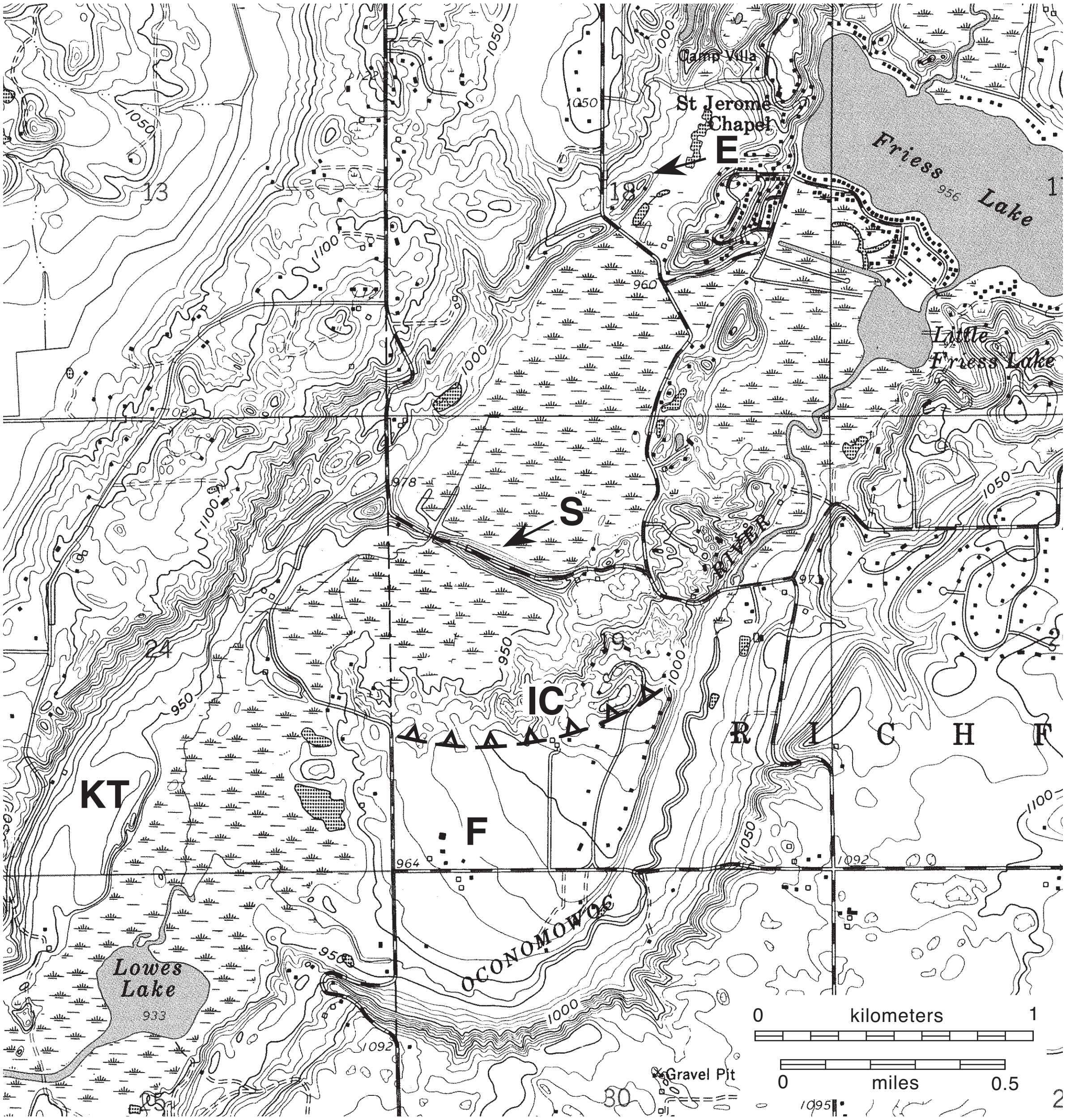


Figure 19. *Part of Merton Quadrangle, Wisconsin (U.S. Geological Survey, 7.5-minute series, topographic, 1994), showing the Friess channel with ice-contact face (IC), ice-contact fan (F), ice-walled stream deposit (S), esker (E), and kame terrace (KT), T9N, R18 and 19E.*

Ozaukee area was probably ice-free for only a short time. An ice advance from the northeast into the two-county area deposited diamicton of the Waubeka Member. Because the regional slope of the land surface is eastward from the Kettle Moraine to Lake Michigan, ice advancing up this slope tended to dam lakes in front of the ice margin, resulting in deposits of sand and gravel and finer lake sediment. This is particularly true of the Milwaukee River drainage, which was dammed a few kilometers east of West Bend along the Waubeka ice margin.

Diamicton of the Waubeka Member is fairly thin, and apparently this advance did little to modify the drumlin terrain produced by the earlier New Berlin advance. A small end moraine parallel to and just north of Highway 41 marks the maximum southwestern position of this ice advance in Ozaukee and Washington Counties (fig. 21; plate 1). The moraine is narrow (only 200 or 300 m wide), fairly low (10 m high), and composed of Waubeka diamicton, where sampled. Meltwater from this ice margin flowed southeastward, parallel to the ice margin and then southward through the Menomonee River drainage (fig. 21).

Farther north, the ice margin terminated in an extensive lake, the last phase of glacial Lake Farmington. This lake extended from the vicinity of Jackson northward into Sheboygan County as ice advanced and water was dammed between the Kettle Moraine and the ice. Lake deposits (map units **Wip** and **Wih**, plate 1) indicate that the lake abutted an ice margin that did not build an end moraine. Numerous eskers are present east of this margin position in the area southwest of Newburg (fig. 22). Lake sediment is present as high as 330 m above sea level. The highest lake outlet was along a series of what are now out-

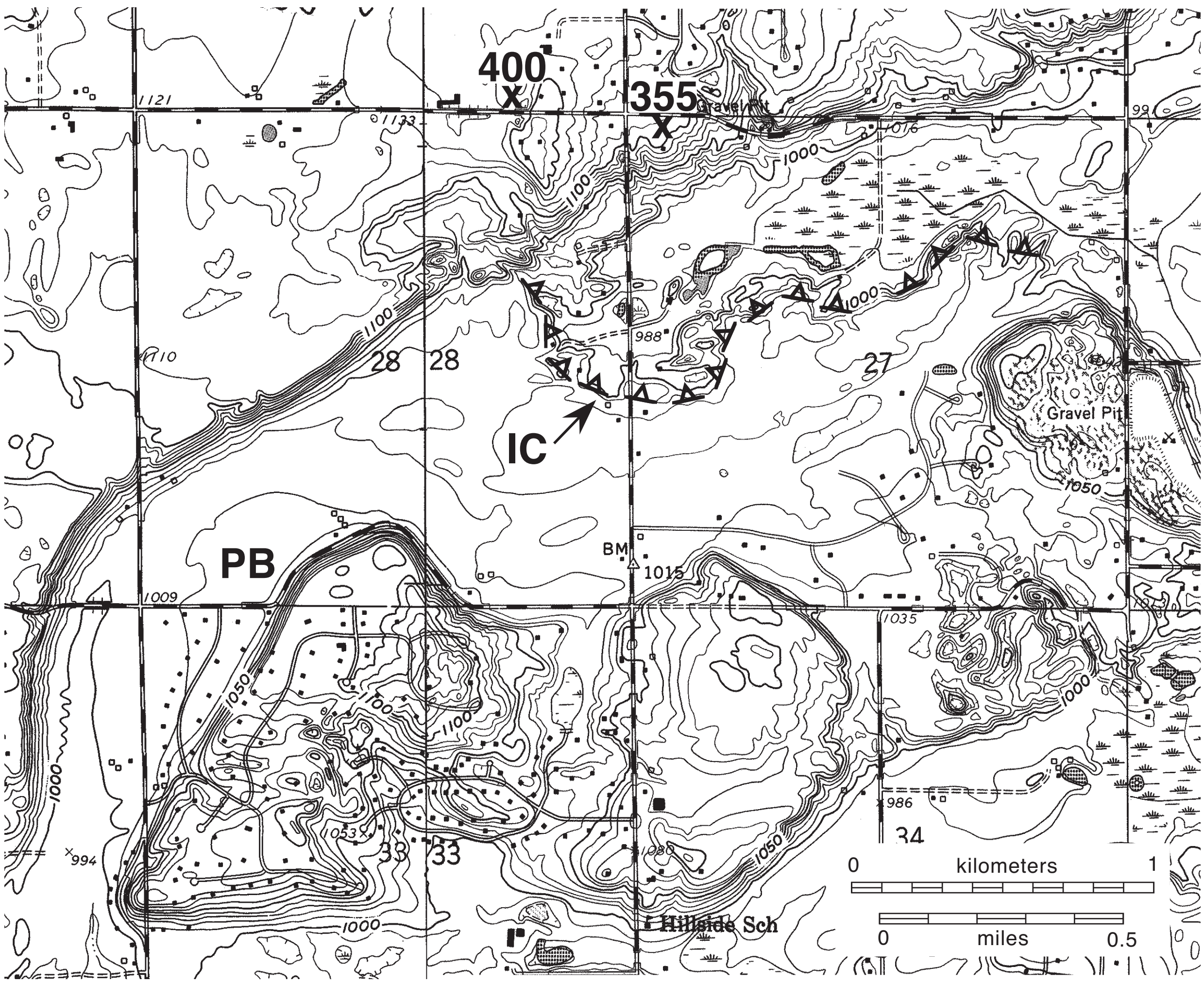


Figure 20. *Part of Merton and Sussex Quadrangles, Wisconsin (U.S. Geological Survey, 7.5-minute series, topographic, 1994), showing the Bark channel system (T9N, R19E), point bar (PB), and ice-contact face (IC). Depth to bedrock (x) shown in feet.*

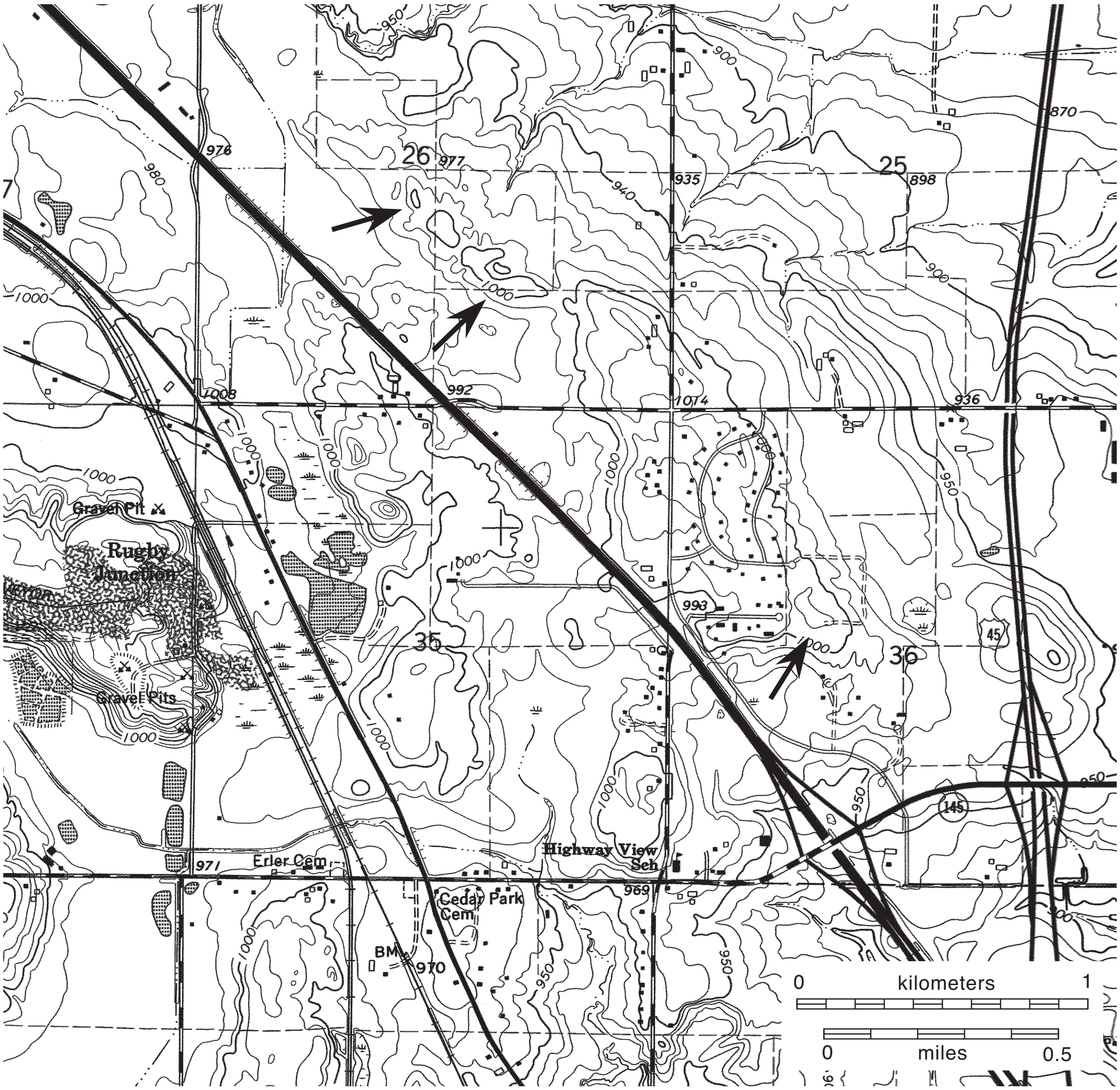


Figure 21. *Part of Jackson Quadrangle, Wisconsin (U.S. Geological Survey, 7.5-minute series, topographic, 1994), showing the moraine built during the Waubeka advance, T10N, R19E.*

wash terraces about 4 km west of Jackson (map unit **Wsp**, plate 1) and, as suggested earlier, this water may have flowed down the Friess channel. Evidence for catastrophic drainage of any phase of glacial Lake Farmington is lacking. Most deposits associated with this outlet are collapsed, suggesting that New Berlin ice had not melted completely before the Waubeka advance. A fairly extensive lake must have remained in the basin east and northeast of West Bend until the ice had retreated east of Waubeka, where ice-marginal drainage to the south allowed the lake to empty. Part of this area is now covered by deposits of younger advances, and much of the lake sediment is collapsed, destroying evidence for this lake outlet.

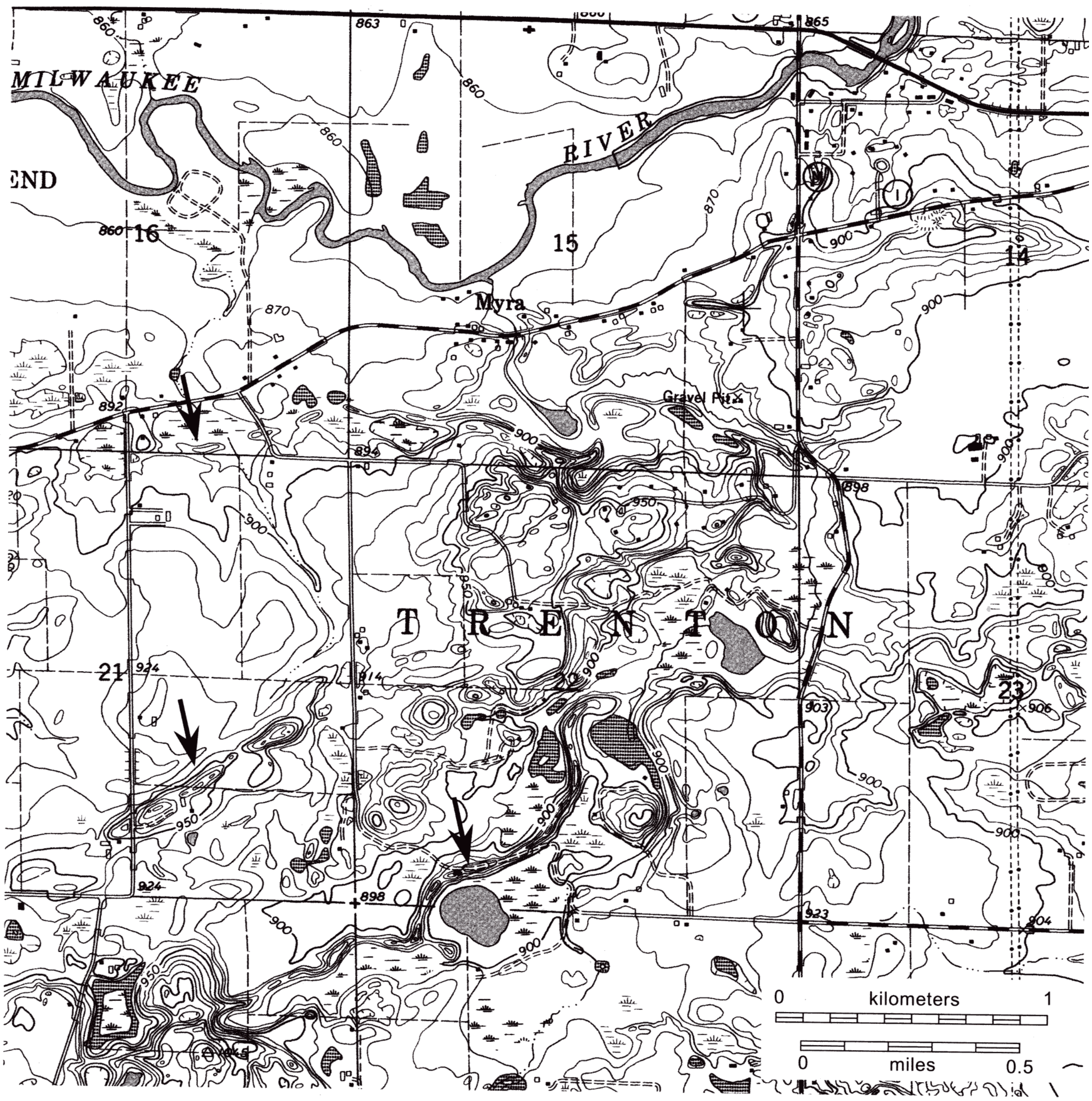


Figure 22. *Part of Newburg Quadrangle, Wisconsin (U.S. Geological Survey, 7.5-minute series, topographic, 1994), showing eskers (arrows) and disintegration ridges near western extent of the Waubeka advance, T11N, R20E.*

Landforms associated with Oak Creek Formation

The Lake Michigan Lobe deposited diamicton of the Oak Creek Formation during a series of advances that terminated near the south end of present-day Lake Michigan. It appears that during some of those advances, the glacier expanded farther out of the basin in Racine and Kenosha Counties than it did in Ozaukee County.

The advance to the Oak Creek margin (plates 1 and 2) produced a small end-moraine ridge from Germantown northward to the vicinity of Cedarburg Bog. Subsequent advances built small southwest–northeast trending moraines from there eastward to the Milwaukee River. The landscape in this area is complex because northeast–southwest trending bedrock ridges also are present. Many of these higher ridges were accented by marginal drainage along the ice front of the Lake Michigan Lobe as it retreated into Lake Michigan and readvanced in Ozaukee County several times. End moraines are several hundred meters wide and up to 30 m high. Only continuous ridges of hummocky topography were mapped as end moraines on plate 1 (map unit **Othe**), even though patches of hummocky till (map unit **Oth**) are on some of the uplands. It seems likely that many of these patches are not moraines, but were isolated by ice-marginal drainage.

It appears that no drumlins or other glacial landforms, with the exception of moraines, formed during the Oak Creek advances. Some terraces along the outwash valleys formed as water flowed southward, parallel to the ice margin, as the ice retreated in central and eastern Ozaukee County.

Landforms associated with Ozaukee Member

The most recent ice advance into Ozaukee County produced massive end moraines that run more or less north–south from the Sheboygan County line to the Milwaukee County line (map unit **Zthe**, plate 1) (Acomb, 1978; Acomb and others, 1982). The moraines produced by this advance have a north–south orientation and are characterized by low-relief hummocky topography.

Ice-marginal drainage flowing from north to south along several former ice-margin positions is marked by sand and gravel outwash or lake deposits between diamicton ridges (for example, Sauk Creek, Sucker Creek, and part of the Milwaukee River). When ice advanced to deposit diamicton of the Ozaukee Member, Lake Michigan was at a higher level than present. In northeastern Ozaukee County, several levels in the landscape indicate the existence of flat or gently rolling lake terrace surfaces (fig. 23), some of which were overrun by the Ozaukee advance. These terraces were formed by wave action at times when the lake was higher than it is now. High terraces cut before the Ozaukee advance are now covered with diamicton of the Ozaukee Member. Younger terraces were cut into the diamicton and are covered by sand deposits.

LATE PLEISTOCENE AND HOLOCENE HISTORY

Each glacial advance in eastern Wisconsin left its own unique “footprint”—a characteristic set of deposits that can be correlated from one place to another. This allows us to piece together the glacial history of the region. No radiocarbon dates exist for early advances into Washington or Ozaukee County, and very few dates exist for the younger events. Ages for events described in this report are those of Clayton and Moran (1982), Mickelson and others (1983), and Hansel and others (1985). A series of diagrammatic sketches in figure 24 shows major events in Ozaukee and Washington Counties during deglaciation.

Early advances of ice

The earliest glacial event recognized in the area is the advance of the Lake Michigan Lobe that deposited diamicton of the Tiskilwa Member of the Zenda Formation. This advance reached at least as far west as Allenton and Hubertus in Washington County. Diamicton of this

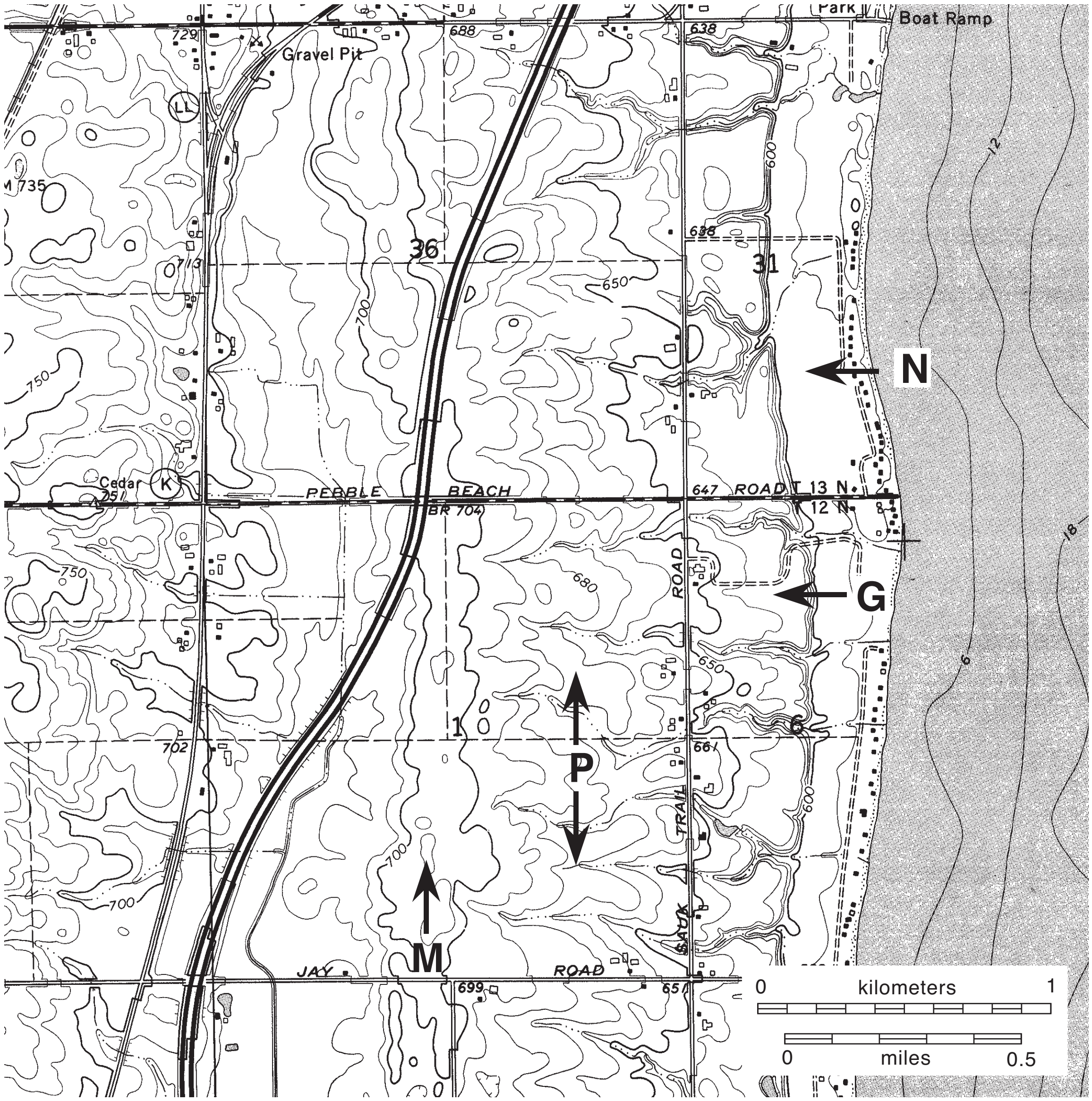
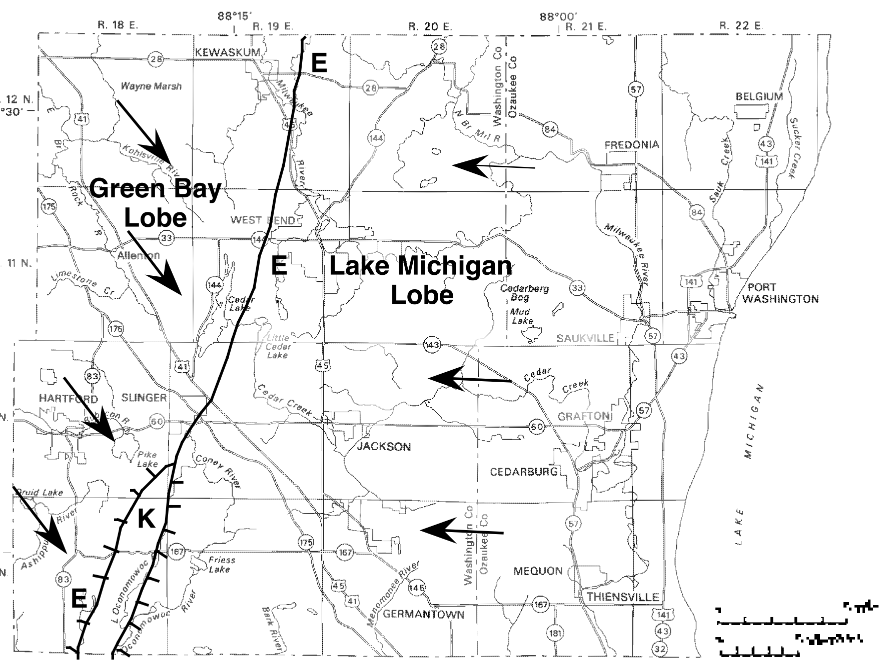


Figure 23. *Part of Cedar Grove Quadrangle, Wisconsin (U.S. Geological Survey, 7.5-minute series, topographic, 1974), showing wave-cut terraces on Lake Michigan shoreline (T12N, R23E). M is moraine crest, P is likely a palimpsest (till-covered) wave-cut terrace, G is Glenwood shore terrace and N is Nipissing shore terrace.*

unit has been encountered in only three excavations in the two-county area, so little can be said about its extent in the subsurface. There are no radiocarbon dates anywhere in Wisconsin associated with this glacial advance. Dates from what is presumably the same unit in Illinois range from 25,000 to 20,000 years BP (Johnson, 1986), and there is no reason to think that the advance into Wisconsin was at a significantly different time. The Green Bay Lobe must have advanced at about the same time. This advance may have deposited a silty gray diamicton (informally named the Kekoskee Member by Battista, 1990, p. 65) below diamicton of the Horicon Member in eastern Dodge County. This unit probably exists in the subsurface of western Washington County, but we did not find evidence of it during this study.

The extent of glacier retreat after deposition of the Tiskilwa diamicton is unknown. Throughout most of the part of southeastern Wisconsin that was covered by the Lake Michigan Lobe, an extensive, thick, sandy gravel layer is present above the Tiskilwa diamicton and below diamicton of the younger New Berlin Member (plate 2). This nearly continuous gravel layer extends from at least the vicinity of Hubertus in Washington County to south of the Wisconsin–Illinois border. It may represent a long period with a stable ice-margin position across northern Washington and Ozaukee Counties, into the Lake Michigan basin, and across the basin to the state of Michigan. This gravel may have been deposited by outwash streams for several thousand years before ice readvanced westward to its maximum position at the Kettle Moraine and southward into Illinois. This gravel was a source for sand and gravel particles that were incorporated into the ice and deposited as diamicton of the New Berlin Member.



Maps showing deglaciation history of Washington and Ozaukee Counties. In the following set of figures, arrows without shaft indicate meltwater-flow direction; arrows with shaft indicate ice-flow direction; hachures indicate ice-margin position.

Figure 24A. *The retreating ice margin enters Washington County about 15,000 BP. Ice thins throughout the area, and meltwater is concentrated in the interlobate trough. Sand and gravel is deposited on and adjacent to stagnant ice (later to become Kettle Moraine ridge). Subglacial streams (E) flow in northern Washington County; most drumlins and large moulin kames (region K) near Holy Hill have already formed.*

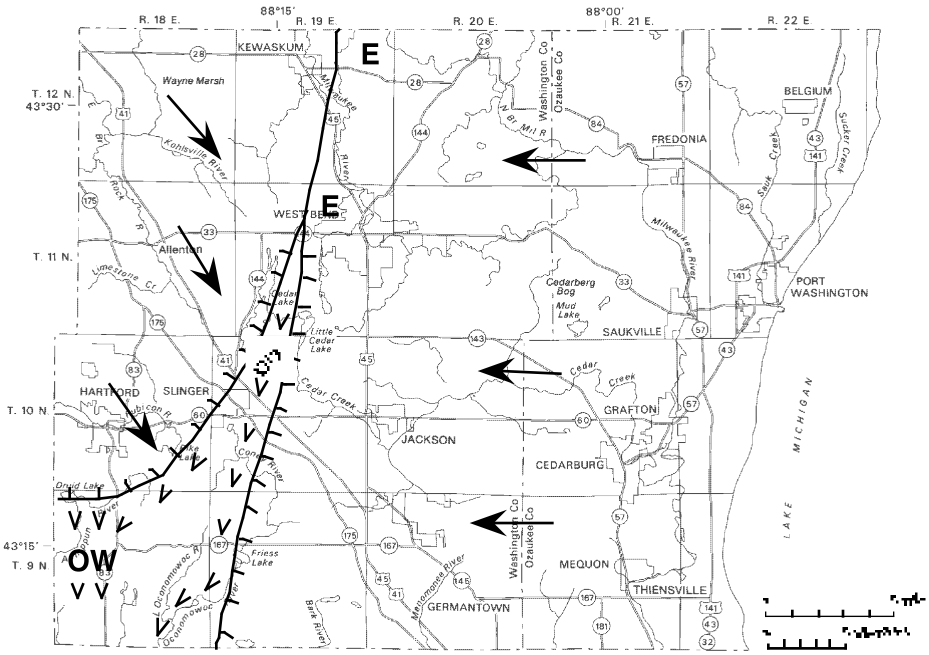


Figure 24B. *Probably within a few hundred years, the ice margin stabilizes south of present-day Pike Lake. Meltwater deposits outwash (OW) in southwestern Washington County and in the interlobate corridor. Subaerial streams use Friess channel. Eskers (E) form in northern Washington County.*

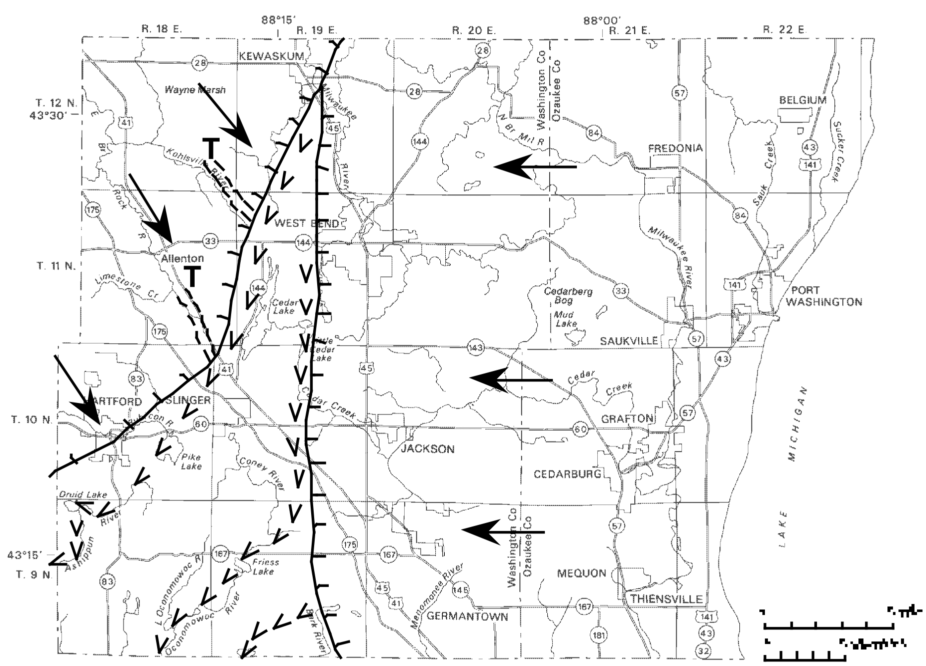


Figure 24C. *Ice continues to retreat and expose the Kettle Moraine area. Green Bay Lobe tunnel channels (T) form at this time, and meltwater flows southwestward along the Kettle Moraine and out via the Ashippun River.*

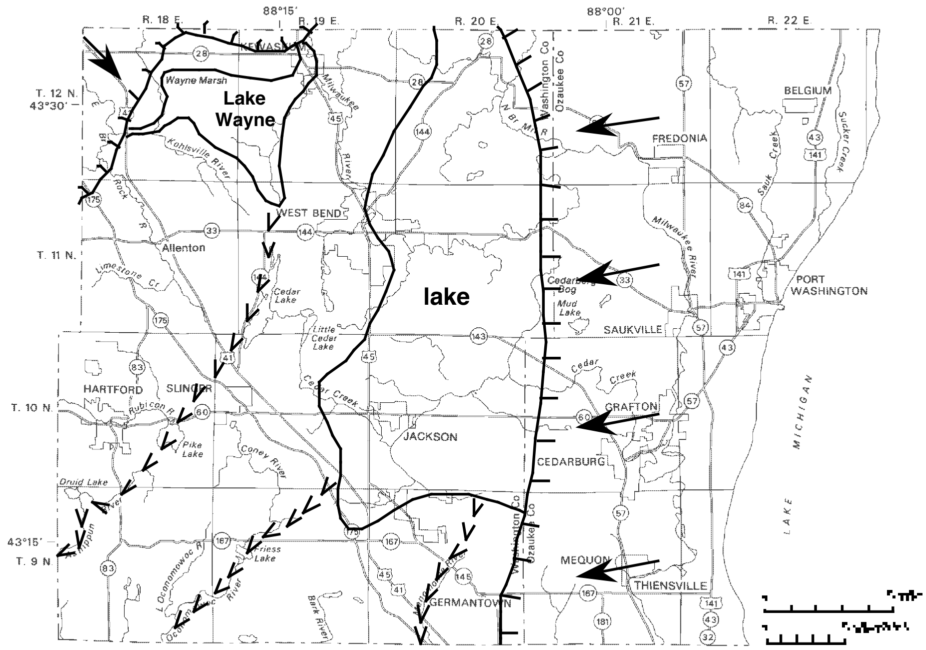


Figure 24D. *The interlobate corridor continues to extend north into Sheboygan County. Proglacial Lake Wayne forms west of the Kettle Moraine and drains southward via the Ashippun River. An early phase of Lake Farmington forms east of West Bend and drains first along the east edge of the Kettle Moraine, and then its level drops as water drains southward down the Menomonee River. The lake may drain completely as ice continues to retreat.*

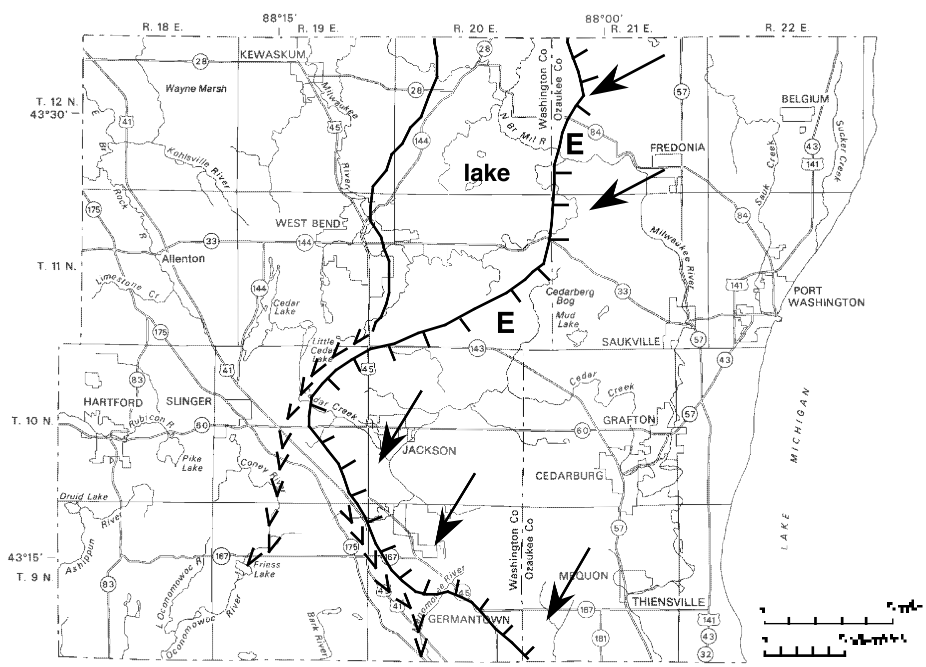


Figure 24E. *Ice then readvances from the northeast and deposits diamicton of the Waubeka Member. This later phase of Lake Farmington drains along the ice margin to the Friess channel. Eskers (E) form behind a calving margin that is releasing icebergs to the lake.*

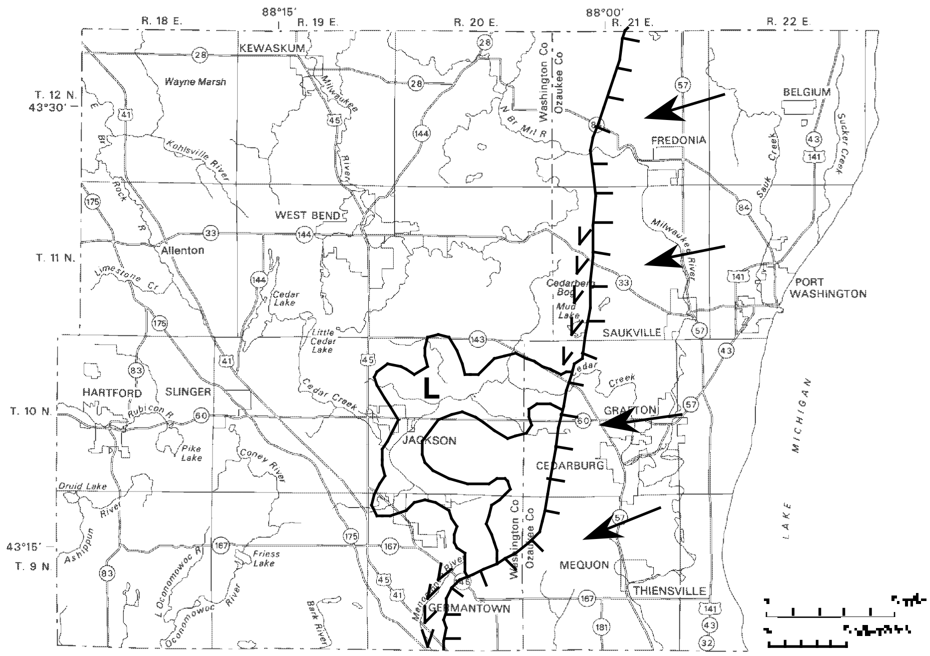


Figure 24F. *Several hundred years later, ice reaches another maximum position and deposits diamicton of the Oak Creek Formation. Lake Jackson (L) is dammed along the margin. It is not as deep or extensive as Lake Farmington during previous ice advances because lower outlets are available. Subsequent Oak Creek advances are not shown.*

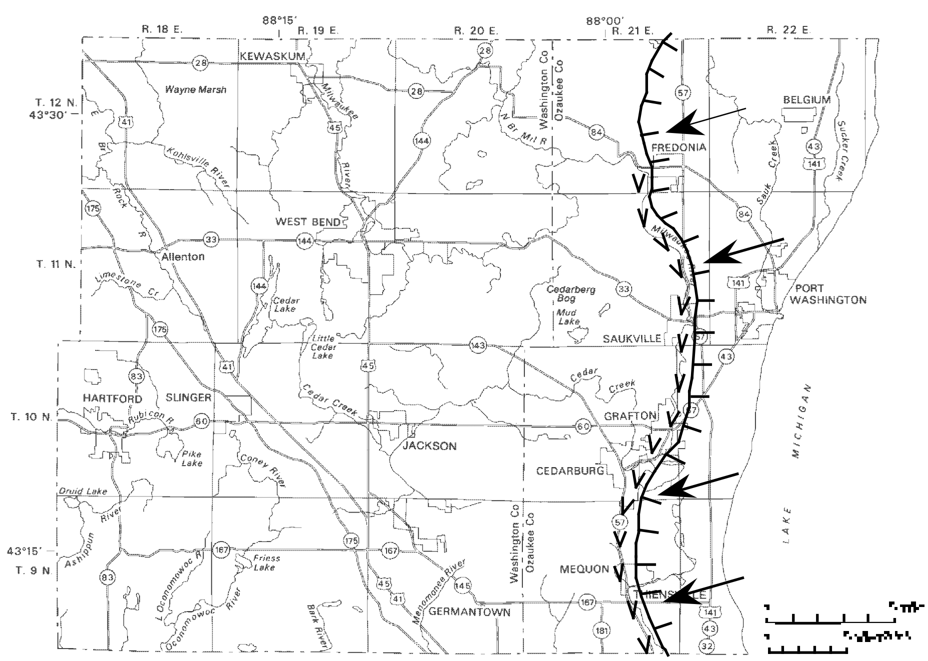


Figure 24G. *By about 13,000 B.P. ice advances from the northern end of Lake Michigan to the vicinity of Milwaukee and deposits diamicton of the Ozaukee Member. The southerly flowing Milwaukee River is an ice-marginal channel.*

The glacial maximum

Probably at about 18,500 BP the Green Bay and Lake Michigan Lobes advanced, depositing diamicton of the Horicon and New Berlin Members. Correlations suggest that ice reached its maximum thickness about 16,000 years ago and that the two-county area was completely covered by ice for 2,000 or 3,000 years. During this time the Green Bay and Lake Michigan Lobes reached their maximum extents in southern Wisconsin, and the area of the present-day Kettle Moraine was a low trough on the ice surface. Both lobes then retreated more or less synchronously until the ice margin had retreated northward into southern Washington County. Sand and gravel was deposited by meltwater streams flowing away from the glacier lobes during this retreat. The temperature was very cold at that time and the ground remained frozen constantly, a condition called permafrost. Ice-wedge polygons are permafrost features that formed on Horicon and New Berlin Member deposits. Syverson (1988) described these features in the Kettle Moraine of southern Washington County; locations of ice-wedge polygons are shown on plate 1.

Retreat from the interlobate zone

Figure 24A represents a time when the margins of the Green Bay and Lake Michigan Lobes were retreating in southern Washington County. Meltwater flowed away from the ice margins and then southwest down the axis of the interlobate zone. Presumably, by this time the large moulin kames or sinkhole kames in the Kettle Moraine had formed. Tunnels along the interlobate axis where eskers would later be deposited may have been forming at that time as well. We estimate that this was taking place about 15,000 years ago.

The ice continued to waste away until the margin of the Green Bay Lobe separated from the interlobate region south of present-day Pike Lake (fig. 24B). Outwash plains in the Kettle Moraine between West Bend and Pike Lake formed at that time. Meltwater flowed in subglacial tunnels in the Kewaskum area. Simultaneously, water from the Green Bay Lobe deposited extensive outwash in southwestern Washington County. Meltwater also began to flow through the ice-filled Friess channel as the Lake Michigan Lobe wasted away.

Much of the sediment in the Kettle Moraine was deposited on stagnant ice that could have remained for thousands of years after the active glaciers had retreated from Washington County. Ice filled what are now low areas in the Kettle Moraine and created a barrier to meltwater flow throughout the Kettle Moraine. For this reason, meltwater was channeled into the topographic lows on either side of the high, ice-cored Kettle Moraine as the interlobate corridor opened northward.

Rivers and lakes along the ice margin

Following formation of the outwash plain in southwestern Washington County, the Green Bay Lobe wasted back from the margin south of Pike Lake and an ice-marginal stream eroded a valley occupied by the Ashippun River (fig. 24C). Meltwater from the Green Bay Lobe flowed southwestward, adjacent to the Kettle Moraine, and formed a younger, lower outwash plain. The meltwater-stream sediment buried blocks of stagnant ice adjacent to the Kettle Moraine in the present-day Cedar Lake and Pike Lake areas. The Green Bay Lobe tunnel channels were carved at the same time. Ice blocking the Milwaukee River drainage system forced water to flow south along the east side of the Kettle Moraine. This meltwater deposited sediment that buried large blocks of ice abutting the Kettle Moraine to the east.

Eventually, the interlobate corridor extended northward into Sheboygan County (fig. 24D). Proglacial Lake Wayne was dammed against the ice as the Green Bay Lobe wasted northward beyond the Milwaukee River drainage divide and stagnant ice blocked the east branch of the Rock River (Syverson, 1988). Water discharged south into the Ashippun River system via an outlet north of Cedar Lake in sec. 8, T11N, R19E, at an elevation of 323 to 326 m.

Meltwater from the Lake Michigan Lobe and buried, melting ice in the Kettle Moraine was ponded east of West Bend several times. The present-day Milwaukee River flows to the east, and this drainage was dammed whenever ice occupied eastern Washington County (fig. 24D). As the New Berlin ice margin retreated, an early phase of glacial Lake Farmington developed east of West Bend and drained toward the southwest on surfaces that are now gravel terraces. When the ice margin reached the Germantown area, the lake level must have dropped as water used the lower Menomonee River outlet. The lake drained completely when retreating ice no longer blocked Cedar Creek and the Milwaukee River. Details about this early phase of Lake Farmington are unclear because they were masked by later events.

Ice advance from the northeast

The extent of Lake Michigan Lobe retreat after deposition of sediment of the New Berlin and Horicon Members is not known. It appears that the Green Bay Lobe did not readvance again into Washington County. However, along the shoreline of Ozaukee County south of Port Washington (plate 2) and in Milwaukee County, the New Berlin diamicton can be distinguished from the overlying Waubeka diamicton (stratigraphic sections, plate 1). Therefore, we conclude that the ice retreated at least into the lake basin before it readvanced to deposit sediment of the Waubeka Member. It seems unlikely that a great distance of retreat and readvance took place because the Waubeka diamicton is similar to the New Berlin diamicton, except that silt and clay, presumably from lake sediment, were incorporated into the sandy, gravelly diamicton and outwash of the New Berlin Member to produce diamicton of the Waubeka Member.

Ice of the Lake Michigan Lobe flowed from the northeast toward the southwest when it readvanced to deposit diamicton of the Waubeka Member, probably at about 14,000 to 14,500 BP, rather than directly from the east as it did when drumlins were formed in eastern Washington and western Ozaukee Counties (fig. 24E). Ice from this advance did little to obscure the orientation of the older drumlins, but a discontinuous blanket of diamicton up to a few meters thick was deposited over much of the landscape. The ice margin advanced to a position just north of Germantown (fig. 24E; plate 1) and the ice margin extended to the southeast at least to southern Milwaukee County. The extent of this diamicton farther to the east under Lake Michigan is not known.

The western limit of the Waubeka advance terminated in a later phase of Lake Farmington, which had been dammed by the ice. This large lake extended northward into Sheboygan County. It drained along the ice margin between Slinger and Jackson, and then probably into the Friess channel. The margin of the glacier was, at least for a time, a steep calving margin with many esker tunnels entering the lake at the base of the glacier. Many of these small eskers are present southwest of Newburg (fig. 24E). The margin of the ice then retreated far into the Lake Michigan basin.

It is not clear whether the ice margin continued to retreat out of the northern part of the Lake Michigan basin, but in all likelihood it did not. At that time, the level of Lake Michigan was about 20 m higher than it is today because the present-day outlet at the north end of Lake Michigan was blocked by ice and the lake drained through an outlet near what is now Chicago (Hansel and others, 1985; Hansel and Mickelson, 1988). The lake level would have dropped well below its present-day level if ice had retreated out of the Lake Michigan basin. Stream channels would then have been cut through diamicton of the New Berlin and Waubeka Members exposed at the shoreline before deposition of the younger Oak Creek diamicton. There is no evidence that this downcutting occurred along the shoreline of Ozaukee or Milwaukee Counties.

Rapid readvances of ice

A series of advances and retreats of the Lake Michigan Lobe took place shortly thereafter (probably between 14,000 and 13,300 years ago) (fig. 24F; plate 1). These rapid advances deposited the Oak Creek diamicton units in the southeastern corner of Washington County and southern Ozaukee County, as well as in Milwaukee, Racine, and Kenosha Counties to the south (Schneider, 1983). Cedar Creek was dammed by the ice, and glacial Lake Jackson formed in the vicinity of present-day Jackson. Glacial Lake Jackson had lower outlets than the older glacial Lake Farmington, so it was less extensive than Lake Farmington.

It appears that the most extensive Oak Creek advance into Ozaukee and Washington Counties may have been the Tinley or younger Lake Border advance. Material of the older Valparaiso advance, which was most extensive farther south in Racine and Kenosha Counties (Schneider, 1983), appears to be covered by younger deposits in Milwaukee County and farther north.

The advances associated with the Oak Creek diamicton were rapid, and it is possible that a surging glacier deposited these units. Only 1,000 years, or perhaps less, are available for at least four advances and retreats (Simpkins 1989; Brown, 1990). By about 13,000 BP, the glacier had retreated north of the Lake Michigan basin, and a low outlet through the Straits of Mackinac allowed drainage to the east. At that time, lake level dropped well below the present level. Tundra still covered much of the landscape, and ice evidently remained in the eastern part of the Lake Superior basin. At that time, water carrying red silt and clay from Lake Superior flowed into the Lake Michigan basin.

The subsequent readvance of the glacier incorporated this reddish-brown, fine-grained sediment and deposited diamicton of the Ozaukee Member along the Lake Michigan shoreline of Ozaukee County (fig. 24G; plate 1). This advance occurred about 13,000 BP and was confined mainly to the Lake Michigan basin, coming only a few kilometers onto land. At that time, much of the north–south segment of the Milwaukee River valley was deeply incised by a large ice-marginal river that flowed along the western edge of the glacier. Diamicton of the Ozaukee advance extends southward along the Lake Michigan shoreline as far south as St. Francis in Milwaukee County. From there the ice margin crossed the lake to the state of Michigan.

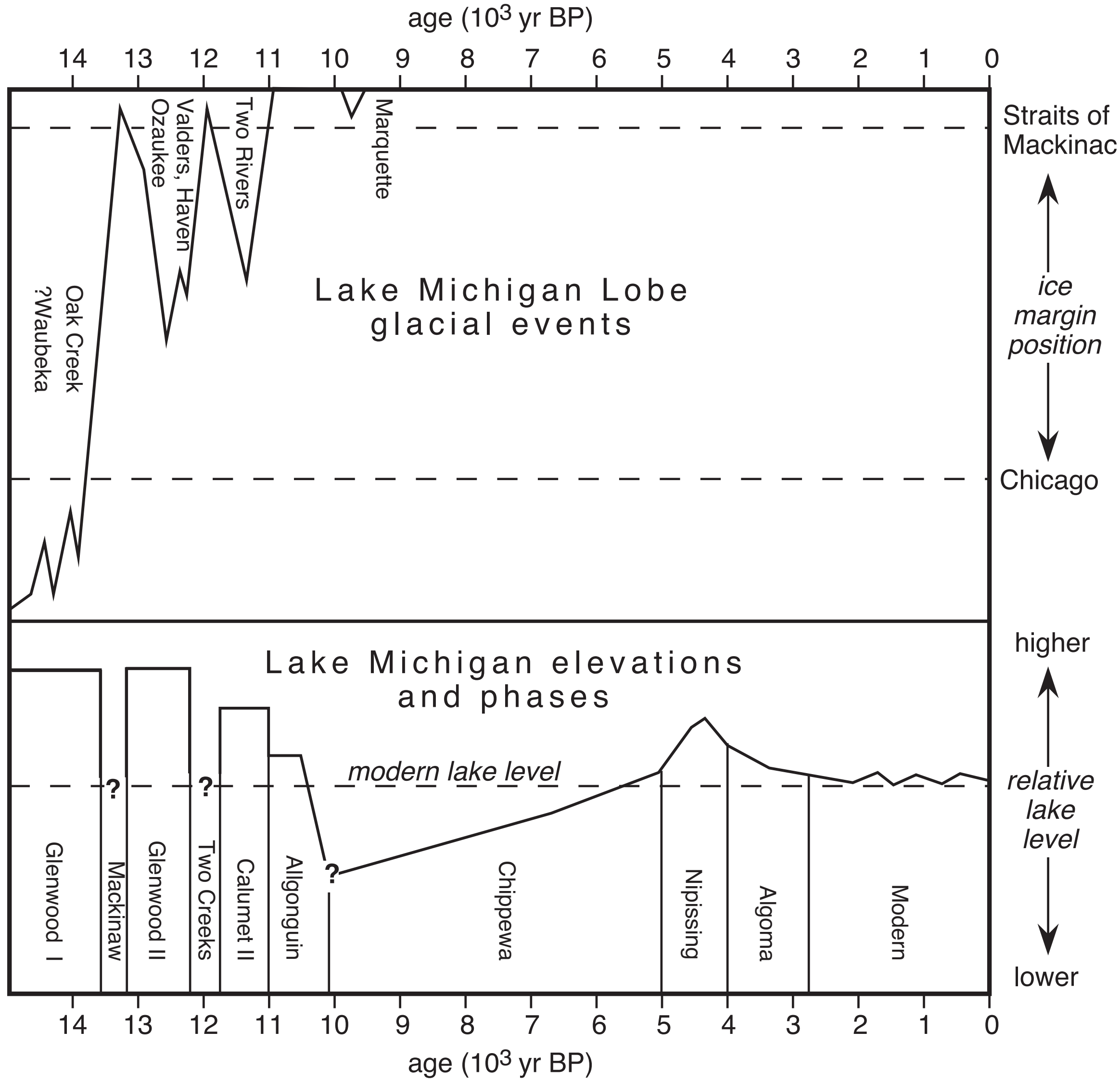


Figure 25. *Time-distance diagram illustrating relationships of lake phases and glacial advances (modified from Hansel and Mickelson, 1988).*

The final retreat

A glacier never again entered Washington or Ozaukee Counties after the ice margin retreated following deposition of sediment of the Ozaukee Member. Several later advances, however, deposited reddish-brown diamicton in Sheboygan, Manitowoc, and other counties to the north (Acomb and others, 1982). It was not until about 11,000 BP that ice melted out of the Lake Michigan basin for the last time. The lake level dropped dramatically (probably almost 100 m) when this occurred, and a large expanse of lake bottom was exposed to erosion (fig. 25). The northern outlet of Lake Michigan then rebounded slowly during the Holocene Epoch (10,000 BP to present, fig. 1) as the weight of the glacier was removed. The rise in the outlet elevation caused a rise in lake level, and it appears that the lake returned to more or less its present level by about 5,000 years ago (Hansel and Mickelson, 1988). It then continued to rise above its present level and cut low terraces with an elevation of about 184 m along much of the Lake Michigan shoreline during the Nipissing phase (fig. 25). These wave-eroded terraces have a thin cover of sand over the diamicton or whatever sediment happened to be at an elevation of 184 m, where the erosion took place. Lake level has slowly dropped from the 184-m level to the present level of 177 m since that time.

One of the most active postglacial geologic processes in the area is shoreline erosion. Presumably, erosion took place during the entire time that water levels were rising and falling while the lake was above its present level. For thousands of years lakeshore erosion has continued, and many of the terraces that were formed during the higher lake levels of the Nipissing and older lake phases have been removed. Remnants of these terraces, however, are preserved along much of the Ozaukee County shoreline north of Port Washington (fig. 23; plate 1). This natural process of shoreline erosion will continue in the future as lake-level fluctuations produced by changes in precipitation erode the base of bluffs by wave action.

SUMMARY

Glaciers advanced into Ozaukee and Washington Counties numerous times during the last 1.6 million years. Only evidence of the most recent advances remains because deposits of many of the earlier advances have been eroded. The earliest recorded advance into the two-county area was that of the Lake Michigan Lobe when it deposited diamicton of the Tiskilwa Member as early as 20,000 years ago. This reddish-brown silty diamicton extends at least as far west as Allenton and Hubertus, and may be correlative with a gray silty diamicton found in Dodge County that was deposited by the Green Bay Lobe.

The major glacial event to affect the counties was the advance of the Green Bay and the Lake Michigan Lobes about 18,500 years ago. At that time, thick ice covered all of Washington and Ozaukee Counties, and the sandy diamicton of the Horicon and New Berlin Members was deposited in drumlins and rolling land surfaces. Meltwater gathering in the interlobate trough deposited large amounts of sand and gravel in contact with stagnant ice. The stagnant ice later melted to produce the hummocky Kettle Moraine. In addition, streams flowing in subglacial tunnels deposited sand and gravel now found in eskers. These eskers form much of the Kettle Moraine topography north of Kewaskum.

Subsequent readvances of the Green Bay Lobe did not reach Washington County. However, the Lake Michigan Lobe readvanced toward the southwest out of the lake basin and deposited diamicton and sand and gravel of the Waubeka Member. This advance did little to modify the underlying landscape; however, a small end moraine, numerous eskers, and extensive lake sediment were deposited.

A series of later advances deposited the gray clayey diamicton of the Oak Creek Formation between about 14,500 and 13,000 years ago. The final ice advance into Ozaukee County deposited diamicton of the Ozaukee Member in eastern Ozaukee County. This reddish-brown clayey diamicton covers the land surface in a strip several kilometers wide adjacent to the shoreline, and it is the uppermost material along most of the Lake Michigan bluff.

Subsequent fluctuations of the level of Lake Michigan have produced wave-cut terraces that are still preserved north of Port Washington. South of Port Washington, any lake terraces that did form have been removed by more recent wave erosion, and the bluffs themselves are being eroded.

ACKNOWLEDGMENTS

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APPENDIX: FORMAL DEFINITION OF NEW LITHOSTRATIGRAPHIC UNITS

Holy Hill Formation

Kent M. Syverson and David M. Mickelson

Source of name. Large hill with a church at the crest of the Kettle Moraine in southern Washington County, Wisconsin, sec. 14, T9N, R18E.

Location of type section. Exposures in pit at Slinger Speedway, Slinger, Wisconsin. Located north of Highway AA, approximately 2 km north–northeast of the junction of Highways 60 and 144 in the SE1/4 SW1/4 SW1/4 sec. 8, T10N, R19E, Washington County; Hartford East Quadrangle, Wisconsin (U.S. Geological Survey, 7.5-minute series, topographic, 1971; fig. A1). Fresh exposures are located in fenced area east of the raceway.

Description of type section. The gravel pit is located in a high relief, hummocky area within the Kettle Moraine. The north-facing exposure contains brown sandy silt, sand, and sandy gravel. Bedding is overturned in places. The 15-m high south-facing exposure contains steeply dipping sediment, first described by Syverson (1988). Light yellowish-brown gravelly diamicton is interbedded with poorly to moderately well sorted gravel, sandy gravel, and gravelly sand. Sandy and gravelly beds weather faster than the cohesive diamicton beds, causing a ribbed or pillared appearance in the outcrop. Most beds dip to the east at a 65^{o} angle, but in the western part of the outcrop, beds of diamicton and sandy gravel are nearly vertical and overturned. This may have been caused by pushing of ice or intrusion of a diapir from below.

Most clasts in the sediment are dolomite, although numerous Precambrian granite, gabbro, and gneiss boulders are present. Precambrian boulders are abundant near the crest of the hill. Large Precambrian rocks of this type are far-traveled (greater than 300 km) and generally associated with supraglacial sediment in southeastern Wisconsin. Clasts range from well rounded to angular, and striated clasts are especially abundant in diamicton beds.

Location of reference sections. The type sections for members of this formation serve as reference sections for this unit.

Description of unit. The Holy Hill Formation includes till and associated lake and stream sediment. The till is generally yellowish brown to brown (10YR–7.5YR), or less commonly, reddish brown (5YR), sandy, and contains abundant carbonate where unleached. Sand content varies considerably and generally ranges from 50 to 80 percent. Till is finer grained (21–42% sand) where it overlies shale of the Maquoketa Formation in the Green Bay lowland (Battista, 1990). Gravel up to 12 m thick forms the basal unit of the Holy Hill Formation east of the Kettle Moraine from southern Sheboygan County to Walworth County. Details about pebble lithology, clay mineralogy, and grain size are presented in the member descriptions.

Nature of contacts. This formation is the surficial unit in much of south-central and southeastern Wisconsin, including the Kettle Moraine region. West of the Kettle Moraine, the formation lies directly on bedrock, on pink diamicton of unknown

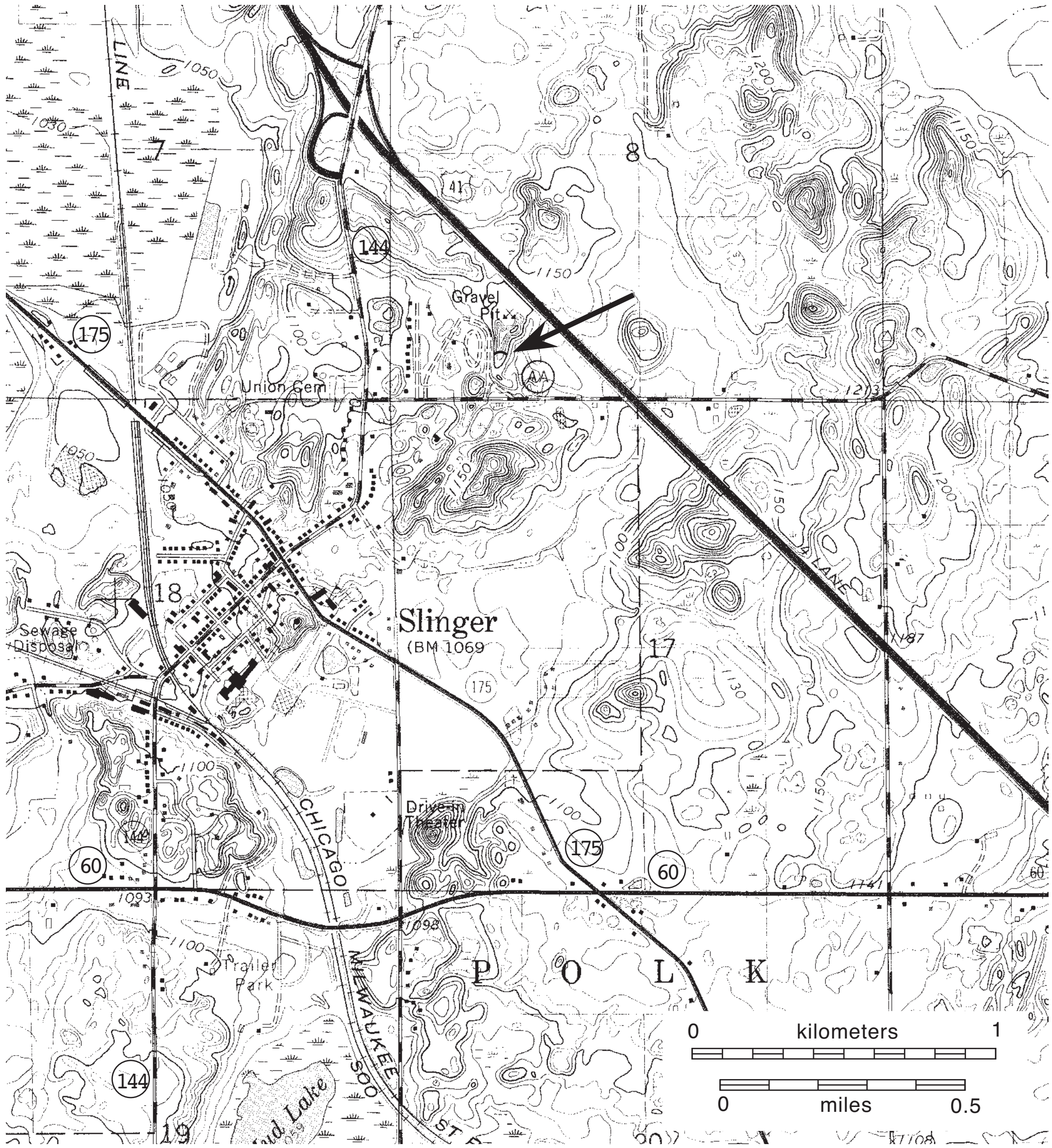

Figure A1. *Part of the Hartford East Quadrangle, Wisconsin (U.S. Geological Survey, 7.5-minute series, topographic, 1971), showing location of type section for Holy Hill Formation.*

origin, or on sand and gravel with a sharp contact. In northeastern and eastern Wisconsin, Holy Hill till is overlain by reddish-brown, finer-grained till of the Kewaunee Formation. East of the Kettle Moraine and south of Port Washington, the till is underlain by till of the Tiskilwa Member of the Zenda Formation and overlain by diamicton of the Oak Creek Formation. These contacts are generally sharp, although silt and sand beds between these units remain undifferentiated.

Differentiation from other units. Till of the Holy Hill Formation is distinguished in the field easily by its yellowish-brown to brown color, abundant pebbles, sandy texture, and abundant carbonate. The till is generally stonier, less silty, and lighter in color than the older Tiskilwa Member of the Zenda Formation. The till is much stonier and less clayey than the younger diamicton of the Oak Creek Formation. The younger Kewaunee Formation to the north is much redder (2.5YR or 5YR) and finer grained than the Holy Hill till.

Regional extent and thickness. The Holy Hill Formation is the surficial unit throughout much of south-central and southeastern Wisconsin. It can be traced in the subsurface to the Lake Michigan shoreline in Ozaukee and Milwaukee Counties. The Holy Hill Formation is at least 100 m thick in parts of the Kettle Moraine. West of the Kettle Moraine, the formation ranges from less than 1 m thick along the Niagaran Escarpment to greater than 100 m thick in buried valleys. The formation is generally at least 22 m thick east of the Kettle Moraine.

Origin. The Holy Hill Formation was deposited by ice and meltwater associated with the Green Bay and Lake Michigan Lobes. Till of the Horicon, Keene, Mapleview, and Liberty Grove Members was deposited by the Green Bay Lobe (fig. A2). Till of the New Berlin and Waubeka Members was deposited by the Lake Michigan Lobe. Stratified gravel and sand of the Holy Hill Formation found in the Kettle Moraine region was deposited in the interlobate corridor, predominantly by meltwater flowing in subaerial streams and subglacial tunnels.

Age and correlation. The Holy Hill Formation was deposited during the late Wisconsin, approximately 18,000 to 13,000 BP. No radiocarbon ages are available to limit the time of deposition of this formation. The formation correlates with at least part of the Haeger Till Member of the Wedron Formation of northeastern Illinois (Willman and Frye, 1970).

Previous use of name. This report uses this name for the first time. Previously named units have been incorporated into the Holy Hill Formation. The Horicon and New Berlin Members (previously defined as the Horicon and New Berlin Formations in Mickelson and others, 1984), the Mapleview and Liberty Grove Members (defined in Mickelson and others, 1984), the Keene Member (defined in Attig and others, 1988), and the Waubeka Member (defined in this report) are all now considered members of the Holy Hill Formation (fig. A2).

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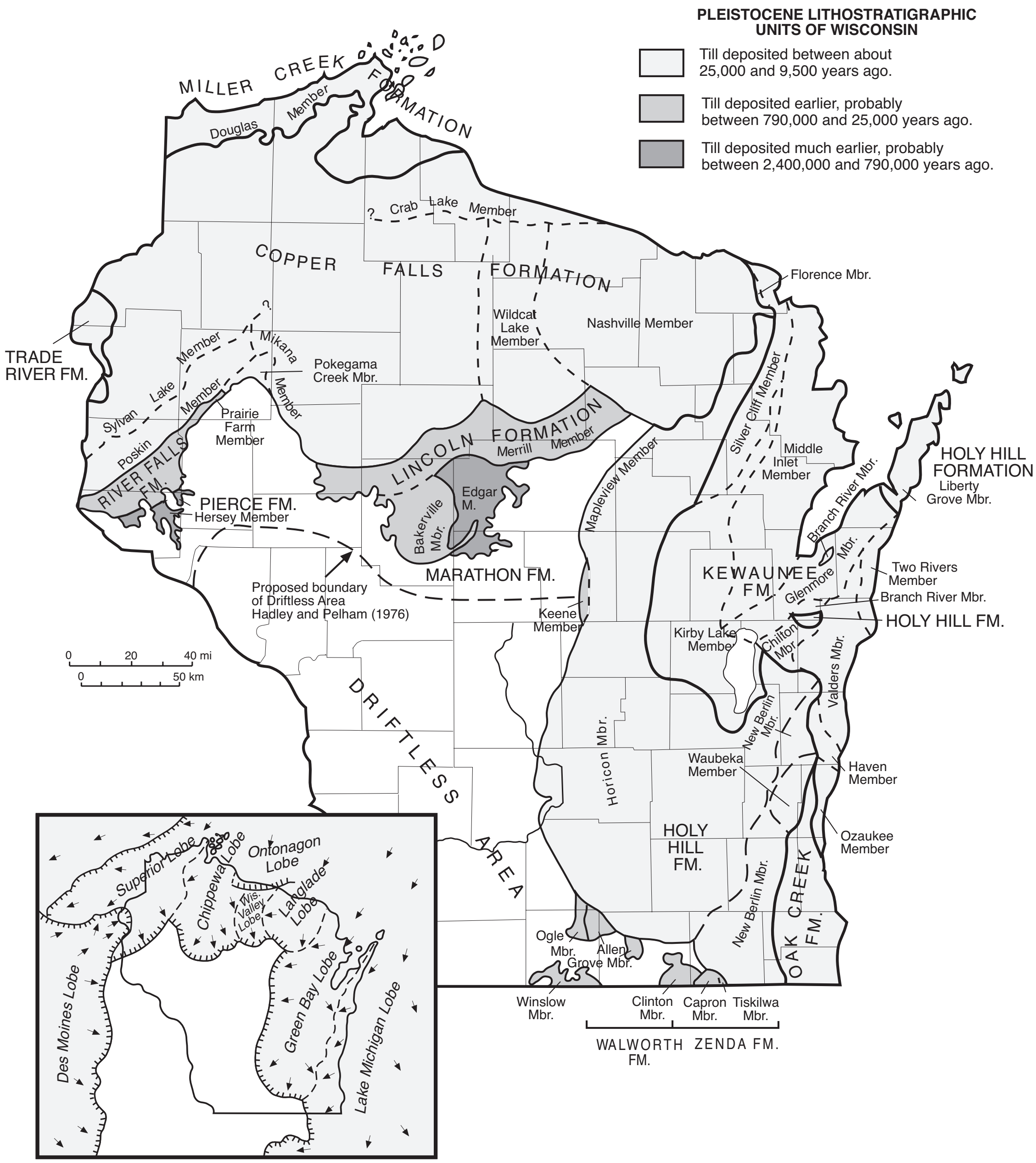

Figure A2. *Pleistocene lithostratigraphic units map of Wisconsin (modified from Clayton and others, 1992). The Holy Hill Formation and Waubeka Member of the Holy Hill Formation are shown. The Liberty Grove (not shown), Mapleview, and Keene Members of the Holy Hill Formation formerly were members of the Horicon Formation. The Horicon and New Berlin Members of the Holy Hill Formation formerly were separate formations. The Trade River Formation in western Wisconsin has been named by Johnson (in press).*

Waubeka Member of the Holy Hill Formation

David M. Mickelson and Kent M. Syverson

Source of name. Waubeka, Wisconsin, in Ozaukee County.

Location of type section. Exposure in gravel pit at southeast edge of Newburg, 300 m east of the intersection of Wisconsin Highway 33 and Highway I in the NW1/4 SW1/4 SE1/4 sec. 12, T11N, R20E, Washington County; Newburg Quadrangle, Wisconsin (U.S. Geological Survey, 7.5-minute series, topographic, 1971; fig. A3).

Description of type section. The gravel pit is located in a drumlin that trends east–west. This drumlin is smaller than an adjacent drumlin to the south, but shows roughly the same orientation. The 5-m high exposure on the south side of the pit contains 1 to 2 m of till of the Waubeka Member overlying stratified sand and gravel. The sand and gravel is cemented at the western end of the pit, but it is typically not cemented at the eastern

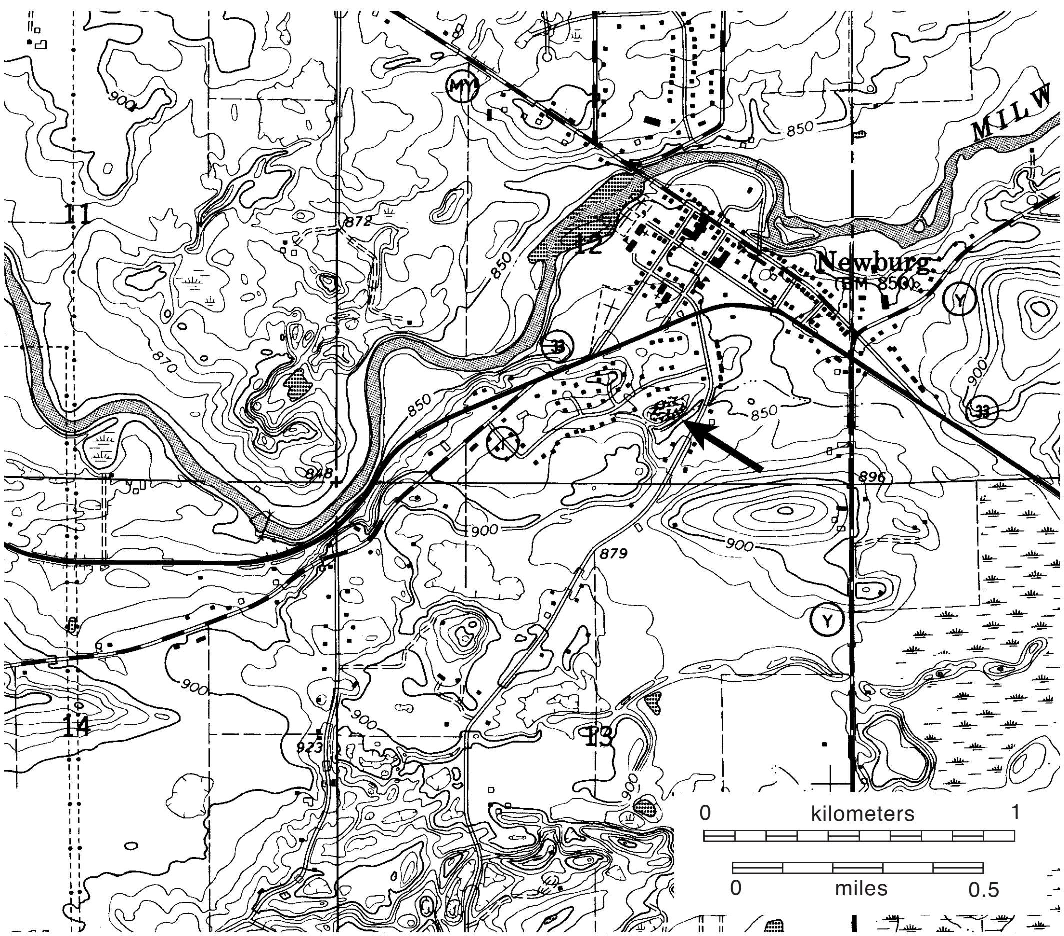

Figure A3. *Part of Newburg Quadrangle, Wisconsin (U.S. Geological Survey, 7.5-minute series, topographic, 1971), showing location of type section for Waubeka Member of Holy Hill Formation.*

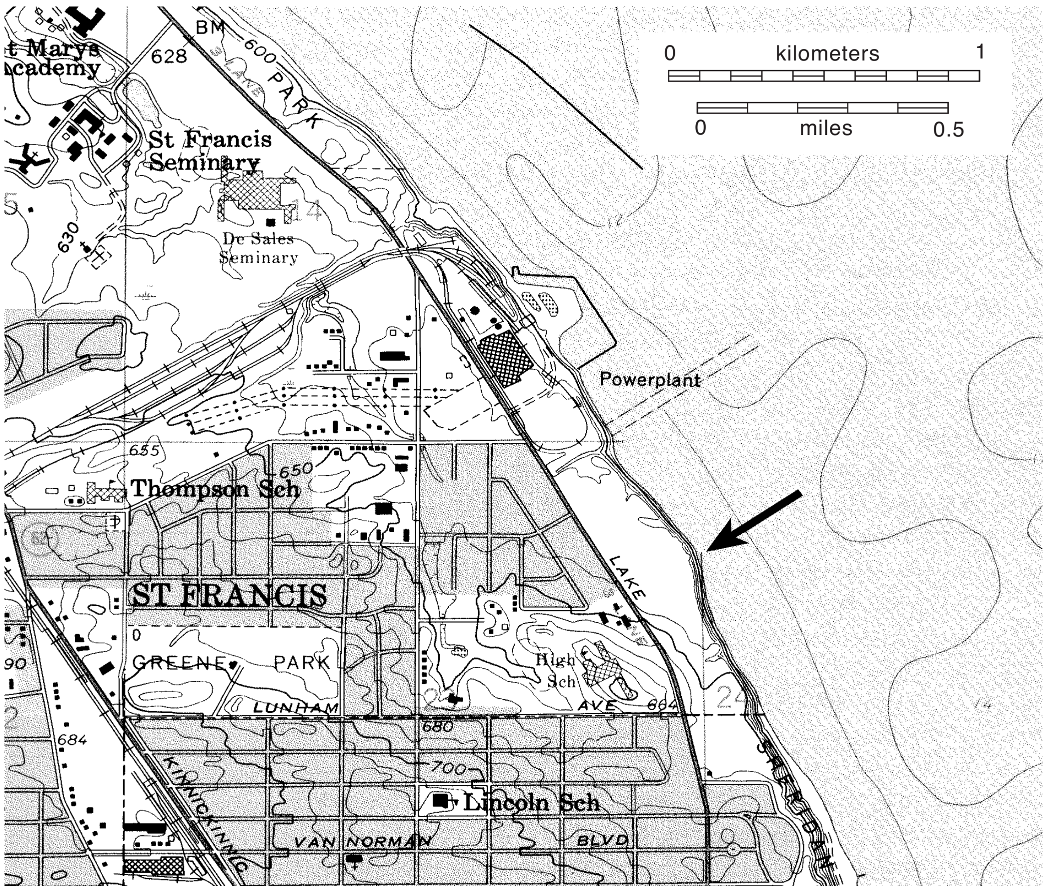

Figure A4. A. *Part of South Milwaukee Quadrangle, Wisconsin (U.S. Geological Survey, 7.5- minute series, topographic, 1971), showing location of one reference section for Waubeka Member of Holy Hill Formation.*

end. The drumlin orientation at this site does not agree with the ice-flow direction suggested by the outermost edge of the Waubeka Member. We suggest that the till at the type section lies on an unconformity developed on gravel of the New Berlin Member.

Location of reference sections. One reference section is located along the Lake Michigan shoreline in the city of St. Francis in NE1/4 NE1/4 NE1/4 sec. 23, T6N, R22E, Milwaukee County, shown on the South Milwaukee Quadrangle, Wisconsin (U.S. Geological Survey, 7.5-minute series, topographic, 1971; fig A4A). It lies above till of the New Berlin Member and below sand and gravel that is undifferentiated. Another section is a roadcut located at the intersection of St. Finbars Road and Shady Lane Road, about 4 km east of the type section in NW1/4 SW1/4 SW1/4 sec. 9, T11N, R21E, shown on the Port Washington West and Newburg Quadrangles, Wisconsin (U.S. Geological Survey, 7.5-minute series,

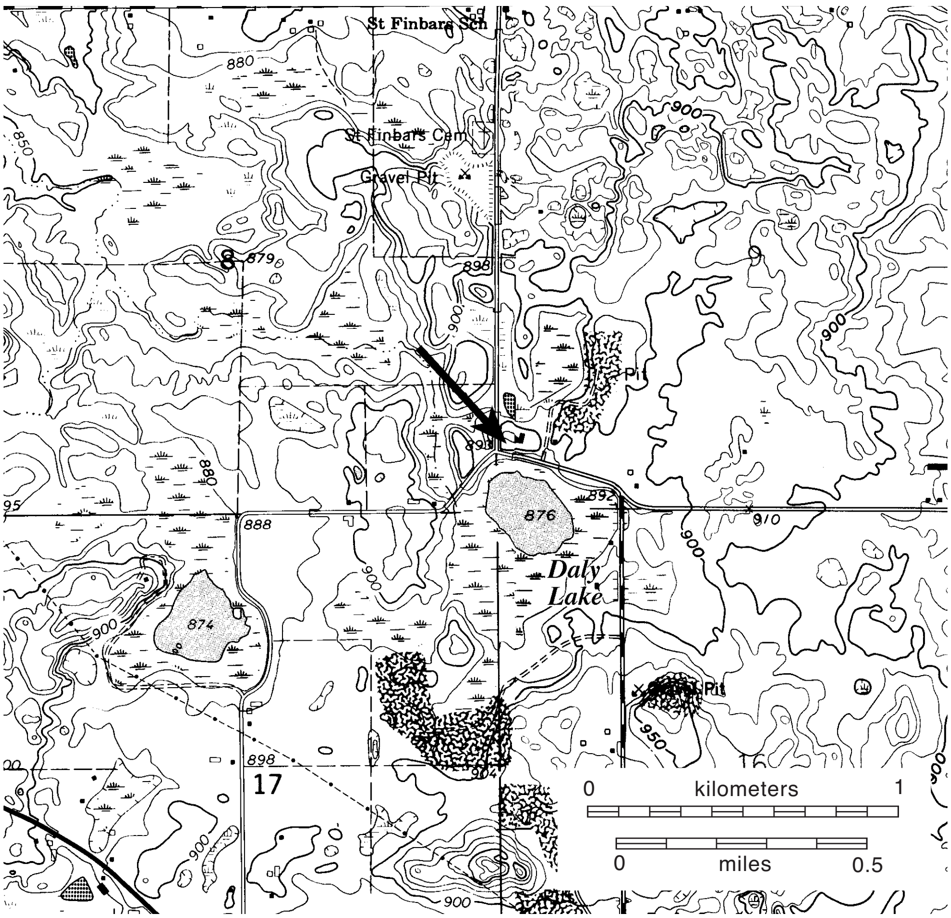

Figure A4. B. *Part of Port Washington West and Newburg Quadrangles, Wisconsin (U.S. Geological Survey, 7.5-minute series, topographic, 1976), showing location of another reference section.*

topographic, 1976; fig. A4B). Diamicton is about 5 m thick, overlying compact silt.

Description of unit. The Waubeka Member includes till and associated lake and stream sediment. The till is generally yellowish brown to brown (10YR to 7.5 YR) and is grayer where unoxidized. Texture of the till of this member is intermediate in composition between that of the underlying New Berlin Member, and the overlying till of the Oak Creek Formation. The till averages 35 percent sand, 51 percent silt, and 14 percent clay where it was sampled in Ozaukee and Washington Counties. The unit is calcareous and rich in dolomite clasts.

Nature of contacts. In eastern Washington County, till of the Waubeka Member overlies sand and gravel in places. The contact often shows till mixing with the underlying sand and gravel, which has not been assigned to a lithostratigraphic unit. One drillhole in southern Ozaukee County (OZ-539) penetrated thick Oak Creek till over till of the Waubeka Member with an abrupt contact.

Differentiation from other units. Till of the Waubeka Member is distinguished in the field from till of the overlying Oak Creek Formation by its greater sand content and correspondingly lower silt and clay content. It is clearly distinguished from till of the Kewaunee Formation by its gray to brown color. Waubeka Member till has less sand and more silt and clay than till of the New Berlin Member.

Regional extent of thickness. The Waubeka Member is the surficial unit in western Ozaukee and eastern Washington Counties. It can be traced in the subsurface as far south as St. Francis (Milwaukee County) along the Lake Michigan shoreline. It is exposed at several locations along the northern Milwaukee County shoreline and has been identified as unit 2B by Mickelson and others (1977).

Origin. The Waubeka Member was deposited by the Lake Michigan Lobe and meltwater flowing away from the glacier into streams and lakes. Ice-flow direction appears to have been from the northeast. This is more northerly than the flow direction of ice that deposited the underlying New Berlin Member. The small end moraine built by ice that deposited the Waubeka Member is truncated north of Germantown by the outermost moraine containing till of the Oak Creek Formation. This implies that ice flowed from a more easterly direction during deposition of the overlying till of the Oak Creek Formation.

Age and correlation. The Waubeka Member was deposited during the late Wisconsin, approximately 15,000 to 13,500 BP. No radiocarbon ages are available to limit the time of deposition of this member. Although texturally similar to some formations above the Haeger Formation of northeast Illinois, the Waubeka Member must be younger than those formations. It represents a relatively minor readvance of the Lake Michigan Lobe during general retreat of the glacier that deposited till of the New Berlin Member.

Previous use of name. This report uses this name for the first time. It was previously referred to as till 2B by Mickelson and others (1977) and in subsequent papers.

References

Mickelson, D.M., and others, 1977, Shoreline erosion and bluff stability along Lake Michigan and Lake Superior shorelines of Wisconsin: Shore Erosion Technical Study Technical Report, Wisconsin Coastal Management Program, State Planning Office, 199 p. plus appendices.

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COOPERATIVE EXTENSION

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Cover: *Photograph of esker in tunnel channel (NE 1/4 NW 1/4 sec. 1, T11N, R18E); part of Allenton Quadrangle, Wisconsin (U.S. Geological Survey, 7.5-minute series, topographic, 1971).*