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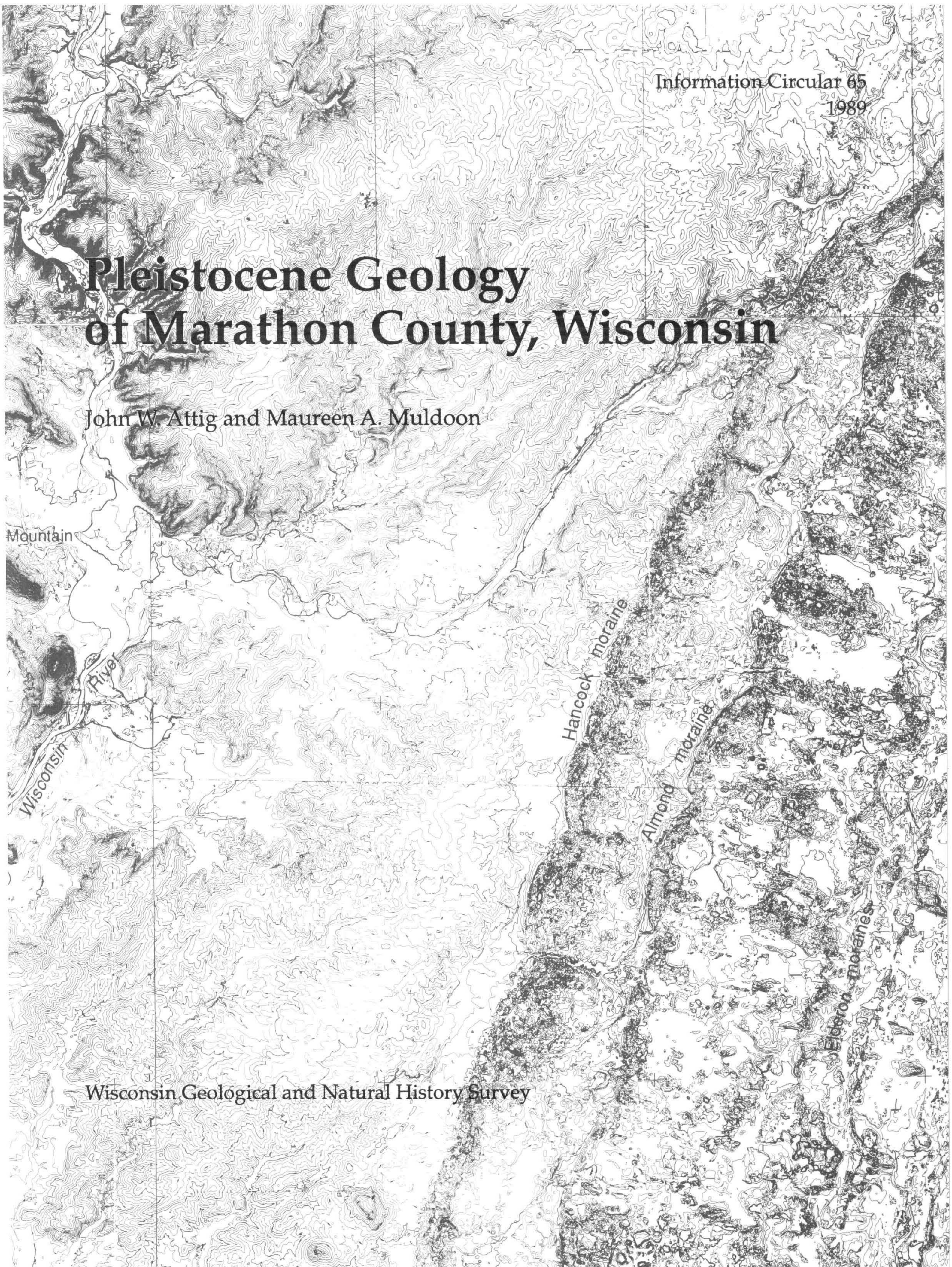
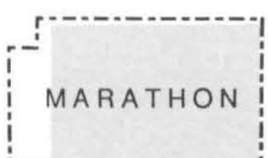
Pleistocene Geology of Marathon County, Wisconsin

John W. Attig and Maureen A. Muldoon



Wisconsin Geological and Natural History Survey

Cover: *This map is reduced from a mosaic of the contour lines from the most recent 7.5-minute (1:24,000) topographic maps of part of Marathon County.*



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Pleistocene Geology of Marathon County, Wisconsin

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Abstract

East-central and southeastern Marathon County was glaciated during the last part of the Wisconsin Glaciation. The remainder of the county was glaciated earlier in the Pleistocene or during the late Pliocene. Most glacial sediment has been eroded from the central part of Marathon County; there, the only remaining indications of glaciation are till or till-like material of the Marathon Formation and scattered glacially transported clasts mixed with weathering products from the underlying Cambrian and Precambrian rock. In the western part of the county two members of the Marathon Formation are recognized. The gray, silty, calcitic till of the Medford Member was deposited during the Stetsonville Phase; the brown, silty, calcitic till of the Edgar Member, during the Milan Phase. The lithology of the Medford and Edgar Members indicates a northwest source area. The till of the Bakerville Member was deposited in the southwestern part of the county during the Nasonville Phase; the till of the Merrill Member, in the northern part of the county during the Hamburg Phase. The till of these members, both of the Lincoln Formation, is red, sandy, noncalcareous, and derived from a northern source area. The brown, sandy, dolomitic till of the Mapleview Member of the Horicon Formation was deposited in the eastern part of the county during the Hancock, Almond, and Elderon Phases.

Field measurements of hydraulic conductivity indicate that the Medford and Edgar Members form a distinct hydrogeologic unit, as do the Bakerville and Merrill Members.

Introduction

Marathon County is located in central Wisconsin and covers about 4,100 km^2 (fig. 1). The east-central and southeastern areas of the county were glaciated during the last part of the Wisconsin Glaciation, between about 25,000 and 13,000 years ago. The remainder of the county was glaciated earlier in the Pleistocene or during the late Pliocene.

In this report we discuss the nature, distribution, and history of Pleistocene material in Marathon County and the hydrogeologic properties of the till units in the western part of the county. We based our report on field and laboratory studies completed during 1984, 1985, and 1986. We conducted field work using standard field techniques, including drilling with a truck-mounted drill that allowed samples to be collected from either continuous-flight augers or a split-spoon sampler. Fifty-nine holes (holes MR-1101 to MR-1159) were drilled to determine the stratigraphy of Pleistocene material. Samples were collected from the drill bit about every 1.5 m. On the basis of the logs of holes MR-1101 to MR-1159, we chose sites for holes MR-1160 to MR-1170, in which piezometers were installed and from which continuous core was collected. The physical and hydrogeologic properties of selected sediment samples were determined in laboratories at the University of Wisconsin-Madison. The number and location of the holes drilled as part of this study are shown on plate 1, and a geologic log for each of these holes is available from the Wisconsin Geological and Natural History Survey (WGNHS) (fig. 2). A complete list of laboratory data from analyses of sediment samples is given by Muldoon (1987).

Acknowledgments

We thank Lee Clayton, William N. Mode, Robert W. Baker, and Frederick W. Madison for reviewing a preliminary version of this report and providing many helpful suggestions. We thank Lee

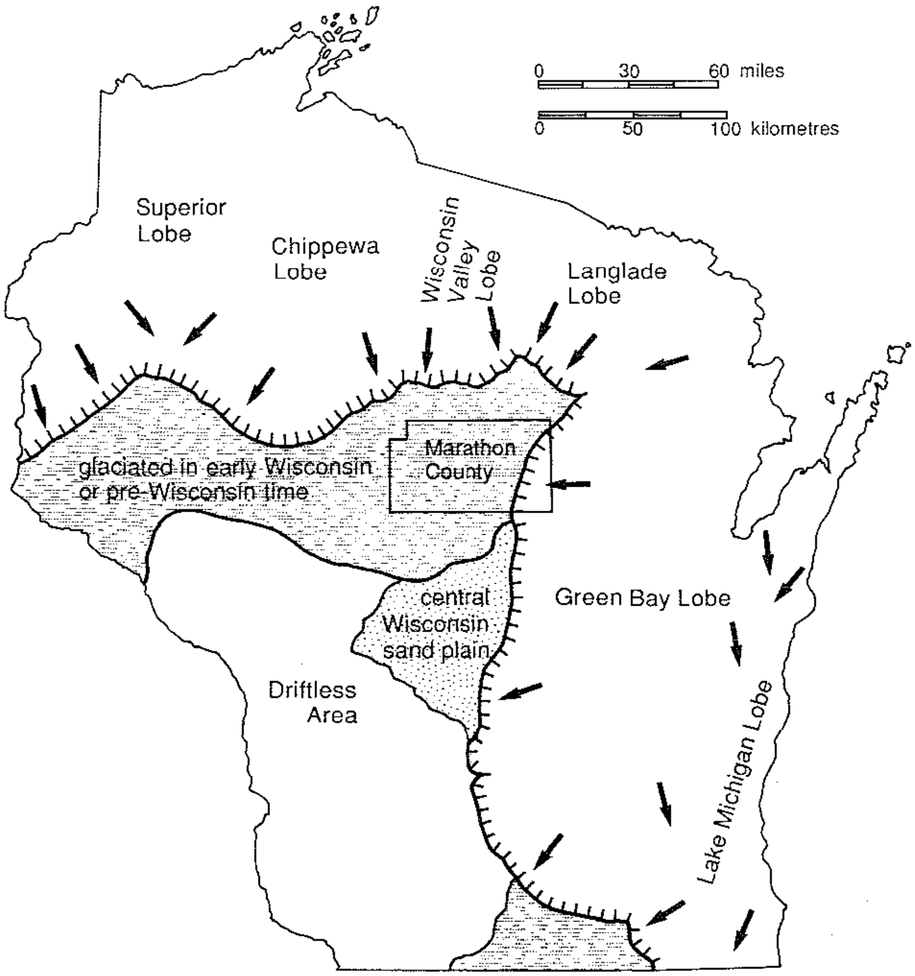


Figure 1. *Location of Marathon County and the extent of glaciation in Wisconsin. The arrows show the direction of late Wisconsin ice flow.*

Clayton, William N. Mode, Robert W. Baker, and William Fiala for visiting the field area and providing thought-provoking discussions throughout the course of our research. Randy Boness logged stratigraphic holes and performed clay-mineral analyses; William Fiala (U.S. Soil Conservation Service) made unpublished soil maps available for our use.

Precambrian and Cambrian rock

Exposures of Precambrian rock are common in central Marathon County, where the typical thickness of overlying material is 2 m or less (area of map unit **gu** on plate 1). In the remainder of the county, where the material overlying Precambrian rock is typically 2 m or more thick, exposures of Precambrian rock are less common. The Precambrian rock consists of Archean and lower and middle Proterozoic metavolcanic, metasedimentary, and intrusive rock (LaBerge and Myers, 1983). The Middle Proterozoic Wolf River batholith, a large body of coarse-grained, porphyritic quartz monzonite, underlies a large part of eastern Marathon County. Several large syenite plutons occur in central Marathon County; Rib Mountain, the highest point in the county (summit elevation, 586 m), is a quartzite inclusion in one of these plutons. LaBerge and Myers (1983) gave a detailed description of the Precambrian geology of Marathon County; their report in-

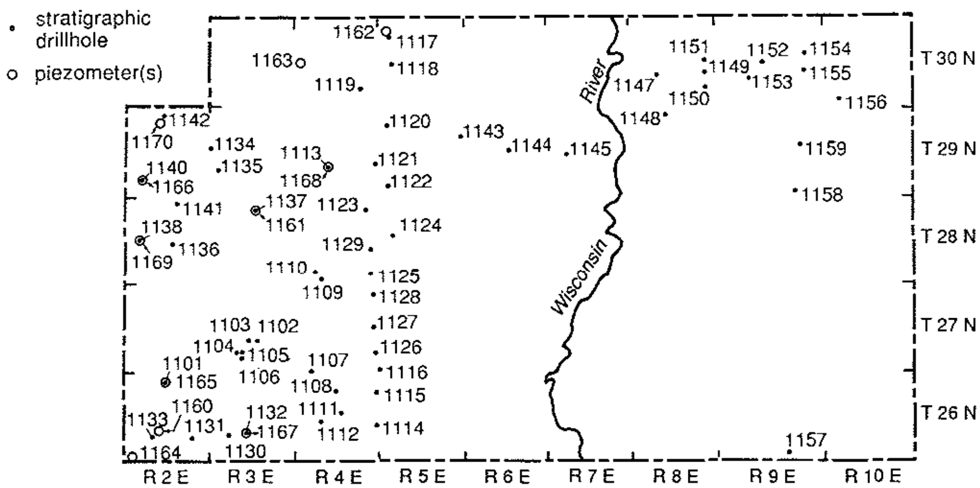


Figure 2. *Location of holes drilled to sample sediment and install piezometers.*

cludes a 1:100,000 map (the same scale as plate 1).

Cambrian sandstone overlies Precambrian rock in several areas in southern and western Marathon County. Well cemented, medium- to coarse-grained sandstone with ripple-marked bedding planes underlies two prominent hills in T26N, R8E, and crops out in a quarry in SW1/4 sec. 33, T26N, R2E. LaBerge and Myers (1983, p. 67) reported several other exposures of sandstone in the south-central part of the county. Construction logs of some water wells report sandstone in the subsurface in the western part of T28N, R2E; in most of T26N, R2E; and in the southern parts of T26N, R3E, 4E, 5E, 6E, and 7E.

The Cambrian sandstone and later Paleozoic rock, which once were more extensive in central Wisconsin, have mostly been eroded away. A few fragments of oolitic chert found in the central part of the county may be residual from the Ordovician carbonate rock that formerly extended over the area. Little is known about the geologic history of the area for the period between the deposition of the sandstone (about 500 million years ago) and the deposition of the oldest glacial deposits in the area (possibly about 2 million years ago).

The surface of the Precambrian and Cambrian rock has been extensively weathered. In the central part of the county, where Pleistocene sediment is thin or absent, coarse-grained Precambrian rock may be disaggregated to depths of tens of metres (LaBerge and Myers, 1983). The weathering of fine-grained Precambrian and Cambrian rock produced clay-rich material. This material is a major component of map unit **gu** on plate 1 and is encountered in most drillholes that penetrate to the rock surface in other parts of the county (that is, in areas not shown as map unit **gu**) This clay-rich material was used for making bricks in several parts of the county (Buckley, 1901) and is now used as a low-permeability liner for landfills. The disaggregated coarse-grained rock is used for landscaping and construction material.

Pleistocene geology

The uplands of Marathon County can be divided into five areas that correspond to map units **gu**, **ge**, **gb**, and **gm** on plate 1 and the area east of the Hancock moraine (mainly map units gh and sh). The Pleistocene material in Marathon County, as in other areas of Wisconsin, has been divided into lithostratigraphic units on the basis of color, grain-size distribution, mineralogy, magnetic susceptibility, and stratigraphic position (fig. 3). (Mickelson and others, 1984; Attig and others, 1988).

Marathon Formation

Marathon Formation, undifferentiated
Material that is included in the Marathon Formation but not designated as a member covers much of central Marathon County (map unit **gu** on

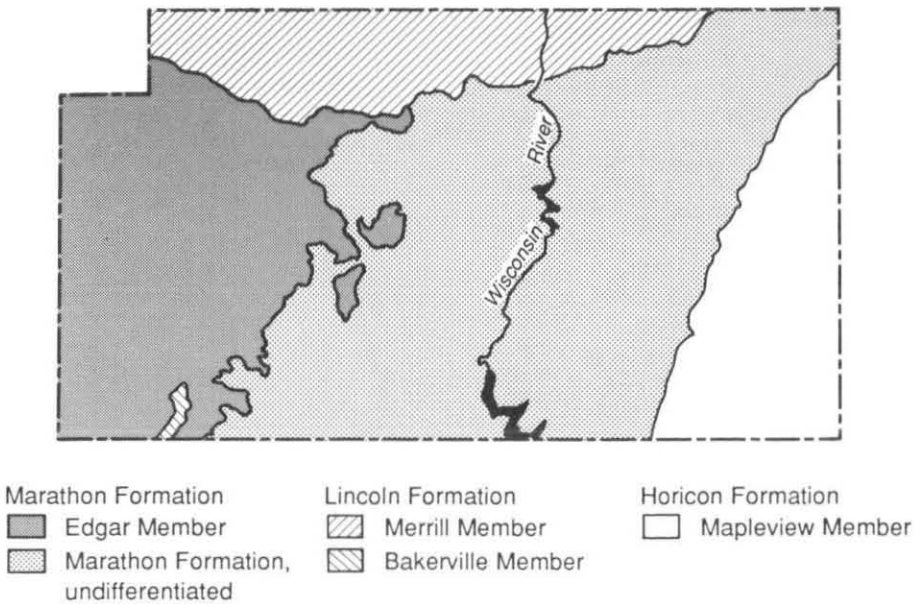


Figure 3. *General distribution of lithostratigraphic units in Marathon County.*

plate 1). Material included in map unit **gu** overlies Precambrian rock and contains material interpreted to be predominantly hillslope sediment derived from the weathering of Cambrian and Precambrian rock; this unit also includes some glacially transported material. Map unit **gu** is similar to map unit **h** of Clayton (1986) in adjacent Portage County and map unit **hp** of Clayton (in press) in adjacent Wood County.

The thickness of the undifferentiated Marathon Formation is typically about 2 m or less throughout most of central Marathon County but reaches 15 m in places. Throughout the area mapped as **gu**, the surface topography is nearly the same as that of the underlying rock and exposures of Precambrian rock are numerous. In a few places, there are large areas of Precambrian or Cambrian rock (units **P€** and **€** on plate 1). The material included in the undifferentiated Marathon Formation is typically thin and poorly exposed. As a result, it is impossible to separate till from hillslope sediment or residuum. Many of the small exposures that we examined show at least some crude stratification, and the contact with the underlying rock is typically sharp. The sharp contact indicates that although the weathered material is locally derived, it is not in place; the crude stratification indicates that in most places slope processes have mixed and transported the glacial and residual components of the material shown as map unit **gu** on plate 1.

Map unit **gu** includes the Wausau Member of the Marathon Formation. The Wausau Member, first recognized and informally named the "Wausau drift" by LaBerge and Myers (1983 and earlier progress reports), was later formally named in Mickelson and others (1984). We recognized till-like material, possibly of the Wausau Member, in some areas; however, its extent could not be determined and shown on plate 1. Map unit **gu** also includes small, thin outliers of the Edgar Member of the Marathon Formation in the west-central part of the county. The area mapped as **gu** corresponds approximately to the area interpreted by Weidman (1907) to be unglaciated.

Our eighty samples of undifferentiated material from the Marathon Formation had an average ratio of sand:silt:clay of 39:44:17 for the finer-than-2-mm fraction (fig. 4; table 1). These results are similar to those given by Mode (1976) from 15 Marathon County samples of the Wausau Member of the Marathon Formation; he reported a ratio of sand:silt:clay of 43:34:23. Mickelson (1986) reported a sand:silt:clay ratio of 52:34:14 for till of the Wausau Member in adjacent Langlade County. Our results from the samples of Marathon Formation, undifferentiated, show variability in grain-size distribution (figs. 4 and 5),

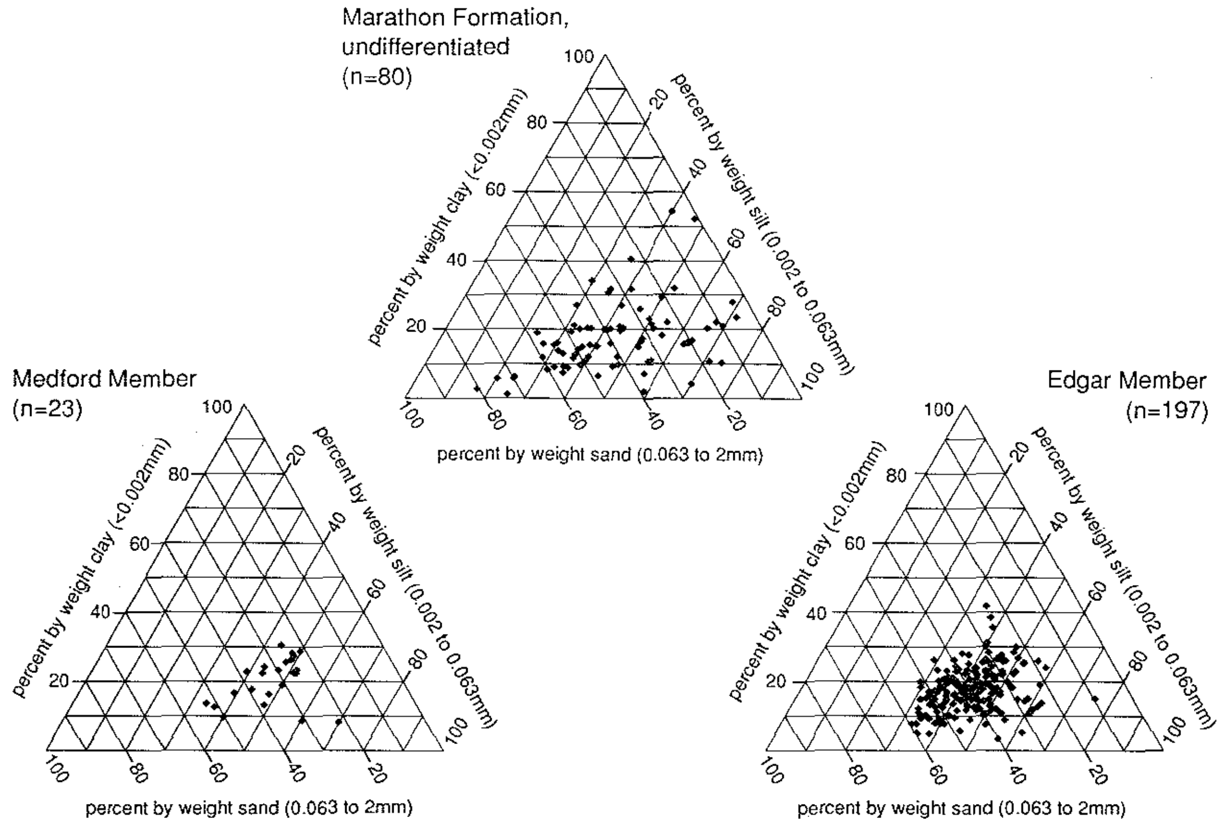


Figure 4. *Grain-size distribution of the finer-than-2-mm fraction of samples from the Marathon Formation. The plots showing data for the Edgar and Medford Members show only results from samples of till. The plot for the undifferentiated Marathon Formation includes samples that may be from till, residuum, or hillslope sediment.*

Table 1. Summary of the lithologic properties of till units deposited prior to late Wisconsin time. The percentages of sand, silt, and clay have been determined for the finer-than-2-mm fraction of the sample.

Lithostratigraphic unit	Number of samples	Sand (%)	Silt (%)	Clay (%)	Median diameter (mm)	Magnetic susceptibility
Marathon Formation						
Undifferentiated	80	38.7	43.8	17.5	0.043	7.3×10^{-4}
Medford Member	23	32.8	47.1	20.1	0.023	1.4×10^{-3}
Edgar Member	197	39.2	42.9	17.9	0.039	1.3×10^{-3}
Lincoln Formation						
Bakerville Member	8	56.7	30.2	13.1	0.114	1.8×10^{-3}
Merrill Member	11	49.0	38.5	12.5	0.074	1.3×10^{-3}

presumably because several types of sediment are included in the unit. The undifferentiated material in the Marathon Formation is noncalcareous and field color ranges from reddish brown (5YR 4/4) to olive (5Y 4/3). Typically, the material is dark brown or brown (10YR 4/3) to olive brown (2.5Y 4/4). The magnetic susceptibility of samples of the Marathon Formation, undifferentiated,

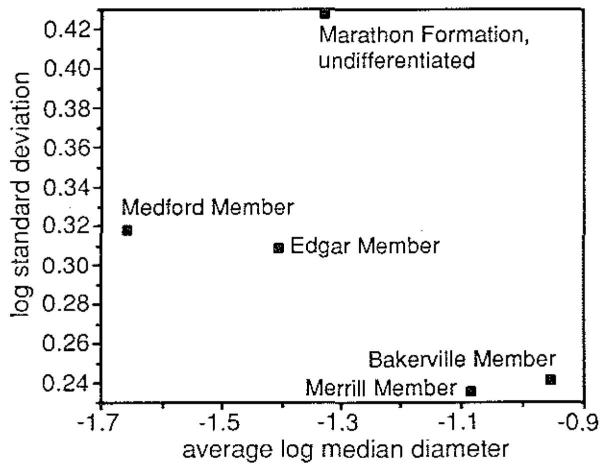


Figure 5. *Grain-size variation of the till units deposited prior to late Wisconsin time. The median diameter of a sample is used to characterize grain-size distribution. The diagram shows a plot of the log_{10} average median diameter of each unit against the log_{10} standard deviation around that diameter.*

ranges from 7.2×10^{-5} to 7.8×10^{-3} (S.I. units); this is the greatest range of any of the units. The median magnetic susceptibility of samples is 7.3×10^{-4} (S.I. units) (see table 1). The variation in magnetic susceptibility is probably related to the characteristics of the underlying rock and the degree of weathering of magnetic minerals.

Till of the Medford Member

The gray, slightly gravelly, silty, calcitic till of the Medford Member of the Marathon Formation (Attig and Muldoon, 1988) is not known to be exposed at the surface in Marathon County. The areal extent of this unit is poorly known. This till unit has been observed in one outcrop along the south bank of the Little Black River in the SE1/4 NE1/4 SE1/4, sec. 3, T30N, R1E in adjacent southeastern Taylor County, and as far west as Gilman in Taylor County. Several drillholes in northwestern Marathon County penetrate till of the Medford Member (WGNHS Geologic Logs MR-1135, MR-1138, MR-1169, MR-1140, and MR-1166; cross-section unit **gd** on section B-B′, plate 1).

Data from drillholes indicate that the till of the Medford Member is typically about 6 m thick. Twenty-three samples of till of the Medford Member showed an average ratio of sand:silt:clay of 33:47:20 for the finer-than-2-mm fraction (figs. 4 and 5; table 1). Coarse sand grains composed of siliceous limestone are common in the Medford Member, and samples of Medford till effervesce strongly when treated with dilute hydrochloric acid. Very coarse sand and pebble-size fragments of limestone in the Medford till contain fossils too poorly preserved to be identified. The limestone fragments are typically leached from the upper several metres of Medford till. In the field this till is typically gray (10YR 3/1 to 2.5Y 5/1), although the color ranges to grayish brown (2.5Y 5/3). Small fragments of gray shale are also quite common in the Medford Member; incorporation of this shale may account for the color of the unit. The median magnetic susceptibility of samples taken from the till of the Medford Member is 1.4×10^{-3} (S.I. units) (see table 1).

Till of the Edgar Member

The till of the Edgar Member of the Marathon Formation (Mode, 1976; Mickelson and others, 1984) underlies much of western Marathon County (map unit **ge** on plate 1). The landscape underlain by the Edgar till consists of broad uplands and deeply incised valleys. The Edgar till is usually overlain by about 1 m of wind-blown sandy silt. Edgar till is yellowish brown, slightly gravelly, silty, and calcitic. Red and orange iron-oxide staining and black manganese oxide staining are quite common.

The till of the Edgar Member is typically 6 to 15 m thick and in places is up to 25 m thick. The Edgar till thins and becomes patchy eastward; originally this unit extended farther eastward (plate 1). The ratio of sand:silt:clay in the finer-than-2-mm fraction of our 197 samples of Edgar till averaged 39:43:18 (fig. 4; table 1). The till typically contains less than 10 percent gravel-size particles. On the basis of 17 samples from Marathon County, Mode (1976) found an average ratio of sand:silt:clay of 33:43:24. Clayton (in press) reported that the Edgar till in Wood County contains 20 to 55 percent sand, 30 to 45 percent silt, and 10 to 35 percent clay. The median diameter of samples from the Edgar till in Marathon County is variable (fig. 5). Field color is typically dark yellowish brown (10YR 4/4) to brown or dark brown (7.5YR 4/4).

The physical characteristics of the Edgar Member show considerable down-section variability (fig. 6) due to a number of factors, including weathering of the upper parts of the section and mixing of material in the upper parts of the section with material transported by subsequent ice advances. Although the Edgar Member in Marathon County is characterized by thick till deposits, in several places the till includes layers of lake sediment, stream-deposited sand and gravel, till-like debris-flow sediment, or organic material.

Field testing of samples of Edgar till with dilute hydrochloric acid indicated that the till is typically leached of carbonate to a depth of 2 to 5 m, but in a few areas carbonate is present within 0.5 m of the surface. These field tests also indicated that unleached till samples contain enough calcium carbonate to effervesce strongly. Our laboratory testing of samples from the Edgar till using a Chittick apparatus (Dreimanis, 1962) found little calcite in the coarse-silt fraction. The gravel, very coarse sand, and fine sand fractions of samples from four drillholes (WGNHS Geologic Logs MR-1101, MR-1132, MR-1138, and MR-1140) were treated with dilute hydrochloric acid and found to contain some calcite. Hole (1943) reported that till of the Edgar Member in northwestern Wood County is about 20 percent by weight calcium carbonate and that about 90 percent of the 2 to 4 mm grains are composed of calcium carbonate. Mode (1976) found limestone but no dolomite in the coarse-sand fraction of samples from the Edgar till in western Marathon County. Clayton (in press) reported that the Edgar till in Wood County contains considerable calcite in bulk samples, but that Chittick analyses indicated little calcite in the coarse-silt fraction of 30 samples.

The till and fluvial gravel of the Edgar Member contain fossiliferous pebbles. In northwestern Wood County, Hole (1943) reported a segment of a crinoid stem in till of the Edgar Member; Mode (1976) noted fragments of Paleozoic crinoids and bryozoans in western Marathon County. In Wood County, Clayton (in press) reported finding pebbles of silicified limestone that contain fossils of the Silurian tabulate coral *Favosites favosus* and a rugose coral, *Streptelasma sp.* (Ordovician, Silurian, or Devonian), in meltwater-stream sediment (which Clayton included in the Edgar Member) underlying Edgar till in the SW1/4 NW1/4 sec. 2, T25N, R3E. Several very coarse

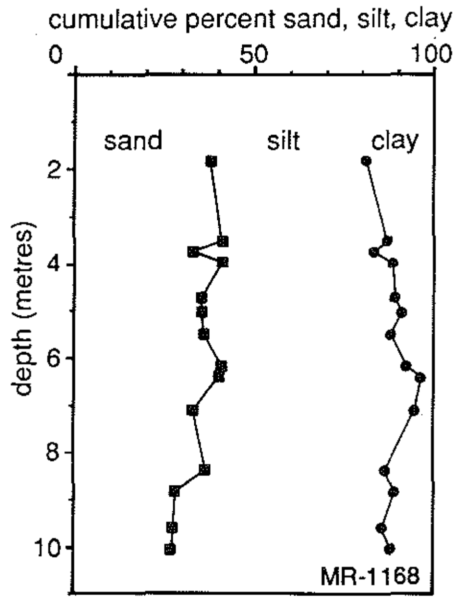


Figure 6. *Down-section variability of the grain-size distribution of the finer-than-2-mm fraction for the till of the Edgar Member of the Marathon Formation.*

sand and pebble-size fragments of siliceous limestone from samples of the Edgar till in Marathon County are fossiliferous, but no fossils were preserved well enough to be identified.

Lincoln Formation

Till of the Bakerville Member

The till of the Bakerville Member of the Lincoln Formation (Mode, 1976; Mickelson and others, 1984) occurs at the surface in a small area of southwestern Marathon County (map unit **gb** on plate 1). The till is brown to reddish brown, slightly gravelly, clayey, silty sand that contains many rock fragments derived from the Lake Superior basin. We found few exposures of Bakerville till, and few holes that we drilled penetrated Bakerville till. However, the till of the Bakerville Member forms a fairly continuous cover over the crest of a broad ridge in southwestern Marathon County (map unit gb on plate 1). The Bakerville Member is typically less than 3 m thick, but near the crest of the ridge it can be up to 25 m thick. This ridge is the northeastern part of what Weidman (1907) called the Marshfield moraine. Small patches of reddish-brown, sandy

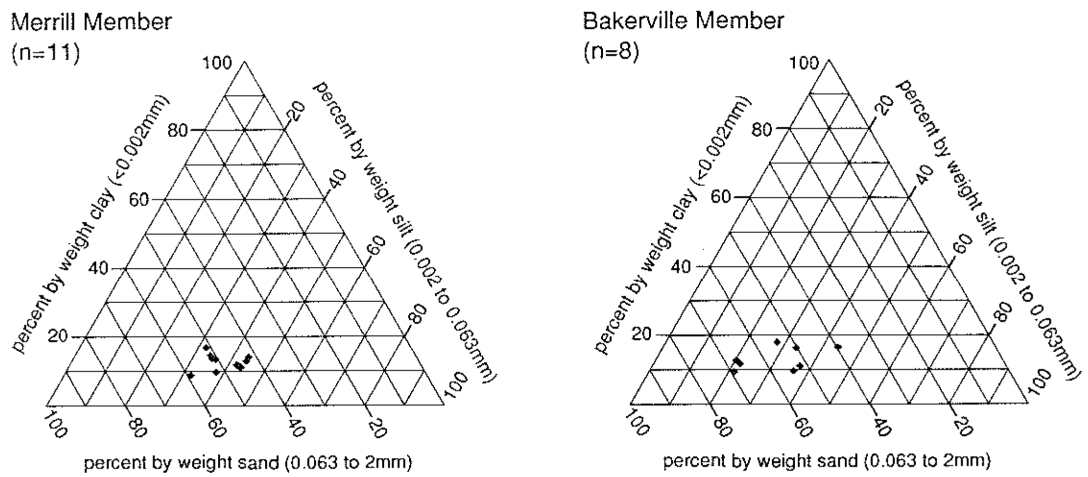


Figure 7. *Grain-size distribution of the finer-than-2-mm fraction of samples of till of the Merrill and Bakerville Members of the Lincoln Formation.*

sediment occur in the southwestern and western parts of the county; these patches of sediment may also be Bakerville till, hillslope sediment derived from Bakerville till, or material of the Edgar Member mixed with Bakerville till. These small patches of Bakerville-like sediment are included in map unit **ge** on plate 1 because they are too small to be shown individually.

Because small-scale glacial topography is lacking on the Marshfield moraine and because the distribution of Bakerville till is patchy outside the Marshfield moraine, extensive erosion has probably occurred since deposition of the Bakerville till. Its original extent to the east and southeast is unknown.

The ratio of sand:silt:clay for the finer-than-2-mm fraction of our eight samples of Bakerville till averaged 57:30:13 (figs. 5 and 7; table 1). These results are similar to those of Mode (1976), who reported an average ratio of sand:silt:clay of 62:25:13 for 15 samples from Marathon County. The Bakerville till typically contains 10 to 15 percent gravel-size particles. Till of the Bakerville Member is typically brown (7.5YR 4/4) to reddish brown (5YR 4/4) and noncalcareous. The median magnetic susceptibility of our samples of the Bakerville till is 1.8×10^{-3} (S.I. units) (see table 1). This value is less than the lower end of the range of magnetic susceptibility values reported for the Bakerville Member in adjacent Wood County (Clayton, in press). The samples that we collected in Marathon County came from relatively thin areas of Bakerville till; the magnetic susceptibility values for these samples may be low because magnetite has been weathered from the near-surface materials. Weathering of near-surface materials is suggested by data from two drillholes (WGNHS Geologic Logs MR-1160 and MR-1164), in which magnetic susceptibility increased with depth. The samples from Wood County for which magnetic susceptibility was determined generally came from greater depths than those from Marathon County.

Till of the Merrill Member

Like the till of the Bakerville Member, the till of the Merrill Member is brown to reddish brown, sandy, and contains rock fragments derived from the Lake Superior basin. The Merrill Member of the Lincoln Formation (Mickelson and others, 1984) occurs at the surface in a broad area of north-central and northwestern Marathon County (map unit **gm** on plate 1) and in adjacent parts of Taylor, Lincoln, and Langlade Counties. The Merrill till thickens to the north in Marathon County; well records indicate that the unit reaches thicknesses of at least 10 m near the northern border of the county. Near its southern limit, the Merrill till thins and becomes patchy; in some places the Edgar Member is exposed at the surface in the area shown as map unit **gm** on plate 1. Where a large drainageway such as that of the Wisconsin or Rib River crosses the area of unit **gm** (plate 1), the Merrill till is patchy on the steep slopes flanking the drainageway, and exposures of Precambrian rock are common.

The till of the Merrill Member is a noncalcareous, slightly gravelly, clayey, silty sand, and it is typically strong brown (7.5YR 4/6) to reddish brown (5YR 4/3). Eleven samples of till from this unit had an average sand:silt:clay ratio of 49:38:13 in the finer-than-2-mm fraction. This average grain-size distribution is less sandy and more silty than the sand:silt:clay ratio of 62:28:10 reported by Mode (1976) in western Marathon County, the 60:30:10 ratio reported by Stewart (1973), or the ratio of 63:28:10 found by Mickelson (1986) in Langlade County. Inspection of outcrops throughout the area suggests that the till of the Merrill Member has a consistent grain-size distribution; this is further supported by the results of laboratory grain-size analyses (figs. 5 and 7; table 1). Samples collected for grain-size analysis were obtained from drillholes; some samples may contain Merrill till that has incorporated some of the underlying, leached Edgar till. If this is the case, it would explain the lower sand and higher silt content of our samples as compared to the results of Mode (1976), Stewart (1973), and Mickelson (1986). The median magnetic susceptibility of samples collected from the till of the Merrill Member is 1.3 x 10^{-3} (S.I. units) (see table 1).

Horicon Formation

Till of the Mapleview Member

The till of the Mapleview Member of the Horicon Formation (Mickelson and others, 1984) occurs at the surface in eastern Marathon County (map units gh and ghh on plate 1). The till of the Mapleview Member is a brown, dolomitic, gravelly to slightly gravelly, clayey, silty sand. The Mapleview till becomes somewhat sandier from north to south in Marathon County, presumably because the ice of the Green Bay Lobe that flowed into the southern part of the county would have crossed more Cambrian sandstone than the ice that flowed into the northern part of the county.

Samples of the till of the Mapleview Member collected in Langlade County typically have a ratio of sand:silt:clay of about 77:16:7 for the finer-than-2-mm fraction (Mickelson, 1986). To the south in Portage County, the till of the Mapleview Member contains 80 to 90 percent sand, 5 to 10 percent silt, and 5 to 10 percent clay (Clayton, 1986). In Marathon County the Mapleview till is typically brown to dark brown (7.5YR 4/4) and is leached of carbonate to a depth of about 2 m. The thickness of Mapleview till is poorly known, but construction logs of water wells indicate that the till is typically 10 m or more thick and that it is typically underlain by sand and gravel. Sections D-D′ and E-E′ on plate 1 show that the glacial advances to the Hancock, Almond, and Elderon moraines (fig. 8) resulted in the interlayering of Mapleview till and meltwater-stream sediment. The till of the Mapleview Member occurs in broad areas of hummocky glacial topography, in drumlins, and in moraines (plate 1).

Late Wisconsin landforms

Only in eastern Marathon County, in the area glaciated by the Green Bay Lobe during the last part of the Wisconsin Glaciation, are glacial landforms well preserved. The remainder of Marathon County was glaciated earlier in the Pleistocene or during the late Pliocene, and glacial landforms have, for the most part, been obliterated by slope processes. Permafrost probably existed throughout Marathon County when the Green Bay Lobe advanced into the eastern part of the county; solifluction during this interval probably accelerated the erosion of glacial materials and landforms in the area lying in front of the ice.

Moraines

The outermost moraine of the Green Bay Lobe in Marathon County is the Hancock moraine (fig. 8), which is typically 1 to 1.5 km wide but in places reaches a width of about 3 km. In most areas the front of the moraine is steep; most of the moraine is hummocky and boulders are common on the surface. Distinct ice-marginal ridges (plate 1) are visible on aerial photographs (1:20,000 scale), and in some areas these ridges are apparent on topographic maps (1:24,000 scale). Segments of an ice-marginal ridge can be seen in figure 9. The Hancock moraine is cut by tunnel channels and contains ice-walled-lake plains. The Almond moraine is similar to the Hancock moraine, but the Elderon moraines (fig. 8) are distinctly different. The Elderon moraines consist of narrow, discontinuous ice-marginal ridges and lack the broad areas of hummocky topography, tunnel channels, and ice-walled-lake plains that are typical of the Han-

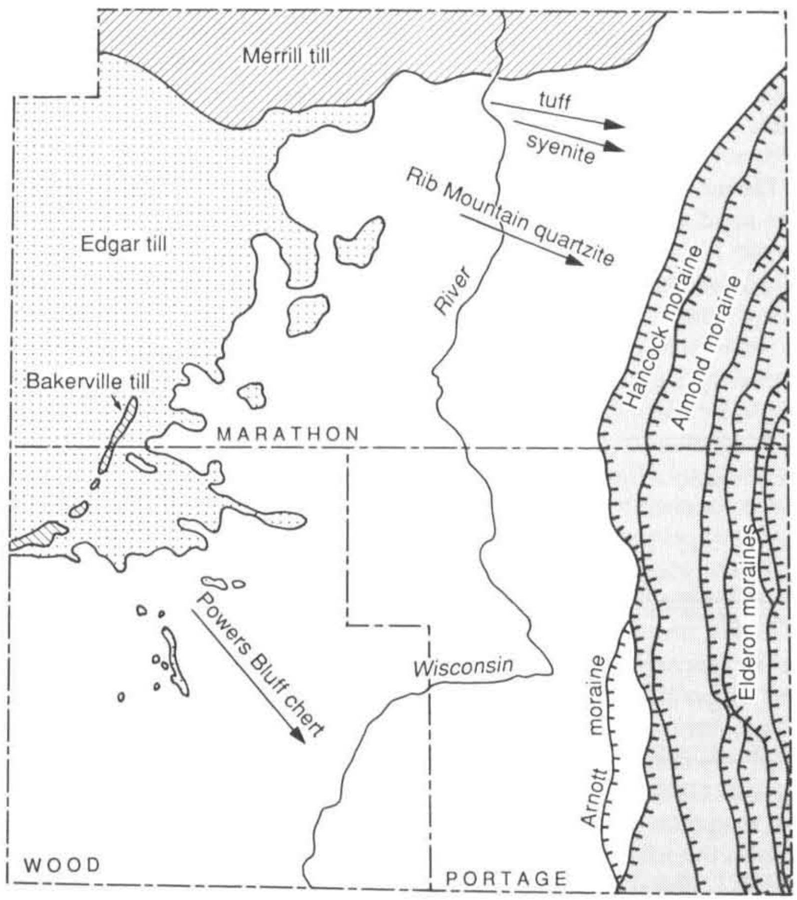


Figure 8. *Distribution of till units and the location and orientation of glacial dispersal fans in central Wisconsin. Arrows show the direction of transport of the rock types. The Powers Bluff chert train was first noted by Weidman (1907) and recently mapped by Clayton (in press). The eastward dispersal of quartzite, syenite, and tuff in north-central Marathon County was recognized by LaBerge and Myers (1983).*

cock and Almond moraines. In addition, drumlins are associated with the Elderon moraines, but none are found in the area of the Hancock and Almond moraines.

Attig and others (1988) have suggested that the outer 5 to 20 km of the ice sheet was frozen to its bed during and shortly after the maximum extent of late Wisconsin ice. A frozen-bed zone along the glacier margin may explain the stacking and accumulation of thick supraglacial sediment that produced the hummocky topography in the Hancock and Almond moraines and the cutting of the tunnel channels. By the time the Elderon moraines were forming, the glacier was no longer frozen to its bed but was sliding and producing the drumlins associated with the Elderon moraines. A thawed bed may also explain why broad zones of hummocky glacial topography did not form after deposition of the Almond moraine.

Tunnel channels

Plate 1 and figure 9 show that broad areas of collapsed meltwater-stream sediment occur in channels cut through the Hancock and Almond moraines. These channels formed in a 5 to 20 km wide zone along the margin of the late Wisconsin glacier when it stood at its maximum extent in Wisconsin (Attig and others, 1988). Large sediment fans at the mouths of the tunnel channels indicate that water carried large amounts of sediment from beneath the ice to the ice margin. In Marathon County and adjacent areas, many of the channels slope upward to the ice margin, indicating flow in a tunnel.

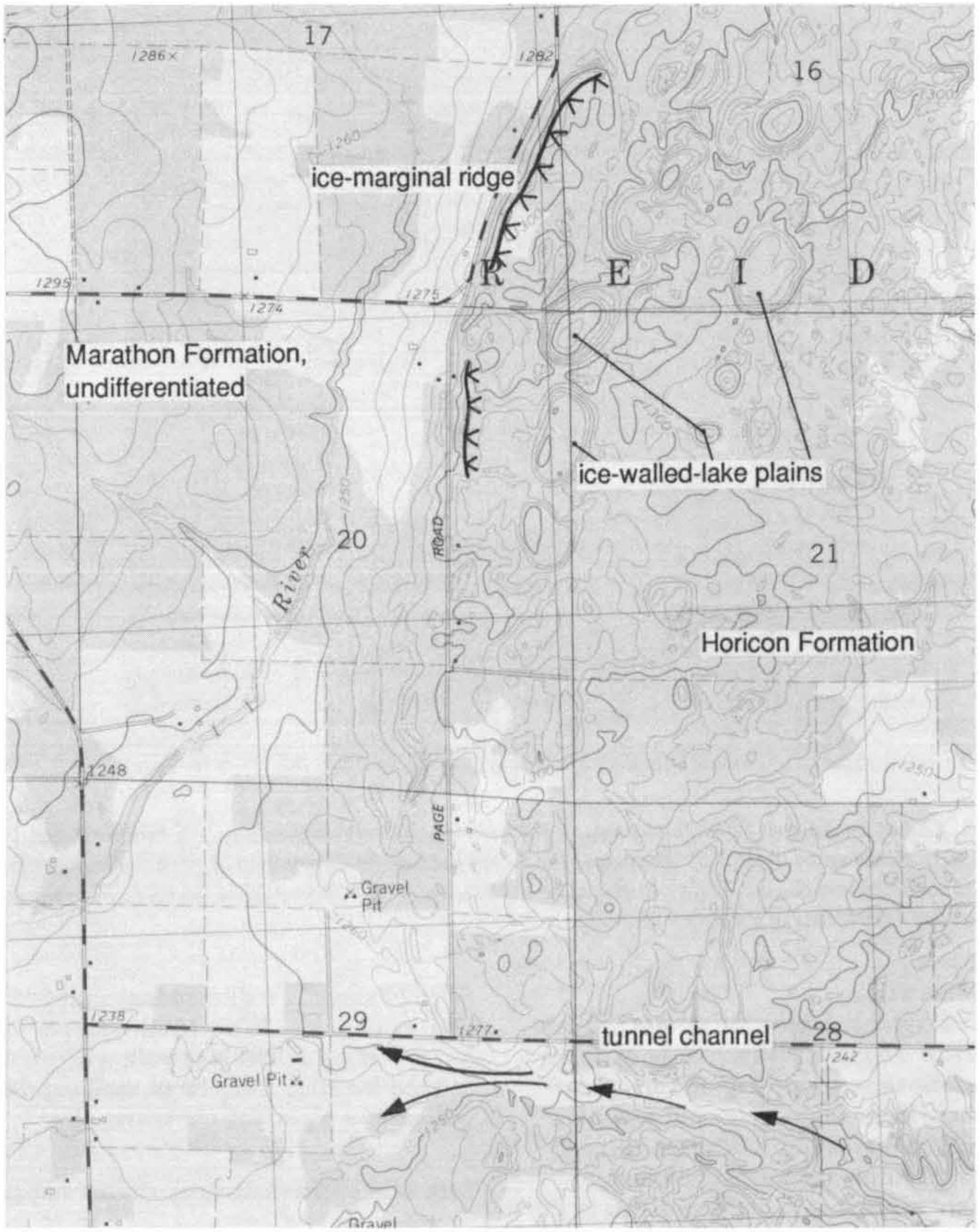


Figure 9. *Part of the Bevent Quadrangle, Wisconsin (U.S. Geological Survey, 7.5-minute series, topographic, 1982), showing part of the Hancock moraine. A tunnel channel cuts through the moraine in the lower part of the area shown. Note the hummocky topography in the Hancock moraine.*

The large size and close spacing of the tunnel channels suggest that they functioned episodically. The tunnel channels appear to have formed when meltwater from thawed-bed areas 5 to 20 km behind the ice margin drained through the frozen-bed zone along the glacier margin. Wright (1973) interpreted similar features along the margin of the Superior Lobe in Minnesota to have formed when meltwater drained through a frozen-bed zone along the margin of the ice.

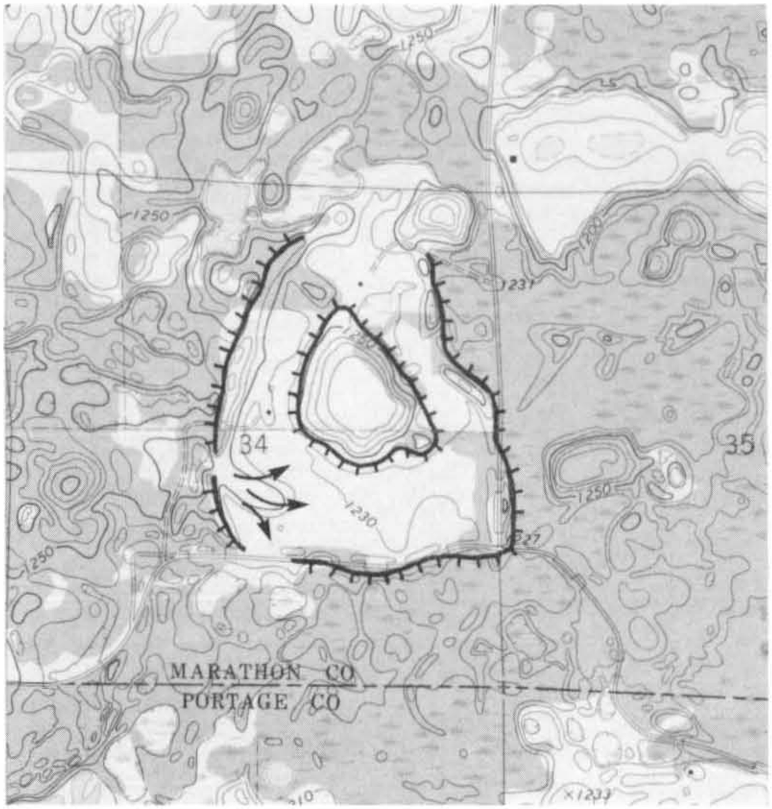


Figure 10. *Part of the Rosholt NW Quadrangle, Wisconsin (U.S. Geological Survey, 7.5-minute series, topographic, 1969), showing an ice-walled-lake plain. Hachured lines show the position of gravelly ice-marginal ridges that formed at the edge of the lake plain; arrows show the position of a delta formed in the lake. Note the other small ice-walled-lake plains in the area.*

Ice-walled-lake plains

Several ice-walled-lake plains are shown on plate 1 (map unit **lh**). The lake plains consist of flat to nearly flat areas, the centers of which are underlain by offshore lake-bottom fine sand and silt. The flat areas are high in the landscape because the lakes were bounded by ice. When the ice melted, the sediment that had accumulated in the lake basin was left as a high area. One ice-walled-lake plain in the southern part of the Almond moraine (figs. 8 and 10) apparently developed in two phases. During the first phase the higher, central part of the lake plain formed. Later, the ice bounding the lake wasted back and a more extensive lake formed at a lower level. The hachured lines in figure 10 show the two ice-margin positions. Other features of ice-walled-lake plains can also be seen in figure 10. The lower surface is surrounded by a discontinuous ridge of gravelly sediment that slumped off the surrounding ice. In the southwest part of the lower surface a delta was built where a stream entered the lake. Only large, well expressed ice-walled-lake plains are shown on plate 1.

Late Wisconsin meltwater-stream sediment

Sandy gravel, gravelly sand, and sand deposited by meltwater streams flowing from the late Wisconsin Green Bay Lobe are shown on plate 1 as map units **sh** and **shc** and are included in the Horicon Formation. Sandy gravel, gravelly sand, and sand deposited by meltwater streams flowing from the late Wisconsin Langlade and Wisconsin Valley Lobes (fig. 1) are shown on plate 1 as map unit **sc** and are included in the Copper Falls Formation. In areas where the sediment deposited by meltwater streams flowing from the Green

Bay Lobe cannot be distinguished from sediment deposited by meltwater streams flowing from the Wisconsin Valley and Langlade Lobes, the sediment is shown as map unit **sl** on plate 1. Map units **sh**, **sc**, and **sl** may contain some areas of nonglacial stream sediment or meltwater-stream sediment deposited before late Wisconsin time.

Late Wisconsin meltwater-stream sediment underlies conspicuous terraces along the Wisconsin, Rib, Little Rib, Eau Claire, Little Eau Claire, and Plover Rivers and some smaller tributary streams. Most late Wisconsin meltwater-stream sediment underlying terraces along the larger rivers in Marathon County was deposited well beyond the ice margin where the stream gradient was gentle; therefore, mostly sand was deposited. In general, the sediment in the terraces contains small amounts of gravel in areas where the valleys are wide, but some deposits contain considerable amounts of gravel where the valleys are narrow. These gravel deposits are common in the upper parts of the Rib and Wisconsin River valleys in Marathon County. Apparently, where the valleys are narrow, meltwater streams deposited gravel and transported sand farther downstream.

Broad plains underlain by meltwater-stream sediment occur behind and along the distal side of the Hancock moraine (map units **sh**, **shc**, and **sl**). In channels cut through the Hancock and Almond moraines and in other areas behind the Hancock moraine, meltwater-stream sediment was deposited on top of ice. The meltwater-stream sediment collapsed when the ice melted, leaving an irregular landscape. These collapse areas are shown on plate 1 as map unit **shc**. Sediment fans deposited at the mouths of tunnel channels that cut through the Hancock and Almond moraines typically contain gravelly sediment. Typically, gravelly meltwater-stream sediment is found only within about 0.5 to 0.75 km in front of the moraines shown on plate 1.

Pleistocene history

In the following discussion the term "phase" is used as a geologic event term and is an interpretation based on a reconstruction of glacial events. It is not a diachronic unit because it is not descriptive and is not defined on the basis of a type section.

Possible pre-Stetsonville glaciation

In the central part of Marathon County, glacially transported stones, till or till-like material (Wausau Member of the Marathon Formation) and possible glacial dispersal fans indicate that the central Marathon County area has been glaciated (fig. 8). Because the glacial sediment in the central part of the county has been reworked or completely stripped from the landscape, the extent of glaciation, the number of glaciations, and the relationship to the better understood glacial record in western Marathon County is obscure.

In central Marathon County, about 95 percent of the surface clasts have the same lithology as the underlying or nearby Precambrian or Cambrian rock. The remaining 5 percent are a variety of igneous and metamorphic rock types, including some fragments of amygdaloidal or porphyritic volcanic rock and rounded or wind-abraded quartzose rock. Thwaites (1943) suggested that the fragments of amygdaloidal or porphyritic volcanic rock were most likely derived from the Upper Peninsula of Michigan and were glacially transported to central Wisconsin. Because they occur high in the landscape and typically are not rounded, stream transport does not seem a likely explanation for their distribution.

The rounded quartzose pebbles and cobbles (maximum diameter, about 0.2 m) may have been abraded and deposited by streams as the landscape was stripped of Paleozoic and younger material. The cobbles may be derived from the Cretaceous or early Cenozoic Windrow Formation, if that unit extended as far north as Marathon County. Similar cobbles have been described from the Windrow Formation in southwestern Wisconsin (Thwaites and Twenhofel, 1921). Alternatively, some of the rounded clasts may be derived from conglomeratic zones near the base of the Cambrian sandstone. Many of the rounded quartzose rocks are wind-polished and faceted. LaBerge and Myers (1983, p. 68) recognized glacial dispersal fans composed of white quartzite, nepheline syenite, and a purplish-brown tuff in the area of map unit **gu** on plate 1 (fig. 8). These fans indicate that ice flowed from the northwest, as does a dispersal fan of chert from Powers Bluff in adjacent Wood County (Weidman, 1907; Clayton, in press). The eastward extent of ice during the Stetsonville and Milan

Phases is not known. It is clear, however, that the glacier that deposited the Edgar till during the Milan Phase extended southeastward beyond Powers Bluff in Wood County (Clayton, in press; fig. 8). Clayton suggests that the Powers Bluff chert fan was deposited during the Milan Phase, the last glacial advance to cover the area. If that interpretation is correct, probably all of western and central Marathon County was glaciated during the Milan Phase. The orientation of the dispersal fans noted by LaBerge and Myers (1983) indicates that they could have been formed by the same glacier that formed the Powers Bluff chert fan. The Edgar till in western Marathon County contains some fragments of amygdaloidal and porphyritic volcanic rock. The dispersal fans and the glacially transported rock found in central Marathon County could be the result of glaciation during the Milan Phase.

The clay mineralogy of the Wausau Member (type section in central Marathon County) indicates it has undergone considerable weathering (Stewart and Mickelson, 1976). The Wausau Member may have been deposited by a pre-Stetsonville advance, may be deeply weathered Medford or Edgar till, or may be slopewash sediment derived from deeply weathered Medford or Edgar till.

Stetsonville Phase

During the Stetsonville Phase a glacier advanced from the west-northwest at least as far as northwest Marathon County and deposited the till of the Medford Member of the Marathon Formation (Attig and Muldoon, 1988). Small patches of the till of the Medford Member occur in the subsurface at least as far west as western Taylor County. This unit is not known to extend southeast beyond northwestern Marathon County, but its patchy distribution in the subsurface suggests that it was stripped from much of the landscape, probably early in the Pleistocene; therefore, its original extent is unknown.

Data from the measurement of the orientation of the long axis of pebbles at the only known outcrop of till of the Medford Member (in adjacent Taylor County) indicate that the glacier that deposited the Medford Member advanced from the west or west-northwest. Medford till contains many fragments of hard, gray shale as well as fragments of siliceous, fossiliferous limestone. These shale fragments are most likely derived from the upper part of the Upper Cretaceous section in eastern North Dakota and southern Manitoba. Some of the shale may be derived from parts of the generally less hard shale in the lower part of the Upper Cretaceous section and from Lower Cretaceous material in northwestern Minnesota. The fragments of shale suggest flow lines extending from Manitoba across eastern North Dakota and Minnesota to central Wisconsin. The fossils in the siliceous limestone fragments in the Medford till are not identifiable, but Clayton (in press) suggested that the Edgar till, the till unit that overlies the Medford Member and contains fossiliferous pebbles, was derived from the Winnipeg lowlands. The Edgar till contains few fragments of hard shale, indicating flow lines somewhat east of those during the Stetsonville Phase. The Edgar and Medford Members were apparently deposited by ice flowing southeastward out of the Manitoba area. The incorporation of soft shale from lower Upper Cretaceous and Lower Cretaceous rock may account for the silty nature of the Medford and the Edgar till units.

The gray color and common fragments of shale and limestone in the till of the Medford Member are similar to characteristics of till units in west-central Wisconsin (Baker and others, 1987) and units described by Goldstein (1987) in Minnesota. The Medford Member of the Marathon Formation is the only gray, silty, calcitic till unit known in central Wisconsin. Two lithologically similar till units, the Woodville (older) and Hersey (younger) Members of the Pierce Formation, have been identified in west-central Wisconsin (Mickelson and others, 1984; Baker, 1988). Reversed paleomagnetic remanence of the Hersey Member indicates that the Pierce Formation was deposited at least 730,000 years ago, and possibly as early as about 2 million years ago (Baker and others, 1983; Baker, 1986). Baker and others (1987) speculated that the Medford Member of the Marathon Formation and one or both of the gray till units of the Pierce Formation were deposited by an extensive pre-Illinoian advance of ice across Minnesota into west-central and central Wisconsin. If this interpretation is correct, the Stetsonville Phase occurred in the early Pleistocene or late Pliocene.

Milan Phase

During the Milan Phase a glacier advanced, probably several times, and covered all of western and probably central Marathon County and deposited the Edgar Member of the Marathon Formation. The orientation of the long axis of pebbles in Edgar till indicates ice flow from the north or northwest (Mode, 1976). The Edgar Member thins and becomes patchy to the east. It has apparently been stripped from the landscape in the central part of the county, where streams are deeply incised and slopes are relatively steep. The Edgar till also thins and becomes patchy southeastward in Wood County (Clayton, in press; fig. 8). Clayton suggests that Edgar till may have extended as far as the Wisconsin Rapids area and may have been deposited by the same glacier that deposited the Powers Bluff chert fan. If this is true, Milan Phase ice must have covered all of Marathon County and probably deposited the dispersal fans noted by LaBerge and Myers (1983) in central Marathon County.

Clayton (in press) suggested that the fossiliferous pebbles found in Wood County in stream sediment associated with the Edgar till indicate a source area in Manitoba. Other possible sources of carbonate rock are either too small to account for the large amount of calcite in the Edgar till or are not located up the flow lines indicated by the orientation of pebbles in the till. Carbonate rock from the James Bay area is not present in large quantities south of Lake Superior.

In Marathon County the Edgar Member locally contains two till units separated by non-glacial sediment. In several drillholes, the stratigraphic sequence consists of till leached of carbonate material overlying unleached till, which overlies a layer of nonglacial sediment, which in turn overlies a second till unit, the upper part of which is leached. Data from these drillholes indicate that the till of the Edgar Member was deposited by at least two ice advances. The till units are indistinguishable and therefore not differentiated on plate 1. In Wood County, Clayton (in press) recognized three subdivisions in the till of the Edgar Member.

Nasonville Phase

Sometime after the Milan Phase, but prior to the Hamburg Phase, ice advanced out of the Superior basin and deposited the red, sandy, noncalcareous till of the Bakerville Member of the Marathon Formation in western Marathon County and adjacent Wood and Clark Counties. A flow path out of the Superior basin is indicated by the presence of many clasts of red sandstone and unaltered volcanic rock, probably from the Keweenawan Supergroup, and by the orientation of pebbles in the till of the Bakerville Member (Mode, 1976).

The till of the Bakerville Member clearly overlies the till of the Edgar Member; therefore, the Nasonville Phase occurred after the Milan Phase. Small-scale glacial topography on the till of the Bakerville Member has been destroyed by erosion, but small-scale glacial topography survives in many places on the till of the Merrill Member. This suggests that the Nasonville Phase occurred earlier than the Hamburg Phase. Although the sandy Bakerville Member and the silty Edgar Member are lithologically distinct, the soil of the Withee series is mapped on both units in much of western Marathon County and adjacent parts of Clark and Wood Counties. Near the surface the lithologic distinction between the Bakerville and Edgar Members is apparently masked by extensive mixing of material derived from these two units as well as mixing with windblown sediment and residual material, and local development of thick, clay-rich soil horizons.

In Marathon County the Bakerville Member has been stripped from the landscape in most places except where it forms a fairly continuous cover on the Marshfield moraine, a conspicuous highland that extends about 5 km into Marathon County from adjacent Wood County (map unit gb on plate 1). In Marathon County the sediment in the Marshfield moraine is poorly exposed and, therefore, the depositional history of the moraine is poorly understood. In adjacent Wood County, Clayton (in press) concluded that the Bakerville Member caps a moraine formed during an earlier glacial phase, the Marshfield Phase. According to Clayton, this phase occurred after the Milan Phase but prior to the Nasonville Phase. No evidence for the Marshfield Phase is recognized in Marathon County.

Hamburg Phase

The till of the Merrill Member of the Lincoln Formation was deposited in north-central and northwestern Marathon County during the Hamburg Phase. The Merrill Member, like the Bakerville Member, is reddish brown, sandy, and contains gravel rich in rock types derived from the Lake Superior basin. Measurements of the orientation of the long axis of pebbles in till of the Merrill Member at two sites indicate ice flow from the north or northwest. These results agree with those of Stewart (1973). The surface underlain by the Merrill till is the only till surface deposited prior to the late Wisconsin in Marathon County that displays hummocky glacial topography. The topography is subdued as a result of erosion but is evident on aerial photographs of the area of map unit **gm** on plate 1. Some of the hummocky areas may be erosionally subdued moraines. The drainage in the area underlain by the Merrill Member is less well integrated than on the older till surfaces in western Marathon County. As a result, there are more wetlands and undrained depressions. No small-scale glacial topography is evident on surfaces underlain by the Bakerville Member; therefore, the Merrill Member is believed to be younger than the Bakerville Member, although the time of deposition of the Merrill Member is not well defined. The Merrill Member clearly lies beyond the prominent, well preserved moraines deposited during the maximum extent of the Wisconsin Valley and Langlade Lobes in late Wisconsin time, and is therefore older. Two radiocarbon dates from organic-rich silt and clay overlying the Merrill Member are 40,800 BP$\pm$ 2,000 (IGS-256) and older than 36,800 BP (IGS-262) (Stewart and Mickelson, 1976). If correct, these dates provide a minimum age for the Merrill Member. Stewart and Mickelson (1976) and Mode (1976) reported that clay minerals in the Merrill till are less intensely weathered than those in the Wausau and Edgar Members of the Marathon Formation; however, they are more weathered than those in late Wisconsin till units. The Merrill Member was probably deposited early in the Wisconsin Glaciation.

Hancock, Almond, and Elderon Phases

During the last part of the Wisconsin Glaciation, between about 25,000 and 13,000 years ago (Attig and others, 1985), ice from the expanding Green Bay Lobe (fig. 1) advanced from the east-southeast into eastern Marathon County and deposited the till and associated lake and stream sediment of the Mapleview Member of the Horicon Formation. Three distinct glacial phases are recognized in the well preserved ice-marginal deposits in the eastern part of the county.

During the Hancock Phase the Green Bay Lobe advanced to its most extensive late Wisconsin position and formed the Hancock moraine (fig. 8). The Hancock moraine is cut by a series of tunnel channels (plate 1; fig. 9). During the Hancock Phase, most meltwater flowed westward down the Eau Claire or Little Eau Claire Rivers.

After the Hancock Phase the ice margin wasted back and then readvanced and formed the Almond moraine (fig. 8). The Almond moraine is also cut by a number of tunnel channels, indicating that the margin of the glacier was still frozen to its bed during the Almond Phase. During this phase, meltwater flowed southward down the Plover River. The Hancock and Almond ice-margin positions are marked by broad areas of hummocky glacial topography that contain discrete ice-marginal ridges (plate 1).

In contrast, the later Elderon ice-margin positions are marked by discontinuous, narrow ridges that have no broad areas of hummocky glacial topography. Tunnel channels were not cut through the Elderon moraines. A few areas of streamlined glacial topography occur between the Elderon moraines, indicating that by the time of the Elderon Phase the margin of the glacier was no longer frozen to its bed.

Hydrogeologic properties

Fractured igneous and metamorphic Precambrian rock yields sufficient water to be used as a water source by many rural residents in Marathon County. Wells drawing water from fractures in these rocks typically provide sufficient water for domestic use, yielding 1.3×10^{-6} to 9.5×10^{-4} m^3/sec (0.02 to 15 gallons per minute). In the south and southwestern parts of the county, the Cambrian sandstone is a dependable, moderately productive source of groundwater with yields ranging from 6.3×10^{-5} to 4.7×10^{-3} m^3/sec (1 to 75 gallons per minute) (Bell and Sherrill, 1974).

Pleistocene sediment yields water in sufficient quantities to be used for water supply by many municipalities. Meltwater-stream sediment

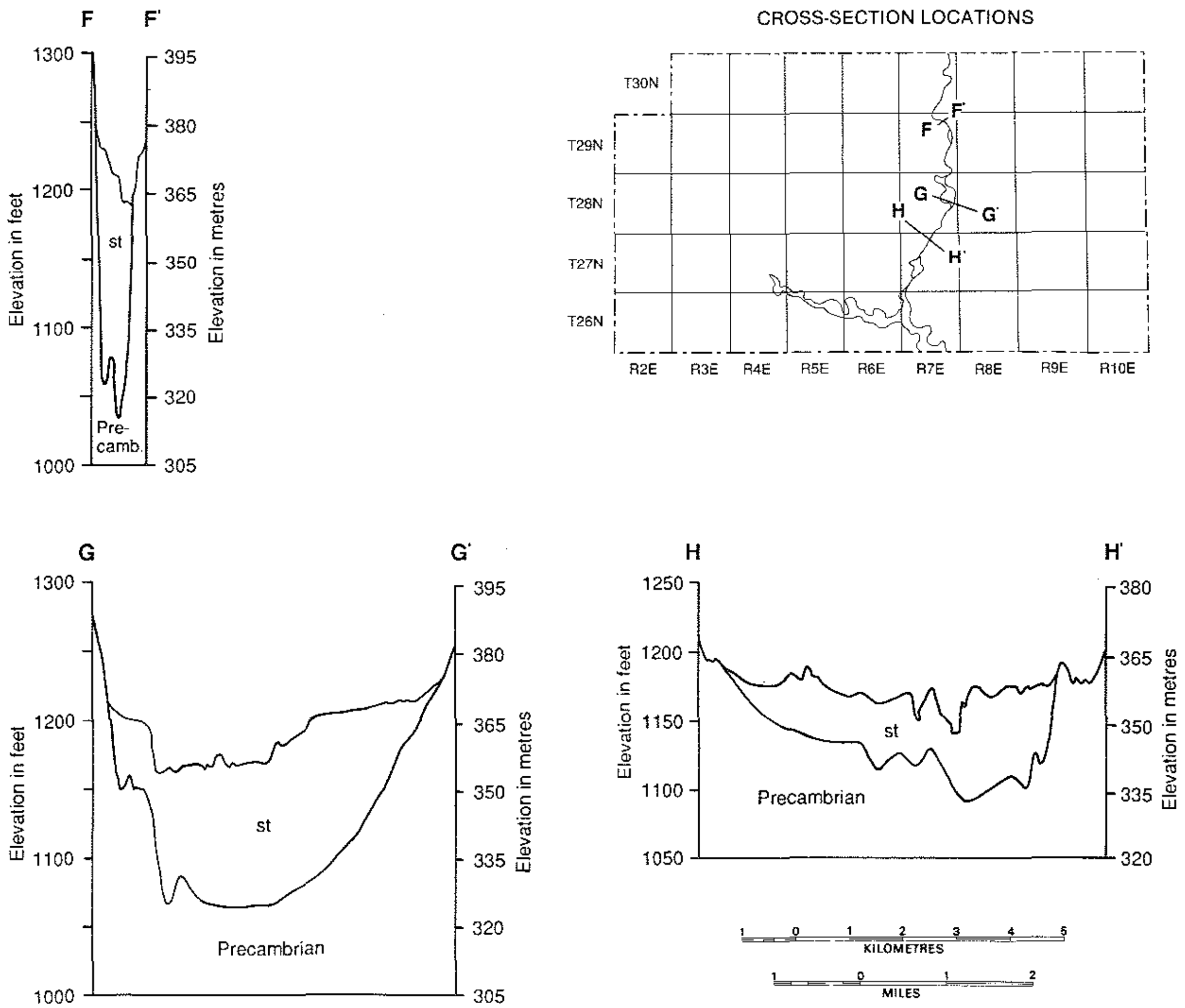


Figure 11. *Cross sections showing thickness of meltwater-stream sediment (unit st) near Wausau (modified from Kendy, 1986).*

(cross-section unit **st**, section B-B' on plate 1), deposited during glacial phases prior to the late Wisconsin and subsequently buried, is an important source of water for many small communities in the western half of the county. Abbotsford, Athens, Colby, Edgar, Marshfield, Spencer, and Stratford obtain most of their water from buried sand and gravel deposits. Wells constructed in this material typically produce from 1.3 x 10^{-3} to 2.5 x 10^{-2} m^3/sec (20 to 400 gallons per minute) (Bell and Sherrill, 1974).

The silty and clayey glacial materials of the Marathon and Lincoln Formations (map units **ge**, **gu**, **gd**, **gb**, and **gm**, plate 1) deposited prior to the late Wisconsin are poor sources of water; wells typically yield less than 1.3 x 10^{-4} m^3/sec (2.0 gallons per minute) (Bell and Sherrill, 1974).

Late Wisconsin meltwater-stream sediment (cross-section unit **st** on the sections in fig. 11; these sections were modified from Kendy, 1986) typically yields up to 2.8 x 10^{-2} m^3/sec to wells (450 gallons per minute) (Kendy, 1986). Kendy (1986) recently completed a detailed study of the valley-fill sediment near Wausau. She concluded that (1) the hydraulic conductivity of the valley-fill sediment ranges from 10^{-4} to 10^{-2} cm/s, and in general, hydraulic conductivity is higher to the north; (2) the groundwater-flow pattern has been greatly altered by the construction of dams and the initiation of large-scale pumping; and (3) the soil overlying the valley-fill sediment provides poor protection from contaminants.

Several agencies, including the WGNHS, the Wisconsin Department of Natural Resources, and the University of Wisconsin Water Resources Center, are using the Pleistocene lithostratigraphy of Wisconsin of Mickelson and others (1984) and Attig and others (1988) as a framework for assigning hydraulic conductivity values to glacial materials. For this report, we determined the hydraulic conductivity of the till of four Pleistocene lithostratigraphic units on the basis of field tests, laboratory tests, and empirical estimates based on grain-size distribution curves; we used this information to outline hydrogeologic units. A hydrogeologic unit is a stratigraphic unit that is areally extensive and able to be differentiated from surrounding units on the basis of hydraulic conductivity. A hydraulic conductivity difference of more than one order of magnitude was considered a sufficient difference to distinguish hydrogeologic units.

Field tests

Piezometer tests were the only measure of field hydraulic conductivity used in this study. Piezometers were installed at 11 sites (WGNHS Geologic Logs MR-1160 to MR-1170, fig. 2). The sites were selected in an attempt to sample the full range of grain-size distributions for each unit. At each site one or more piezometers, consisting of 3.2 cm PVC pipe with a PVC screen, were installed. Each screen was surrounded by a silica sand pack, a bentonite seal was placed above the sand pack, and the remainder of the hole was backfilled with material recovered during drilling. The geologic log and piezometer-construction diagram for hole MR-1162 is shown in fig. 12. Slug tests were conducted either by adding a known volume of water to the piezometer or by displacing a known volume of water and then recording the recovery of the water level over time. The Hvorslev method (1951) was used to analyze data from 25 slug tests on 17 piezometers.

Laboratory tests

In the laboratory, 13 samples were tested using a triaxial cell as a flexible-wall permeameter (fig. 13). In a flexible-wall permeameter a confining pressure is applied to the sample to hold an impermeable membrane tightly against it; this greatly reduces the chances of piping that can occur with rigid-walled permeameters (Dunn and Mitchell, 1984).

Undisturbed core samples for testing were collected from holes MR-1160 to MR-1170 (fig. 2) by using an overshot-split-spoon sampler. Of the 13 samples tested, seven are from the Marathon Formation and six are from the Lincoln Formation. The Edgar Member contains at least two distinct till units, separated by organic, fluvial, or lacustrine sediments; therefore, two sets of Edgar samples were tested and one set of samples from each of the other units was tested. For each unit, the samples tested were recovered from a single drillhole.

The core samples were trimmed, placed in the triaxial cell, and enclosed in two rubber membranes. Once the sample was saturated, it was consolidated to the calculated field overburden pressure. The permeability test was initiated by applying air pressure to the burettes and establishing an upward gradient across the sample. After the gradient had been applied, inflow and outflow volumes were recorded at approximately two-hour intervals. After steady state had been achieved, two to eight additional inflow/outflow measurements were recorded and used to calculate the hydraulic conductivity using the equation for a constant-head permeameter test (Olson and Daniel, 1981).

Grain-size estimates

Many researchers have tried to establish empirical relationships between hydraulic conductivity and more easily measured physical properties of unconsolidated materials. Bedinger (1961), Hazen (1893), and Rose and Smith (1957) have established relationships between some measure of "effective grain-size" and hydraulic conductivity. Krumbein and Monk (1943) and Masch and Denny (1966) expanded the effective diameter relationships by including a measure of sorting of the sample. Two recent studies (Cosby and

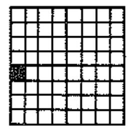
Symbols

bentonite seal

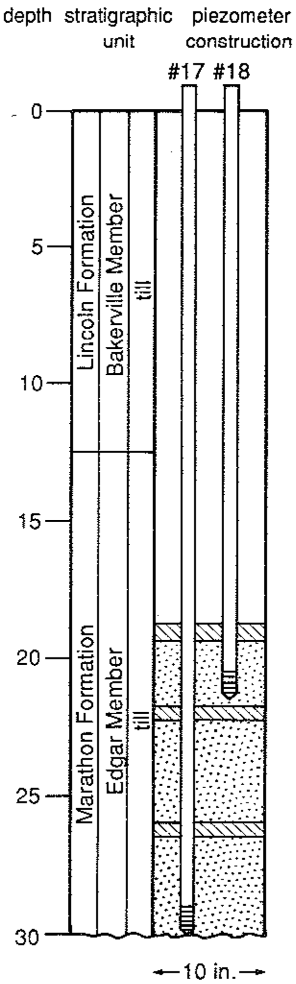
sand pack

fill

Location



Sec. 3
T. 26 N.
R. 2 E.
Quad. Spencer North



Geologic description

0 to 11.5 ft - Dark brown to strong brown (7.5YR 4/4 - 4/6, moist) medium to fine silty sand with clay, few pebbles (< 5%), grain-size distribution is 51.5% sand, 34.0% silt, 14.5% clay. Some orange mottles (iron staining?) present, noncalcareous, no laminations.

11.6 to 13.5 ft - Gradational zone between above and below units. Dark yellowish brown (10YR 4/4, moist) sandy silt with clay, few pebbles (approx. 35.8% sand, 45.1% silt, 19.1% clay). Occasional orange mottling present, noncalcareous, no laminations.

13.6 to 19.5 ft - Dark grayish brown (10YR 4/2 on top grading to 2.5Y 4/2 on bottom, moist colors) sandy, clayey silt with few pebbles (approx. 5%), grain size distribution is 28.4% sand, 49.0% silt, 22.6% clay; sand tends to be fine. More mottling than above, mottles are more sharply defined (5YR 5/8). Material is noncalcareous, no laminations.

19.6 to 30 ft - Yellowish brown (10YR 5/5, on top grading to 10YR 5/6 on bottom, moist colors) sandy silt with clay and few pebbles (approx. 36.4% sand, 45.3% silt, 18.3% clay).
- From 21 to 25 ft - weakly developed fractures are present, along fractures there is black manganese (?) staining.
- From 25 to 29.5 ft - fractures are strongly developed, both iron staining (7.5YR 5/8) and manganese staining are present along fracture faces.
- At 20.75 ft - material changes from noncalcareous to very calcareous, stays calcareous to end of hole.

Ended hole because material was very tight and drilling was very slow.

Figure 12. *WGNHS Geologic Log of hole MR-1165 showing piezometer construction and description of geologic materials. Depth is recorded in feet.*

others, 1984; Puckett and others, 1985) determined that the hydraulic conductivity was best estimated from the percentage of the sample that fell within a given size class.

Methods used to estimate hydraulic conductivity include those developed by Bedinger (1961), Hazen (1893), Krumbein and Monk (1943), Puckett and others (1985), and Cosby and others (1984). The relationships established by Masch and Denny (1966) and Rose and Smith (1957) were developed for well sorted sand and could not be extended to the samples collected in this study.

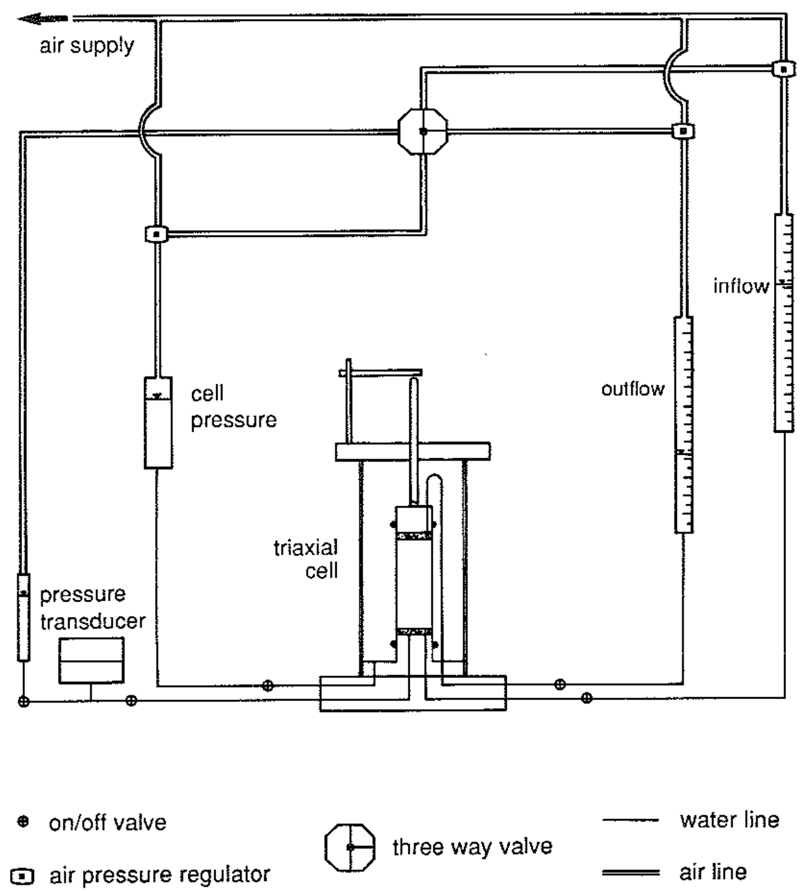


Figure 13. *Schematic diagram of the flexible-wall permeameter used to determine laboratory hydraulic conductivity values (modified from Edil and Erickson, 1985). The triaxial cell is filled with water and pressurized to the field overburden pressure; air pressure applied to the inflow and outflow burrettes is used to create a gradient across the sample.*

Detailed grain-size analyses were performed on 111 samples. For each sample a cumulative grain-size distribution curve was plotted and the grain diameters needed for the hydraulic conductivity calculations were then determined from these curves. To compare the results of the different methods, all permeability values were converted to hydraulic conductivity values and all hydraulic conductivity values were converted to cm/s.

Results

The methods used to determine hydraulic conductivity produced widely varying results. In general, the field-measured values were 2.5 to 3 orders of magnitude greater than the laboratory values, and the grain-size estimates of hydraulic conductivity produced a range of values covering 3 to 4 orders of magnitude for any given till unit. The results obtained using each method are summarized below; a more detailed presentation of these results is given by Muldoon (1987).

Results of all piezometer tests are summarized in table 2 and shown graphically in figure 14. Most piezometers were placed within the till of the Edgar Member because this unit has the broadest geographic distribution and the greatest saturated thickness of all of the units tested. The results from the Edgar till suggest that the field hydraulic conductivity is log-normally distributed (fig. 14). The two hydraulic

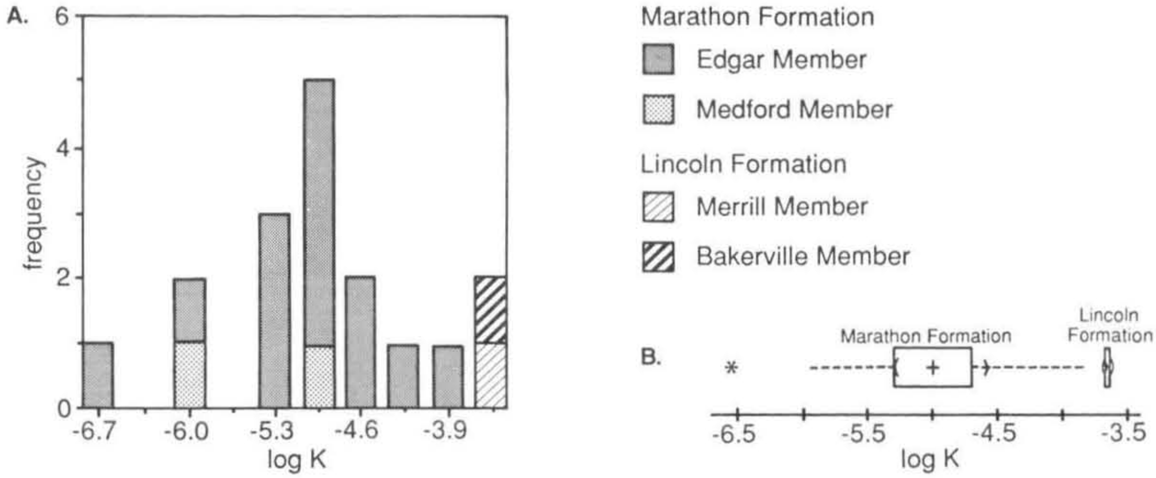


Figure 14. *Summary of results of piezometer tests. A) Histogram of log_{10} transformed field hydraulic conductivity results from 17 piezometers (original data were in units of cm/s). Each frequency unit represents the results from one piezometer. B) Boxplot showing the median value (+), the approximate 95 percent confidence interval (parentheses), and the central 50 percent of the data (boxed area). The dashed lines extend over the range of the population unless the extreme data points lie more than a specified distance from the median, in which case the extreme value is represented by an asterisk (*).*

Table 2. Summary of field and laboratory measurements of hydraulic conductivity (cm/s).

Lithostratigraphic unit	Field tests: Number of piezometers	Field tests: Number of tests	Field tests: Geometric mean	Laboratory tests: Number of tests	Laboratory tests: Geometric mean
Marathon Formation	15	20	5.8×10^{-6}	7	3.4×10^{-8}
Medford Member	2	4	3.6×10^{-5}	5	6.4×10^{-8}
Edgar Member	13	16	9.5×10^{-6}	2	1.8×10^{-8}
Lincoln Formation	2	5	2.3×10^{-4}	6	1.1×10^{-7}
Bakerville Member	1	2	2.5×10^{-4}	2	1.4×10^{-7}
Merrill Member	1	3	2.2×10^{-4}	4	9.2×10^{-8}

conductivity values for the Medford till fall within the range of the Edgar results, indicating that these units could be treated as a single hydrogeologic unit.

The small number of results from the Lincoln Formation reflects the distribution of these till units in the landscape. The Merrill and the Bakerville tills are thin surficial units that lie above the saturated zone in most areas. One piezometer was located in each of these units and the slug-test results indicate that there is little difference in hydraulic conductivity between the Bakerville and Merrill Members.

The few results available for the Lincoln Formation make it difficult to assess whether the field results represent two distinct populations. Nonparametric boxplots were chosen as the method to compare the results from the two formations (fig. 14). Nonparametric statistics use the median value rather than the mean; as a result, they are less sensitive to extreme values. Boxplots provide an easy way to compare two populations because they display the median value, the 95 percent confidence limits around the median, and the spread of the data with extreme values highlighted. Figure 14 shows that the 95

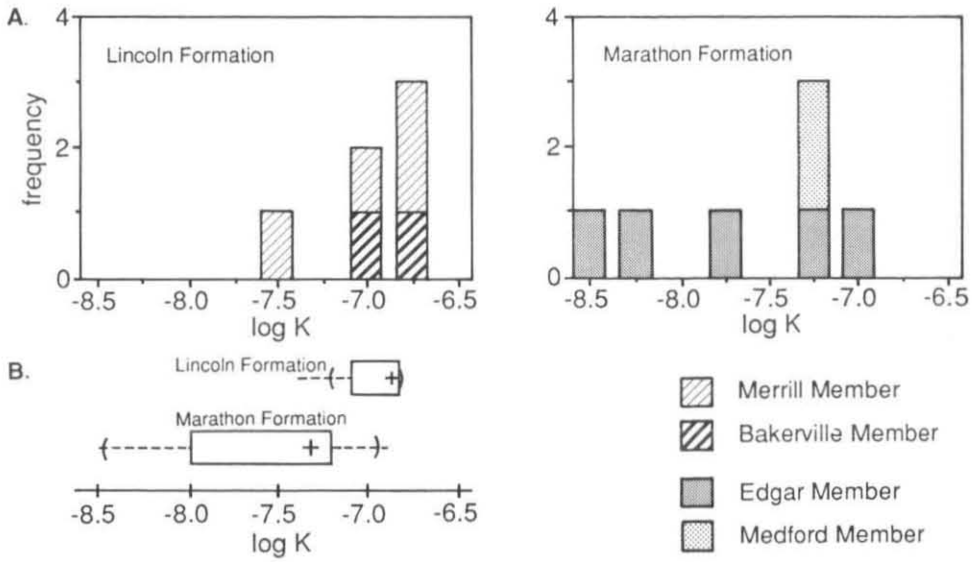


Figure 15. *Summary of results of laboratory tests of hydraulic conductivity. A) Histogram of $\log_{10}$ transformed laboratory hydraulic conductivity results from 13 samples (original data were in units of cm/s). Each frequency unit represents the results from one sample. B) Boxplot showing the median value (+), the approximate 95 percent confidence interval (parentheses), and the central 50 percent of the data (boxed area). The dashed lines extend over the range of the population.*

percent confidence limits around the median hydraulic conductivity values of the two formations do not overlap; this suggests that the Marathon and Lincoln Formations are separate hydrogeologic units.

Table 2 and figure 15 summarize the results of the laboratory-measured hydraulic conductivity values. These results, compared at the formation level, show more overlap than the field results (figs. 14 and 15). Geometric means of the laboratory results for the two formations are 2.5 to 3 orders of magnitude smaller than the field results (table 2). In addition, the laboratory results show less variation between the two formations than do the field results. The boxplot in figure 15 shows that the 95 percent confidence limits around the median hydraulic conductivity value of the Lincoln Formation fall almost entirely within the 95 percent confidence limits of the Marathon Formation. This indicates that the samples of the two formations that were tested in the laboratory do not show a significant difference in hydraulic conductivity.

The difference between laboratory and field-measured hydraulic conductivity values is comparable to that observed by Herzog and Morse (1984) for similar tests on the fine-grained Vandalia Till Member of Illinois. Because many till units have only weakly developed horizontal fabric, such large discrepancies between field and laboratory results cannot be explained by vertical anisotropy alone. The difference in scale between the two tests probably caused a large part of the discrepancy (Bradbury and Muldoon, in press).

The geometric means of the hydraulic conductivity values calculated for each till unit using grain-size distributions are given in table 3 and shown graphically in figure 16. For the following equations used to estimate hydraulic conductivity, D50 = median diameter (mm), D10 = diameter (mm) at which 10 percent of the sample is finer, Dm = mean diameter (mm), σ_ϕ = phi standard deviation, % sa = percentage of the total sample that is coarser than 0.05 mm, % cl = percentage of the total sample that is finer than 0.002 mm.

The equation developed by Bedinger (1961)

$$K_{(gal/day/ft^2)} = 2000 \times D50^2 \quad (1)$$

tends to overestimate hydraulic conductivity in comparison to values determined in the field. Hydraulic conductivity estimates for the Edgar

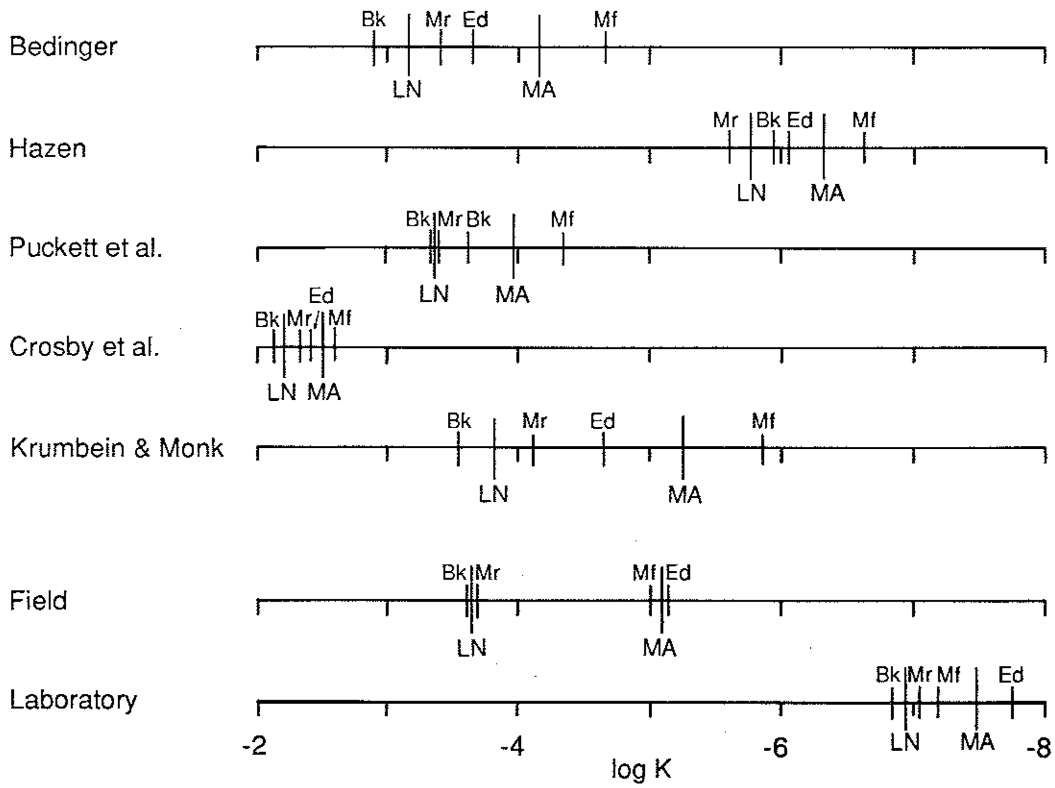


Figure 16. *Plot of the $\log_{10}$ transformed geometric means of hydraulic conductivity values as estimated from grain-size distribution curves using various empirical equations (original data were in units of cm/s). Field and laboratory results are shown for comparison. MA = Marathon Formation, LN = Lincoln Formation, Mf = Medford Member, Ed = Edgar Member, Bk = Bakerville Member, Mr = Merrill Member.*

Table 3. Comparison of different methods of calculating hydraulic conductivity values (cm/s) estimated from grain-size distribution, expressed as geometric means.

		Method				
Lithostratigraphic unit	**Number of samples**	**Bedinger**	**Hazen**	**Krumbein and Monk**	**Cosby**	**Puckett**
Marathon Formation	98	7.8×10^{-5}	6.0×10^{-7}	3.6×10^{-6}	3.2×10^{-3}	1.3×10^{-4}
Medford Member	13	2.7×10^{-5}	3.8×10^{-7}	1.5×10^{-6}	2.6×10^{-3}	7.1×10^{-4}
Edgar Member	85	2.3×10^{-4}	9.5×10^{-7}	8.4×10^{-6}	4.0×10^{-3}	2.4×10^{-4}
Lincoln Formation	13	7.1×10^{-4}	1.7×10^{-6}	3.2×10^{-5}	6.0×10^{-3}	4.0×10^{-4}
Bakerville Member	7	1.2×10^{-3}	1.2×10^{-6}	4.1×10^{-5}	7.4×10^{-3}	4.0×10^{-4}
Merrill Member	6	4.1×10^{-4}	2.5×10^{-6}	2.5×10^{-5}	4.8×10^{-3}	4.1×10^{-4}

and Bakerville till were 1 to 2.5 orders of magnitude greater than the field measurements of hydraulic conductivity (fig. 16). This method does, however, provide one of the estimates closest to the field-measured hydraulic conductivity of the Medford and Merrill till units.

Hazen's (1893) approximation,

$$K_{(cm/s)} = D10^2 \qquad (2)$$

which is similar in form to Bedinger's, consistently underestimates the hydraulic conductivity, compared to field results, by 1 to 2 orders of magnitude. This method provides the closest agreement with the laboratory-measured values; it consistently overestimated hydraulic conductivity values by approximately 1 order of magnitude (fig. 16).

The equation of Krumbein and Monk (1943)

$$k_{(darcies)} = 760 \times Dm^2 \times e^{(-1.31 \times \sigma_\phi)} \qquad (3)$$

is the only one used in this study that takes into account the sorting of a sample. This method predicts conductivity values that are closest to the field values of hydraulic conductivity of the till of the Edgar Member of the Marathon Formation (fig. 16). The empirical estimates for the other three till units differ from field values by approximately 1 order of magnitude or less.

The equation developed by Cosby and others (1984),

$$\log K_{(in/hr)} = (0.0153 \times \%sa) - 0.884 \qquad (4)$$

overestimates hydraulic conductivity, as compared to both field- and laboratory-derived results, by several orders of magnitude. Estimated hydraulic conductivity values are 1 to 3.5 orders of magnitude greater than field-measured values and 3.5 to 5 orders of magnitude greater than values measured in the lab (fig. 16).

The equation of Puckett and others (1985),

$$K_{(m/sec)} = 4.36 \times 10^{-5} \times e^{(-0.1975 \times \%cl)} \qquad (5)$$

which uses the percentage of clay in the finer-than-2-mm fraction of a sample, provides good estimates of field hydraulic conductivity for most of the till units. This equation predicts hydraulic conductivity values that are closest to the field values of the Merrill and Bakerville till units. The estimate for the Medford till was within 0.5 order of magnitude of the field results, and the hydraulic conductivity value predicted for the Edgar till was 1 order of magnitude greater than that measured in the field.

Comparison of the results from all five methods suggests that grain-size estimates of hydraulic conductivity should be used with caution; the five methods used in this study provide estimates of hydraulic conductivity that range over 3 to 4 orders of magnitude for any given lithostratigraphic unit. Each method is applicable for the sediments used to derive it and probably should not be extended to other materials. The methods of Krumbein and Monk (1943) and Puckett and others (1985) most closely predict the field hydraulic conductivities of the units studied. The sorting parameter included in Krumbein and Monk's method may account for the wide applicability of this equation. The method of Puckett and others was derived for fine-grained materials that may be similar, in terms of grain-size distribution, to the till of the Lincoln and Marathon Formations. Similar grain-size distributions could explain the good predictive capability of this equation.

Hydrogeologic units

Because hydraulic conductivity is dependent on lithologic properties, lithostratigraphic units could be expected to correlate with hydrogeologic units. This correlation may not hold for all glacial lithostratigraphic units because these units are differentiated on the basis of carbonate content, clay mineralogy, coarse-sand and pebble-fraction mineralogy, magnetic susceptibility, and stratigraphic position as well as grain-size distribution.

In western Marathon County, the Pleistocene materials can be divided into two distinct hydrogeologic units on the basis of field-measured hydraulic conductivity values. The first unit contains the Medford and Edgar till units and the second unit contains the Bakerville and Merrill Members. In both of these hydrogeologic units, the members are stratigraphically adjacent and the geometric mean hydraulic conductivities of the two members are within 0.5 order of magnitude of each other. These two hydrogeologic units display a hydraulic conductivity difference of 1.5 to 2 orders of magnitude. The direct correlation of Pleistocene formations to hydrogeologic units works well in western Marathon County because the two formations studied contain mostly till with only minor amounts of sand and gravel, lake sediment, or hillslope debris, and because these two formations have markedly different grain-size distributions as a result of having different source areas.

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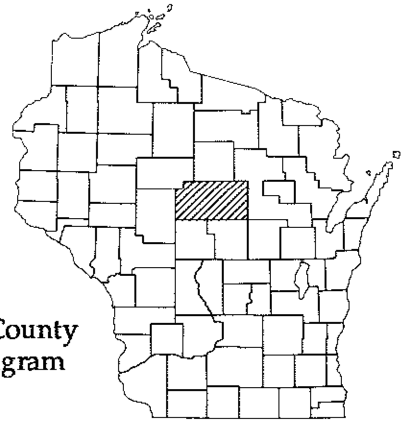
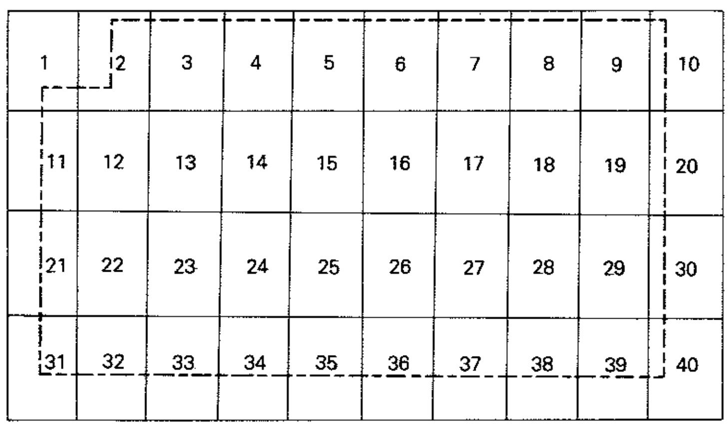


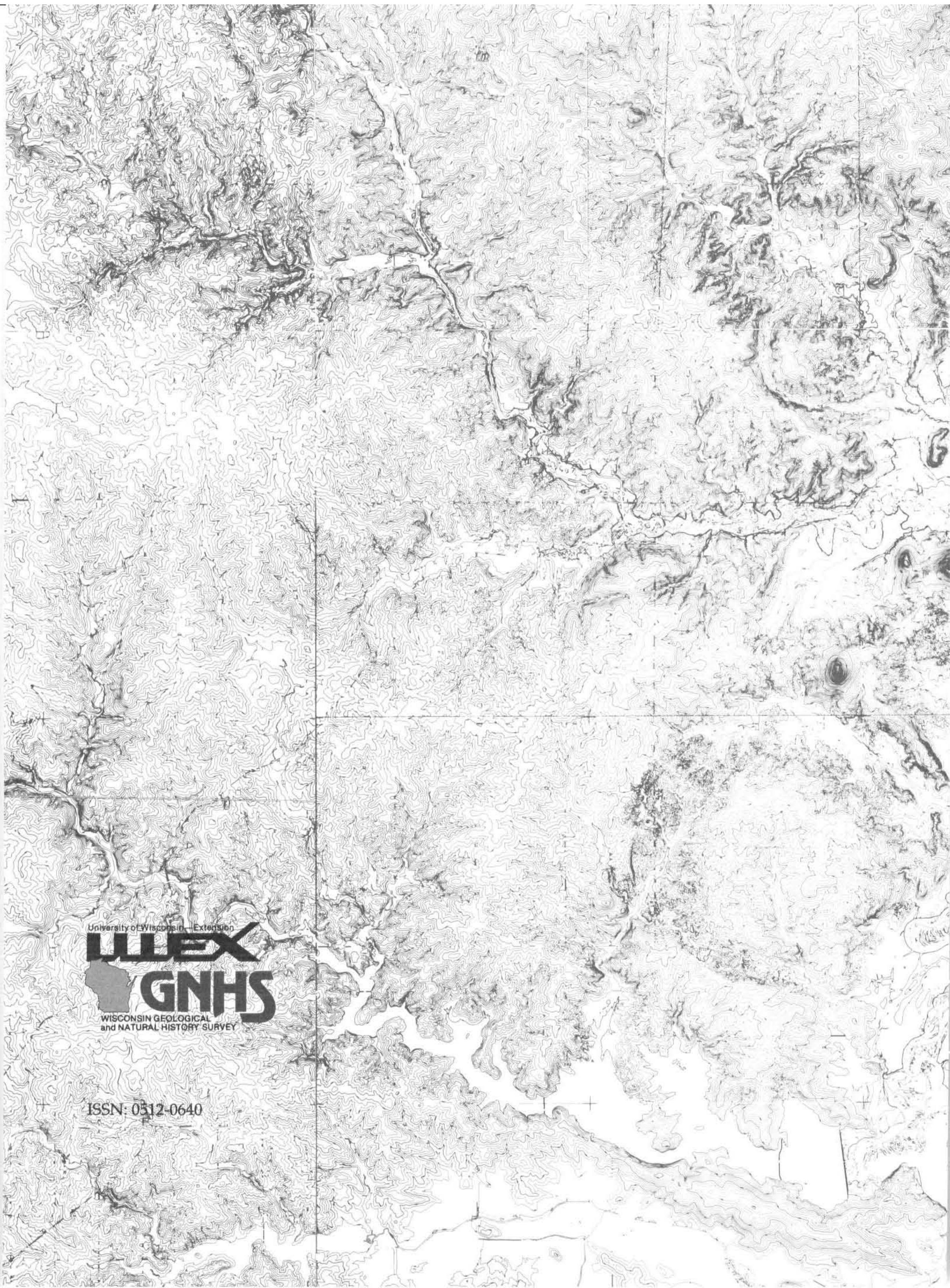
Marathon County
location diagram

Index to U.S. Geological Survey topographic quadrangles
(scale 1:24,000)



1 Stetsonville–1969
2 Corinth–1980
3 Athens–1980
4 Hamburg–1978
5 Little Chicago–1978
6 Brokaw–1982
7 Nutterville–1982
8 Kalinke–1973
9 Hogarty–1973
10 Aniwa–1973
11 Abbotsford–1981
12 Milan–1981
13 Wien–1982
14 Edgar–1981
15 Marathon–1981
16 Wausau West–1963 (78 PR)
17 Wausau East–1963 (78 PR)
18 Ringle–1982
19 Hatley–1982
20 Birnamwood–1982
21 Spencer North–1981
22 Little Rose–1981
23 Stratford–1981
24 Marathon SW–1981
25 Halder–1981
26 Mosinee–1982
27 Peplin–1982
28 Bevent–1982
29 Mission Lake–1982
30 Wittenberg–1982
31 Spencer South–1979
32 Marshfield–1979
33 Hewitt–1979
34 Honey Island–1970
35 Big Eau Pleine Reservoir–1970
36 Dancy–1970 (78 PR)
37 Dewey Marsh–1970
38 Rosholt NW–1969
39 Rosholt–1969
40 Tigerton NW–1970

PR Photorevised



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