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WISCONSIN GEOLOGICAL AND NATURAL HISTORY SURVEY

Quaternary Geology of Door County, Wisconsin

Bulletin 109 • 2016

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Front: Cave Point County Park, © Eric C. Carson
Back: Niagara Escarpment at Peninsula State Park, © Linda Deith


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Abstract

Door County, located in northeastern Wisconsin, forms the peninsula that separates Green Bay from Lake Michigan. The area has been glaciated numerous times during the Pleistocene Epoch, although deposits are most abundant from the most recent, or Late Wisconsin, glaciation. Till from earlier glaciations is lacking in Door County, although a compact silty, gray till identified in several boreholes may correlate to pre-Wisconsin deposits identified by Chapel (2000). The pebbly, sandy till of the Liberty Grove Member of the Holy Hill Formation was deposited during and following the Late Wisconsin maximum extent between about 26,000 and 18,000 calendar years ago (22,000 and 15,000 ^{14}C yr BP). The reddish-brown, clayey till of the Glenmore Member of the Kewaunee Formation was deposited following the Two Creeks interval after 13,500 calendar years ago (11,700 ^{14}C yr BP). Glenmore till is typically very thin in southern Door County, and almost entirely absent in the north. Thick deposits of Glenmore till are present at the base of the Niagara Escarpment and along the flanks of streamlined promontories in the southern part of the county.

The bedrock exposed at and near the surface in Door County is Silurian dolostone that has been sculpted by multiple glaciations. Because of the thin sediment cover, bedrock topography largely controls the ground surface topography. In southern Door County, several valleys in the bedrock are partially filled with Quaternary sediment. One such valley wraps around the northern edge of the streamlined promontory south of Brussels, where it meets the Ahnapee valley. A second runs parallel to the Ahnapee valley, about 2 miles (3.2 km) to the east. The trends of all valleys in Door County match well with the dominant joint orientations of the bedrock. Few large-scale karst features are clearly expressed at the surface in Door County, aside from the large depression in the middle of Rock Island and west of Whitefish Dunes State Park. However, karst features likely play a larger, though more subtle, role in landscape formation throughout the Peninsula.

Ice flow indicators—striations, drumlins, moraines, streamlined promontories, and pebble fabrics—all show flow directions coming from the Green Bay basin, even in the extreme southeastern part of the county. Striations are most commonly oriented due south to south-southeast, with a few striae oriented south-southwest (parallel to the axis of the peninsula). Streamlined bedrock hills and drumlins, both on land and on the floor of Lake Michigan, indicate ice flow from the north to northwest, out of the Green Bay basin. Pebble fabrics from two different till units also indicate ice flow from the northwest, even in exposures on the Lake Michigan side of the peninsula. Rapid retreat of the Lake Michigan Lobe due to calving would have left the eastern margin of the Green Bay Lobe unconfined, allowing subsequent advances of the Green Bay Lobe to cross the peninsula.

Glenmore ice may have covered the northern part of the Door Peninsula, but deposited very little sediment there. The steepness and height of the Niagara Escarpment in northern Door County, along with the bedrock ridge in Green Bay north of Chambers Island, possibly prevented the deposition of Glenmore till (reworked lake clay) in northern Door County. The presence of the Sturgeon Bay lowland, along with the fact that the escarpment is gentler south of there, may have allowed basal debris to top the escarpment and be deposited across southern Door County.

Cave Point County Park

Linda G. Deith

Introduction

Door County is located in northeastern Wisconsin and occupies the majority of the Door Peninsula that separates Green Bay from Lake Michigan (fig. 1). The county has been entirely glaciated numerous times during the Pleistocene Epoch, including during the Wisconsin Glaciation (fig. 2).

Unconsolidated sediments provide only a thin cover over bedrock, and are less than 5 ft (1.5 m) thick in many parts of the county. Generally, the thickness of unconsolidated sediment cover increases toward the southern parts of the county.

The topography throughout the county is largely controlled by the underlying bedrock topography.

The resistant Silurian Niagara Dolomite forms prominent escarpments and bluffs along the western (Green Bay) shore of the Door Peninsula, and the locations of several bays and inlets along the coast are dictated by bedrock valleys that cut across the peninsula.

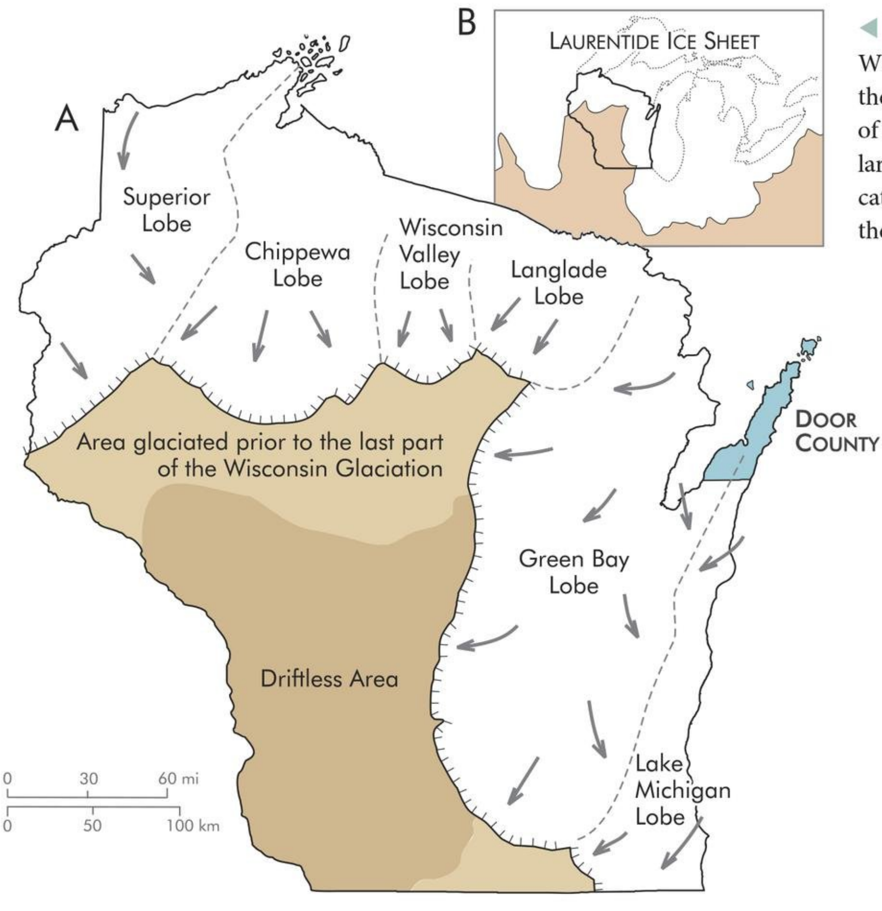


Figure 1. Location of Door County, Wisconsin, in relation to: (A) the lobes of the Laurentide Ice Sheet during the height of the Wisconsin glaciation, and (B) the larger Laurentide Ice Sheet. Arrows indicate ice flow directions; hachures indicate the margin of the ice sheet.

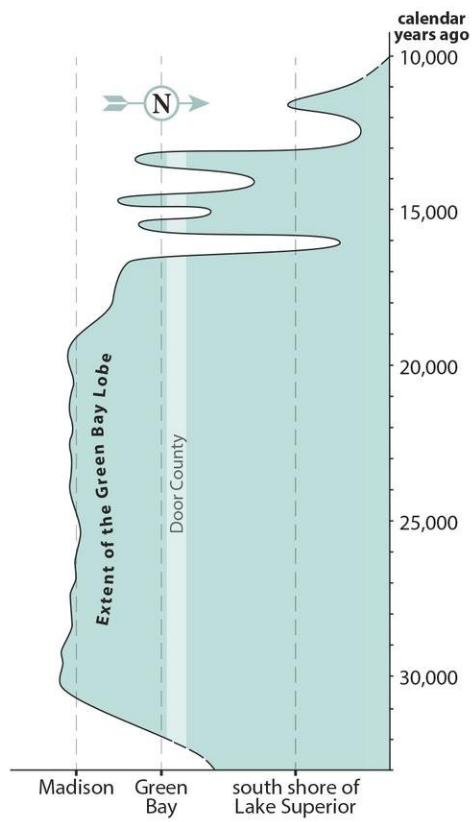


Figure 2. Time-distance diagram showing the extent of the Green Bay Lobe of the Laurentide Ice Sheet during the late Wisconsin Glaciation. The horizontal axis represents the approximate distance from southern to northern Wisconsin. Modified from Attig, Bricknell, and others (2011).

Elevations in the county range from approximately 579 ft (176 m) at the Lake Michigan water level to roughly 860 ft (262 m) at the highest points. Local relief is typically no more than 30 to 60 ft (10 to 20 m) throughout the county except in the vicinity of the bedrock escarpment along the western shore, where relief is as much as 150 ft (45 m).

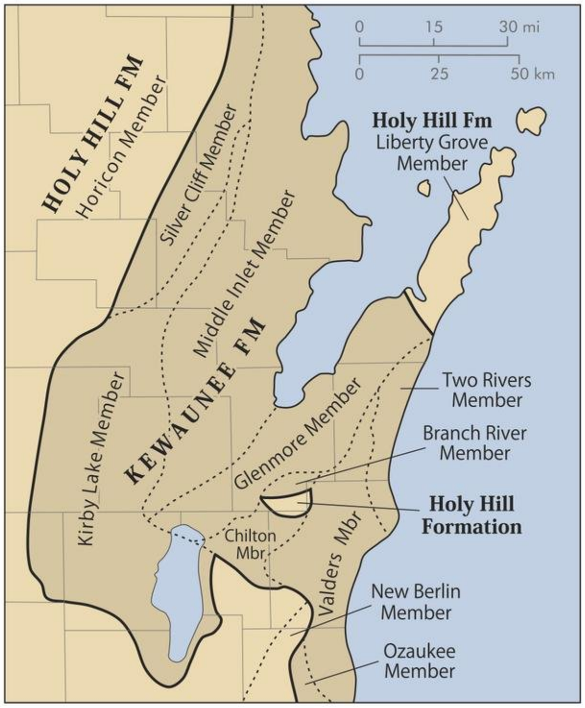


Figure 3. Surface distribution of lithostratigraphic units of the Green Bay and Lake Michigan Lobes in northeastern Wisconsin. Modified from Syverson and others, 2011.

Regional glacial history

The glacial history of eastern Wisconsin consists of repeated advances of the Green Bay and Lake Michigan Lobes of the Laurentide Ice Sheet that are represented by a sequence of tills (fig. 3).

Pre-Wisconsin deposits (older than about 100,000 years) are largely absent in Wisconsin, except in the south-central part of the state and just north of the Driftless Area of western Wisconsin (Baker and others, 1983; Miller, 2000). Some pre-Wisconsin till may be present at depth in east-central Wisconsin, in Sheboygan County, but can only be found in borings (Chapel, 2000). The majority of the surficial glacial material in Wisconsin is from the late Wisconsin Glaciation, beginning with the Holy Hill Formation, which was deposited about 26,000 to 18,000 calendar years ago (Syverson and others, 2011).

Preliminary data from the Baraboo Hills in south-central Wisconsin suggests that the Green Bay Lobe began to retreat about 18,500 calendar years ago (Attig, Hanson, and others, 2011), although it is debated whether the retreat was rapid or slow (Colgan and others, 1998; Colgan, 1999). At some time during the retreat, ice melted back far enough to allow water from the Lake Superior basin to enter Green Bay and Lake Michigan through the Whitefish–Au Train channel. Red sediment from the Lake Superior basin was carried along the glacier front, or possibly beneath the glacier, into the Green Bay and Lake Michigan basins (Alden, 1918). Subsequent re-advances of the Green Bay and Lake Michigan Lobes, each terminating farther north than the previous advance, reworked this red lake clay and deposited the reddish-brown members of the Kewaunee Formation. Chamberlin (1877) originally described these deposits as lake clay, but Alden (1918) recognized them as till of a single advance, based on their position on the landscape and the disturbance of underlying sediment. In the 1970s, extensive field work in Manitowoc County revealed that the Valders red till mapped by Alden (1918) consists of several different units, with only the latest advance being post–Two Creekan in age (Evenson 1973a, 1973b; Evenson and Mickelson, 1974; Mickelson and Evenson, 1975; Evenson and others, 1976; Schneider, 1990a).

The water levels in Green Bay and Lake Michigan fluctuated drastically with the advance and retreat of glacier ice. As the lobes retreated into their respective basins, water ponded against the glacier fronts, forming proglacial lakes. As the glaciers retreated farther, successively lower outlets were uncovered, allowing the water level in the lakes to drop. The opposite occurred as the lobes advanced. Water levels also fluctuated with the amount of water flowing in and out of the basin, the downcutting of outlets, and the rate and pattern of isostatic uplift due to removal of the weight of the glaciers (Hansel and Mickelson, 1987; Larsen, 1987). This series of events created raised shorelines, marked by a variety of wave-cut and wave-deposited features (Goldthwait, 1907; Kowalke, 1946; Schneider, 1993a, 1993c).

Sources of information

U.S. Geological Survey 7.5-minute topographic maps were the primary base for fieldwork and mapping. Aerial photographs (scale 1:20,400) and the Soil Survey of Door County (Link and others, 1978) were used to produce a preliminary 1:24,000-scale surficial glacial geology map of Door County.

Field data were collected during the summers of 1999 and 2000 by examining road cuts, foundation exposures, gravel pits, quarries, and other excavations. We collected 153 sediment samples at various localities for laboratory analysis. Where bedrock was exposed, we measured the directions of striations. We also collected split spoon drill-core samples from 22 drill holes and retrieved core samples from an additional 37 holes using solid-stem auger sampling.

Till samples were analyzed for grain size, color, and carbonate content at the University of Wisconsin–Madison Department of Geoscience's Quaternary Laboratory (Grant, 1978). Grain sizes were grouped into three fractions: sand (0.625 to 2.0 mm), silt (0.002 to 0.625 mm), and clay (<0.002 mm). The color of each sample was taken from suspended silt and clay fractions. Calcite/dolomite ratios of the coarse silt fraction were determined for selected samples by Chittick analysis (Dreimanis, 1962).

A preliminary map of the distribution of Door County's Quaternary deposits was constructed using Link and others' (1978) soil survey and a digitized ArcView soil map coverage. Soil series were grouped according to parent material, as suggested in the soil definitions, or inferred from profile and textural descriptions. All soil series from similar parent material were combined within ArcView to form a coverage to be used as a proxy for surficial sediment. Many of the soil series are partially defined by the presence of bedrock within 5 ft (1.5 m) of the ground surface and thus a map of thin sediment cover was also constructed.

Following the completion of mapping, lidar (Light Detection and Ranging) coverage for the entirety of Door County was produced. This became available in 2002, and has been used in figures and the glacial geology map (plate 1).

Previous work

Thwaites and Bertrand (1957) initially mapped the Pleistocene geology of the Door Peninsula at 1:500,000 following the stratigraphic classification scheme set up by Alden (1918). Because this classification scheme has since been modified, the Wisconsin Geological and Natural History Survey and the United States Geological Survey provided funding to map the Quaternary deposits of Wisconsin, using the modern stratigraphic framework, at a scale of 1:100,000. Brown and Kewaunee Counties, south of Door County, have been mapped by Need (1985) and Clayton (2013), respectively. Maps of counties farther south, such as Calumet and Manitowoc (Mickelson and Socha, in press), Sheboygan (Carlson and others, 2011), and Washington and Ozaukee (Mickelson and Syverson, 1997), have been completed or are in progress.

Whitefish Dunes State Park

Linda G. Deith

Since the map of Thwaites and Bertrand (1957) was published, there has been little formal mapping in Door County. Schneider (1981, 1982, 1988, 1989, and 1993a–c) has summarized various aspects of the glacial geology and geomorphology of the peninsula. A soil survey of the county was completed in 1978 (Link and others), replacing the survey by Whitson and others (1919). The karst geomorphology has been studied by Rosen (1984), Rosen and others (1987), Johnson (1987), and Johnson and Stieglitz (1990). In 1993, Stieglitz and Schuster prepared a summary of the Door Peninsula's karst features.

Many detailed groundwater studies have been conducted in Door County, as the potential for groundwater contamination in the area is very high due to thin surficial sediment cover and pervasively jointed bedrock. Sherrill (1978) compiled the first detailed study of groundwater flow in the county, followed by Blanchard (1988). Bradbury and Muldoon (1992) and Underwood (1999) have studied fracture flow at several sites near Sturgeon Bay. Summaries and discussions of groundwater and associated contamination in Door County have been summarized by Stieglitz and Schuster (1988) and by Bradbury (1990).

Figure 4. Major geographic features of Door County.

Pre-Pleistocene geology

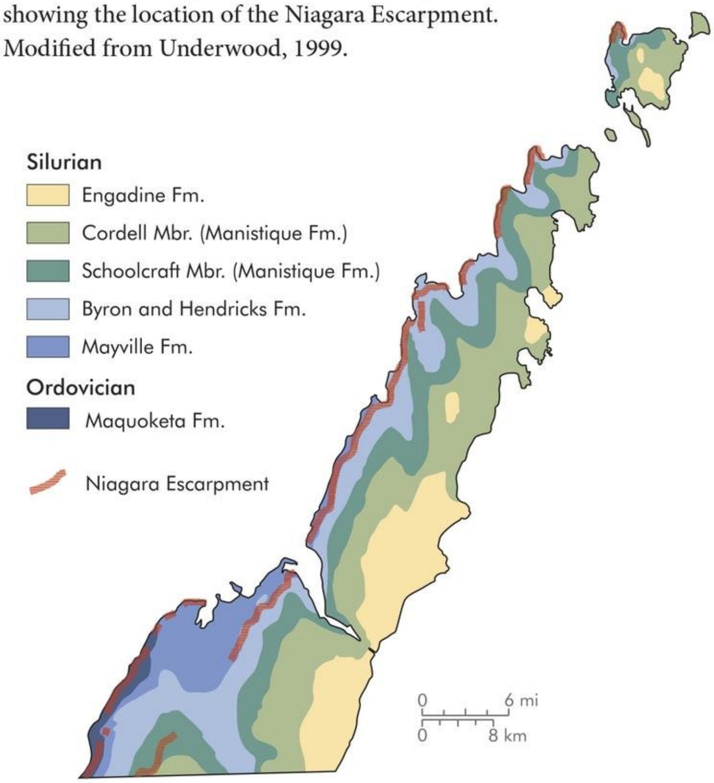
The landscape of the Door Peninsula is primarily a product of differential glacial erosion of Paleozoic dolomite and shale. Door County is located near the northwestern edge of the Michigan structural basin, so the bedrock dips gently toward the southeast.

Ordovician shale and carbonates outcropping to the west of the county and soft Devonian and Mississippian rocks to the east were eroded by lobes of ice advancing from Canada numerous times during the Pleistocene, leaving a cuesta of resistant Silurian dolomite, called the Niagara Escarpment, which forms the Door Peninsula. The Niagara Escarpment trends northeast–southwest in Door County (fig. 5), and is continuous through the Upper Peninsula of Michigan, Ontario, and New York, where it is present at Niagara Falls. The escarpment rises to about 200 ft (60 m) above lake level on the western side of the peninsula, and in many places drops sharply beneath the lake to depths of about 100 ft (30 m).

Door County is underlain by Paleozoic sedimentary rocks, which are in places as much as 1,850 ft (560 m) thick (Kluessendorf and Mikulic, 1989). Precambrian crystalline rocks are not exposed at the surface in Door County, but have been described in cores. Cambrian units, mainly sandstone and interbedded shale, though not present at the surface in Door County, are encountered at depths of about 1,000 ft (305 m) in wells and are up to about 400 ft (122 m) thick (Sherrill, 1978). Less-resistant Ordovician rocks underlie Green Bay, with the youngest unit, the Maquoketa shale, outcropping in the very southwestern corner of Door County (fig. 5). Less-resistant post-Silurian strata underlie the Lake Michigan basin to the east.

Five formations of Silurian dolomite are exposed at the surface of the Door Peninsula (fig. 5). The Mayville, Byron, and Hendricks Formations are the main cliff formers along the western edge of the escarpment (Underwood, 1999). The Schoolcraft Member of the Manistique Formation is present at the top of the escarpment, often expressed as bedrock promontories rising above the main escarpment. The Cordell Member of the Manistique Formation occupies the gently sloping eastern part of the peninsula, with minor outliers of the Engadine Formation exposed along the eastern shoreline of the county.

Figure 5. Bedrock geology of Door County showing the location of the Niagara Escarpment. Modified from Underwood, 1999.



Pleistocene deposits

Glacial deposits

There are at least two different glacial units present in Door County. The oldest is the Liberty Grove Member of the Holy Hill Formation (fig. 6). It was deposited by the Green Bay Lobe between about 18,000 and 17,000 calendar years ago (Syverson and others, 2011). Overlying the Liberty Grove Member in some parts of the county is the Glenmore Member of the Kewaunee Formation. This unit was deposited by the last advance of the Green Bay Lobe into Wisconsin. Other members of the Green Bay Lobe Kewaunee Formation, the Chilton and the Branch River (fig. 6), have not been positively identified in Door County, but they are present in counties to the south. The Two Rivers Member of the Kewaunee Formation may extend into the southeast corner of the county (McCartney and Mickelson, 1982), but it was not found during this study. Kewaunee Formation deposits from the Lake Michigan Lobe are present in Kewaunee County, just south of Door County (Clayton, 2013).

Liberty Grove Member of the Holy Hill Formation

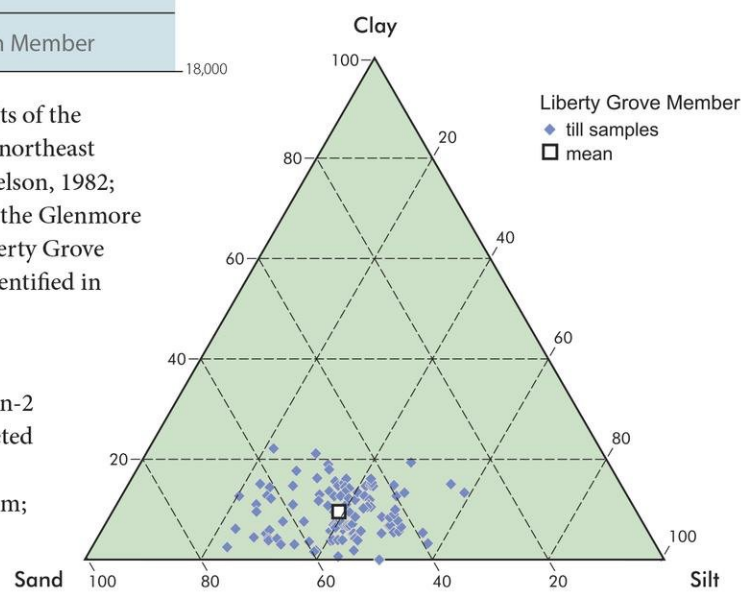
The Liberty Grove Member was first described by Schneider (1981) and formally classified as a member of the Holy Hill Formation by Mickelson and Syverson (1997). The type section is located in northern Door County (SE¼, SE¼, SW¼, sec. 35, T32N, R28E).

The till of the Liberty Grove Member typically has abundant sand and silt, averaging 52 percent sand, 38 percent silt, and 10 percent clay (with standard deviations of 9, 8, and 5 percent, respectively) (fig. 7). It is most commonly very pale brown to yellowish brown (10YR 7/4 to 5/6), but in places is slightly redder (7.5YR 6/4 to 5/6). Large cobbles and some boulders are common within the deposit, and more than 75 percent of these are locally derived dolomite (Thwaites and Bertrand, 1957).

The Liberty Grove till varies in thickness from less than 1 ft (0.3 m) to more

FORMATIONS	MEMBERS: GREEN BAY LOBE	MEMBERS: LAKE MICHIGAN LOBE	calendar years ago
KEWAUNEE	Glenmore Member	Two Rivers Member	
			13,100
KEWAUNEE	TWO CREEKS FOREST BED		
			14,400
KEWAUNEE	Chilton Member	Valders Member	
KEWAUNEE	Branch River Member	Ozaukee Member	
			17,000
HOLY HILL	Liberty Grove Member	Waubeka Member	
HOLY HILL		New Berlin Member	
			18,000

▲ **Figure 6.** Late Wisconsin lithostratigraphic units of the Green Bay and Lake Michigan Lobes as found in northeast Wisconsin (compiled from McCartney and Mickelson, 1982; Mickelson and others, 1984; Chapel, 2000). Only the Glenmore Member of the Kewaunee Formation and the Liberty Grove Member of the Holy Hill Formation have been identified in Door County.



▶ **Figure 7.** Grain-size distribution of the less-than-2 mm fraction for Door County sediments interpreted to be Liberty Grove till, with average grain size shown by square. Size ranges: sand, 0.0625–2.0 mm; silt, 0.002–0.0625 mm; clay, <0.002 mm.

than 50 ft (15 m). On upland areas it is rarely thicker than 10 ft (3 m), and is commonly so thin that it has been totally altered by soil formation. Typically, the Liberty Grove Member is distributed in gently rolling topography (map units *Ltr* and *Ltrw*, plate 1); however, some areas have a streamlined topography (fig. 8; map units *Lts* and *Ltsw*, plate 1). Liberty Grove deposits are thicker in valleys, but even there they are rarely more than 30 ft (9 m) thick.

In three boreholes drilled near Sturgeon Bay, a gray silty till was found below the Liberty Grove till (Brown, 2001). The texture of the till is similar to what is interpreted as Liberty Grove till, but is slightly more compact and contains pebbles that are more angular. In Sheboygan County, Chapel (2000) noted the presence of silty gray till in several drill cores below sediments of the Kewaunee Formation, and she suggests a pre-Late Wisconsin age. Socha (2007) also described a gray, compact, silty till at Valders Quarry in Manitowoc County, which she named the Hayton Formation. If these units are correlative with the gray till in Door County, and Chapel's suggestion that this unit is a pre-Late Wisconsin till is correct, then it is possible that the gray till of Door County is a separate unit from the Liberty Grove Member. No distinct contact or sorted sediments have been noted between the typical Liberty Grove till and the gray till, and therefore this unit is interpreted here as an unoxidized variant of the Liberty Grove Member. If it is, in fact, a separate unit, its scattered occurrence in the boreholes drilled in the county makes its distribution impossible to map at this time.

Schneider (1990b, 1993b) has observed a pink sandy till overlying the Liberty Grove Member at a few locations north and northeast of Sturgeon Bay. Schneider (1993b) suggested that it may be a sandy facies of the Glenmore till, or that it may represent the mixing of Liberty Grove till into the Glenmore till. Many of these exposures have long been covered or destroyed, and no such contact was observed in the current study. It is possible that this deposit represents a completely separate advance. While the presence of such a deposit is worth noting here, the lack of exposure in the area makes it impossible to map at this time.

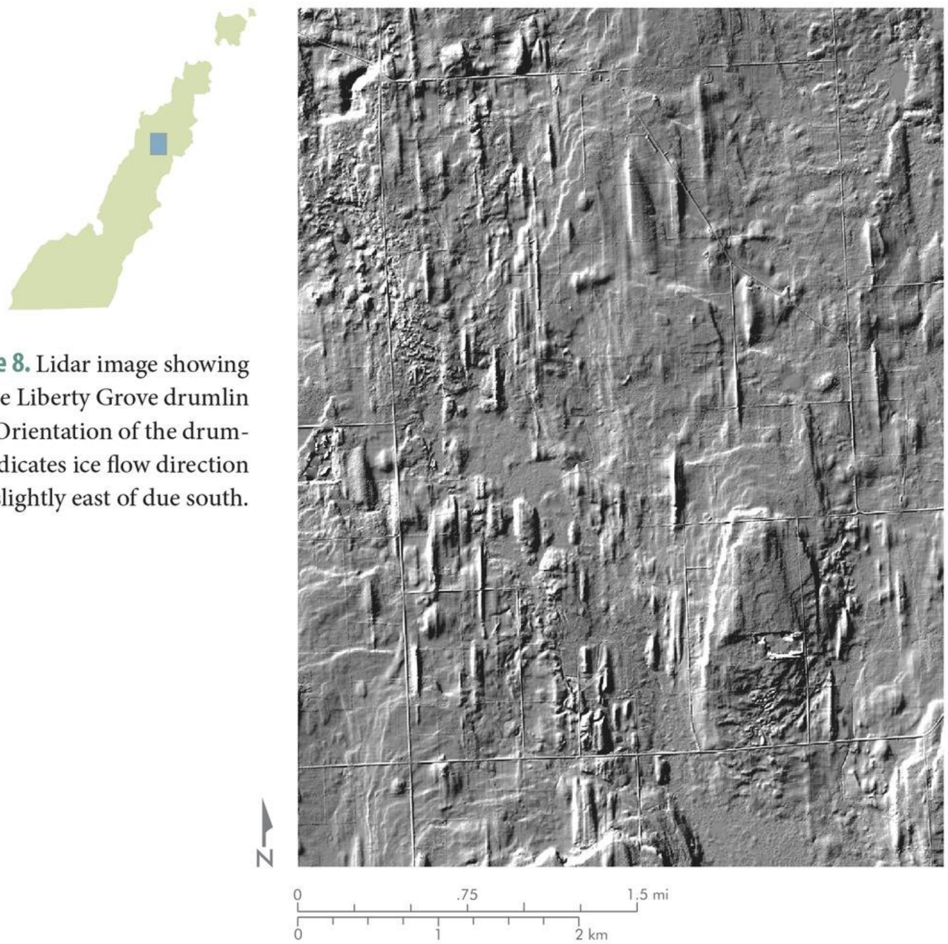


Figure 8. Lidar image showing the Liberty Grove drumlin field. Orientation of the drumlins indicates ice flow direction was slightly east of due south.

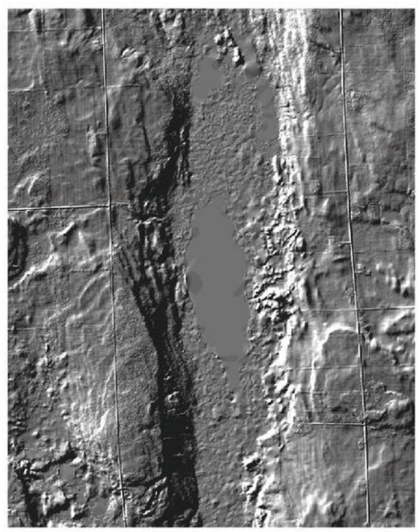
Undifferentiated hummocky till and outwash

Within the valleys of the central and southern parts of the peninsula, a hummocky landscape is present, although there is a distinct lack of the closed depressions that would be expected in a typical hummocky topography (map unit *Lnh*, plate 1). These hummocks appear to be composed of till that is similar in texture to what has been interpreted as Liberty Grove till, but are typically much more poorly consolidated. Cutting through the hummocks is a series of discontinuous fluvial channels, filled with several feet (about 1 m) of well-sorted to poorly sorted sand and gravel. These channels are commonly short features and have undulating long profiles, suggesting formation on stagnant ice or more recent mass wasting into the channel bottom. In some areas, this hummocky topography is present at the base of the valley, while in others the hummocks and channels occur along the valley walls (fig. 9a).

The channelized, hummocky landscape is well expressed in several areas in northern Door County. In the Piel Creek valley (fig. 9a), just north of Kangaroo Lake (sec. 11, T30N, R27E) channels can be seen cutting through a landscape of streamlined landforms. A similar landscape is present southeast of Egg Harbor (SE¼, sec. 31, T30N, R27E), with a hummocky landscape at the center of the valley. Just east of Lost Lake, further down the valley (NW¼, sec. 8, T29N, R27E), hummocks and channels are present along the valley wall (fig. 9b).

A section through one of the hummocks in the Donlans Creek valley (SE¼, SW¼, sec. 30, T29N, R26E) is the only exposure that shows the internal structure of these hummocks. A wide mix of deposits is present at this site. The dominant sediment present is a light yellowish-brown till that is sandy and gravelly with many large cobbles and small boulders (Brown, 2001). At the northern end of the pit, sediment overlies a mound of moderately well-sorted, massive, fine sand with gravel and small cobbles. The eastern face exposes a wedge-shaped structure of large, bedded, angular clasts. These clasts fit together so well that it seems they are the result of a large slab of bedrock that was lifted up into the ice and broken up, without being deformed.

A



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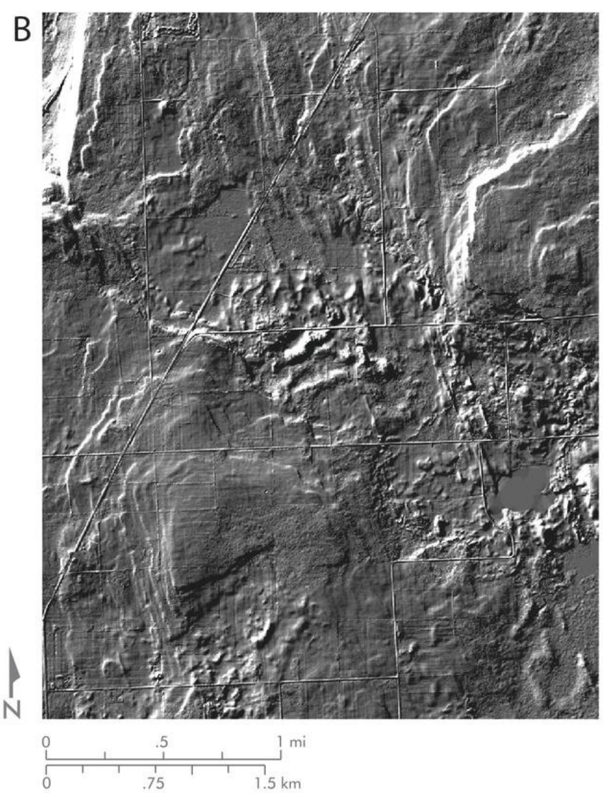
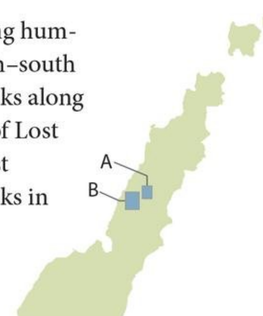


Figure 9. Lidar images showing hummocky topography: (A) North–south trending valley with hummocks along valley wall immediately east of Lost Lake. (B) Northwest-southeast trending valley with hummocks in the middle.



Glenmore Member of the Kewaunee Formation

The Glenmore Member of the Kewaunee Formation was the last unit to be deposited in Wisconsin by the Green Bay Lobe (Syverson and others, 2011). Till of this member is reddish brown and silt- and clay-rich. In Door County, samples have a sand:silt:clay content averaging 25:41:34 percent with standard deviations of 11, 5, and 9 percent (fig. 10) (Brown, 2001). Lab colors of silt and clay measured in settling tubes range from yellowish red to pale brown (5YR 4/6 to 10YR 6/3); however, field colors are typically deep brown (7.5YR 4/6) where oxidized near the surface to reddish brown (5YR 4/4) at depth in boreholes.

Tentative identification of this unit as the Glenmore Member is based, in part, on a date from a piece of spruce or larch wood, recovered from 35 ft (10.5 m) in borehole B-41-00 (Brown, 2001). This wood was dated at 13,800 to 13,400 calendar years ago (11,740±70 ^{14}C yr BP) (Beta Analytic, sample no. 148508), which is within the range of the Two Creeks interval. Such a date from wood contained within the till indicates that the advance followed Two Creeks time. In addition, all flow indicators in Door County suggest ice movement leaving the Green Bay basin, further supporting the interpretation that the reddish-brown clay till at the surface is the Glenmore Member.

Because of the textural similarity of the Glenmore Member to other members of the Kewaunee Formation (especially the Chilton Member), some of the clay till at depth in Door County may be pre–Two Creekan in age. However, no positive evidence of more than one Kewaunee advance was seen in this study, either in surface exposure or in borehole samples. For this reason all clay till in Door County, even at depth, is interpreted as Glenmore deposits.

Till of the Glenmore Member covers less than about 30 percent of Door County, and is present almost exclusively in the southern part of the county (plate 1). North of Sturgeon Bay, there are very few sites where Glenmore deposits are exposed, and the majority of them occur close to Sturgeon Bay on the western side of the peninsula.

In the southern part of Door County, Glenmore till ranges in thickness from a thin veneer to more than 50 ft (15 m); in many places the clayey sediment is entirely absent. Many parts of this area are covered with a layer of till so thin that it has been completely altered by soil-forming processes or eroded away, so that now it exists only in small, patchy areas scattered across the landscape. It is also likely that there are places where no Glenmore till was deposited by the glacier.

Thick Glenmore deposits do occur in some areas of the county. At least

Sven's Bluff, Peninsula State Park

Wisconsin Department of Natural Resources

50 ft (15 m) of homogeneous reddish-brown clay till is present at the base of the Niagara Escarpment in two places in southwestern Door County (Brown, 2001). In both cases, the till was deposited against a steep bedrock rise as a ramp of sediment sloping up toward the escarpment lip. The till is very uniform, with grain sizes of sand, silt, and clay varying less than 10 percent from the top of the deposit to the bottom (fig. 11). The color did change with depth in each borehole, most likely because of oxidation of the near-surface sediments rather than the result of a separate glacial advance.

Another thick layer of Glenmore till is present just east of the Ahnapee River, where it crosses Wisconsin Highway 57 (NE¼, SW¼, sec. 31, T27N, R25E). Here, 27 ft (8.2 m) of reddish-brown clayey till is present over lake silt deposited in a bedrock valley (Brown, 2001). The till is less uniform than the Glenmore till deposited at the base of the Niagara Escarpment. It contains a layer with considerably more gravel and sand, but the clay percentage is very consistent throughout.

In the southeastern part of the county, the Glenmore deposits show significantly different grain-size characteristics than in the southwestern part of the county. The till in this area contains about 11 percent less clay and 17 percent more coarse sand than till to the west (fig. 10). The grain-size distribution in the southeast is actually more similar to that of the Liberty Grove Member than the Glenmore Member, but it is slightly darker brown-red in color and commonly overlies sediment interpreted as lake sediment associated with the Glenmore advance (this topic is discussed in more detail in the following section on Calumet lake deposits). While it could be argued that this till was deposited by a different ice mass than the more clay-rich till to the west (possibly by the Lake Michigan Lobe), pebble fabrics from two sites in this area suggest deposition by the Green Bay Lobe flowing from the northwest. The texture difference is most likely due to the presence of sorted sand and gravel on the eastern side of the peninsula that was worked into the Glenmore till.

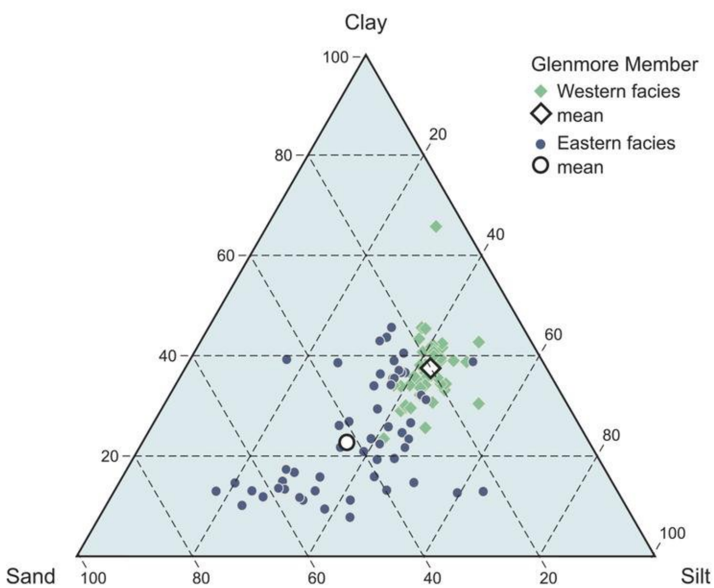


Figure 10. Grain-size distribution of the less-than-2 mm fraction for Door County sediments interpreted to be Glenmore till, with averages for the clayey western and the sandy eastern facies. Size ranges: sand, 0.0625–2.0 mm; silt, 0.002–0.0625 mm; clay, <0.002 mm.

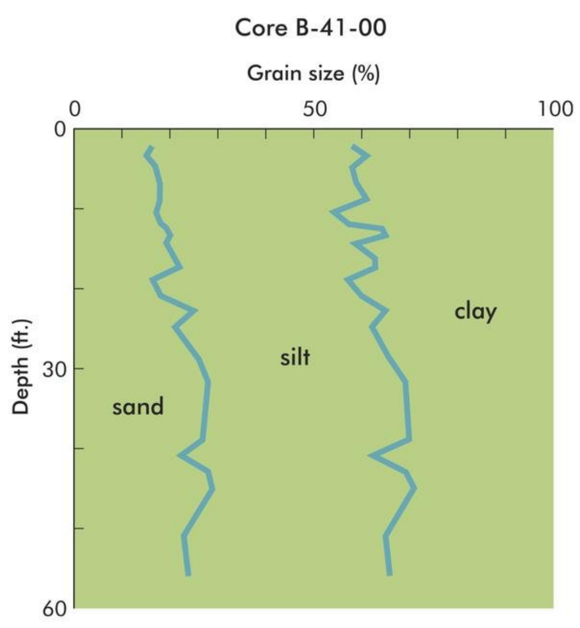


Figure 11. Grain-size distributions in borehole B-41-00, showing the uniform grain-size distribution with depth.

Many boreholes in the southeastern part of the county reveal a complex stratigraphy (Brown, 2001). Graphs plotting grain-size distribution at various depths show a wide distribution of materials in the subsurface that can be difficult to correlate between holes. In general, though, the boreholes show a till that is reddish to tan in color and changing from sandy at the surface to more clayey at depth. Lower down is a sandier till, often containing small lenses of sand and gravel (fig. 12). Variability between boreholes has been interpreted as a result of incorporation of sandy sediments into the clay-rich debris at the base of the ice.

These examples from southeastern Door County are markedly different from the homogeneous deposits along the escarpment to the west. This variability may suggest that the till in this area was deposited near the ice margin, where meltwater was available to winnow away some of the fines and produce a variety of deposits. Alternatively, it may be due to variation in freeze-on and incorporation of the underlying sand into the basal ice. Fine laminations in one of the boreholes (B-37-00) suggest debris flow events, or cyclic till deposition in water, which supports the first interpretation.

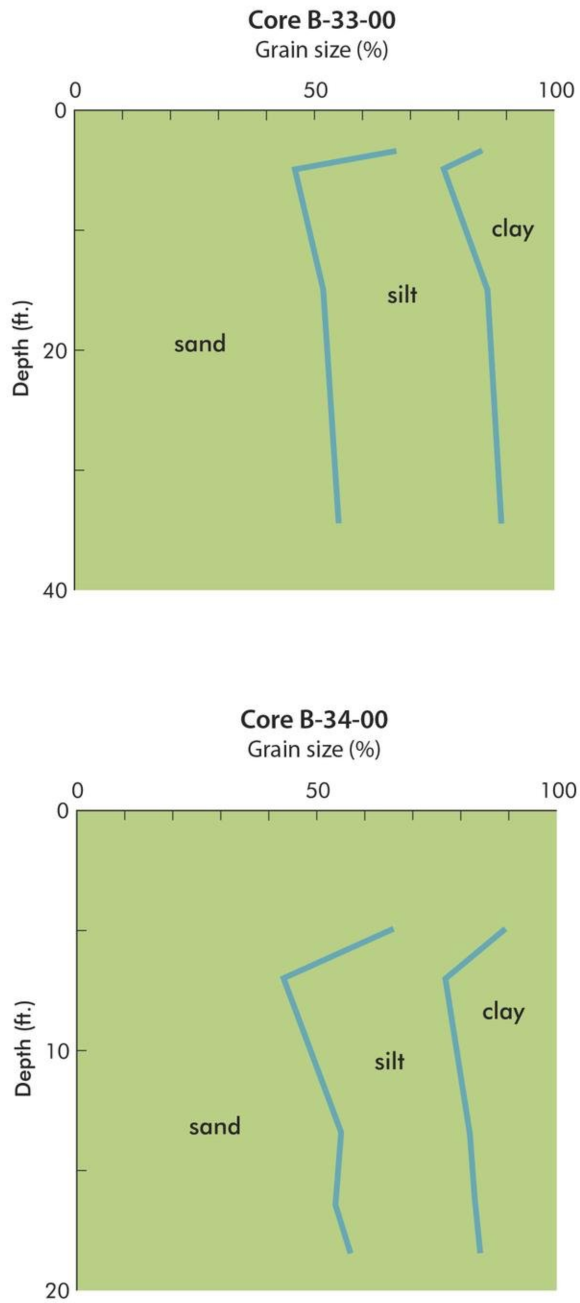


Figure 12. Grain-size distributions in boreholes B-33-00 and B-34-00 in southeastern Door County.

Lake deposits and shoreline features

Lake levels in the Lake Michigan basin fluctuated greatly in the past due to the advance and retreat of the Laurentide Ice Sheet and due to isostatic rebound caused by the unloading of ice at the end of the Pleistocene.

As the Lake Michigan Lobe retreated from its maximum extent, glacial Lake Chicago formed between the glacier front and the Lake Border Moraines, and drained to the south through the Chicago outlet. The highest shoreline elevation of glacial Lake Chicago is the Glenwood level at 640 ft (195 m) above sea level in the southern part of the Lake Michigan basin (Goldthwait, 1907). The lake reached this height when the glacial margin attained a stable position north of modern-day Chicago, and again when ice readvanced to deposit the pre–Two Creekan layer of the Kewaunee Formation; this sequence of events is documented at the Glenwood I and Glenwood II phases (fig. 13). Because shorelines of this level were overridden by subsequent ice readvances, there are no Glenwood shorelines present in the northern part of the Lake Michigan basin (Evenson, 1973a).

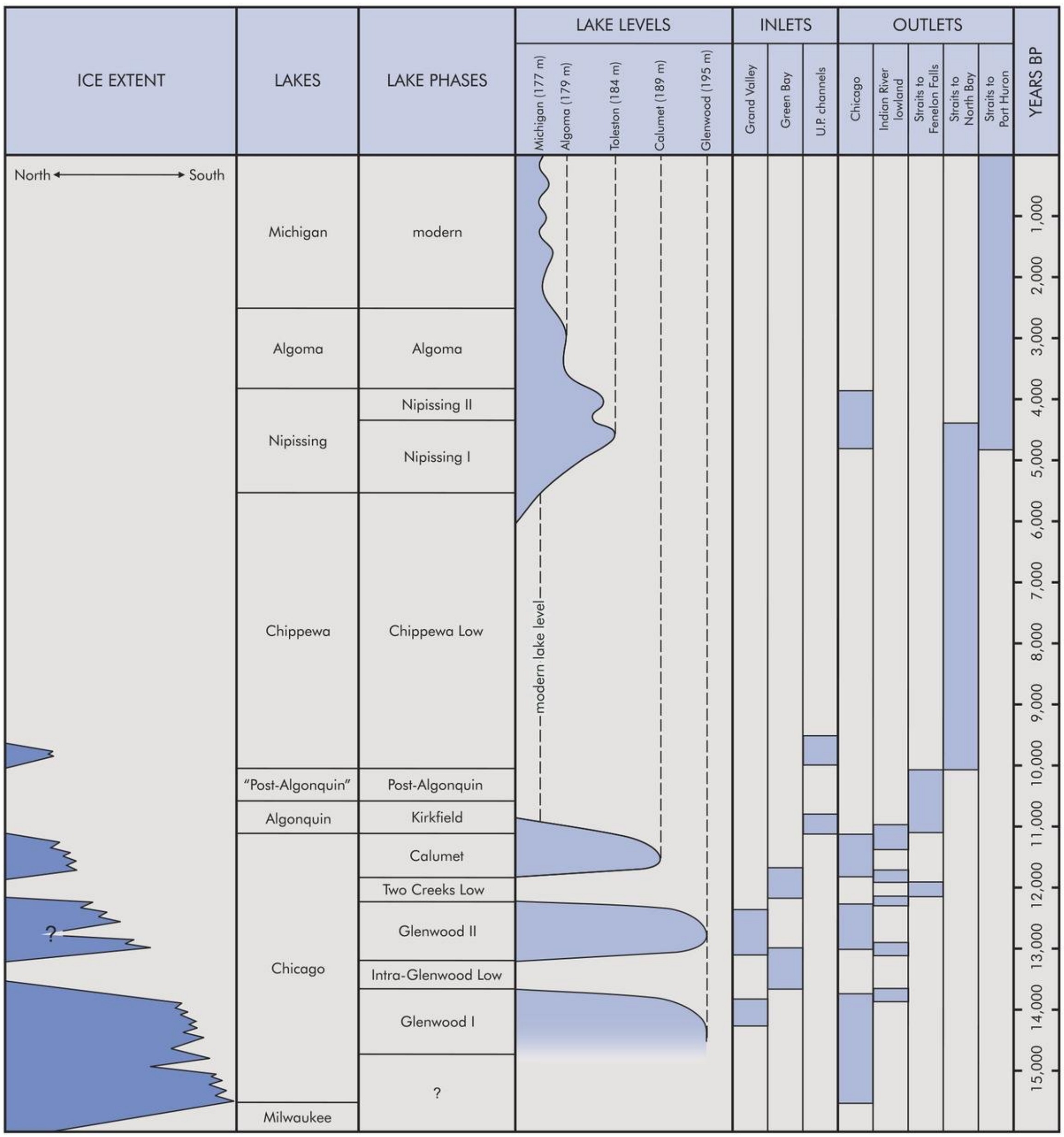


Figure 13. Late Pleistocene lake level history in the Lake Michigan basin. Shaded bars represent times when different inlets and outlets were active. Modified from Hansel and others, 1985.

A lowstand occurred in the Lake Michigan basin during Two Creeks time, a warm period when the Lake Michigan Lobe retreated far enough north to expose the Straits of Mackinac. During this time, a spruce forest covered much of northeastern Wisconsin. Wood from this interval has been radiocarbon dated at about 14,400 to 13,100 calendar years ago (Broecker and Farrand, 1963; Hooyer, 2007).

With the advance of the post–Two Creeks ice, the water level in the Lake Michigan basin rose to about 620 ft (189 m) above sea level, draining out of the Chicago outlet. This level of glacial Lake Chicago is called the Calumet phase. The shoreline is at a lower elevation than the earlier Glenwood shoreline due either to downcutting of the Chicago outlet (Bretz, 1951) or to a decrease in the amount of water entering the basin (Hansel and Mickelson, 1988).

As the Lake Michigan Lobe retreated for the final time, water dropped from the Calumet level as lower outlets were uncovered. These lower levels are collectively referred to as glacial Lake Algonquin up to the time when the lake was no longer bounded by ice and the outlet was controlled solely by basin topography and isostatic adjustment at the North Bay outlet in Lake Huron. The lowstand in the Lake Michigan basin following deglaciation, due to the uncovering of a low northern outlet, is called Lake Chippewa. Eventual uplift of the northern outlet of the lake caused a transgression, culminating in the Nipissing highstand, with an elevation of 605 ft (183 m), at about 5,500 calendar years ago (Hansel and others, 1985; Larsen, 1987).

The following discussion describes the geologic signatures left on the landscape by the Calumet, Algonquin, and Nipissing lake phases.

Calumet shorelines and deposits

The earliest record of glacial lakes in Door County, the Calumet phase, is present in the southern part of the county, mainly on the eastern side of the peninsula. Bedded fine sand and silt, interpreted as offshore lake sediment, and well-sorted medium to coarse sand and cobbles, interpreted as near-shore and beach deposits, were encountered in 16 drill holes in southern Door County. In each case, these lake deposits underlie till of the Kewaunee Formation. In some boreholes, the lake sediments overlie gray or yellowish brown Liberty Grove till. The thickness of lake sediment generally increases toward the southeast, with several cores near LaSalle Park in the southeastern corner of the county containing over 75 ft (23 m) of laminated and cross-bedded fine sand.

An exposure in a gravel pit off Highway U contains at least 20 ft (6 m) of bedded medium-fine sand, grading upward into coarse sand and rounded gravel (SW¼, SE¼, sec. 17, T27N, R26E). Overlying this unit is about 8 ft (2 m) of Kewaunee till, with a sharp contact between the two units (see Schneider, 1990b). This coarsening-upward sequence likely represents some combination of shallowing of the lake and basin filling.

If the reddish-brown till overlying the lake deposits is in fact post–Two Creekan in age, and the coarsening-upward sequence represents the advance of Glenmore ice, then at least the uppermost lake deposits are associated with the Calumet level of glacial Lake Chicago (fig. 13). It is also possible, however, that they are older Glenwood-level deposits, and that no Calumet deposits are present in Door County.

In the southern part of the Lake Michigan basin, the Calumet shoreline features are at an elevation of 620 ft (189 m), or 40 ft (12 m) above current lake level (Hansel and others, 1985). Due to isostatic uplift, however, the Calumet deposits in Door County are expected to be significantly higher. Clark and Ehlers (1993) have modeled the uplift of the Door Peninsula following deglaciation and suggest that the Calumet shoreline should be at an elevation of 740 ft (225 m) at the southern end of the county and up to 787 ft (240 m) at the tip of the peninsula.

Algonquin shorelines and deposits

As the last glacier receded from the area, about 13,300 calendar years ago, much of Door County was covered by large proglacial lakes. The water levels may have been different in the Green Bay and Lake Michigan basins until the Sturgeon Bay lowland was uncovered, at which time the two basins flowed together (Thwaites and Bertrand, 1957). Sand and cobble beach ridges were formed around the isostatically depressed Door Peninsula at this time. Water initially drained through the Chicago outlet, but the water level dropped as lower outlets became free of ice. The drop in water level was accentuated by isostatic uplift of the peninsula due to the removal of the weight of the glacier. This phase of Lake Michigan has been named glacial Lake Algonquin.

Algonquin shorelines are present throughout Door County (plate 1). They exist as gravel and cobble beach ridges, sand and gravel beach and near-shore deposits, and wave-cut cliffs cut into bedrock (Goldthwait, 1907; Schneider, 1988, 1990a, 1993c). In places these features can be traced over significant distances on air photos, but they are by no means continuous throughout the peninsula.

Several separate Algonquin and late-Algonquin levels are recorded on the peninsula. They are best expressed on the northern tip of the peninsula, where a higher uplift rate during formation better separated particular lake level events (Goldthwait, 1907; Kowalke and Kowalke, 1938). Here, the shorelines are most often represented as cobble beach ridges. While many of the features described by Goldthwait have been excavated or destroyed by construction, good examples of Algonquin shorelines still exist. A series of 12 or 13 cobble beach ridges is present at the head of Little Sister Bay (Schneider, 1993a). One especially prominent beach ridge is present east of the Liberty Grove drumlin field and, in fact, truncates several of the drumlins.

In some places in the county, Algonquin shoreline features are absent, probably because a flat-lying bedrock surface just below water level prevented waves from reaching the shore (Thwaites, 1943). One such location is the bedrock ridge east of Kangaroo Lake, which separates the lake from Lake Michigan (plate 1).

Beach ridges present on the western side of Kangaroo Lake show an elevation of 650 ft (198 m) for the highest Algonquin shoreline. In the photograph below, the ridge rises about 4 ft (1.2 m) above the surrounding landscape. On the eastern side of the lake, several feet (tens of centimeters) of sand and gravel are present in places at much lower elevations. Some are as high as 635 ft (194 m), deposited at or after the highest Algonquin stage, but the majority of the upland—which barely reaches an elevation of 650 ft (198 m)—is covered with only a thin veneer of soil.

Nipissing shorelines and deposits

By about 12,000 calendar years ago, the glacier had receded north of the North Bay outlet, and the Lake Michigan lowland was no longer bounded to the north by ice (Larsen, 1987; Lewis and Anderson, 1989; Coleman and others, 1994b). Due to isostatic depression, this outlet had a very low elevation and the water in the Lake Michigan basin was at least 260 ft (80 m) below current lake level (Hough, 1955, 1958, 1963; Coleman and others, 1994b). This lowstand is called the Chippewa phase. Subsequent uplift of the North Bay outlet caused a rise in water levels within the Michigan and Huron basins, and the two lakes merged at the Straits of Mackinac by about 9,000 calendar years ago, marking the beginning of the Nipissing transgression (Larsen, 1987). Several dates and elevations mark this rise. A buried forest near Chicago at a present depth of 79 ft (24 m) below lake level yielded a date of about 9,200 calendar years ago (Chrzastowski and others, 1990; Pranschke and others, 1990). The lake rose above current lake level and the Port Huron outlet was activated by about 6,900 calendar years ago (Larsen, 1987). Lake Nipissing reached the Chicago outlet and its maximum elevation at about 5,500 calendar years ago (Larsen, 1987), while still draining through the Port Huron and North Bay outlets (Hansel and others, 1985). Downcutting of the Port Huron outlet of Lake Huron through glacial deposits caused a drop in water level to the current elevation of about 580 ft (177 m) (Hough, 1958).

Algonquin beach ridge (west of Kangaroo Lake)

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The Nipissing highstand is represented in Door County by a well-developed shoreline at an elevation just above 600 ft (183 m), about 20 ft (6 m) higher than present-day lake level (plate 1). While this shoreline is not continuous around the entire peninsula, it is generally better expressed than the Algonquin shoreline. The few places where Nipissing features are absent are areas where more-recent wave action has cut back far enough to erode the Nipissing features, or where the water would have stretched far inland in narrow valleys, resulting in very subdued, if any, wave action.

In the southeastern corner of the county, the Nipissing shoreline is present as a bluff/terrace feature, cut into a thick deposit of Kewaunee till and underlying lake silt and sand (see picture below). A similar terrace is present on the extreme southwestern side of the peninsula, where the shoreline cuts into a thick deposit of sand and possibly till stacked up against the escarpment (sec. 21/22/28, T26N, R28E). Toward the north on the Green Bay side of the county (at Peninsula State Park, for example), the Nipissing shoreline is typically present as a dolomite cliff and terrace on the headlands and a beach ridge complex at the heads of the bays. A Nipissing beach is also present along much of the eastern shore.

Nipissing dune complexes are also present on the eastern side of the peninsula (map unit *d*, plate 1). The most prominent dunes occur at the southern edges of the three large lakes of Door County: Europe, Kangaroo, and Clark Lakes (plate 1). In each case, the dunes separate the lake from Lake Michigan. The aerial picture (below) shows the dune complex near Clark Lake; parallel dunes are highlighted by snow filling depressions between each ridge. It is most probable that the lakes were initially bays of Lake Michigan, and were subsequently isolated by the building of a longshore bar out from the rocky headlands on the eastern side of the lakes. With the drop in the Nipissing lake level, the bar was exposed and dunes began to form (Schneider, 1993a). Similar parallel dunes are also found at the northern shore of several other bays on the eastern side of the peninsula, most prominently at Bailey's Harbor (Johnson and others, 1990; Thompson and Baedke, 1997).

Nipissing dune complex (near Clark Lake)

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Nipissing wave-cut bluff (south of Sturgeon Bay)

Eric C. Carson

Pleistocene and Holocene history

Bedrock topography

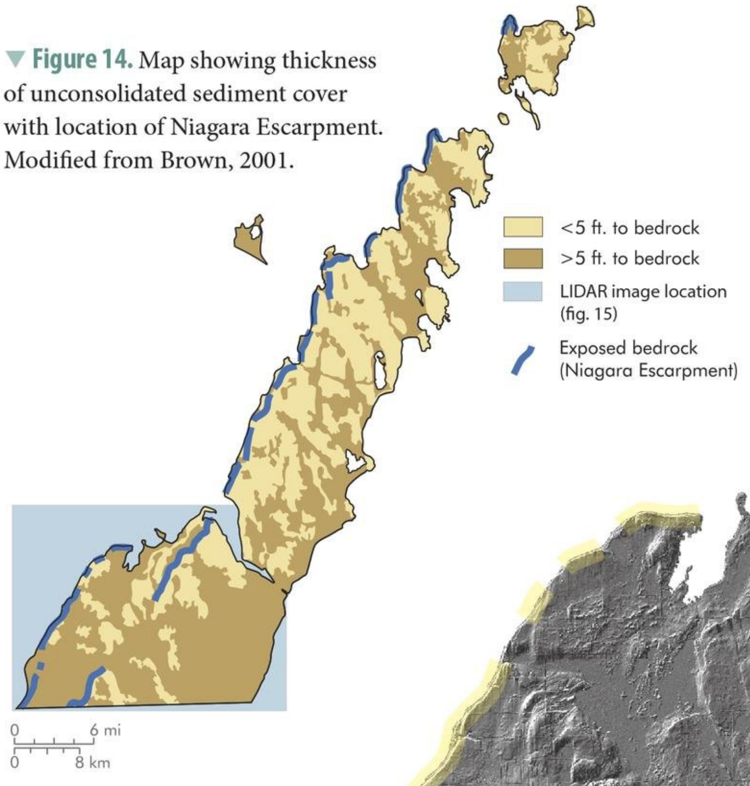
The bedrock surface of Silurian dolomite is the primary control of land surface topography throughout much of Door County. Bedrock is commonly exposed in road cuts and drainage ditches, and is spectacularly displayed on the western side of the peninsula where it outcrops as steep cliffs of the Niagara Escarpment. Joint patterns in farm fields can be seen in many aerial photos of the county, an expression of the thin sediment cover over bedrock.

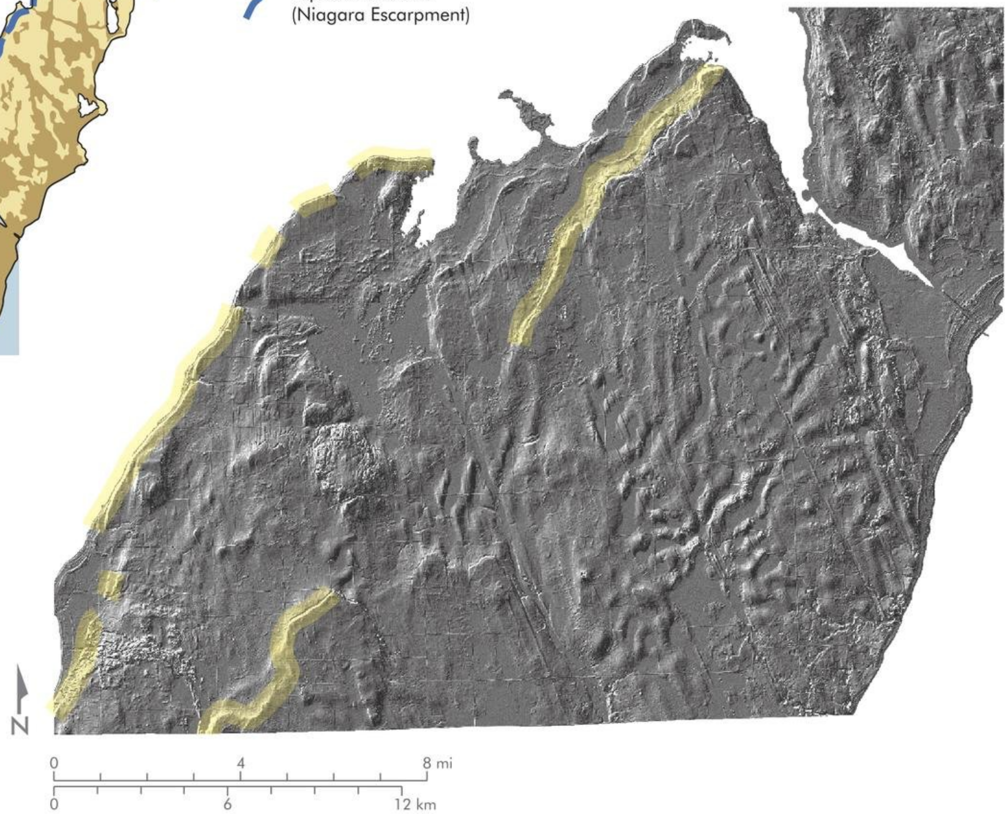
Despite the prominent surface expression of the bedrock topography throughout much of the county, the construction of a bedrock topography and sediment thickness map for Door County was deemed necessary to determine depth to bedrock within valleys and in the southeastern part of the county, where a thick layer of glacial sediment obscures the bedrock topography. A bedrock topography map was constructed by Sherrill (1978) with a 50-foot contour interval.

Several prominent bedrock features are expressed in the surface topography of northern Door County. The most striking feature is the Niagara Escarpment, which forms the steep bluffs along the county's western shoreline. Here, the resistant Silurian dolomite rises sharply above Green Bay, a trough eroded by the glaciers through the soft Maquoketa shale and older carbonates that underlie the Niagara dolostone.

In the southern part of the county, the Mayville Formation and the Schoolcraft Member outcrops are expressed as a double escarpment, with two rises separated by about 5 miles (8 km) (figs. 14 and 15). In the northern part of the county, only the upper main escarpment is present on land, rising steeply above the Green Bay shoreline. The lower

▼ **Figure 14.** Map showing thickness of unconsolidated sediment cover with location of Niagara Escarpment. Modified from Brown, 2001.





▶ **Figure 15.** Lidar image of southern Door County, showing the double escarpment (highlighted in yellow).

escarpment is present below water level, expressed as a high ridge on the bathymetric map of Green Bay (fig. 16). Several small outlier islands between Chambers Island and the Door Peninsula are present where this lower escarpment breaks the water surface.

In general, the escarpment is much steeper in the northern part of the county than in the south. At Death's Door Bluff, on the tip of the peninsula, in the space of just 1 mile (1.6 km), the escarpment rises almost 300 ft (91 m) above the bottom of Green Bay. West of Egg Harbor, the escarpment rises about 270 ft (82 m) in 2 miles (3.2 km). In southern Door County, the lower escarpment rises only 100 ft (30 m) above the bottom of Green Bay near Little Sturgeon Bay. Here, the upper escarpment rises only about 80 ft (24 m) above the landscape.

The Niagara Escarpment is dissected in several places by broad bays. Sturgeon Bay is the largest, but Egg Harbor, Fish Creek Harbor, Eagle Harbor, Sister Bay, and Ellison Bay are also superb examples. Each of these re-entrant valleys is connected to a similar broad bay on the opposite side of the peninsula (Chamberlin, 1877; Schneider, 1989, 1990a, 1993c) by linear lowlands (fig. 17, plate 1). The valley at Sturgeon Bay crosses the peninsula

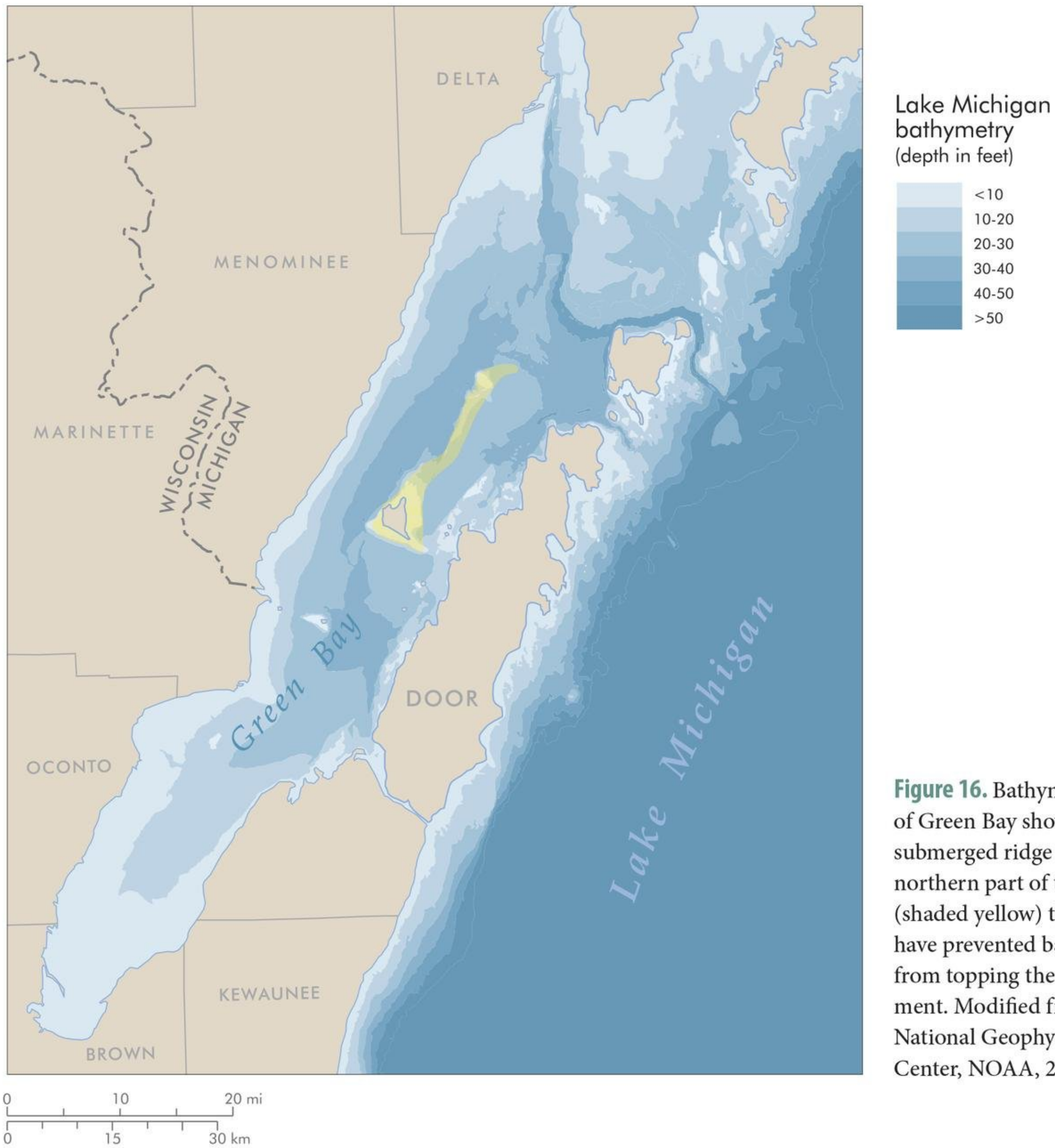


Figure 16. Bathymetric map of Green Bay showing the submerged ridge in the northern part of the bay (shaded yellow) that may have prevented basal ice from topping the escarpment. Modified from National Geophysical Data Center, NOAA, 2000.

by the ship canal. Egg Harbor connects with Whitefish Bay through the Logan Creek Valley. Fish Creek Bay matches with Piel Creek and Kangaroo Lake, while Eagle Harbor lines up with Baileys Harbor and Moonlight Bay. Sister Bay connects with North Bay, while Ellison Bay and Garret Bay connect with Rowley Bay.

The valley mouths, where they meet the Green Bay basin, are typically very deep. On the southwest side of Ellison Bay (NE¼, sec. 15, T32N, R28E), a private well log records a depth to bedrock of 128 ft (39 m). The escarpment rises sharply to an elevation of 750 ft (229 m) less than 0.5 miles (0.8 km) south of the well, making the total depth of the valley mouth over 250 ft (76 m). Across the peninsula, at Rowley Bay, bedrock is more than 40 ft (12 m) below the surface on the south shore of the bay (Crescent Point) and is exposed along the shoreline on the opposite side of the bay.

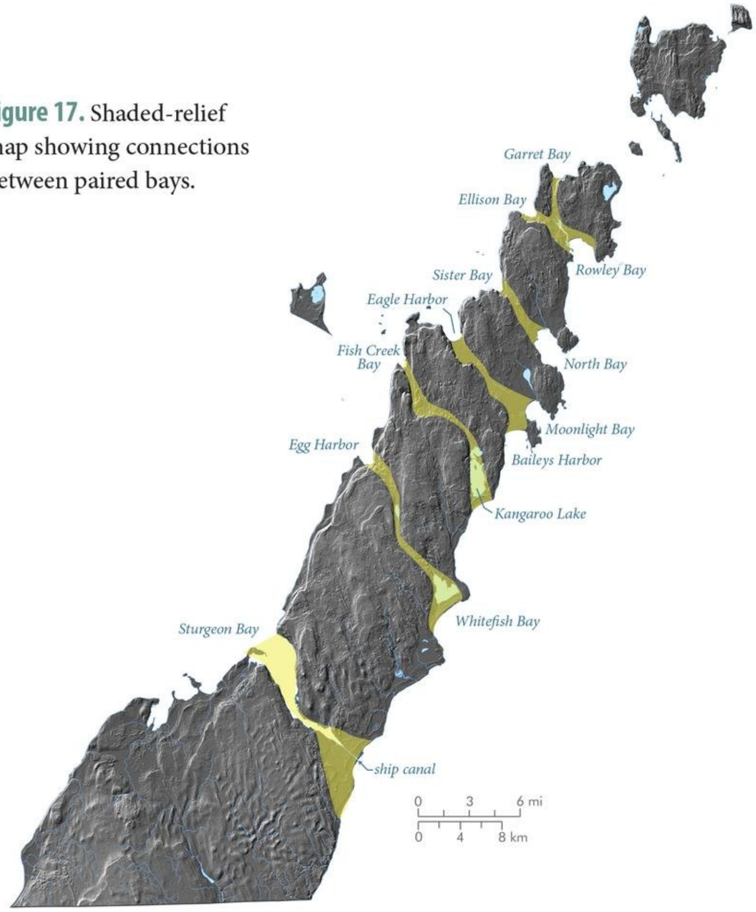


Figure 17. Shaded-relief map showing connections between paired bays.

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The depth to bedrock in the central parts of the valleys is also poorly constrained. Private wells in these areas are uncommon due to the marshy land surface, and the bedrock surface was generally difficult to recognize in the few sample borings drilled in this study, due to the stony nature of the valley fill (typically Liberty Grove till). Data points that are available for the depth of valley fill are typically located near the edges of the valleys, making records of the deepest areas sparse.

The valleys trend south-southeast across the peninsula, oblique to the dip of the bedrock but consistent with one of the major joint trends in the dolomite (fig. 18). Martin (1916) suggested that Sturgeon Bay is actually a preglacial valley that crosses the peninsula from the western shore of Green Bay to a river in the Lake Michigan lowland. Evidence for this interpretation is lacking, although the theory is plausible. Dutch (1980) and Schneider (1993a) proposed that these preglacial valleys were deepened and widened by advancing ice prior to the general glaciation of the upland surface.

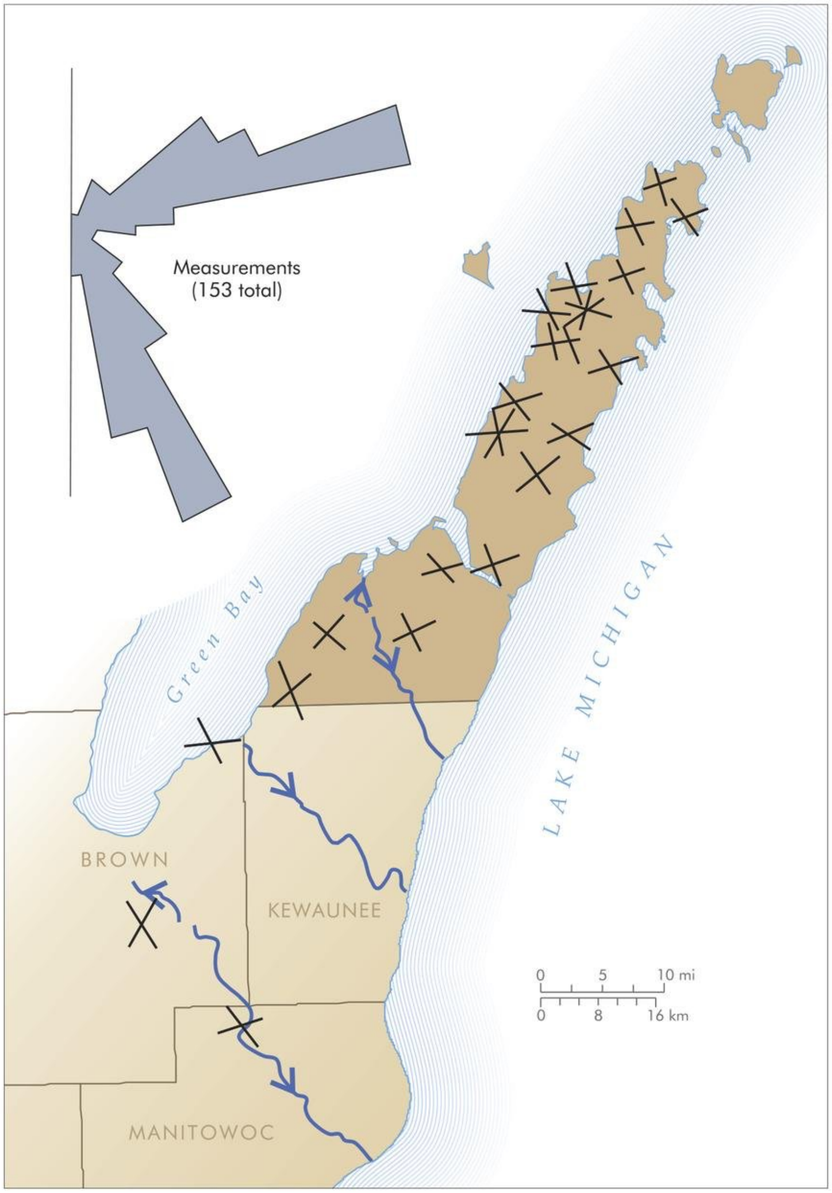
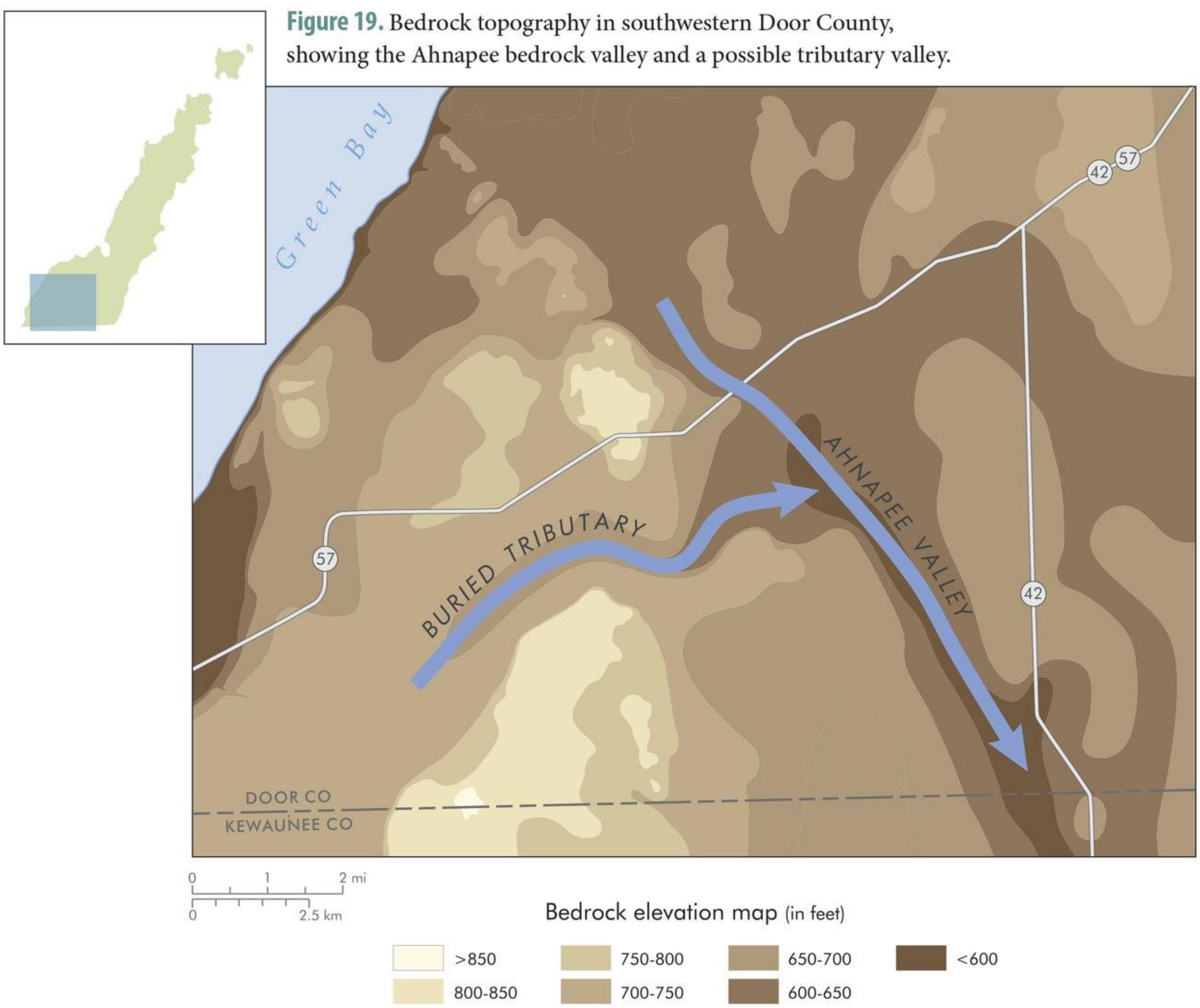


Figure 18. Major bedrock joint orientations and stream valleys along the Door Peninsula. Modified from Dutch, 1980.

In the southern part of Door County, the bedrock topography is not as evident because of the thicker cover of unconsolidated sediment. Dolomite outcrops are scarce away from the escarpment, though some resistant knobs do protrude through the Quaternary sediment. The most prominent bedrock valley in southern Door County is that of the Ahnapee River and northward its extension into Gardner Swamp. The bedrock valley deviates from the modern river course just east of Brussels, with the former valley veering closer to Brussels Hill than the modern channel (fig. 19). A second major buried valley is present east of Forestville, underlying the Stony Creek, Silver Creek, and Maplewood swamps. This valley parallels the Ahnapee valley, but appears to be much broader (although this may just be an artifact of the lack of data points). The head of the valley lies just to the west of Maplewood swamp, where it is truncated by the Ahnapee valley. Continuation of this valley into Kewaunee County, under the Silver Creek swamp, is based on the preliminary bedrock topography map by Clayton (2013). Alternatively, this valley may trend to the east just north of Carnot, following the modern Bear Creek valley. However, based on the south-southeast trend of the majority of the valleys in Door County, the first interpretation seems most plausible.

Figure 19. Bedrock topography in southwestern Door County, showing the Ahnapee bedrock valley and a possible tributary valley.



Influence of karst

One factor that complicates the construction of the bedrock elevation map is the effect of karst in the area. Karst features, such as caves, abandoned river channels, stepped bedrock surfaces, and bedrock pavements, have been identified by Rosen (1984), Rosen and others (1987), Johnson (1987), Johnson and Stieglitz (1990), Stieglitz and Schuster (1993), and Brozowski and Day (1994). While most of these features are fairly small scale and cannot be resolved on this bedrock map, there is a good chance that karst may have affected the bedrock topography on a countywide scale.

In the construction of the bedrock topography map (Brown, 2001), closed depressions were not drawn unless ample core data confirmed their existence. For the most part, isolated deep areas were connected to nearby valleys, rather than identified as karstic sinkholes. Making these connections was often an easy task, as data points are scarce in the lowlands. This lack of data, though, also makes the interpretations in these areas very tentative.

Many of the valleys traversing the peninsula have irregular, step-like, long profiles. Marshy lowlands within the valleys, representing flat areas, are connected by small streams cut into a gradually sloping segment of the valley. William Schuster of the Door County Soil and Water Conservation Department (oral communication, 2000) has interpreted marshy areas as representing collapsed portions of a linear cave system, while the streams run over more stable regions of the karstic zone. While this interpretation may have merit, it is contradicted by the lack of extensive karst fluvial systems in the county, and it seems more likely that the irregular valley profiles are due to differences in thickness of glacial fill. Stream stretches often cut through landscape that is somewhat hummocky in nature, suggesting that the areas between marshes were formed at marginal ice-stagnation positions. Extensive drilling within the valleys would prove helpful in determining their true character and genetic history.

One major sinkhole is on Rock Island, at the northern end of the county (fig. 20). Two sub-basins are present within this feature, one 30 ft (9 m) deep and the other 40 ft (12 m) deep; they are separated by a ridge that is only 10 ft (3 m) below the lip of the depression. Both basins are somewhat linear, trending south to south-southeast, suggesting joint control as in the other, larger valleys described above. While the existence of this feature seems to support the hypothesis that valleys in Door County are karst-derived, the valleys may also be the result of differential glacial erosion of the bedrock surface.

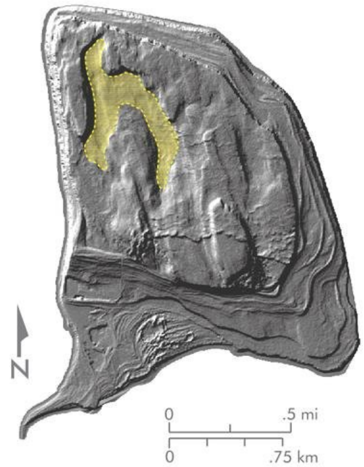


Figure 20. Lidar image of Rock Island showing the large sinkhole (shaded in yellow).

Eric C. Carson

Flow indicators of the Green Bay Lobe

Striations

As a wet-bedded glacier slides over a bedrock surface, debris incorporated into the base of the glacier gouge the underlying bedrock, etching scratches and grooves in the rock surface (see picture below). These striations leave a record of the direction of ice movement (parallel to the striation trend). Striations have been used in many studies to determine ice dynamics and flow directions (Gemmell and others, 1986; Kleman, 1990; Iverson, 1991).

Because of the abundance of bedrock exposures in Door County, ample striation data are available. Striations are found on bedrock surfaces exposed in road ditches, gravel pits, dolostone quarries, and foundation excavations. The marks are typically 1 to 5 ft (0.3 to 1.5 m) long, although some are several tens of feet (several meters) long. The depths range from 0.04 to 0.1 inches (1 to 3 mm), with shallower striations most common. Striations are most commonly found in areas that have been covered with at least several inches (tens of centimeters) of sediment, as the sediment cover serves to neutralize acidic water that would otherwise slowly dissolve the bedrock surface (Stieglitz and Schuster, 1993).

Other small-scale scoured bedrock forms are also present. In exposures where dolostone contains small chert nodules, it's common to find tiny rock ridges that are steep on one end and taper off on the other (known as crag and tail, respectively). Because the side that faced an advancing glacier is more abraded than the side facing away, these small features provide confirmation about ice flow direction.

Broad grooves are also present at some locations (NW¼, NE¼, sec. 3, T27N, R26E). These features are usually about 0.4 inches deep (1 cm), 4 to 8 inches wide (10 to 20 cm), and over 10 ft (3 m) long. Striations are present in some of the grooves, most commonly trending the same direction as the grooves, but occasionally crossing the grooves at oblique angles.

Striations commonly show distinctly different trends within the same site. In localities where the sets are not crosscutting, these different trends can be explained by spatial flow variations caused by bedrock topography. In areas where the bedrock is flat or where striations cross at some angle, however, they represent either a shift in the flow direction of the glacier over time, or a completely separate advance (Gray and Lowe, 1982).

We recorded trends of 63 striations, crags and tails, and grooves found at 39 sites during the field seasons of 1999 and 2000. At some sites, several distinct directions were present, and each was recorded separately. The striation measurements were then compiled into an ArcView coverage, with lines extending southward from the striation site (fig. 21).

Striations (pen points in direction of ice flow)

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▶ **Figure 21.** Orientations of glacial striations. Lines trend from the site of measurement in the direction of ice flow (generally southerly).

Two main sets of glacial striations are present in Door County, with a third minor set. The first set trends north–south to 10 degrees west of north (subsequently referred to as the north–south set), and is dominant in the northern two-thirds of the peninsula (north of Sturgeon Bay). Any other striation orientation is typically much fainter. Even with this difference in expression, only in rare cases can a relative age sequence for the striations be determined. The relative age of the two orientations could only be determined for certain at one site, where north–south grooves are crossed by striations that trend north-northwest (Brown, 2001). The grooves must have been formed before the striations, although how long before cannot be determined.

The second main set trends roughly 15 to 30 degrees west of north in the southern part of the county, where it is the dominant striation orientation, and 25 to 35 degrees west of north in the northern part of the county. The north–south set is present in the south, but is typically much more poorly expressed than the north-northwest set. No age relations between the different sets could be determined in the south, so no conclusions can be made as to how they relate to the striation directions in the north.

A minor set of striations trends 20 to 30 degrees east of north, approximately parallel to the axis of the peninsula. They are most common in the southern half of the county and along the eastern shore of northern Door County, but were also recorded at two sites on Washington Island and one site near the base of the escarpment just north of Sturgeon Bay.

Drumlins

Drumlins are long, oval-shaped streamlined hills that formed at the base of glaciers. The long axes are oriented in the direction of glacier flow (Bennett and Glasser, 1996). The process of formation of these landforms has long been debated. Boulton (1987) suggested that drumlins form by subglacial deformation in the lee side of bumps on the bed of the glacier. Whittecar and Mickelson (1977, 1979) argued for subglacial erosion of drumlins. More recently, Shaw (1983) and Shaw and Sharpe (1987) hypothesized that drumlins are eroded by huge subglacial sheet floods. The genesis of drumlins is not addressed here; the importance of these forms in this study is the well-supported theory that drumlins reflect ice-flow direction.

There are multiple small drumlin fields in Door County (fig. 22). The northernmost drumlin field, first described by Kowalke (1952) then by Thwaites and Bertrand (1957) and Schneider (1981, 1989, 1990a, 1993c), is located just east of Sister Bay in the town of Liberty Grove. Several road cuts and one borehole (B-11-99) in the drumlins reveal that they are composed almost entirely of Liberty Grove till. A foot-thick lens of well-sorted, medium to coarse sand was encountered in the borehole, but this is most likely a localized feature and may not be significant in the drumlin's formation. The Liberty Grove drumlins typically range from 10 to 20 ft (3 to 6 m) high, but a few are as much as 40 ft (12 m) high. These drumlins are relatively stubby,

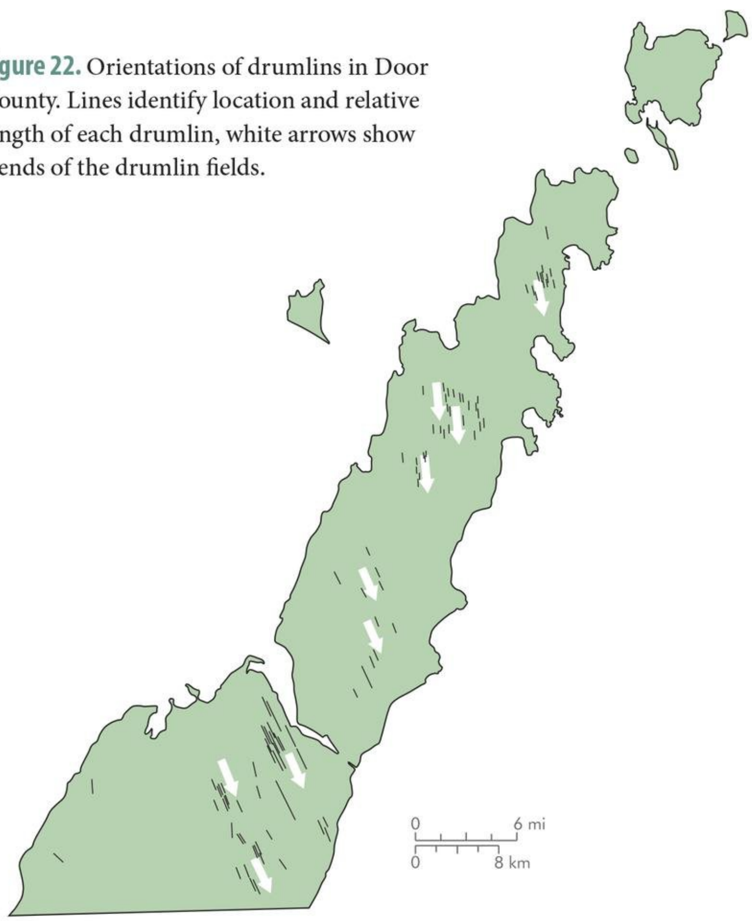

Figure 22. Orientations of drumlins in Door County. Lines identify location and relative length of each drumlin, white arrows show trends of the drumlin fields.

typically less than 0.25 miles (0.4 km) long and an average length-to-width ratio of 4:1 (fig. 23b). The long axes of most of the drumlins trend 10 to 15 degrees east of south. The northern end of the drumlin field is truncated by the east–west trending Wildwood moraine, suggesting that the ice front temporarily stabilized as the glacier retreated or, perhaps more likely, there was a minor readvance of the ice to the position of the moraine.

The second drumlin field is present northwest of Kangaroo Lake (plate 1). They are predominately composed of Liberty Grove till, although two roadcuts across drumlin axes expose well-sorted, massive, fine sand and silt in the drumlin cores (SW¼, sec. 12, T30N, R27E; NW¼, sec. 14, T30N, R27E). These drumlins have a more subdued relief than the field farther north, with an average height of less than 15 ft (4.5 m), but they are otherwise similar in shape (average length-to-width ratio of 5:1). The drumlins in this field trend due south and line up almost perfectly with the section roads.

The third, and largest, drumlin field occurs immediately southwest and south of Sturgeon Bay, with orientations between 20 and 25 degrees east of south (fig. 22) (Thwaites and Bertrand, 1957; Schneider, 1993a, 1993c). While the relief of these drumlins is similar to the drumlins in the north, these drumlins are much more elongate with an average length-to-width ratio of 16:1 (fig. 23a). Some, just south of Sturgeon Bay, are over 2 miles (3.2 km) long. These drumlin clusters also seem to occur over deeper bedrock valleys, whereas in the north the drumlins sit almost directly atop a flat or broadly stepped bedrock surface.

The composition of the drumlins in the south is similar to the other drumlin fields, but may contain more sand and gravel. A gravel pit in the head of one of the drumlins along Highway 42/57 (sec. 13, T27N, R25E) exposes silty Liberty Grove till intermixed with layers of well-sorted sand, gravel, and cobbles, about 3 ft (1 m) thick. In some places the gravel beds are deformed, suggesting that there was at least some modification of the sediment as the drumlin formed. Also, these drumlins are in many places capped with a thin veneer of reddish-brown clay till (Schneider, 1993c) or at least a very clayey soil profile suggestive of a layer of clay that has been mostly eroded away.

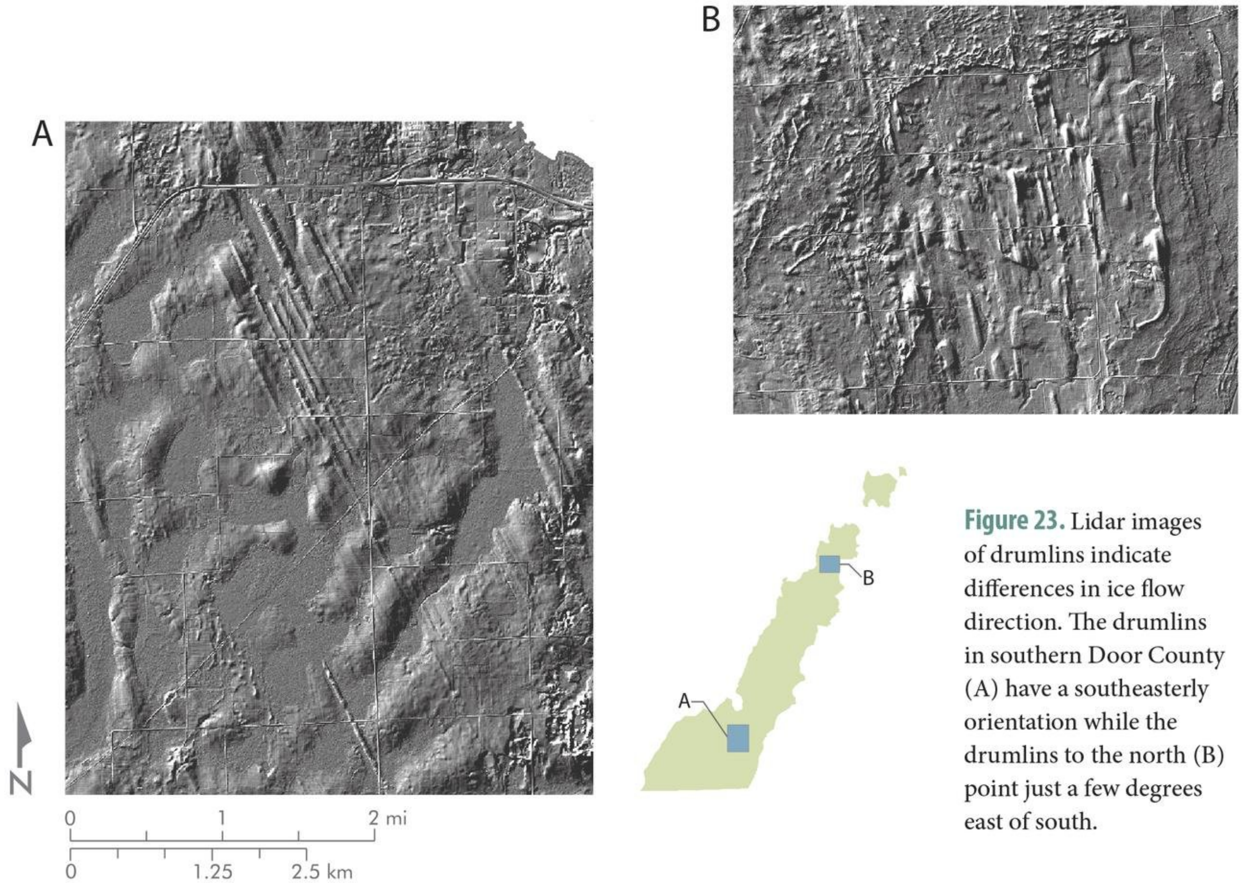

Figure 23. Lidar images of drumlins indicate differences in ice flow direction. The drumlins in southern Door County (A) have a southeasterly orientation while the drumlins to the north (B) point just a few degrees east of south.

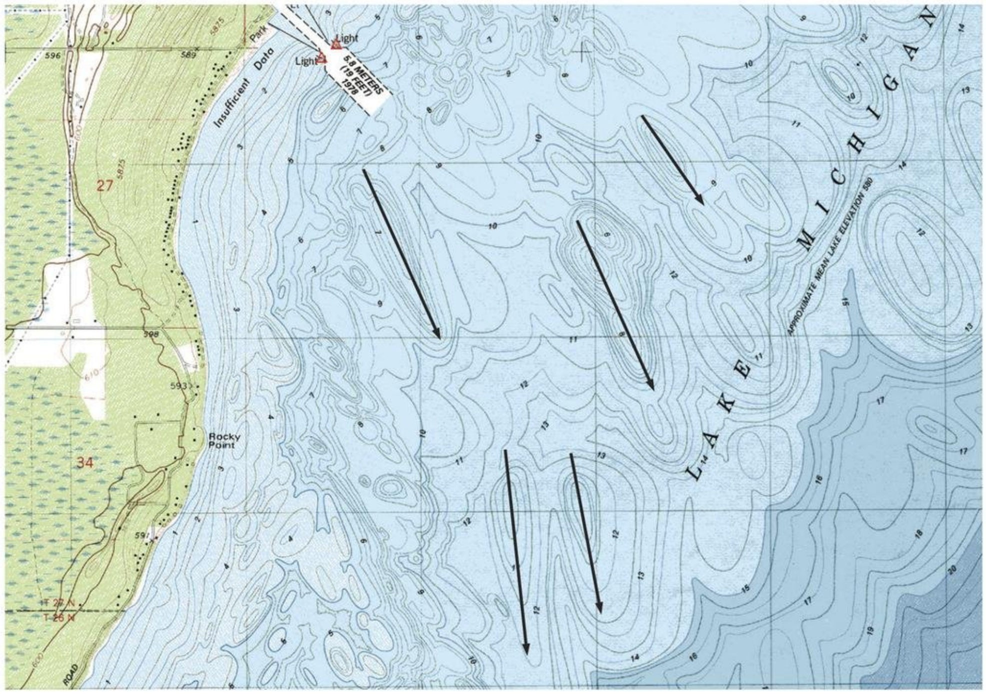

Figure 24. Bathymetry of Lake Michigan showing trends of streamlined features that may be submerged drumlins (part of the Sturgeon Bay East 7.5-minute quadrangle).

Other drumlins are scattered around the county, but the most striking ones are just offshore in Lake Michigan. Detailed bathymetric maps near Sturgeon Bay (printed on the Idlewild, Sturgeon Bay East, and Sturgeon Bay West 1:24,000 quadrangles) provide a view of nearshore topographic features. The presence of many "dimples" in the bed topography suggests that the soundings have been contoured with a computer program, which makes any identification of small-scale forms suspect. However, larger landforms that may be submerged drumlins can be identified with reasonable confidence. Approximately 1 mile (1.6 km) north of Sherwood Point, near the head of Sturgeon Bay, is a large feature with a relief of over 15 ft (4.5 m), a length of about 1 mile (1.6 km), and an orientation of 10 degrees east of south. Another streamlined feature, 0.5 miles (0.8 km) long, is present in the bay just west of downtown, with an orientation of 20 degrees east of south (SW¼, sec. 6, T27N, R26E). At the eastern end of the Sturgeon Bay Ship Canal, there is a series of large streamlined landforms, 0.5 to 1 mile (0.8 to 1.6 km) long, with orientations ranging from 5 to 25 degrees east of south (fig. 24).

Unfortunately, we know nothing of the composition of these sub-aqueous forms. Due to their size and shape they may be drumlins or perhaps streamlined bedrock forms. They are consistent with trends of striations and other drumlins in the area, and thus can be used to extend the glacial flow pattern into the lake basin.

Eskers

Several small, discontinuous eskers are found throughout Door County. The most prominent esker is a large winding ridge southwest of Brussels in Union Township. The feature trends generally southeastward across the county line into northern Kewaunee County, where it follows a gap or reentrant angle in the Niagara Escarpment. Slightly less than half of its 6-mile (10 km) length is in Door County. The feature has a maximum relief of nearly 50 ft (15 m), but its typical height is around 30 to 35 ft (9 to 11 m) (Schneider, 1990b).

Moraines

Stationary glacier fronts accumulate sediment at the margin to form moraines. These ridges of sediment have moderately hummocky topography, commonly with steep down-ice sides (the side facing out from the glacier) and gradually sloping up-ice sides (the side facing towards the glacier). Because ice thins toward the glacier margin, and ice flows toward thinner areas, moraines are deposited approximately perpendicular to the ice flow direction (where ice is not confined in a valley). Thus, it is possible to estimate the flow direction of a glacier by looking at the moraines it deposited.

Moraines are present in Door County in a variety of forms. There are several broad hummocky areas, east of Ephraim for example, that may represent stagnant ice-marginal positions. Hummocky areas in the valleys between swamps may also represent ice-marginal positions. However, these features have no noticeable trend and are therefore not significant in determining flow direction of the ice.

Four linear moraines, shown in figure 25, are present in Door County; they provide further insight as to the direction of ice movement, as they form perpendicular to ice-flow direction. All the moraines are composed of Liberty Grove till, although the southernmost moraine, near Little Sturgeon Bay, is capped with a thin veneer of Glenmore deposits. These linear moraines are also fairly low-relief features, the largest having a maximum relief of only 30 ft (9 m); as such, they are relatively prominent features on high-resolution lidar images, but are fairly subdued features when seen from the ground (fig. 25 and photograph below).

Thwaites and Bertrand (1957) described a morainic belt extending south from Sturgeon Bay along the Lake Michigan shore to Two Rivers, Wisconsin, and correlated it with the Manistee moraine, which may extend across Lake Michigan between Two Rivers and Manistee, Michigan. They described this moraine as either an interlobate moraine where two ice lobes pushed together or a retreat moraine formed as the Lake Michigan Lobe melted back into the basin.

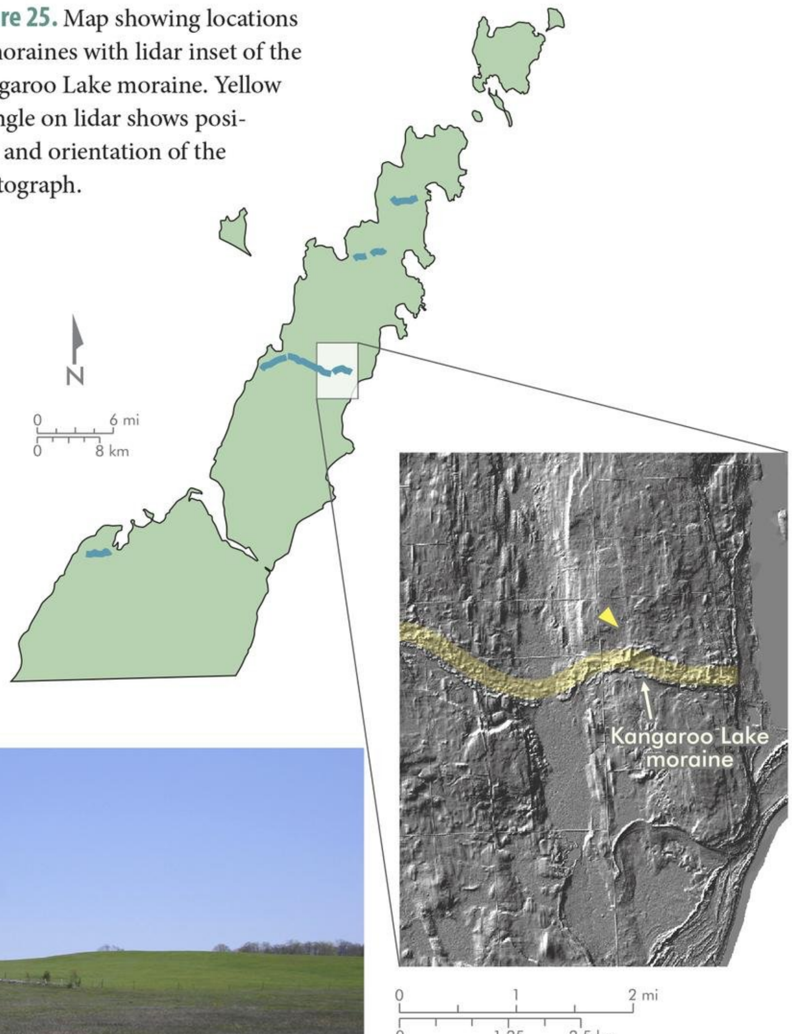

Figure 25. Map showing locations of moraines with lidar inset of the Kangaroo Lake moraine. Yellow triangle on lidar shows position and orientation of the photograph.

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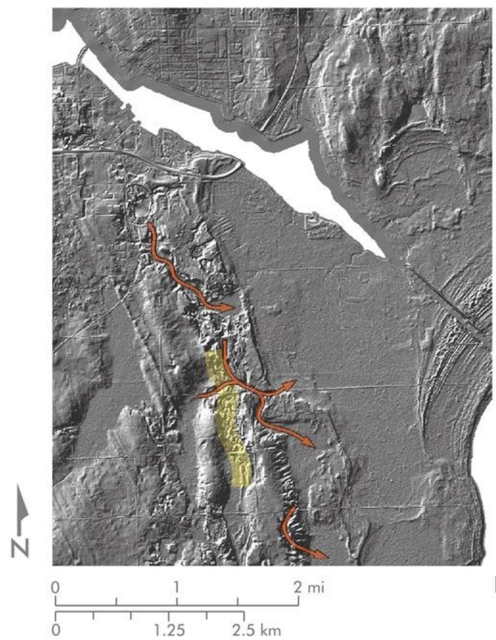
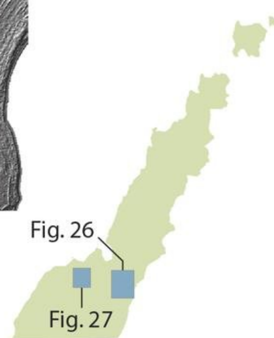
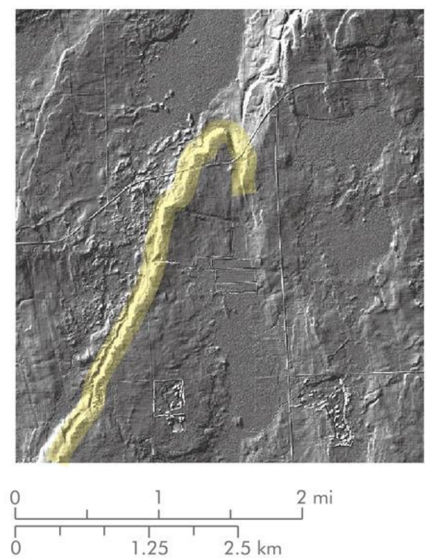


◀ **Figure 26.** Lidar image showing the 'moraine' described by Thwaites and Bertrand (1957). Orange lines trace former meltwater channel paths, the yellow line marks the crest of the esker.



▼ **Figure 27.** Lidar image of a streamlined promontory in southern Door County. The steep topography of the up-ice edge is highlighted in yellow.

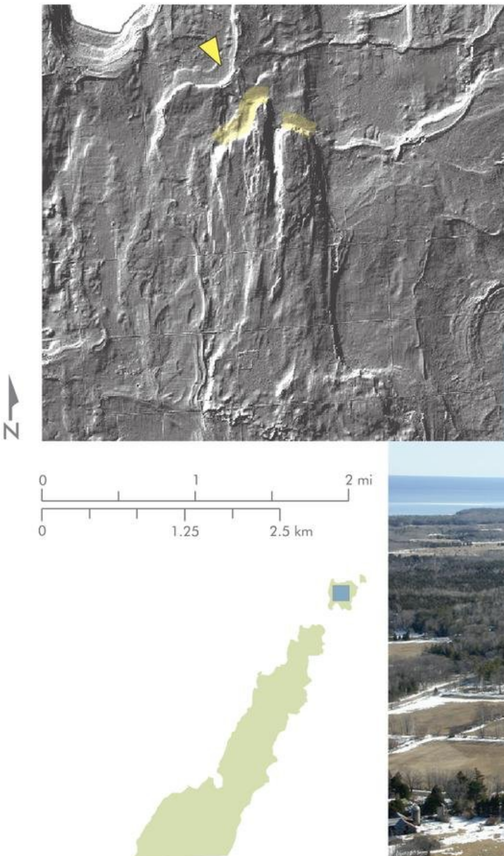


At first inspection, the morphology of this area does appear similar to the Kettle Moraine of east-central Wisconsin (see Syverson, 1988; Chapel, 2000; Carlson and others, 2005). Much sand is present, and many large channels cut through the area (fig. 26). However, most of the sand is nearshore lake sediment that underlies the surface till, and the channels were probably formed by water flowing from large melting ice blocks partially buried in the sand, or by meltwater directly from the glacier margin. A long, undulating esker is present in the bottom of one of the channels, suggesting that this may have been a tunnel channel. If so, it would have formed under the ice, roughly perpendicular to the margin rather than as a crevasse fill or other ice-marginal deposit.

Streamlined bedrock forms

Streamlined bedrock forms are produced by erosion of bedrock protuberances, caused by debris-rich ice or a slurry of water and sediment, as the glacier flows over and around an obstacle. Many different features have been described that vary widely in size. The smallest include striations, micro-crag-and-tail features, and a variety of scoured forms described by Shaw (1994). Medium- and large-scale features include drumlin-shaped bedrock, roches moutonnées (knobby bedrock hills), and whalebacks (long bedrock mounds) (Benn and Evans, 1998).

Door County has several streamlined bedrock features that are about 50 ft (15 m) high and approximately 0.25 miles (0.4 km) across. They are characterized by prominent, steep rises on the northern (up-glacier) sides of the hills and gentler slopes on the southern sides (fig. 27). Glacially

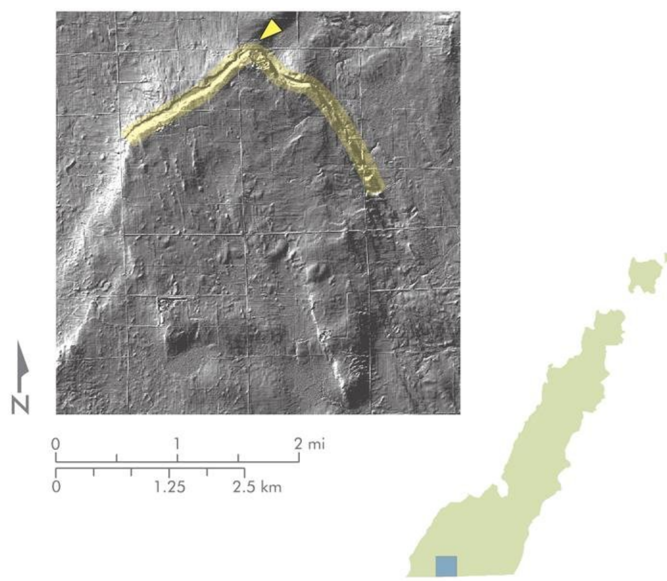


◀ **Figure 28.** Streamlined bedrock promontory on Washington Island. Ice direction, inferred from the shape of the promontory, was from north to south. The yellow triangle on the lidar image shows location and orientation of the photograph. In both images, yellow lines show the base of the northern (up-ice) escarpment.

striated, flat bedrock surfaces commonly occur both at the bases of the hills and at their crests. They are present predominately on the top of the Niagara Escarpment, though some are found in the central and eastern parts of northern Door County. Similar forms have been identified on the Bruce Peninsula in Ontario, Canada (Brown and others, 2000), but widespread discussion of forms of this size is lacking, having only been briefly mentioned by Straw (1968). These features are informally referred to as streamlined promontories. The streamlined nature of these forms is especially evident in the shape of the "mountain" on Washington Island (sec. 31, T34N, R30E; fig. 28). Here, a steep north-facing slope rises from a 660-foot bedrock bench to an elevation of 750 ft (229 m), then slopes gently down to the south. The eastern flank is a steep, north–south trending slope that broadens to the south, while the western flank trends in a southwesterly direction and is not so steep. A deep, north–south valley cuts the landform roughly in half and is graded northward to the lower bedrock surface. Small sea caves are present in the bedrock at the base of the northern side of the promontory, evidence of wave action by the highest Algonquin lake level. While wave erosion certainly steepened the slope, it is unlikely that the entire landform was created by wave action.

A larger streamlined promontory with a considerably different morphology is located in the southern part of the county, just southeast of the town of

Brussels (secs. 20 and 21, T26N, R24E). The flanks of this promontory are very straight and trend almost exactly southwest and southeast from its nose (fig. 29). Given their correlation with the major joint patterns in the dolomite, it is most likely that the orientations of these faces are structurally controlled (fig. 18). Also, the promontory is located at the contact between overlying Manistique Formation and the underlying Byron and Hendricks Formations, suggesting stratigraphic control as well (fig. 5). The bedrock surface drops sharply from the top edge of the promontory to a depth of at least 60 ft (18 m) below the surface, evidenced by a borehole drilled just northwest of the western flank. A thick ramp of homogeneous Glenmore till is present up against both slopes, separated from the promontory by a shallow, undulating channel (fig. 29).



▲ **Figure 29.** Lidar image and photograph showing streamlined bedrock promontory with preserved meltwater channel in southern Door County. Based on the shape of the promontory, ice is inferred to have moved from north to south. Location and orientation of above photograph shown by yellow triangle. Bedrock is less than 5 ft (1.5 m) below the surface to the south of the channel (left side of photograph), and over 50 ft (15 m) below the surface to the north of the channel (right side of photograph).

Similar sediment ramps are present at the base of the main Niagara Escarpment in at least three other places in Door County. The county landfill is built on one such feature (sec. 34, T28N, R25E), which is composed of at least 50 ft (15 m) of homogeneous Glenmore till. A small sediment ramp is present at the base of the escarpment east of Gardner Swamp, with a poorly consolidated sandy/silty till exposed at its surface (sec. 18, T27N, R25E). A sediment ramp is also present in the northern half of the county, northeast of Little Harbor (SE¼, sec. 31, T29N, R26E), but here the crest reaches less than halfway up the escarpment (fig. 30).

The genesis of these sediment ramps remains uncertain. Deposition is normally expected on the lee side of bedrock obstructions, with material being squeezed into cavities between the bedrock and the ice (Bennett and Glasser, 1996). Gaffield (1991), though, presents several mechanisms for stoss-side deposition of till buildups. He favors deposition of till by the stagnation of layers of frozen debris as proposed by Mickelson (1971). While similar in form, the buildups in Door County are on a much larger scale than those identified by Gaffield (1991), and were deposited by a much larger glacier, so the mechanisms may not be similar.

▲ **Figure 30.** Sediment ramp with wave-cut bluff at the base of the Niagara Escarpment. Bedrock is exposed along the escarpment (in the forest cover) and along the shoreline immediately to the northwest (left) of the ramp. The sediment ramp is composed of over 60 ft (18 m) of till.

Pebble fabrics

The orientation of debris deposited by glaciers reveals clues about ice flow direction. As sediment is transported by basal ice, stresses and movement within the ice cause particles to rotate so their long sides are parallel to the direction of ice flow and the leading edges tilt up. As the glacial ice melts, the sediment is deposited, retaining its orientation (Holmes, 1941).

We measured pebble fabrics at four different sites in Door County, from both the Liberty Grove till and the Glenmore till (fig. 31). Fabrics of the Liberty Grove Member were measured at a quarry on Mathey Road (NW¼, SW¼, sec. 23, T28N, R26E) and at a drumlin exposure behind Nebel Construction (NE¼, NW¼, sec. 13, T27N, R25E). Pebble orientations were measured in the Glenmore Member at the county landfill (NW¼, NE¼, sec. 34, T28N, R25E) and in a bluff exposure south of LaSalle Park (NW¼, NE¼, sec. 32, T26N, R26E). At each site we measured between 40 and 50 pebbles with length-to-width ratios greater than 2:1. Clast sizes ranged from small pebbles to small cobbles.

The rose diagram and equal-area plots from the Mathey pit show a strong preferred orientation that trends about 10 degrees west of north (fig. 31, site 1). The rose frequency plot from the Nebel Construction site trends to the northwest, but is much more scattered than the Mathey data (fig. 31, site 2). The equal-area plot at Nebel, however, shows an additional cluster of points trending to the southeast as well as the northwest.

The Glenmore fabrics appear less strongly oriented than the Liberty Grove till. The rose diagram from the

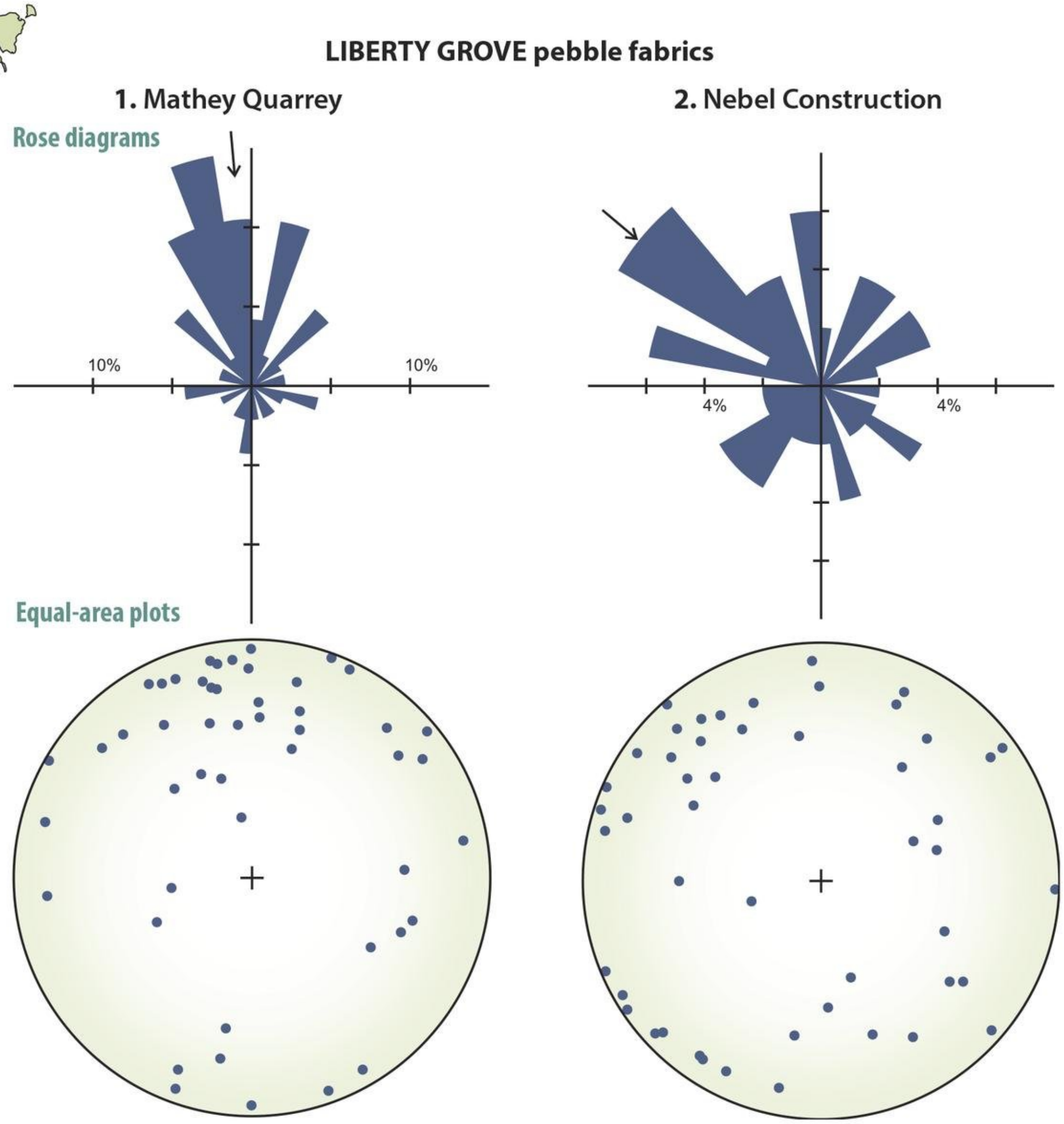


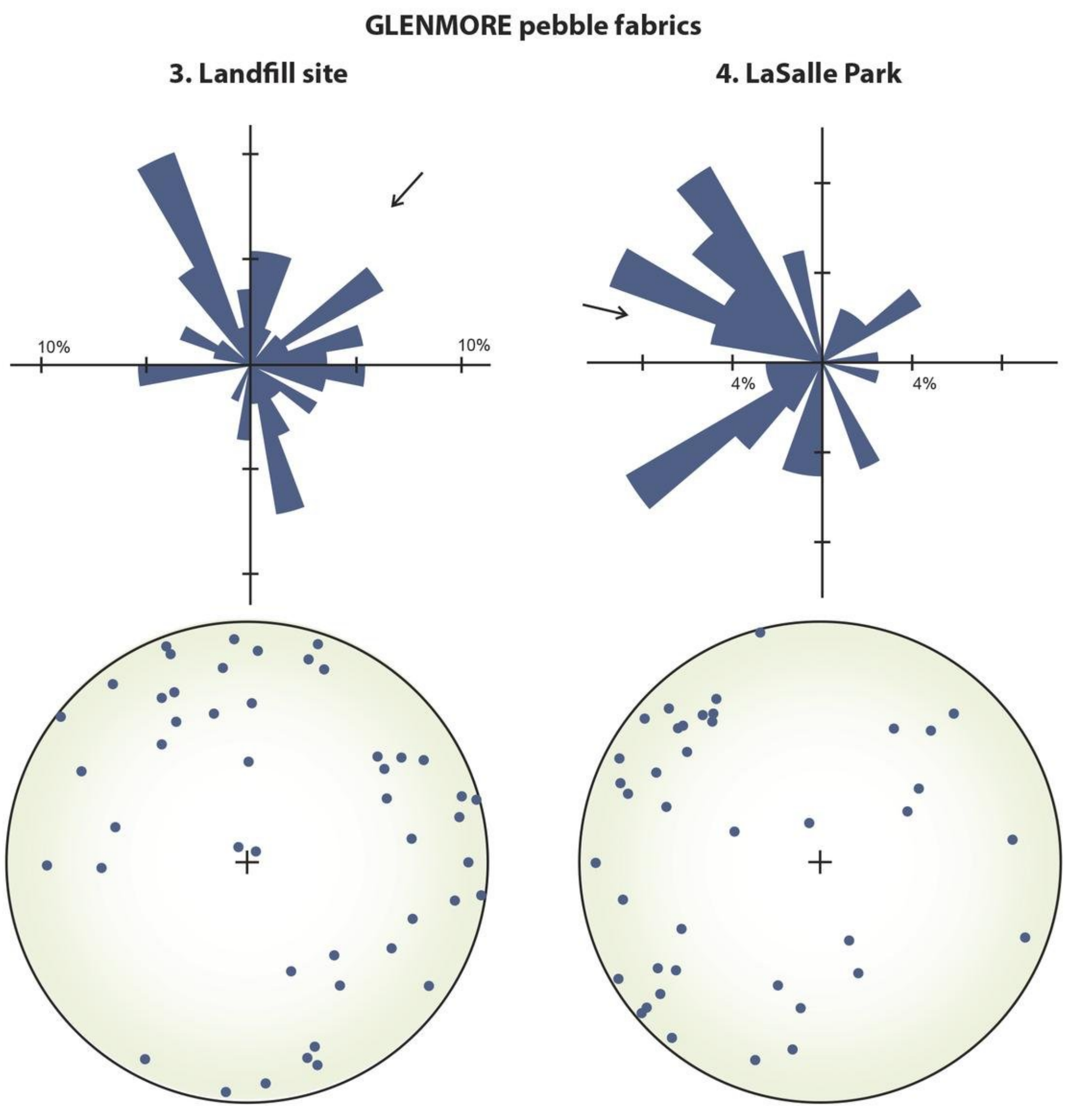
Figure 31. Pebble fabric measurements from four sites in Door County. **Rose diagrams** show the percentage of pebbles oriented in a given direction. **Equal-area plots** depict the orientation of a pebble and how steeply it was dipping. The closer to center a point is, the more vertical the orientation of the pebble; the farther away, the more horizontal the orientation.

landfill site shows a very wide spread of data points with a weak northwest-southeast component (fig. 31, site 3). The LaSalle plots, however, have a bimodal distribution, showing fairly strong fabric toward both the northwest and the southwest (fig. 31, site 4).

In a separate study, Laabs (1999) measured the magnetic orientation (anisotropy) of the fine particles within two Glenmore till fabrics. At LaSalle Park, these clay and silt particles showed a strong trend just west of south, a finding that did not agree well with our analysis of the coarse particles (pebbles) from the same site. The second set of measurements was taken at a gravel pit off Highway U just south of Sturgeon Bay (SW¼, SE¼, sec. 17, T27N, R26E). This fabric shows a strong southerly trend similar to that at LaSalle Park, but it also shows a distinct northwesterly trend, especially in the equal-area plot. This northwesterly trend is also evident in a pebble fabric taken by Hansel and Schneider at the same site (Schneider, 1993a).

Discussion of flow indicators

The five flow indicators described above all aid in interpreting the flow dynamics of the Laurentide Ice Sheet in and around Door County. Some of the flow indicators, such as pebble fabrics, moraines, and possibly drumlins, can be tied to specific depositional events. Striations and streamlined promontories, however, are very hard to tie to a specific event but they still aid in interpreting glacier flow.



In the northern part of the county, strong evidence exists for a dominant southerly (S0W) to southeasterly (S10E) direction of glacial flow. The orientations of the drumlins in the north agree with the dominant striation direction there, though other striation directions are certainly present. Also, the predominately east-west trend of the moraines in this part of the county suggests ice flow from the north out of the Green Bay basin. The fact that moraine trends do not consistently bend in the same direction as ice flow implies the ice front was not extremely lobate across the peninsula at that time.

The glacial flow history in the southern part of the county is more difficult to interpret. Striations suggest flow out of the Green Bay basin, but are only visible on the western side of the peninsula where bedrock is present near the surface. No correlation of striation direction and overlying till is apparent, and thus striation directions cannot be tied to a specific event. Drumlins in southern Door County are roughly parallel to the N20W striations, as opposed to the north–south oriented drumlins in northern Door County. The presence of Glenmore till in southern Door County and not in the north suggests that the different drumlin orientation is due to the advance of the Glenmore ice. However, this interpretation would suggest that Glenmore ice never covered the northern half of the peninsula, which seems implausible. The fabrics from the Glenmore Member generally line up with drumlin orientations, but the drumlins are primarily composed of Liberty Grove till, and the fabric taken in one of the drumlins suggests a southeasterly flow direction for the Liberty Grove ice in this area as well. For this reason it is likely that all of the drumlins in Door County were created by Liberty Grove ice, and were only slightly altered (if at all) by the Glenmore advance.

Streamlined promontories are probably the least reliable of the flow indicators, as their genesis by glacial erosion is only speculative. The strong correlation between promontory limbs and joint orientations, as well as their presence at stratigraphic breaks suggests a primary structural and stratigraphic control, with only minor modification by glacial erosion. Noses of the streamlined promontories almost exclusively point directly north (approximately up-ice), but because the orientation may be predominately structurally controlled by regional joint patterns of the bedrock, they may not point directly into the glacial flow direction.

The correlation of pebble fabrics of the Liberty Grove and Glenmore tills in the south, as well as the shift in both drumlin and dominant striation orientations between the northern and southern parts of the peninsula suggests that the ice depositing the two till units in the county had similar flow characteristics. In the north, flow was due south to south-southeast, while in the south flow was more to the southeast.

Flow dynamics on the Door Peninsula

The Door Peninsula is often proposed as one of the causes for the division of the Green Bay and Lake Michigan Lobes and the boundary between the lobes is commonly drawn down its axis (fig. 32) (Kluessendorf and Mikulic, 1989). However, there is no positive evidence of flow from the Lake Michigan basin in Door County. Only one striation was recorded with a trend west of the axis of the peninsula, and that striation is possibly

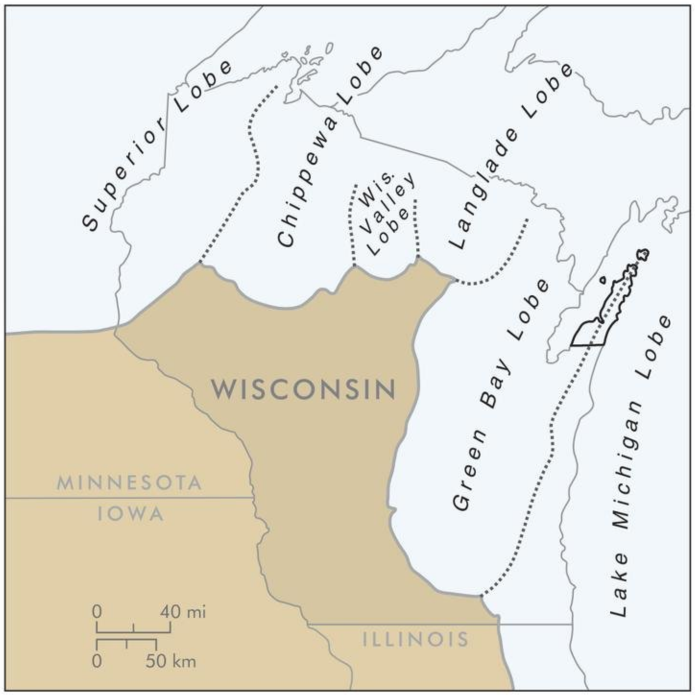


Figure 32. Locations of the maximum extent of glacial lobes of the Laurentide Ice Sheet in Wisconsin during the Last Glacial Maximum (modified from Attig, Bricknell, and others, 2011). Note that the boundary between the Green Bay and Lake Michigan Lobes is drawn through Door County.

non-glacial in origin (for example, it may actually be a bulldozer scrape). All other flow indicators suggest flow out of the Green Bay basin, with some evidence for flow down the axis of the peninsula. Even in the extreme eastern part of the county, submerged drumlins with a northwest trend are present and pebble fabrics show no evidence of flow from the east or northeast.

Possible explanations for the lack of Lake Michigan Lobe influence include: (1) the Lake Michigan Lobe left no ice-flow indicators in Door County; (2) Lake Michigan Lobe ice-flow indicators were eroded by subsequent advances; or (3) flow dynamics were such that the Lake Michigan Lobe did not flow across the peninsula.

Ice flow relative to the peninsula

The flow of the Green Bay Lobe across the peninsula suggests that the interlobe area that divided the Green Bay Lobe from the Lake Michigan Lobe shifted over time. With the interlobate area located roughly coincident with the Door Peninsula, converging ice from the two lobes would have deflected ice of the Green Bay Lobe into a southerly or southwesterly direction. A shift of the interlobe area to the east (into modern Lake Michigan) would have allowed ice of the Green Bay Lobe to flow in a more southeasterly direction across the Peninsula. During the last glacial maximum, ice flow over Door County was probably to the southwest, as there was probably little distinction between the Green Bay and Lake Michigan Lobes in that area. At that time Door County was most likely under an erosive regime, removing most or all of the pre-late Wisconsin deposits and creating striations that are parallel to the axis (fig. 33a). As deglaciation ensued, a shift of the interlobe area eastward would have allowed ice flow of the Green Bay Lobe to shift to a southeasterly trend (fig. 33b).

A repeat of these events may have occurred during subsequent advances as well. This may imply a relatively rapid retreat of the Lake Michigan Lobe (perhaps due to increased calving in that basin due to its greater depth than Green Bay), although this is speculative.

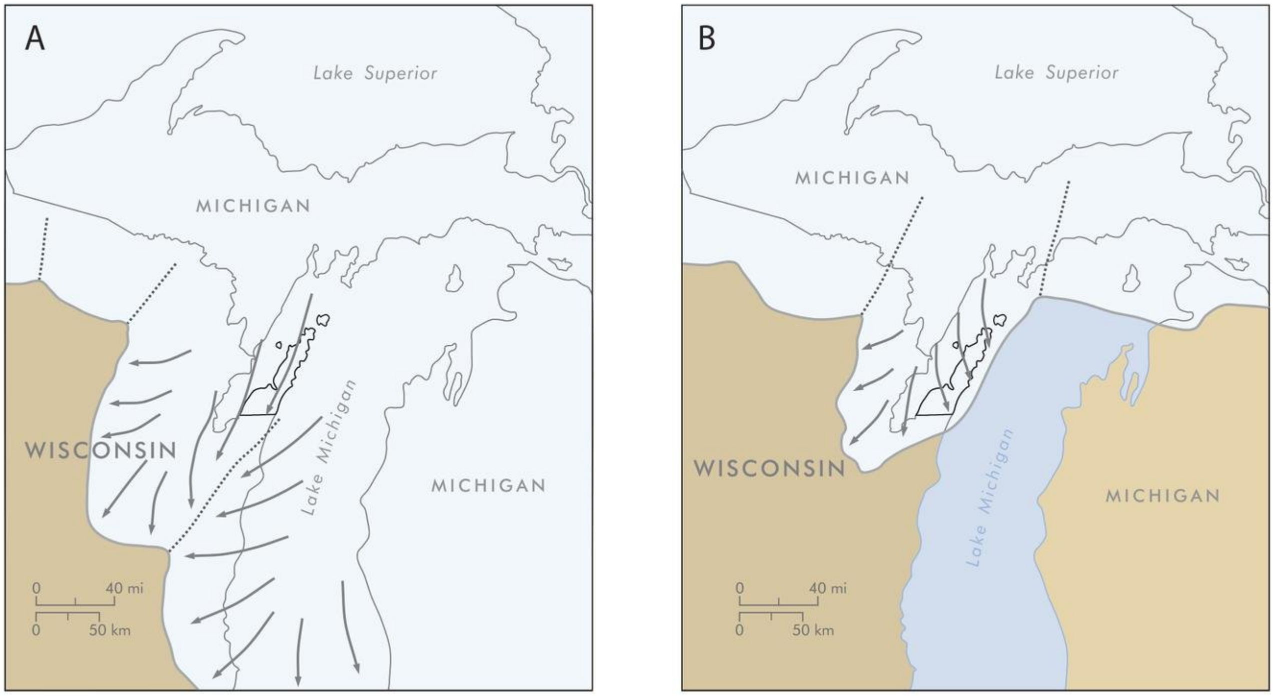


Figure 33. Locations of the Green Bay and Lake Michigan Lobes at two times during glacial retreat, with arrows indicating local ice flow directions. (A) While the Lake Michigan Lobe still completely filled the Lake Michigan basin, the two lobes were probably not clearly differentiated over the Door Peninsula; ice flow was most probably southwest, parallel to the axis of the peninsula. (B) Rapid retreat of the Lake Michigan Lobe due to calving into the Lake Michigan basin left the Green Bay Lobe unconfined, allowing it to advance with a southeasterly ice flow direction across the Door Peninsula.

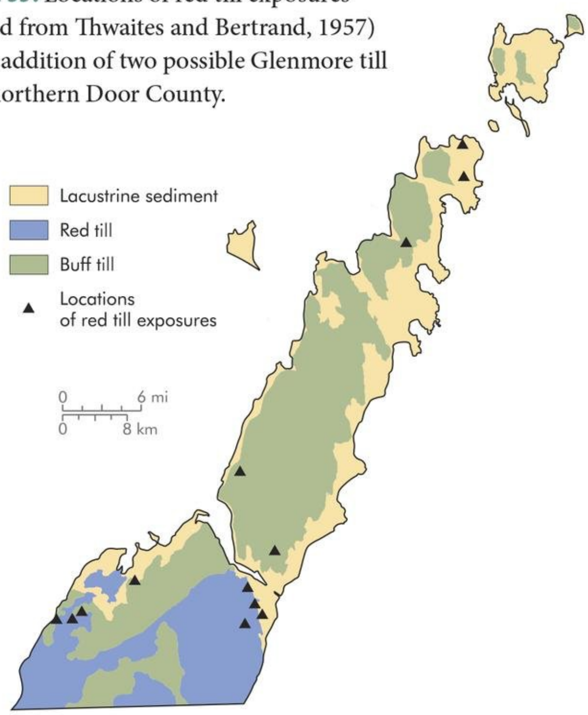
This theory is supported by climate-driven models of the Green Bay and Lake Michigan Lobes that run through the last glacial maximum (fig. 34) (Cutler and others, 2001). While the model does not show a significant difference in position during advance into the region of Door County (about 45° latitude), it does show a very rapid retreat of the Lake Michigan Lobe as the climate warms.

Theories about ice flow during the Glenmore advance

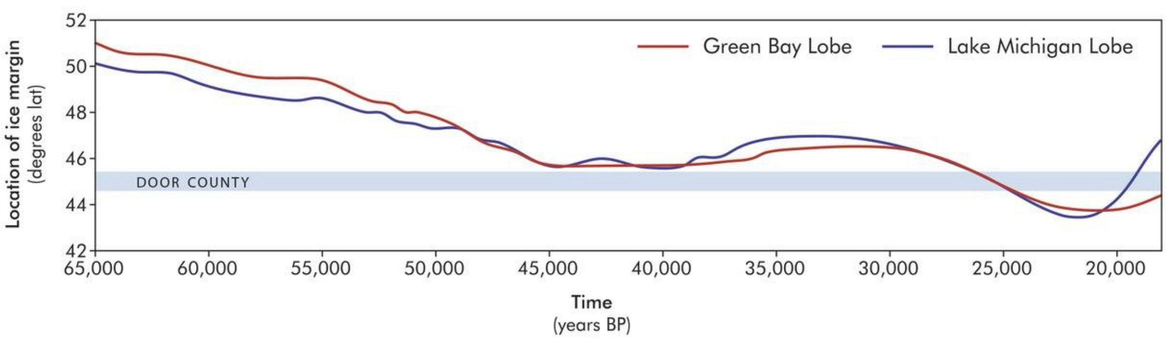
The spotty distribution of Kewaunee Formation deposits (the Glenmore till) in Door County has created a debate about whether or not the Kewaunee ice lobes covered the parts of the peninsula where clay till is absent. Thwaites and Bertrand (1957) argued that the northern part of the peninsula must have been ice covered if the south was covered, based on the fact that the elevations are similar in both areas. Also, they cite small patches of red clay till scattered about the northern part of the county (fig. 35). Alternatively, Schneider (1993b) suggested that the Glenmore ice did not crest the higher parts of the Niagara Escarpment north of Sturgeon Bay, leaving most of the upland in that area ice free, while the Sturgeon Bay lowland offered easy access for the ice to encroach on southern Door County. This is unlikely, however, considering how far south ice extended at that time. Schneider (1993b) also proposed that the clay till sites in northern Door County (described by Thwaites and Bertrand, 1957) are samples of the localized "pink, sandy till" that overlies the Liberty Grove Member. It's possible that this till is instead a variant of the Glenmore till.

The opinion of Thwaites and Bertrand that northern Door County was covered by ice during the Glenmore advance remains the most-likely scenario. Elevations of the escarpment north and south of Sturgeon

▶ **Figure 35.** Locations of red till exposures (modified from Thwaites and Bertrand, 1957) with the addition of two possible Glenmore till sites in northern Door County.



▼ **Figure 34.** Computer model showing ice extent through time for the Green Bay and Lake Michigan Lobes. The lines represent ice advance and retreat from north (top) to south (bottom) with the north–south extent of Door County represented by the shaded horizontal line. Note that following approximately 20,000 years BP, the model indicates a rapid retreat of the Lake Michigan Lobe relative to the Green Bay Lobe. Modified from Cutler and others, 2001.



Bay are similar (up to 800 ft, 244 m), and before isostatic rebound the elevations in northern Door County would have been at least 50 ft (15 m) lower than in the south. In order for ice flow to occur, the glacier must be thicker and the ice surface higher at the up-ice end. Northern Door County is located up-ice (though not directly up-ice) from southern Door County, so if ice were able to top the escarpment in southern Door County it must have been above the escarpment in the north. This interpretation is supported by the presence of three possible Kewaunee Formation till sites in the north, one at a relatively high elevation of 660 ft (200 m) (fig. 35).

In order to accept that Glenmore ice covered all of Door County, it must be accepted that significantly varying bed conditions existed across the Door Peninsula, allowing differential erosion and deposition to occur. Evidence that this was the case includes:

1. Thick sequences of glacial till occur at the base of some steep bedrock rises, which may be the result of melt out of sediment from basal ice.
2. The escarpment north of Sturgeon Bay is generally steeper than in the south, which may have prevented debris-rich basal ice from reaching the top of the escarpment, and therefore affected the distribution of sediment.
3. The bathymetry of Green Bay shows a steep ridge running down the axis of Green Bay along the northern part of the Door Peninsula, ending at Chambers Island (fig. 16). This ridge may also have led to differential transport of debris to the top of the escarpment in northern Door County.
4. A few thin, small patches of possible Kewaunee deposits are present on the uplands in northern Door County, possibly where melt-out of basal sediment occurred (fig. 35).
5. Based on the distribution of Kewaunee deposits (found primarily south of Sturgeon Bay) and the general switch in orientation of dominant flow indicators, the deep break in the escarpment at Sturgeon Bay may have allowed reddish brown clay till to be brought up out of the Green Bay basin and be deposited in southern Door County (plate 1).

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Summary

Most of the record of Pleistocene time is absent in Door County. Numerous advances of the Laurentide Ice Sheet must have crossed the peninsula during the Pleistocene, but the peninsula's high elevation relative to the surrounding area, as well as its position far up-ice from the margin, allowed deposits of former glaciations to be eroded away. Thus, only scattered deposits from the very end of the Pleistocene remain.

The earliest evidence of a glacial advance into Door County may be the presence of a silty gray till, similar to units identified in Sheboygan and Manitowoc Counties that were interpreted as pre-late Wisconsin (Chapel, 2000). In Door County, the unit is not exposed at the surface, and was only identified in a few boreholes scattered throughout the county, always under what is interpreted as Liberty Grove till. This association, along with the absence of any distinct contact, suggests that the gray till is simply an unoxidized variant of the Liberty Grove Member.

The oldest surficial sediment in Door County is the Liberty Grove Member, part of the Holy Hill Formation, which includes deposits extending all the way to the Madison, Wisconsin, area. It is probable that the Liberty Grove Member in Door County is younger than the deposits near Madison, as Door County was most likely undergoing glacial erosion when the ice was at its maximum extent. Much of the Liberty Grove till was deposited as the Green Bay Lobe receded from its maximum extent, as evidenced by the several small recessional moraines present in the county. Because the retreat of the Lake Michigan Lobe was likely faster due to more rapid calving, the Lake Michigan basin was possibly ice-free while the Green Bay Lobe was still present on the peninsula, allowing it to flow south to southeastward and create the drumlin fields in northern and southern Door County.

The Green Bay Lobe then melted back to the northern part of the basin, incorporating red clay from Lake Superior in the bay and in Lake Michigan (Alden, 1918). Subsequent advances of the Green Bay Lobe eroded and then redeposited this sediment into clay-rich till units (members of the Kewaunee Formation). The two earliest Kewaunee advances, the Branch River and the Chilton, have not been identified in Door County but are present in Brown and Kewaunee Counties to the south (Need, 1985; Clayton, 2013). Schneider (1993b) has described a "pink, sandy till" of limited extent in central Door County, which may be correlative to the Branch River Member, but is probably a variant of either Liberty Grove or Glenmore till.

By about 13,100 calendar years ago the ice had retreated back far enough to expose the Straits of Mackinac, allowing lake level to lower significantly, and a spruce forest covered much of eastern Wisconsin (Alden, 1918; McCartney and Mickelson, 1982). Evidence of this forest exists in Door County as several small pieces of wood in till collected from a split-spoon core in southern Door County, dated at 13,800 to 13,400 calendar years ago (B-41-00; Beta Analytic, sample no. 148508). No *in situ* forest beds have been identified in Door County.

A proglacial lake was present in front of the ice as it advanced back into the basin, draining through the Chicago outlet at the southern end of the basin. Thick sequences of well-sorted sand and silt accumulated in the southeastern part of the county as well as at the base of the escarpment in the southwest. The deposits are commonly laminated or cross-bedded, suggesting a nearshore depositional setting. Shoreline features correlating to this lake level are absent in southern Door County, but may be present as high elevation, wave-cut terraces cut into the headlands in the northern part of the county.

The Glenmore Member of the Kewaunee Formation was deposited by a very thin glacier, possibly less than 1600 ft (500 m) thick (Clark and Ehlers, 1993; Socha and others, 1999). Ice likely covered the entire peninsula during this advance, although the depositional record particularly in northern Door County is spotty at best. While more Glenmore deposits are present in the southern half of the county, the glacial record in this area is very complicated. Sediment is thick at the base of the escarpment, but is thin and patchy on the uplands. A sandy variant of the Glenmore Member is present in southern Door County as well, which complicates the interpretation of the stratigraphy, especially in areas of poor exposure.

As the glacier receded out of Door County for the final time, glacial Lake Algonquin was formed, dammed by the ice margin to the north. Well-developed shorelines created by this lake are present in Door County as gravel beach ridges and wave-cut cliffs. As the glacier continued its retreat, successively lower outlets were exposed, allowing the lake level to drop and develop shorelines below the main Algonquin level. These drops were accentuated by differential uplift, creating a fan-like profile of the shoreline elevations. This allowed a more detailed record to be preserved in the northern part of the peninsula where uplift was greater.

The retreat of the glacier north of the North Bay outlet allowed the lake level to drop to at least 260 ft (80 m) below modern lake level in the Lake Michigan basin (Coleman and others, 1994a). Green Bay was completely dry, with a major river flowing south from Little Bay De Noc, Michigan, then turning east just north of Washington and Rock Islands (fig. 36) (Hughes, 1993). A tributary to this river was probably present along the axis of Green Bay, an extension of the modern Fox River.

With isostatic uplift of the northern outlet, the Nipissing transgression ensued. In Door County the shorelines from peak of the Nipissing transgression occur just above 600 ft (183 m). Little differential uplift has affected the elevation of the Nipissing shorelines in Door County, although the shoreline is at a slightly higher elevation in the northernmost part of the Lake Michigan basin (Leverett and Taylor, 1915).

Downcutting of the lake outlet at Port Huron, Michigan, caused lake level to drop to the modern level sometime after 3,500 calendar years ago (Larsen, 1994). Since this time, the landscape has been only slightly altered by natural processes. Few rivers in the county are large enough to develop significant flood plains, the Ahnapee River being a rare exception. Sand and cobble beaches are now being built along the shoreline of the county, and are especially well developed at the heads of the bays. In the southeastern corner of the county, bluffs of glacial till and sand are being eroded by modern wave-action, as are the rocky headlands throughout much of the rest of Door County, such as at Cave Point County Park.

Figure 36. Extent of the Chippewa lowstand in the Lake Michigan basin. Note that Green Bay is dry except for the Au Train and Fox Rivers (modified from Hough, 1955; and Hughes, 1993).

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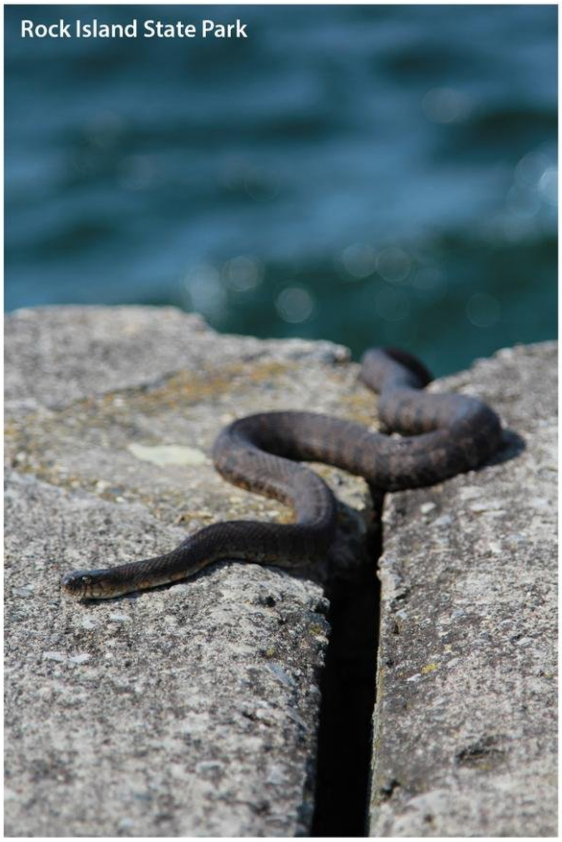

Eric C. Carson

Pocket contents: Plate 1. Quaternary geologic map of Door County, Wisconsin

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

Quaternary Geology *of* Door County, Wisconsin

Eric C. Carson, Scott R. Brown, David M. Mickelson, and Allan F. Schneider

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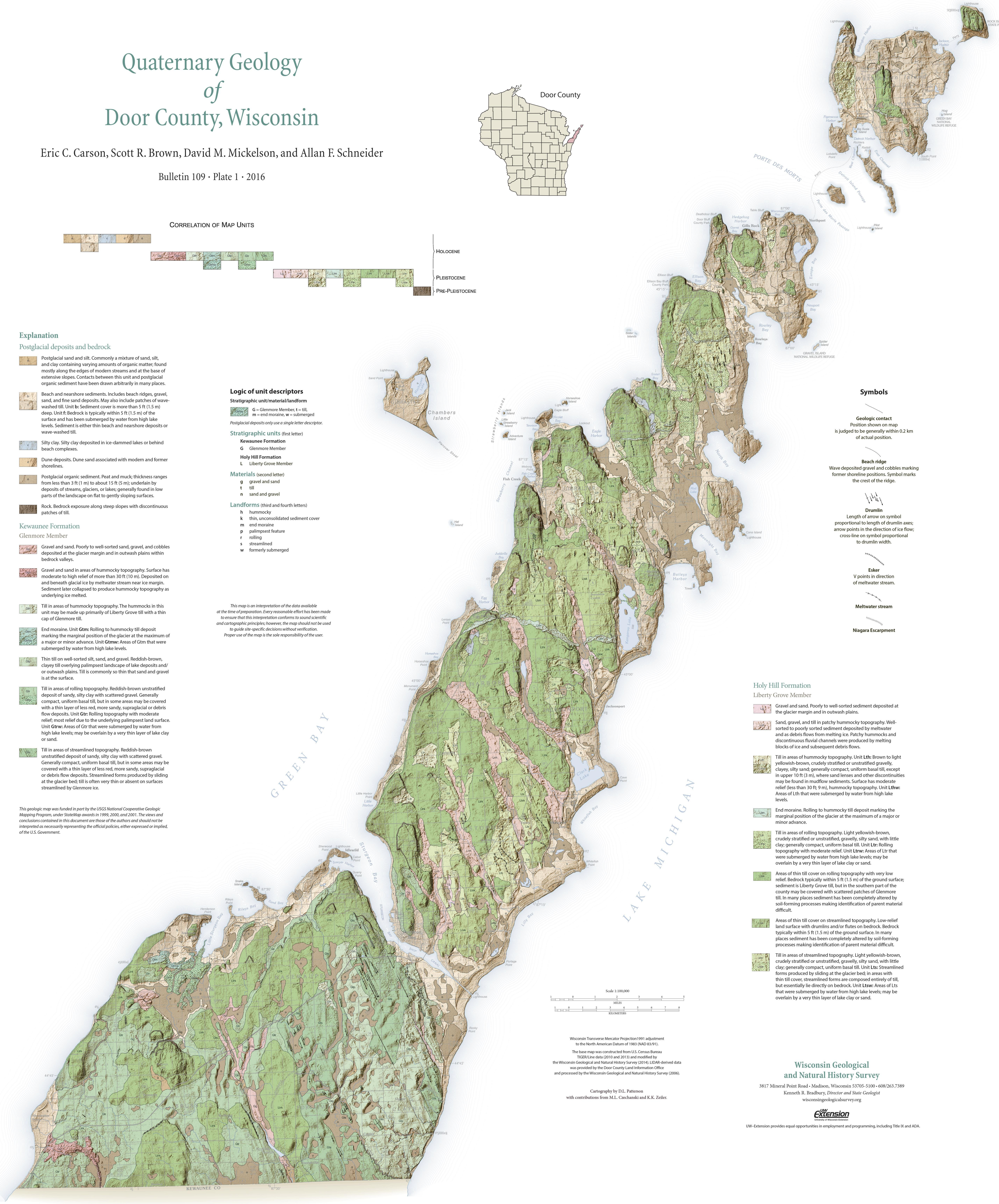
Correlation of Map Units



Explanation

Postglacial deposits and bedrock

a — Postglacial sand and silt. Commonly a mixture of sand, silt, and clay containing varying amounts of organic matter; found mostly along the edges of modern streams and at the base of extensive slopes. Contacts between this unit and postglacial organic sediment have been drawn arbitrarily in many places.

b / f — Beach and nearshore sediments. Includes beach ridges, gravel, sand, and fine sand deposits. May also include patches of wave-washed till. Unit **b:** Sediment cover is more than 5 ft (1.5 m) deep. Unit **f:** Bedrock is typically within 5 ft (1.5 m) of the surface and has been submerged by water from high lake levels. Sediment is either thin beach and nearshore deposits or wave-washed till.

c — Silty clay. Silty clay deposited in ice-dammed lakes or behind beach complexes.

d — Dune deposits. Dune sand associated with modern and former shorelines.

o — Postglacial organic sediment. Peat and muck; thickness ranges from less than 3 ft (1 m) to about 15 ft (5 m); underlain by deposits of streams, glaciers, or lakes; generally found in low parts of the landscape on flat to gently sloping surfaces.

r — Rock. Bedrock exposure along steep slopes with discontinuous patches of till.

Kewaunee Formation

Glenmore Member

Gg — Gravel and sand. Poorly to well-sorted sand, gravel, and cobbles deposited at the glacier margin and in outwash plains within bedrock valleys.

Ggh — Gravel and sand in areas of hummocky topography. Surface has moderate to high relief of more than 30 ft (10 m). Deposited on and beneath glacial ice by meltwater stream near ice margin. Sediment later collapsed to produce hummocky topography as underlying ice melted.

Gth — Till in areas of hummocky topography. The hummocks in this unit may be made up primarily of Liberty Grove till with a thin cap of Glenmore till.

Gtm / Gtmw — End moraine. Unit **Gtm:** Rolling to hummocky till deposit marking the marginal position of the glacier at the maximum of a major or minor advance. Unit **Gtmw:** Areas of Gtm that were submerged by water from high lake levels.

Gtp — Thin till on well-sorted silt, sand, and gravel. Reddish-brown, clayey till overlying palimpsest landscape of lake deposits and/or outwash plains. Till is commonly so thin that sand and gravel is at the surface.

Gtr / Gtrw — Till in areas of rolling topography. Reddish-brown unstratified deposit of sandy, silty clay with scattered gravel. Generally compact, uniform basal till, but in some areas may be covered with a thin layer of less red, more sandy, supraglacial or debris flow deposits. Unit **Gtr:** Rolling topography with moderate relief; most relief due to the underlying palimpsest land surface. Unit **Gtrw:** Areas of Gtr that were submerged by water from high lake levels; may be overlain by a very thin layer of lake clay or sand.

Gts — Till in areas of streamlined topography. Reddish-brown unstratified deposit of sandy, silty clay with scattered gravel. Generally compact, uniform basal till, but in some areas may be covered with a thin layer of less red, more sandy, supraglacial or debris flow deposits. Streamlined forms produced by sliding at the glacier bed; till is often very thin or absent on surfaces streamlined by Glenmore ice.

This geologic map was funded in part by the USGS National Cooperative Geologic Mapping Program, under StateMap awards in 1999, 2000, and 2001. The views and conclusions contained in this document are those of the authors and should not be interpreted as necessarily representing the official policies, either expressed or implied, of the U.S. Government.

Logic of unit descriptors

Stratigraphic unit/material/landform

Gtmw: **G** = Glenmore Member, **t** = till, **m** = end moraine, **w** = submerged

Postglacial deposits only use a single letter descriptor.

Stratigraphic units (first letter)

Kewaunee Formation
- G — Glenmore Member

Holy Hill Formation
- L — Liberty Grove Member

Materials (second letter)
- g — gravel and sand
- t — till
- n — sand and gravel

Landforms (third and fourth letters)
- h — hummocky
- k — thin, unconsolidated sediment cover
- m — end moraine
- p — palimpsest feature
- r — rolling
- s — streamlined
- w — formerly submerged

Symbols

Geologic contact
Position shown on map is judged to be generally within 0.2 km of actual position.

Beach ridge
Wave deposited gravel and cobbles marking former shoreline positions. Symbol marks the crest of the ridge.

Drumlin
Length of arrow on symbol proportional to length of drumlin axes; arrow points in the direction of ice flow; cross-line on symbol proportional to drumlin width.

Esker
V points in direction of meltwater stream.

Meltwater stream

Niagara Escarpment

Holy Hill Formation

Liberty Grove Member

Lg — Gravel and sand. Poorly to well-sorted sediment deposited at the glacier margin and in outwash plains.

Lnh — Sand, gravel, and till in patchy hummocky topography. Well-sorted to poorly sorted sediment deposited by meltwater and as debris flows from melting ice. Patchy hummocks and discontinuous fluvial channels were produced by melting blocks of ice and subsequent debris flows.

Lth / Lthw — Till in areas of hummocky topography. Unit **Lth:** Brown to light yellowish-brown, crudely stratified or unstratified gravelly, clayey, silty sand; generally compact, uniform basal till, except in upper 10 ft (3 m), where sand lenses and other discontinuities may be found in mudflow sediments. Surface has moderate relief (less than 30 ft; 9 m), hummocky topography. Unit **Lthw:** Areas of Lth that were submerged by water from high lake levels.

Ltm — End moraine. Rolling to hummocky till deposit marking the marginal position of the glacier at the maximum of a major or minor advance.

Ltr / Ltrw — Till in areas of rolling topography. Light yellowish-brown, crudely stratified or unstratified, gravelly, silty sand, with little clay; generally compact, uniform basal till. Unit **Ltr:** Rolling topography with moderate relief. Unit **Ltrw:** Areas of Ltr that were submerged by water from high lake levels; may be overlain by a very thin layer of lake clay or sand.

Ltrk — Areas of thin till cover on rolling topography with very low relief. Bedrock typically within 5 ft (1.5 m) of the ground surface; sediment is Liberty Grove till, but in the southern part of the county may be covered with scattered patches of Glenmore till. In many places sediment has been completely altered by soil-forming processes making identification of parent material difficult.

Ltsk — Areas of thin till cover on streamlined topography. Low-relief land surface with drumlins and/or flutes on bedrock. Bedrock typically within 5 ft (1.5 m) of the ground surface. In many places sediment has been completely altered by soil-forming processes making identification of parent material difficult.

Lts / Ltsw — Till in areas of streamlined topography. Light yellowish-brown, crudely stratified or unstratified, gravelly, silty sand, with little clay; generally compact, uniform basal till. Unit **Lts:** Streamlined forms produced by sliding at the glacier bed; in areas with thin till cover, streamlined forms are composed entirely of till, but essentially lie directly on bedrock. Unit **Ltsw:** Areas of Lts that were submerged by water from high lake levels; may be overlain by a very thin layer of lake clay or sand.

Scale 1:100,000

MILES: 1 0 1 2 3 4 5

KILOMETERS: 1 0 1 2 3 4 5 6 7 8

Wisconsin Transverse Mercator Projection1991 adjustment to the North American Datum of 1983 (NAD 83/91).

The base map was constructed from U.S. Census Bureau TIGER/Line data (2010 and 2013) and modified by the Wisconsin Geological and Natural History Survey (2014). LIDAR-derived data was provided by the Door County Land Information Office and processed by the Wisconsin Geological and Natural History Survey (2006).

Cartography by D.L. Patterson with contributions from M.L. Czechanski and K.K. Zeiler.

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