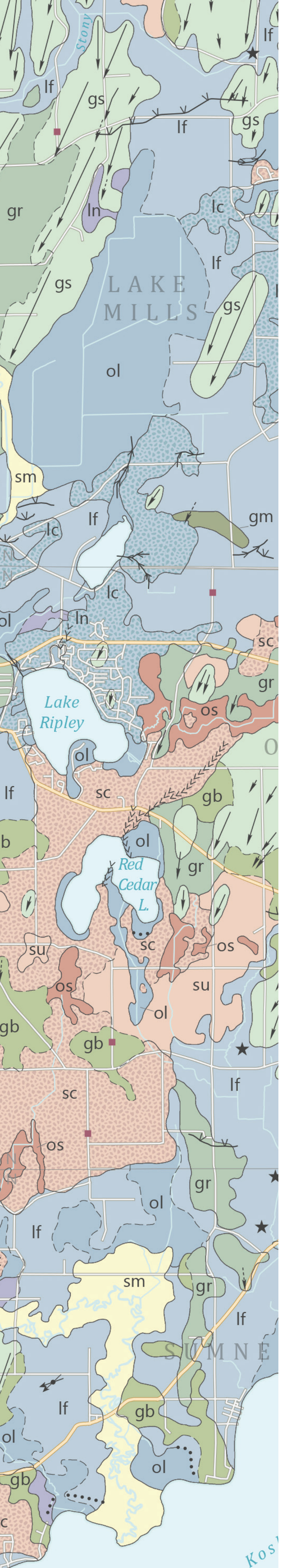

Quaternary Geology of Jefferson County, Wisconsin

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DIVISION OF EXTENSION
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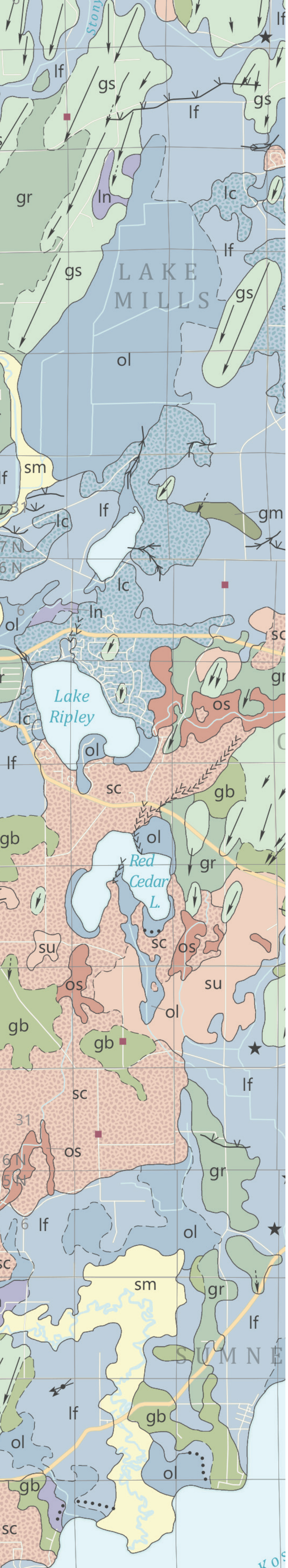
Cover photos

Front: View of the Kettle Moraine ridge from Bald Bluff Nature Trail, Kettle Moraine State Park.

Back: Gravel and cobbles of a supraglacial esker in the Kettle Moraine.



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Available separately at https://doi.org/10.54915/mlnc7835.

Abstract

The Quaternary geologic map of Jefferson County, Wisconsin, provides details about the surficial sediment and landscapes that were formed largely in the footprint of the Laurentide Ice Sheet's southern Green Bay Lobe during the late Wisconsin Glaciation. These landscapes include lowlands underlain by glacial and postglacial lake sediment, uplands composed of streamlined till (drumlins), and meltwater-stream sediment. The southeastern corner of the county includes small sections of the Kettle Moraine, an interlobate zone that formed between the Green Bay and Lake Michigan Lobes of the Laurentide Ice Sheet. Map units are based on sedimentology, stratigraphic position, and landform association. All map units, except the Kettle Moraine and postglacial units, belong to the Horicon Member of the Holy Hill Formation. Older sediment is likely preserved in deep bedrock valleys that underlie the county. Glacial landforms associated with the Green Bay Lobe include active-ice features (drumlins and end moraines), meltwater features (eskers, ice-contact deltas, and outwash plains), and ice-disintegration or collapse features (kettles and hummocky topography).

The southern Kettle Moraine in Jefferson County is composed of collapsed and uncollapsed meltwater-steam sediment. Glacial and postglacial lake sediment is widespread in Jefferson County, including lake plains, sandy nearshore and shoreline landscapes. New radiocarbon ages from bulk plant materials in lake and wetland sediment indicate that the Green Bay Lobe had receded from Jefferson County by approximately 18,000 years before present and that lakes persisted into the Holocene before transitioning to wetlands by approximately 6,900 years before present.

Holy Hill Formation Horicon Member Till

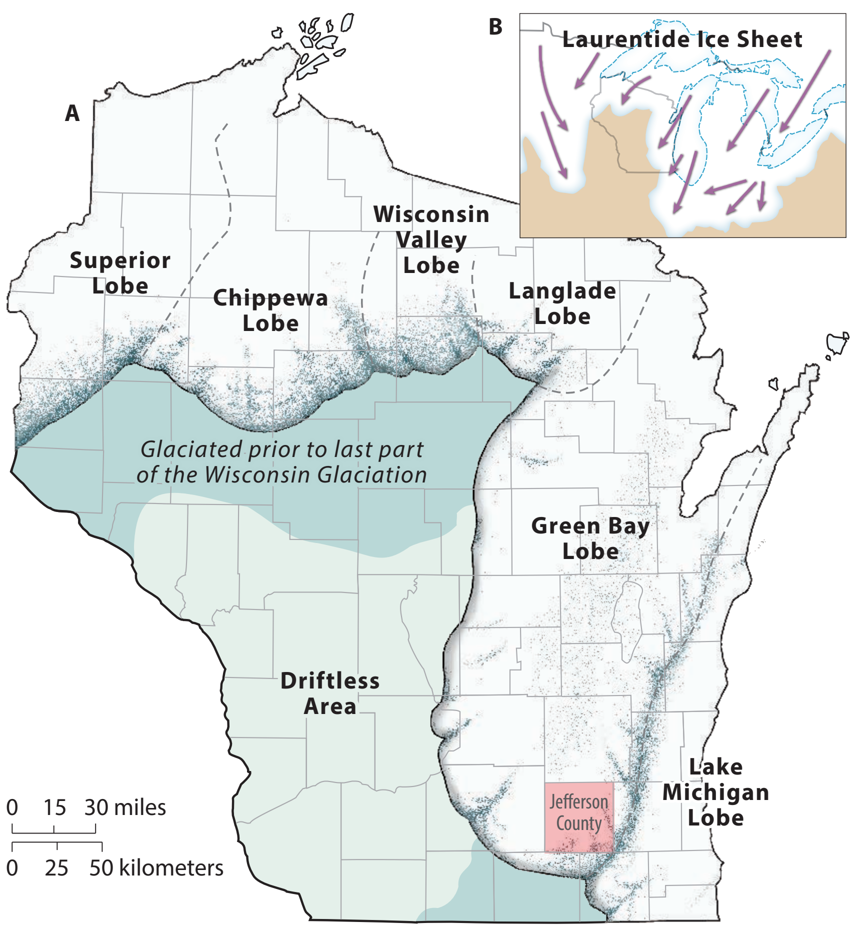
Introduction

Jefferson County is located in southeastern Wisconsin, covers an area of 1,510 square kilometers, and has a population of about 84,750 (U.S. Census Bureau, 2019). The land is primarily used for agriculture (Jefferson County Land and Water Conservation Department, 2021). The Quaternary geology of Jefferson County includes both glacial and postglacial sediment.

The county is dominated by glacial sediment and landforms created by the Laurentide Ice Sheet during the Wisconsin Glaciation, which occurred between about 32 and 11 thousand years ago (ka; Syverson and Colgan, 2011). Some of the glacial land systems in Jefferson County formed before the retreat of the glacier (around 18 ka) and are associated with the Johnstown, Milton, and Lake Mills phases of the Green Bay Lobe of the Laurentide Ice Sheet (plate 1, fig. 1). The moraines created during the Lake Mills phase form a series of continuous ridges across the central part of Jefferson County. The most common glacial landforms in the county are the more than 2,000 streamlined hills (that is, drumlins).

Jefferson County also includes kettles, which are collapsed landscape features that resulted from the melting of buried glacial ice, and eskers. As the Green Bay Lobe receded from the county, extensive meltwater streams and complex, interconnected proglacial lake systems formed. Permafrost existed until about 14 ka. Lake levels gradually decreased following glaciation, which allowed wetlands to develop in the former lake basins. The presence of wetlands from the middle Holocene and through the present resulted in the deposition of substantial peat and muck units throughout the county. The southeastern corner of the county includes the southern Kettle Moraine, an interlobate zone that formed between the Green Bay and Lake Michigan Lobes of the Laurentide Ice Sheet. In addition to contributing sediment to the Kettle Moraine, the Lake Michigan Lobe likely contributed some meltwater and sediment to the proglacial system in Jefferson County as the Green Bay Lobe began to retreat.

The topography of the bedrock surface strongly influences the thickness of the overlying Quaternary sediment in Jefferson County. Shallowly buried bedrock is covered with 1 to 10 meters (m) of till or meltwater-stream sediment (outwash). Bedrock valleys are buried by up to 120 m of Quaternary sediment, including thick sequences of lake sediment.



Political boundaries from Wisconsin Department of Natural Resources, 2011. Wisconsin Transverse Mercator projection, 1991 Adjustment to the North American Datum of 1983 (NAD 83/91); EPSG 3071.

Figure 1. Location of Jefferson County in Wisconsin (A) in relation to the Laurentide Ice Sheet, and (B) its lobes across the Great Lakes region of the United States and Canada during the most recent glaciation. Stippling in A indicates the edge of the ice sheet; arrows in B indicate direction of ice flow. Note that during the late Wisconsin Glaciation, Jefferson County was largely covered by ice of the Green Bay Lobe.

Methods and previous work

This map is based on field and laboratory work completed between 2018 and 2020. This period was affected by the novel coronavirus (COVID-19) pandemic, which limited access to laboratories and thus prevented the grain-size analyses of sediment samples collected as part of this project. Fortunately, field work and core descriptions were not substantially delayed. Map unit contacts were drawn using ArcMap software (Esri, Inc., Redlands, Calif.) and generalized to a scale of 1:100,000. Source data included 1.5-m resolution lidar (light detection and ranging)-derived elevation and shaded-relief models (Jefferson County, 2011), 1:20,000-scale black-and-white aerial photographs (1996 county compilation stored at the Wisconsin Department of Natural Resources) and 1:12,000-scale color-infrared aerial photographs (Wisconsin Regional Orthoimagery Consortium, 2010). Fifty sediment cores were collected to confirm map units and stratigraphic relationships using a direct-push method (Geoprobe Systems, Salina, Kan.; table 1). The cores were sampled, photographed, and described at the Wisconsin Geological and Natural History Survey (WGNHS). Additional lithologic information was derived from the Soil Survey Geographic (SSURGO) database (Soil Survey Staff, undated), a WGNHS soils map and report (Milfred and Hole, 1970), and the unpublished field notes of E.F. Bean, W. Osgood, and F.T. Thwaites (made between 1920 and 1951, stored at WGNHS). Radiocarbon age estimates conducted by Beta Analytic (Miami, Fla.) are reported as calibrated radiocarbon years before present (yr B.P., for which 1950 C.E. is considered as the present) and are based on the Calib v. 8.2 (Stuvier and others, 2021) and IntCal20 calibration programs (Reimer and others, 2020).

Earlier Quaternary mapping in Jefferson County includes work by Chamberlin (1881, scale 1:950,000), Alden (1905, 1918, scale 1:250,000), Hadley and Pelman (1976, scale 1:500,000), and Colgan (2003, scale 1:250,000). The Quaternary geology of the adjacent counties has been mapped at a scale of 1:100,000 as follows: Dane County by Mickelson and McCartney (1979), Mickelson (1983), and Clayton and Attig (1997); Walworth County by Ham and Attig (2004); and Waukesha County by Clayton (2001).

Direct-push coring on roadside in Jefferson County. Photograph by Kacie Stolzman

Table 1. Locations of boreholes in Jefferson County.

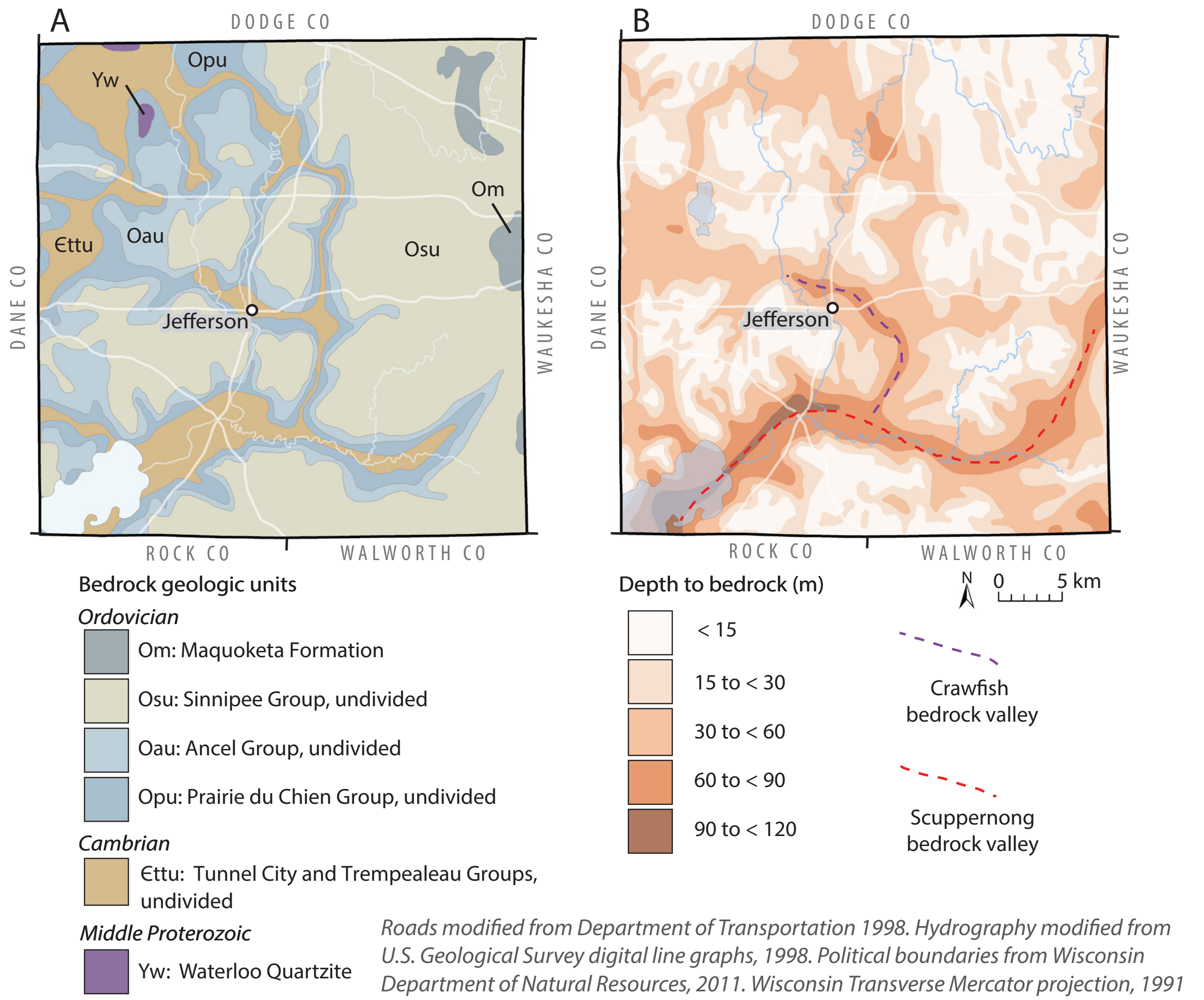
Field identification	Total depth (m)	Collected by	Described by	Latitude (in decimal degrees)	Longitude (in decimal degrees)
BSV-03	5.3	J. Elmo Rawling III	Kacie Stolzman	42.95368747	–88.98390670
BSV-04	7.3	J. Elmo Rawling III	Kacie Stolzman	42.99320716	–88.93501172
BSV-05	10	J. Elmo Rawling III	Kacie Stolzman	42.92039665	–88.90460943
BSV-08	10	J. Elmo Rawling III	Kacie Stolzman	42.94040108	–88.98890382
HEL-01	10	J. Elmo Rawling III	Kacie Stolzman	43.09314600	–88.70116400
HEL-02	6	J. Elmo Rawling III	Kacie Stolzman	43.09318500	–88.70296400
HEL-03	10	J. Elmo Rawling III	Kacie Stolzman	43.09344800	–88.71098500
HEL-05	10	Libby R.W. Ives	Kacie Stolzman	43.09363000	–88.71720000
HEL-06	6.1	Libby R.W. Ives	Kacie Stolzman	43.09405500	–88.72992400
HEL-07	6.1	Libby R.W. Ives	Kacie Stolzman	43.09413500	–88.73299700
HEL-09	4.5	Libby R.W. Ives	Kacie Stolzman	43.02398600	–88.72922800
HEL-10	6.1	Libby R.W. Ives	Kacie Stolzman	43.04225300	–88.71312900
HEL-12	6.1	Libby R.W. Ives	Kacie Stolzman	43.04210900	–88.70190100
IXO-01	2.4	Libby R.W. Ives	Libby R.W. Ives	43.17690300	–88.59459800
IXO-02	10	J. Elmo Rawling III	Kacie Stolzman	43.19321800	–88.54902600
IXO-03	10	J. Elmo Rawling III	Kacie Stolzman	43.18235100	–88.55625000
LKM-01	6.1	Libby R.W. Ives	Kacie Stolzman	43.08653300	–88.99262300
LKM-02	7.6	Libby R.W. Ives	Kacie Stolzman	43.01906400	–88.96288500
LKM-03	6.1	Libby R.W. Ives	Kacie Stolzman	43.02746600	–88.89791100
LKM-04	15.2	Libby R.W. Ives	Kacie Stolzman	43.01021200	–88.92417800
LKM-05	10	J. Elmo Rawling III	Kacie Stolzman	43.00931379	–88.92420961
LMC-01	10	J. Elmo Rawling III	Kacie Stolzman	42.85725506	–88.77648239
LTP-01	16.8	J. Elmo Rawling III	Kacie Stolzman	42.86746564	–88.59638226
LTP-02	12.2	J. Elmo Rawling III	Kacie Stolzman	42.84274607	–88.61345863
LTP-04	6.1	J. Elmo Rawling III	Kacie Stolzman	42.85853295	–88.57930498
OCW-01	10	Libby R.W. Ives	Libby R.W. Ives	43.09110400	–88.57939800
OCW-04	12.8	J. Elmo Rawling III	Kacie Stolzman	43.00357150	–88.57682408
PMY-01	7.6	J. Elmo Rawling III	Kacie Stolzman	42.97570600	–88.56508400

Field identification	Total depth (m)	Collected by	Described by	Latitude (in decimal degrees)	Longitude (in decimal degrees)
PMY-02	11.9	J. Elmo Rawling III	Kacie Stolzman	42.93661783	–88.56171615
PMY-03	7.6	J. Elmo Rawling III	Kacie Stolzman	42.91346745	–88.54226568
PMY-04	10.7	J. Elmo Rawling III	Kacie Stolzman	42.95313873	–88.60405616
PMY-05	7.6	J. Elmo Rawling III	Kacie Stolzman	42.99327101	–88.60519718
PMY-06	7.6	J. Elmo Rawling III	Kacie Stolzman	42.91505138	–88.58327465
RHW-01	10	Libby R.W. Ives	Kacie Stolzman	43.17510300	–88.83888200
RHW-02	6.1	Libby R.W. Ives	Kacie Stolzman	43.12788400	–88.86088900
RKD-01	10	J. Elmo Rawling III	Kacie Stolzman	42.88199090	–89.01002426
RKD-02	1.2	J. Elmo Rawling III	Kacie Stolzman	42.97905511	–89.00858628
ROM-01	15.2	J. Elmo Rawling III	Kacie Stolzman	42.90583402	–88.62973426
ROM-03	10	J. Elmo Rawling III	Kacie Stolzman	42.90310919	–88.74429813
ROM-04	10	J. Elmo Rawling III	Kacie Stolzman	42.92447205	–88.67001642
ROM-05	12.2	J. Elmo Rawling III	Kacie Stolzman	42.99314592	–88.62937605
WTL-01	6.7	J. Elmo Rawling III	Kacie Stolzman	43.17987200	–88.95517700
WTL-02	6.1	Libby R.W. Ives	Libby R.W. Ives	43.18270700	–88.96053800
WTL-03	10	J. Elmo Rawling III	Kacie Stolzman	43.16614800	–88.92076000
WTL-04	6.1	Libby R.W. Ives	Kacie Stolzman	43.16568700	–88.95133700
WTL-05	6.1	Libby R.W. Ives	Kacie Stolzman	43.13970800	–88.92854700
WTT-01	6.1	Libby R.W. Ives	Kacie Stolzman	43.18020300	–88.66524700
WTT-02	4.5	J. Elmo Rawling III	Kacie Stolzman	43.18046300	–88.65725600
WTT-03	5.8	J. Elmo Rawling III	Kacie Stolzman	43.18041800	–88.65816700
WTT-04	8.5	J. Elmo Rawling III	Kacie Stolzman	43.18028300	–88.66178100

Bedrock geology, bedrock elevation, and sediment thickness

The bedrock underlying Jefferson County includes Mesoproterozoic metasedimentary and early Paleozoic sedimentary units (fig. 2A). The county is located at the southwestern edge of the Michigan Basin, where Paleozoic strata lap onto an angular unconformity with Proterozoic provinces (Whitmeyer and Karlstrom, 2007). The only Precambrian unit that crops out in Jefferson County is the Waterloo Quartzite (Yw; Mesoproterozoic); however, none of the rock outcrops in Jefferson County are of sufficient size to be shown at the 1:100,000 scale of the geologic map (plate 1). Paleozoic units underlying the county include the Cambrian Tunnel City and Trempealeau Groups (Єttu; sandstones; shown undivided in fig. 2A); and the Ordovician Prairie du Chien Group (Opu; dolostones), Ancell Group (Oau; sandstones), Sinnipee Group (Osu; dolostones), and Maquoketa Formation (Om; shale). The distribution of near-surface Paleozoic bedrock is likely controlled by low-amplitude folding (Stewart, 2021). Bedrock geologic mapping at a scale of 1:100,000 is available for Dodge County to the north (Stewart,

Figure 2. Generalized maps showing the bedrock units underlying Jefferson County and depth of sediments to the bedrock surface. (A) Distribution of Mesoproterozoic, Cambrian, and Ordovician bedrock (modified from Mudrey and others, 1982). (B) Depth to bedrock (modified from Trotta and Cotter, 1973), showing the locations of the Scuppernong and Crawfish bedrock valleys.

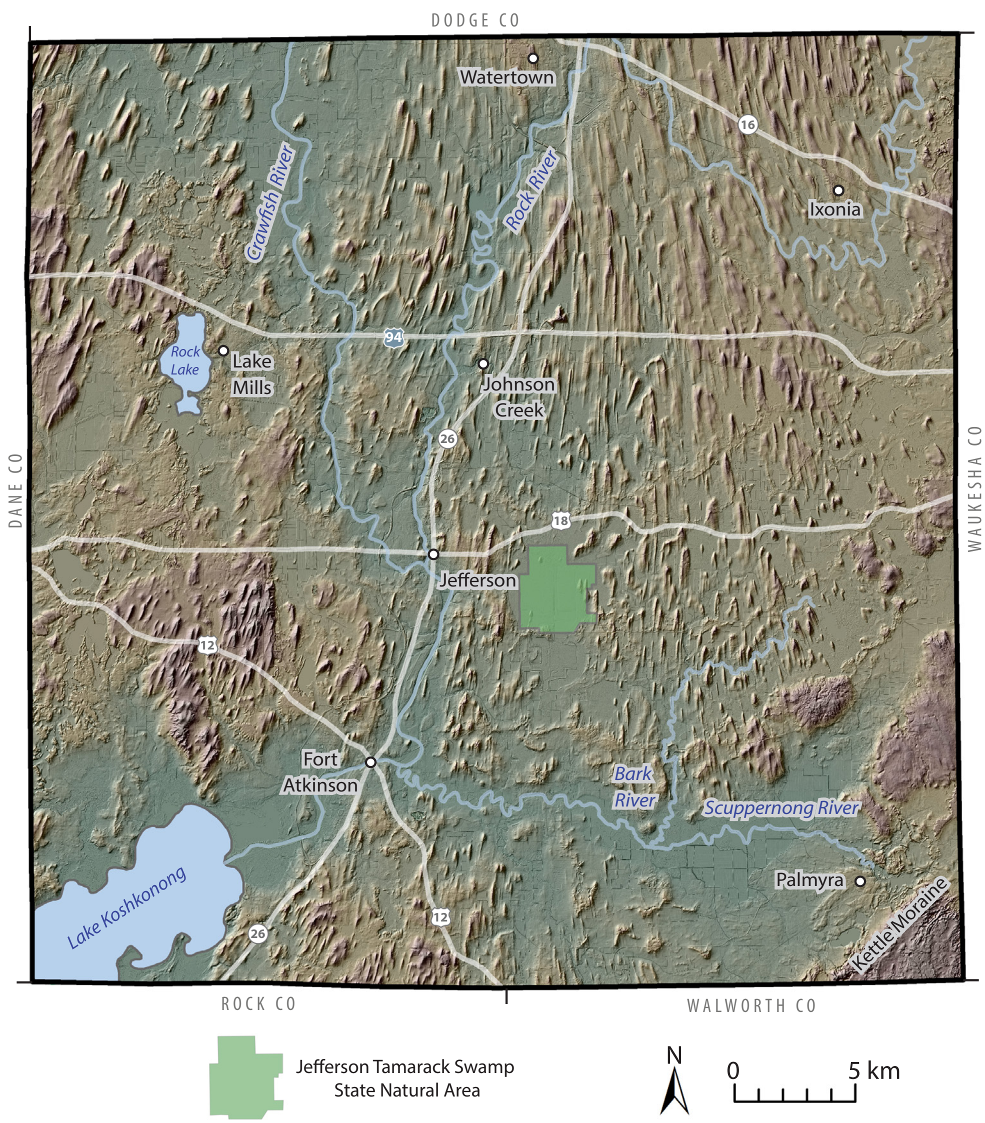


Roads modified from Department of Transportation 1998. Hydrography modified from U.S. Geological Survey digital line graphs, 1998. Political boundaries from Wisconsin Department of Natural Resources, 2011. Wisconsin Transverse Mercator projection, 1991 Adjustment to the North American Datum of 1983 (NAD 83/91); EPSG 3071.

2021) and is ongoing in Jefferson County by WGNHS staff at the time of this report.

The extended exposure of the bedrock units to erosion, weathering, and other processes before glaciation likely resulted in the high-relief bedrock topography now found beneath the unconsolidated sediment of Jefferson County; the bedrock-surface topography in this county is similar to the exposed topography of Wisconsin's Driftless Area (Carson and others, 2019). The most prominent bedrock features underlying the Quaternary sediment in Jefferson County are two deep valleys mostly filled with Quaternary sediment (fig. 2B). The Scuppernong bedrock valley underlying the Scuppernong River, portions of the Bark and Rock Rivers, and Lake Koshkonong is filled with up to 120 m of sediment and trends east to west across the southern half of the county (figs. 2B, 3). Another bedrock valley trends north to south beneath the center of the county, is as much as 75 m deep, and is here referred to as the Crawfish bedrock valley. This valley is likely connected to the ancestral Crawfish River described in Dodge County by Stewart (2021). Unlike the Scuppernong bedrock valley, the bedrock valley underlying the ancestral Crawfish River does not always follow the course of the modern stream. Stretches of the modern Crawfish and Rock Rivers (figs. 2B, 3) may overlie some portion of it. Topographically higher areas of erosion-resistant bedrock located in the western half of

Figure 3. Shaded-relief map of Jefferson County derived from a 1.5-m digital elevation model (Jefferson County, 2011).



Elevation from Jefferson County Elevation Dataset, 2014. Roads modified from Department of Transportation 1998. Hydrography modified from U.S. Geological Survey digital line graphs, 1998. Political boundaries from Wisconsin Department of Natural Resources, 2011. Wisconsin Transverse Mercator projection, 1991 Adjustment to the North American Datum of 1983 (NAD 83/91); EPSG 3071.

Jefferson County are typically composed of dolostones of the Sinnipee Group (Osu) but may also include the Waterloo Quartzite (Yw), as in the far northwestern corner of the county (fig. 2A).

The thickness of unlithified sediment in Jefferson County ranges from 0 to about 120 m (Trotta and Cotter, 1973; fig. 2B). Quaternary sediment cover is generally thin or absent in areas where the underlying bedrock is topographically high, most commonly in the western third of the county. The sediment is thicker (up to about 120 m) where it fills bedrock valleys. In the southeastern corner of the county, parts of the Kettle Moraine rise 45 to 60 m above the surrounding landscape.

Quaternary sediment

The Quaternary sediment of Jefferson County includes units deposited during the last part of the Wisconsin Glaciation (about 32 to 11 ka; late Pleistocene, Marine Isotope Stage 2) and units deposited during the postglacial period (11 ka to the present; Holocene). The glacial sediment in the county is assigned to the Horicon Member of the Holy Hill Formation (Syverson and others, 2011), which was deposited by the Green Bay Lobe of the Laurentide Ice Sheet and in its meltwater streams and lake basins (fig. 1). Older stratigraphic units may be present in the subsurface throughout the county, particularly in bedrock valleys. There are no direct constraints on the maximum age of the Holy Hill Formation in Jefferson County. However, radiocarbon and optically stimulated luminescence ages from sediment deposited at the Green Bay Lobe's margin in Dane and Columbia Counties indicate that the Green Bay Lobe reached its approximate maximum extent around 24.7 ka (Carson and others, 2020). New radiocarbon dates collected for this study show that the Green Bay Lobe had retreated from the northern portion of the Jefferson County by about 17.9 ka (see "Quaternary history," p. 26). For this report, sediment and landforms in Jefferson County are organized into three broad categories: glacial, lake, and stream.

Glacial sediment and landforms

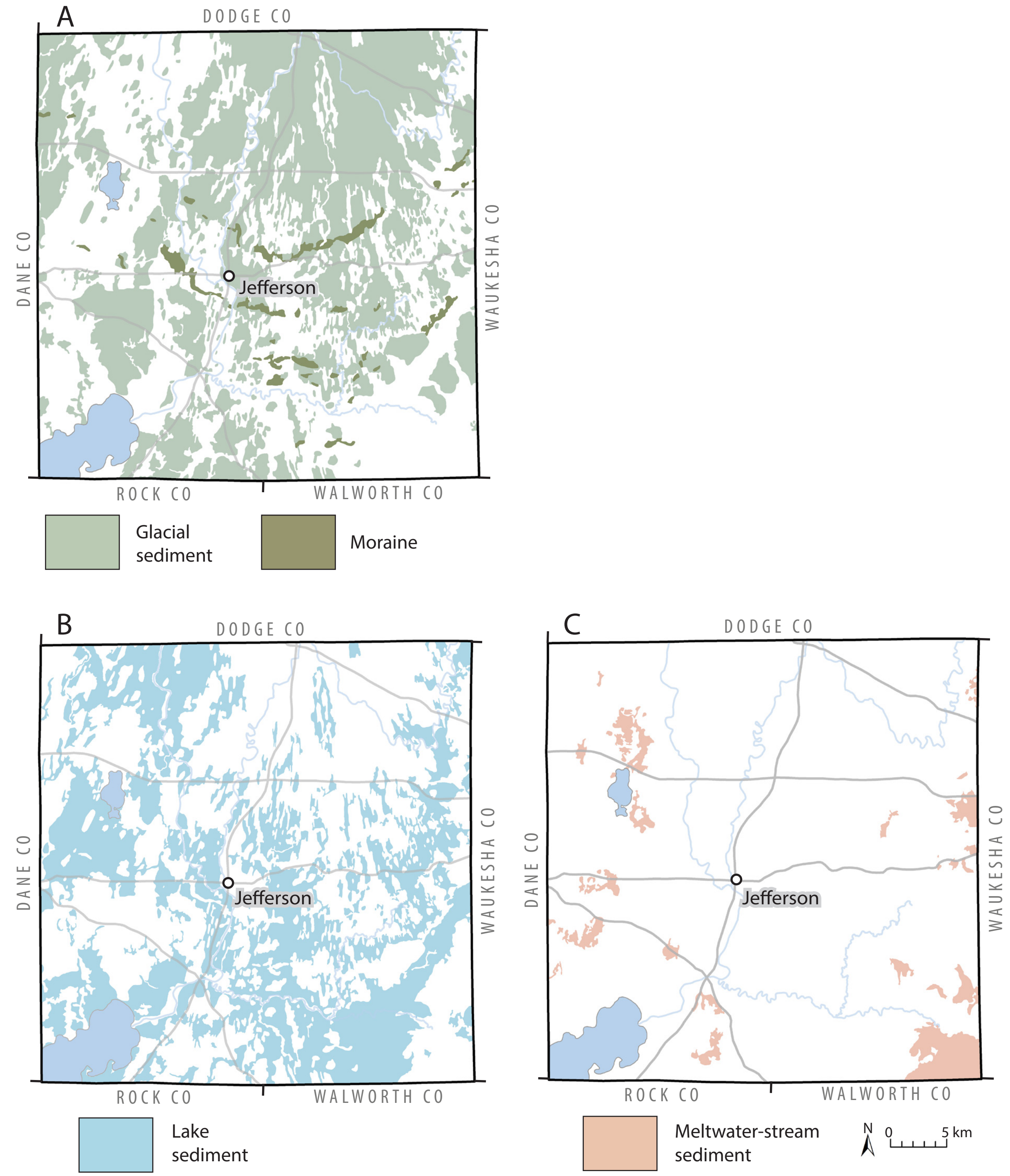
Glacial sediment covers about 46 percent of Jefferson County (fig. 4A). Glacial sediment includes till (map units **gr, gs**, and **gb**) and moraines (map unit **gm**). These are part of the Horicon Member of the Holy Hill Formation (Syverson and others, 2011) in Jefferson County.

Till

Till is a primary glaciogenic sediment (created by uniquely glacial processes) that was deposited at the interface between the base of the glacier and the land surface through some combination of lodgment, bed deformation, clast plowing, and melting processes (Benn and Evans, 2010). The till of the Horicon Member in Jefferson County is "massive, gravelly sand with minor amounts of silt and clay," a description that can also be phrased as "massive, clast-rich, sandy diamicton" (fig. 5; Syverson and others, 2011). The till is a light shade of yellow-red when oxidized (10YR 5/8), and a dark shade of yellow-red when reduced (10YR 6/1). Where observed, till in Jefferson County is bound by sharp upper and lower contacts.

Drumlin near the city of Waterloo

Figure 4. Generalized maps showing the distribution of surficial sediments in Jefferson County. (A) Glacial sediment and moraines. (B) Lake sediment. (C) Meltwater-stream sediment.



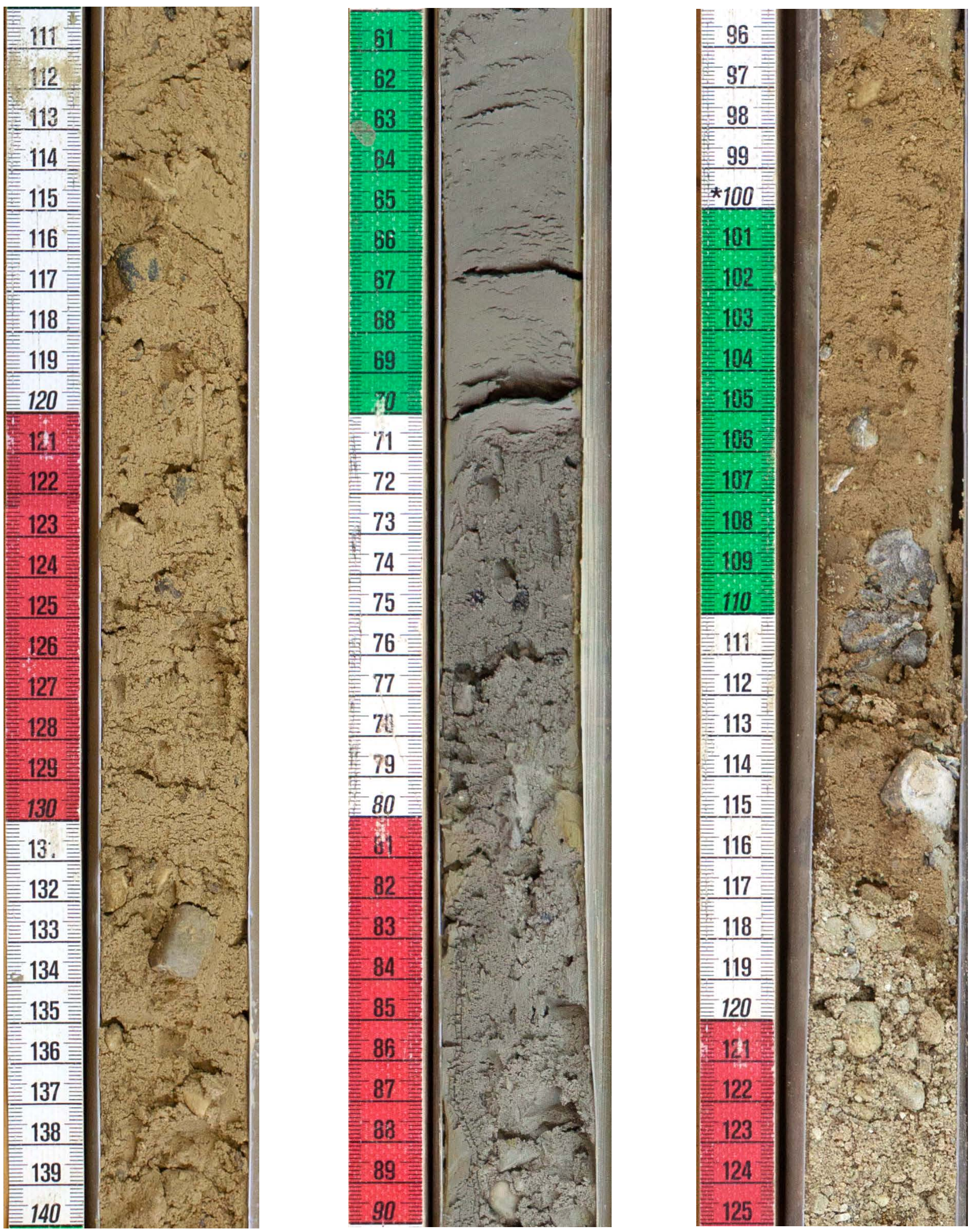
Roads modified from Department of Transportation 1998. Hydrography modified from U.S. Geological Survey digital line graphs, 1998. Political boundaries from Wisconsin Department of Natural Resources, 2011. Wisconsin Transverse Mercator projection, 1991 Adjustment to the North American Datum of 1983 (NAD 83/91); EPSG 3071.

Figure 5. Typical glacial sediment from direct-push cores in Jefferson County, including oxidized till (core WTT-04), reduced till under lake sediment (core WTT-02), and oxidized till above meltwater-stream sediment (core LMC-01). Scale is in centimeters and refers to depth within each 1.5-m-long core segment. Note sharp contacts in core WTT-02 at 70 cm and core LMC-01 at 116 cm.

WTT-04
3 to 4.6 m

WTT-02
3 to 4.3 m

LMC-01
4.6 to 6.1 m



Till of the Horicon Member is the most widely distributed glacial sedimentary unit in Jefferson County. This till was divided into three map units on the basis of landscape morphology: thin (**gb**), rolling (**gr**), and streamlined (**gs**). Unit **gb** occurs mostly in the western half of the county over topographically high bedrock surfaces that are occasionally striated (Colgan, 2003). Striations on bedrock are indicators of subglacial erosion. Unit **gr** is represented by a rolling to flat topography with no specific subglacial landforms. Most of the till in Jefferson County, however, is streamlined (**gs**).

Streamlined till of the Horicon Member (gs)

The streamlined till of the Horicon Member (**gs**) is differentiated from the other till units because streamlined bedforms (drumlins) are the dominant landforms associated with this unit. Streamlined bedforms are elongated, linear to teardrop-shaped hills that are aligned parallel to the direction of the glacier's flow. These landforms were created at the base (bed) of a sliding glacier and are therefore known as bedforms. The physical properties of streamlined bedforms, such as their length-to-width ratios or heights, are used to differentiate types of streamlined bedforms (for example, drumlins, flutes, megaflutes, or megascale glacial lineations), and that information may help infer the subglacial conditions under which these hills formed (for example, Zoet and others, 2021). Although the streamlined bedforms in Jefferson County come in many shapes and sizes, we elected to use the term "drumlin" to refer to all streamlined bedforms on the geologic map (plate 1). This nomenclatural decision was motivated by three factors: First, most of the streamlined bedforms in Jefferson County are drumlins. Second, all streamlined bedforms associated with the Green Bay Lobe have been referred to historically as "drumlins." Third, despite attempts by some authors (Rose, 1987; Clark, 1993), there is currently little consensus among scientists in the glacial geology community on the classifications or names of streamlined bedforms.

Drumlins in Jefferson County have a wide range of shapes and sizes (fig. 6). Their heights range from 1 to 20 m, lengths range from 100 to 2,900 m, and widths range from 35 to 300 m. It is not uncommon for drumlins to be bifurcated or compound with slightly different orientations emanating from the same upglacier area (fig. 6C). Although the shapes of drumlins (height, length, slope, elongation ratio, and so on) are highly variable, those with similar shapes tend to occur together (see fig. 6).

The drumlins' orientations are excellent indicators of the flow direction of glacier ice. In Jefferson County, the drumlins generally radiate obliquely (that is, they fan out) from the center of the county, reflecting the fan-like shape of the Green Bay Lobe. Bifurcated and compound drumlins suggest that the glacier experienced variable local flow directions during the drumlins' formation (Colgan and Mickelson, 1997). The drumlins in Jefferson County likely formed when the Green Bay Lobe was at its maximum extent (Johnstown Phase; Colgan and Mickelson, 1997).

Although drumlins in Jefferson County are primarily composed of till, some drumlins in Jefferson County contain stratified sand and gravel beds (Upham 1894; Alden, 1905; Evenson, 1971; Stanford and Mickelson, 1985; Colgan and Mickelson, 1997). These stratified beds often show evidence of deformation and (or) erosion (see photographs and descriptions in Alden, 1905, and Evenson, 1971). The deposition of this stratified sediment, likely as glacial outwash, either preceded or was contemporaneous with the advance of the ice that formed the drumlins. The drumlins in Jefferson County were most likely formed by subglacial erosion (Vreeland and others, 2015); however, the details of the processes by which drumlins are created remain enigmatic and a topic of much debate among glacial geologists (Zoet and others, 2021).

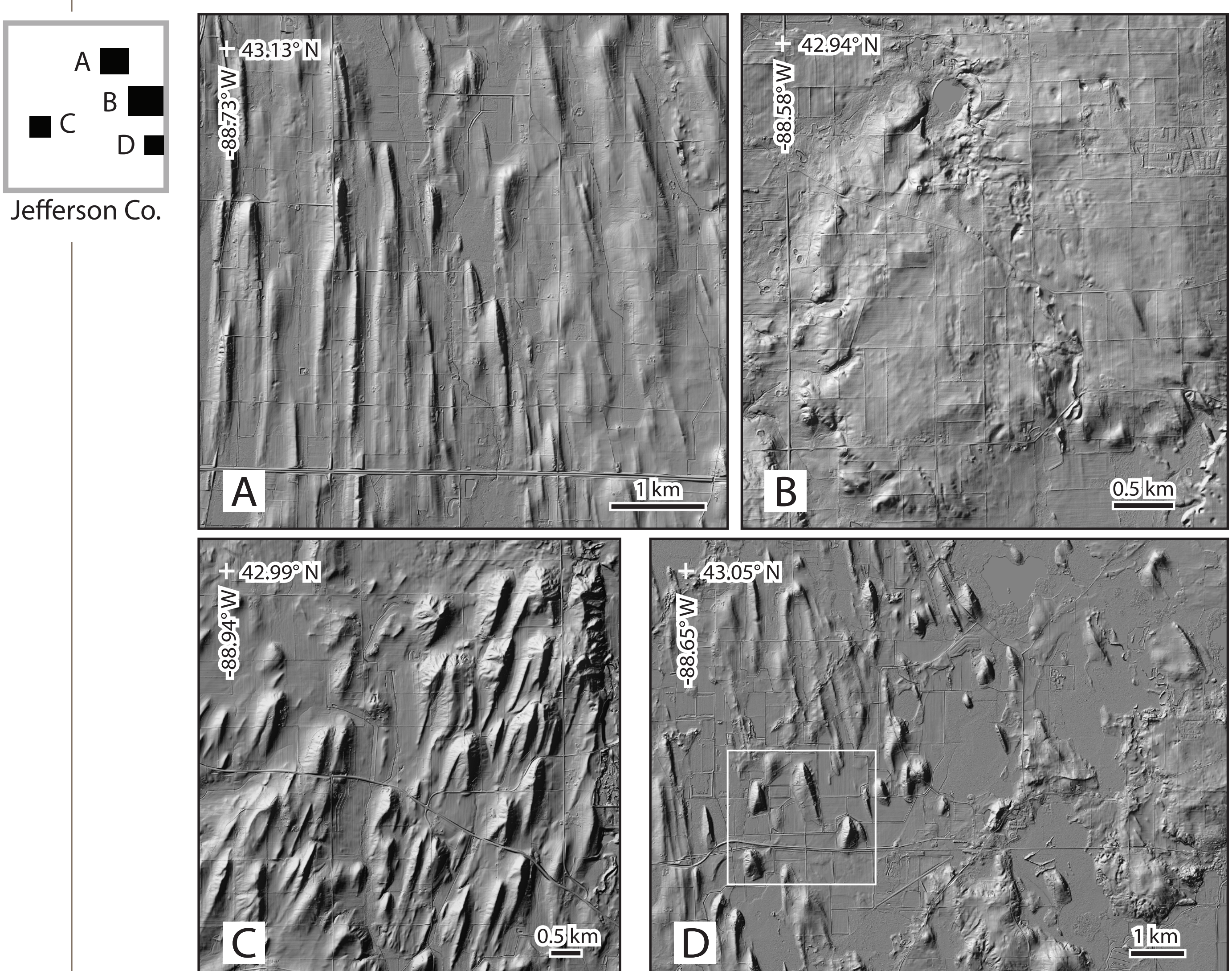
The shape of some drumlins has been modified by postglacial erosion or burial in postglacial sediment. Areas between drumlins also consist primarily of till, although in some places those areas are partially filled with lacustrine sediment or covered by a thin layer of silty sediment. This silty sediment could have been washed downslope from the adjacent hills, settled from suspension in short-lived lakes, or deposited as windblown dust (loess) shortly after deglaciation.

Moraines

End moraines are ridges of sediment that are oriented perpendicular to the direction of a glacier's flow, and they formed as glacier-transported sediment accumulated at the terminus of a glacier (fig. 7). All of the moraines in Jefferson County are classified as end moraines. Three different sizes of end moraines occur in Jefferson County: major, medium, and minor moraines. Major and medium moraines were created when the Green Bay Lobe's margin position was stationary for some time. Although a glacier's margin may be stationary, the ice upstream of the margin is still actively flowing, carrying both subglacial and supraglacial sediment to the glacier's terminus.

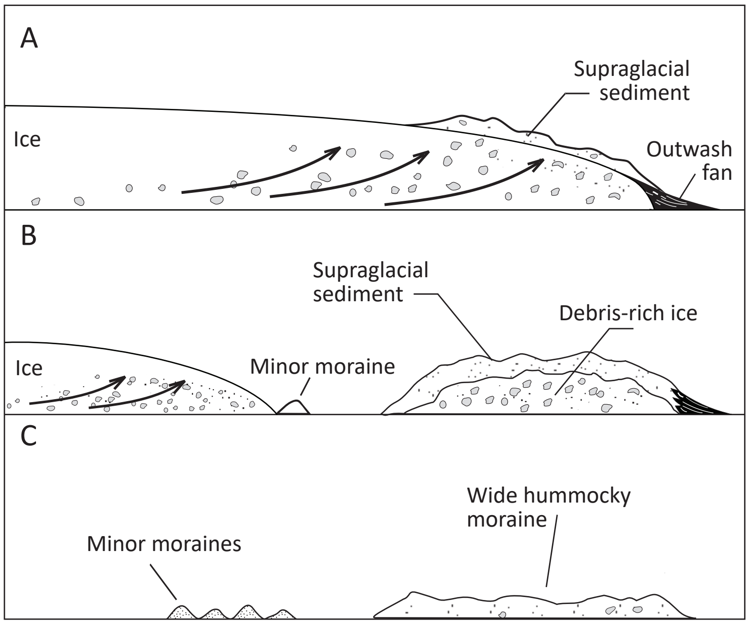
Major moraines are those that are more than 200 m wide (map unit **gm**) and are characterized by a hummocky topography that resulted from the melting and retreat of a debris-rich glacier margin. Major moraines formed where the glacier margin was stationary long enough to accumulate and melt out large amounts of sediment. Medium moraines are 50 to 200 m wide and are represented on plate 1 with a line symbol. These types of moraines likely formed at the end of a glacier that was continually active and transporting sediment to its margin. The resulting medium moraine tends to be a distinct ridge—relatively narrow and not hummocky. Major and medium moraines were created during intervals when the Green Bay

Figure 6. Shaded-relief maps illustrating variations in drumlin morphology across Jefferson County. (A) Typical high-density and tall drumlins. (B) Very subtle northwest-to-southeast streamlining on overridden Kettle Moraine. (C) Field of bifurcated high-relief drumlins that overlie a high-elevation bedrock surface. (D) Wide drumlins (white box highlighting examples).



Elevation from Jefferson County Elevation Dataset, 2014. Wisconsin Transverse Mercator projection, 1991 Adjustment to the North American Datum of 1983 (NAD 83/91); EPSG 3071.

Figure 7. Schematic illustration showing how moraines formed over time. (A) Supraglacial sediment accumulates at a stable ice margin. (B) As glacier retreats, buried ice is preserved under supraglacial sediment and minor moraines form if margin temporarily stabilizes. (C) The distribution of moraines after ice has melted (modified from Attig and Rawling, 2018).



Lobe margin was stationary; that is, the glacier was in equilibrium because it was melting at approximately the same rate as ice was flowing to the margin from upstream.

Minor moraines have low relief (less than 4 m) and are narrow (less than 50 m wide). These moraines most likely formed due to minor readvances of the glacier margin (Ham and Attig, 2001). Small readvances of a glacier's margin can occur on an annual or semiannual basis (Chandler and others, 2016). These readvances can create minor moraines by pushing, squeezing, or bulldozing proglacial sediment (processes broadly categorized as "glaciotectonic"). Another mechanism, known as freeze-on, can contribute to minor moraine formation when previously deposited sediment is overridden by a glacier and (re)incorporated into the basal glacier ice. These processes can occur seasonally at the margins of glaciers and contribute to moraines during annual or semiannual readvances. The reincorporated sediment is often deposited as part of the moraine (for example, Matthews and others, 1995; Reinardy and others, 2013). In modern Icelandic alpine glaciers, similar moraines form annually or subannually during intervals of sustained ice-margin retreat (greater than or equal to 10 years) that coincide with periods of warmer-than-average annual and seasonal air temperatures (Bradwell and others, 2013; Chandler and others, 2016). In these same alpine settings, minor moraines do not tend to form during colder-than-average intervals or during very rapid, meltwater-dominated retreats of glacier margins (Bradwell and others, 2013). Where moraine types (major, medium, and minor) occur in combination with one another, the processes for moraine formation were likely occurring at around the same time.

The sedimentary compositions of the major and medium moraines in Jefferson County are similar. Both are largely composed of massive, clast-rich, matrix-supported, sandy sediment. Sediment of the Horicon Member in these moraines is similar in composition to subglacially deposited till elsewhere in the county, except it is less dense or compacted and not necessarily deposited by subglacial processes. The till-like sediment in these moraines is interlayered with sorted, stratified sand and gravel. In cores HEL-09 and ROM-04, stratified sediment included either silty clay (HEL-09) or fine to medium sand (ROM-04). Evenson (1971) described thick sand and gravel units within major moraines. The sedimentary composition of minor moraines is likely to be highly variable, consisting of some combination of sediment from the glacier and whatever sediment was pushed into the ridge by the glacier's margin.

In Jefferson County, moraines were deposited both during the Milton Phase and Lake Mills Phase of the Green Bay Lobe's retreat (Syverson and others, 2011; plate 1). In Jefferson County, Milton Phase moraines occur south of the Scuppernong bedrock valley and the Lake Mills Phase moraines occur north of the bedrock valley. The major moraines in Jefferson County have been mapped as distinct, curved bands (plate 1; unit **gm**). These bands are traceable westward through Dane County and into Columbia and Green Lake Counties to the northwest (Colgan and Mickelson, 1997; plate 1). The eastern margins of the Lake Mills Phase moraines extend eastward into the far northwestern corner of Waukesha County. The width, height, and morphology of the major moraines within these bands are inconsistent along each band’s length. Minor and medium moraines are less laterally continuous than the major moraines and occur both between and in line with the major moraines (fig. 8). Moraines in Jefferson County were deposited on top of subglacial landforms such as drumlins, indicating that the moraines were deposited after the creation of those landforms (fig. 8A).

Moraines are rare or not present in the southernmost and northernmost parts of Jefferson County, but it is not clear why. Their absence may be explained by erosion, burial, nondeposition (that is, they never formed), or some combination of these processes. If the absence of moraines in these areas was due to nondeposition, then the implication is that the Green Bay Lobe margin likely experienced a steady or a relatively rapid retreat through the moraine-free areas. The nondeposition of major and medium moraines indicates that the glacier margin was not stationary (that is, it did not pause) for any extended intervals during its retreat through these areas, which further suggests that at no point during these intervals was the Green Bay Lobe in equilibrium. Additionally, the nondeposition of minor moraines indicates that the Green Bay Lobe did not experience minor readvances during its retreat, suggesting either that the glacier was responding to colder-than-average air temperatures, or it was retreating extremely rapidly. Because permafrost conditions persisted in southern Wisconsin until well after the Green Bay Lobe margin retreated from Jefferson County (at 14 ka; see “Permafrost,” p. 30, the former was the more likely scenario. The nondeposition of moraines in parts of Jefferson County was most likely the result of a steady retreat of the Green Bay Lobe margin out of this area. Of course, moraines may also be absent from these areas of Jefferson County due to erosion or burial by glacial and postglacial processes, such as erosion by meltwater streams or the deposition of lacustrine sediment.

Moraine controls on meltwater flow

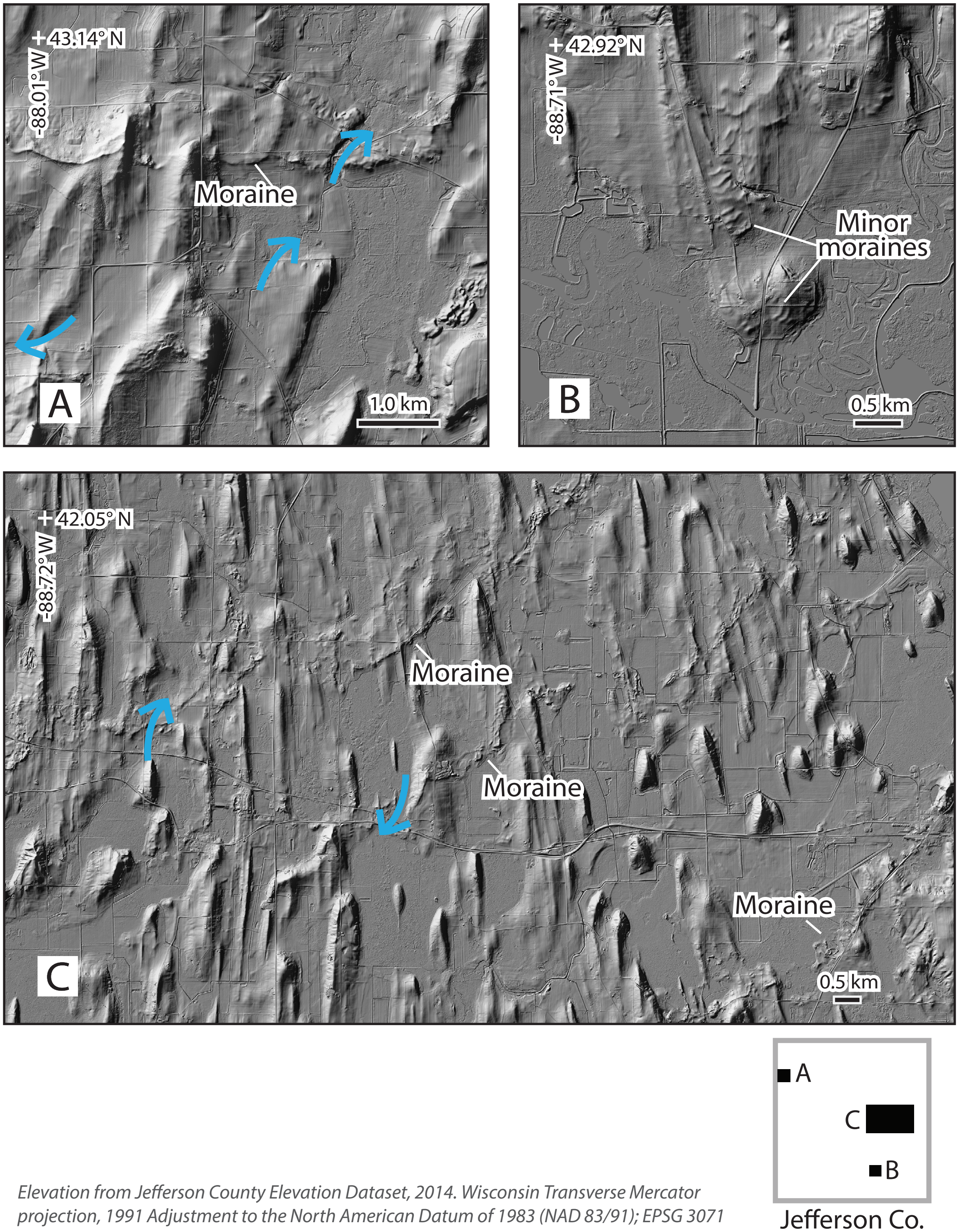
As the Green Bay Lobe retreated, the moraines in Jefferson County acted as barriers to the flow of glacial meltwater. This impoundment resulted in numerous small lake basins and the deposition of lacustrine sediment adjacent to the moraines (see “Lake sediment and landforms,” this page. The overflow of these small basins resulted in channel scars that show where outflow from these lakes eroded through the moraines (fig. 8A, C). Because meltwater from the Green Bay Lobe was the main source of water in Jefferson County during the ice sheet’s retreat, the meltwater would have been impounded upglacier (to the north) of the moraines. These moraine-impounded basins occasionally overfilled and the water cut a channel through the moraine away from the glacier (to the south). Although these cross-moraine channels often indicate that flow occurred from north to south (as expected), they sometimes indicate that flow occurred from south to north (that is, towards the glacier’s margin). This observation suggests that the moraines impounded small lakes both to the north (upglacier) and south (downglacier). These features collectively indicate a dynamic postglacial landscape, with varying amounts of meltwater impounded over time. Regional-scale isostatic loading beneath the Green Bay Lobe and the rebound of recently deglaciated areas likely contributed to rapidly shifting drainage patterns in this landscape.

Lake sediment and landforms

Lake sediment covers about 38 percent of Jefferson County (fig. 4B). Most of this (map units **lf**, **lc**, and **ln**) is part of the Horicon Member of the Holy Hill Formation (that is, they were deposited in proglacial lakes of the Green Bay Lobe) and consist mostly of laminated silty clays with interbeds of fine sand, although other facies do occur (fig. 9). The thick accumulations (greater than 2 m) of postglacial organic sediment (map unit **ol**) that overlie the Horicon Member’s proglacial lake sediment are nonglacial and are therefore not part of the Horicon Member. The lacustrine map units in Jefferson County are defined by their sediment composition and depositional setting. They include fine-grained offshore sediment (map unit **lf**), fine-grained offshore sediment overlain by organic material or organic sediment (map unit **ol**), sandy nearshore sediment (map unit **ln**), and any lacustrine sediment that has a pockmarked or hummocky collapse topography caused by the melting of buried ice (map unit **lc**). Map units are explained in more detail below.

The lacustrine map units are well-distributed throughout Jefferson County and mark the extent of former lakes that existed following the glacier’s retreat (around 20 ka) and persisted in places into the middle Holocene (around 5 ka). The thickest and most extensive lake sediment is located in areas overlying the Scuppernong and Crawfish bedrock valleys, such as the Scuppernong River valley, Crawfish River valley, and the Jefferson Tamarack Swamp State Natural Area just east of the city of Jefferson (figs. 3, 10A). Thinner and less continuous lacustrine sediment is associated with streamlined till, filling the low-lying areas between drumlins (fig. 10B). Most lake sediment in Jefferson

Figure 8. Shaded-relief maps illustrating examples of moraines that formed during the Lake Mills phase of the Wisconsin Glaciation and location of outlets between subbasins of glacial Lake Scuppernong. Blue arrows point in direction of water flow between subbasins of glacial Lake Scuppernong. (A) Moraine draped over drumlins. (B) Minor moraines. (C) Outlets between subbasins of glacial Lake Scuppernong breaching moraines.



Elevation from Jefferson County Elevation Dataset, 2014. Wisconsin Transverse Mercator projection, 1991 Adjustment to the North American Datum of 1983 (NAD 83/91); EPSG 3071

Figure 9. Typical lake sediment from direct-push cores in Jefferson County, including organic sediment (core ROM-01), laminated silty clay with organic material (core WTL-02), and a fine sand bed with laminated silty clay (core BSV-05). Scale is in centimeters and refers to depth within each 1.5-m-long core segment. Radiocarbon samples were collected from the ROM-01 and WTL-02 core segments shown here (see table 2).

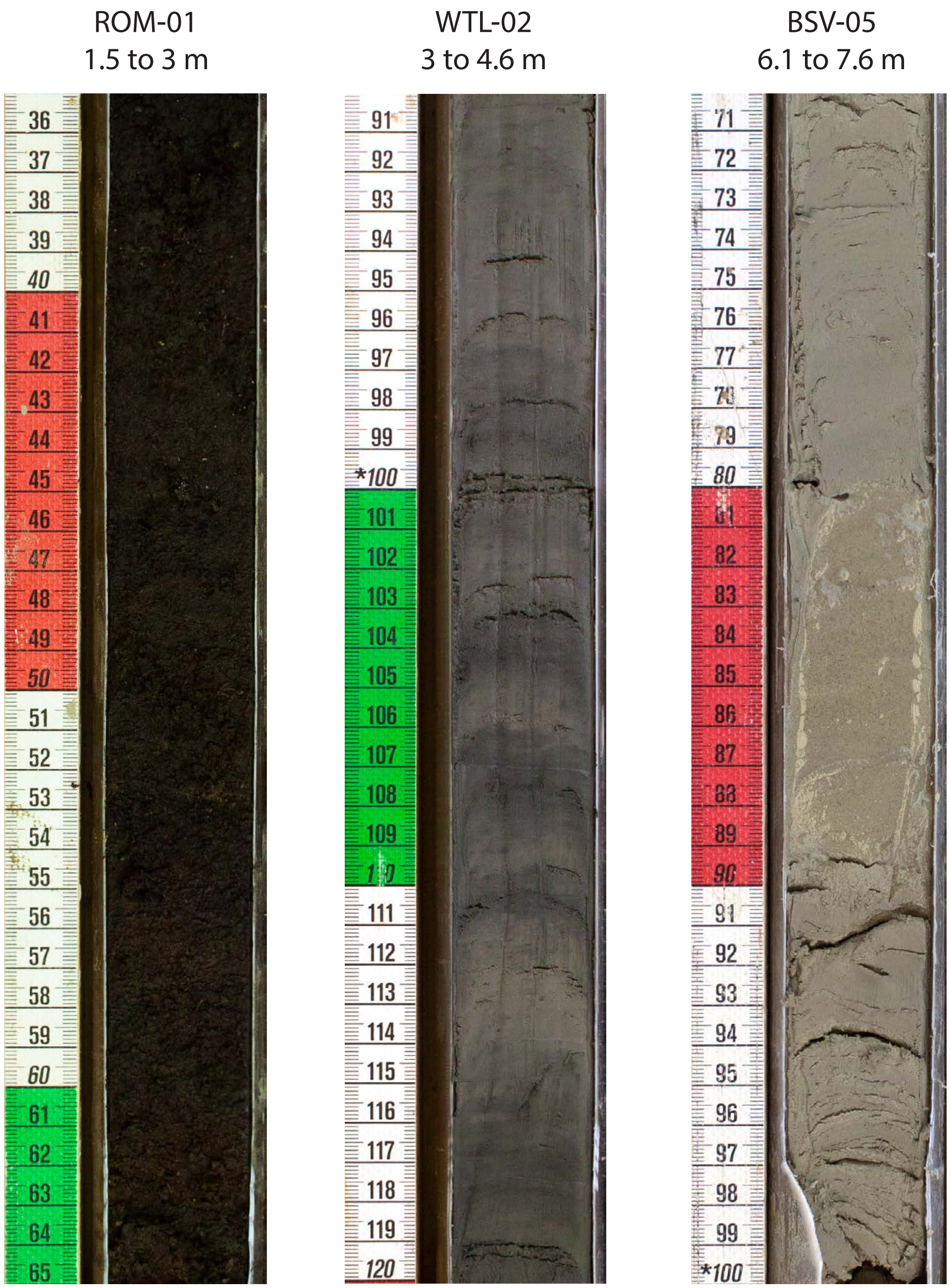
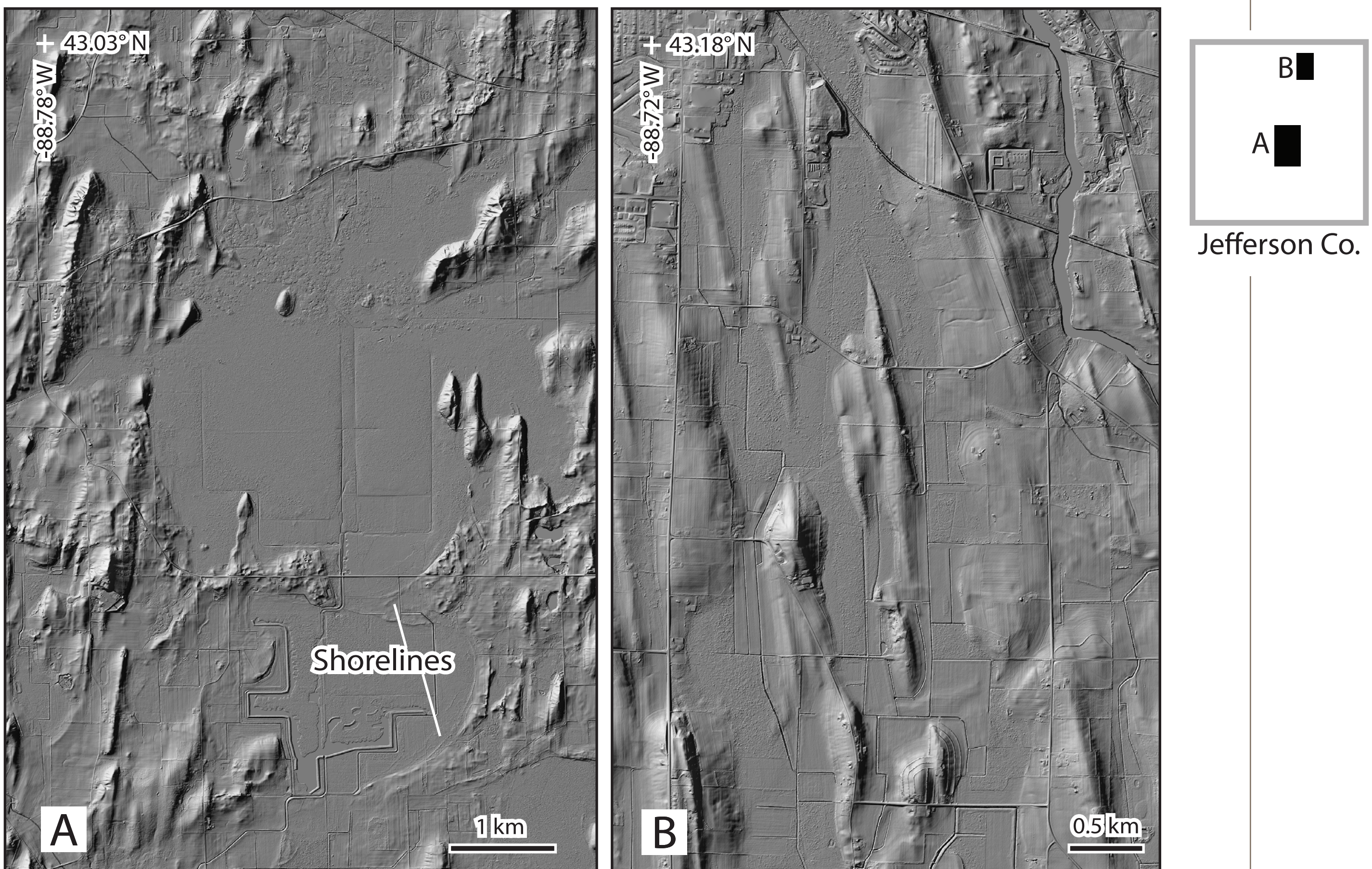


Figure 10. Shaded-relief maps showing lacustrine features. (A) Holocene shorelines in Jefferson Tamarack Swamp State Natural Area. (B) Flat low-lying areas between drumlins that are filled with lake sediment.



Elevation from Jefferson County Elevation Dataset, 2014. Wisconsin Transverse Mercator projection, 1991 Adjustment to the North American Datum of 1983 (NAD 83/91); EPSG 3071

County was likely deposited during and after the retreat of the Green Bay Lobe, beginning around 20 ka; however, the sediment that fills deep bedrock valleys to depths up to 120 m may be older.

The lake sediment in Jefferson County includes fine-grained, organic-rich, and sandy units. The dominant facies are laminated silty clays with interbeds of fine sand. Sediment in map unit **lf** and below the surface in map unit **ol** includes laminae that range from clay to medium sand (with silt and fine sand being the most common) and are well to moderately well sorted. Laminae are internally massive (not graded) and are generally grouped with other laminae of similar grain size. Contacts between lithologies are mostly gradational over 0.5 to 1 m but sometimes can be sharp. Rare intervals of interlaminated clay, silt, and sand with sharp contacts are present. Lacustrine sediment often overlies till of the Horicon Member, and cores indicate that the lower contact between them is sharp (fig. 5; core WTT-02). Very rare, angular, pebble-sized clasts are found within laminated, fine-grained sediment. Many of the former lakes did not persist into the Holocene, or even much longer than the glacier's retreat. Some of the drained lakes are now represented by relatively flat, low-lying areas (lake plains) that contain modern or recently drained wetlands. However, some of the areas occupied by the former lakes did not develop into wetlands. Map unit **lf**, which represents those lake plains that did not develop into wetlands, is the only lacustrine unit in which ice-wedge polygons—features that indicate the former presence of permafrost—have been found. Radiocarbon dates from permafrost features (Clayton and others, 2001) and uranium-thorium ages from speleothems in the unglaciated parts of southwestern Wisconsin (Batchelor and others, 2019) indicate that permafrost conditions were pervasive in southern Wisconsin until around 15 ka (Clayton, 2001). Therefore, most of the sediment in map unit **lf** was likely deposited and then exposed (no longer submerged) before 15 ka.

Organic rich sediment is commonly associated with lacustrine map units. Map unit **lf** may include a cap of organic-rich sediment that is less than 2 m thick. Map unit **ol** is the same as map unit **lf** in terms of lacustrine sediment composition and thickness**,** but it has an overlying layer of organic material that is 2 m thick or greater. In map unit **ol**, the upper contact of the laminated lacustrine sediment with the overlying organic sediment is sharp to gradational.

Sandy lacustrine sediment (map unit **ln**) is composed of coarse to fine sand that is well to moderately well sorted. Thicknesses range from 1 to 3 m and fine upward from coarse or medium sand to silty sand. These units have sharp lower contacts with fine-grained lake sediment. Sandy lacustrine sediment (map unit **ln**) was likely deposited in shallow nearshore and (or) shoreline areas where wave activity would have preferentially deposited sand. Some of these areas appear to be the result of reworked sediment transported into the lakes either by hillslope processes or deltas of small streams. Areas mapped as sandy lacustrine sediment are flat to slightly hummocky and are adjacent to other lacustrine sediment units. Although these sandy areas are low-lying on the landscape, they have a slightly higher elevation (on a scale of 1 to 3 m) than the adjacent lake plains. These sandy areas often separate one or more lake plains, or they follow the border between a lake plain and an upland area. Beach ridges, spits, and other shoreline features are rarely represented by this map unit. Some shoreline features are visible in the basins of Holocene lakes, such as Lake Koshkonong and the Jefferson Tamarack Swamp (figs. 3, 10A).

Map unit **lc** consists of lacustrine sediment with pitted or hummocky topography, which distinguishes them from other lacustrine units. The composition of this map unit is variable and may contain any of the sediment types described in the other lacustrine map units, but likely have similar compositions to adjacent non-hummocky lacustrine sediment. The pitted and hummocky topography of this map unit due to the collapse of buried, stagnant glacier ice. Areas of collapsed lacustrine sediment (map unit **lc**) are rare in Jefferson County. They have been mapped in association with meltwater stream sediment along both the western and eastern edges of the county.

Lake sediment in Jefferson County is yellow-red, although organic-rich sediment is darker in hue, and sands and silts are lighter in hue. Despite the similarities in color, the chemical or mineralogical composition of lake sediment may be variable. Some of the lake sediment in Jefferson County has a high carbonate content; that is, the sediment effervesced strongly on contact with hydrochloric acid. Other lake sediment, however, did not react to hydrochloric acid. The effervescence did not appear to be related to the sediment's grain size, color, oxygen-reduction (redox) conditions, or depth.

Stream sediment and landforms

Stream sediment covers about 5 percent of Jefferson County (fig. 4C). These areas include sediment deposited by glacial meltwater of the Green Bay Lobe (map units **su** and **sc**), glacial meltwater of both the Green Bay and Lakes Michigan Lobes in the Kettle Moraine (map units **suk** and **sck**), glacial-meltwater sediment overlain by more than 2 m of postglacial organic sediment (map unit **os**), and postglacial stream sediment (map unit **sm**). Eskers are also composed of meltwater-stream sediment that was deposited in ice-walled channels. The meltwater-stream sediment observed in cores is well to poorly sorted, fine to very coarse sand and gravel with horizontal to angular bedding and occasional silty beds (fig. 11). Where observed, the contacts with overlying lake or glacial sediment is sharp.

Large boulder along Bald Bluff Nature Trail, Kettle Moraine State Park

Figure 11. Typical meltwater-stream sediment from direct-push cores in Jefferson County, including very coarse sand and gravel (core PMY-03), sand with angular laminations (core RKD-01), and a silty bed within sand and gravel (core WTL-05). Scale is in centimeters and refers to depth within each 1.5-m-long core segment.

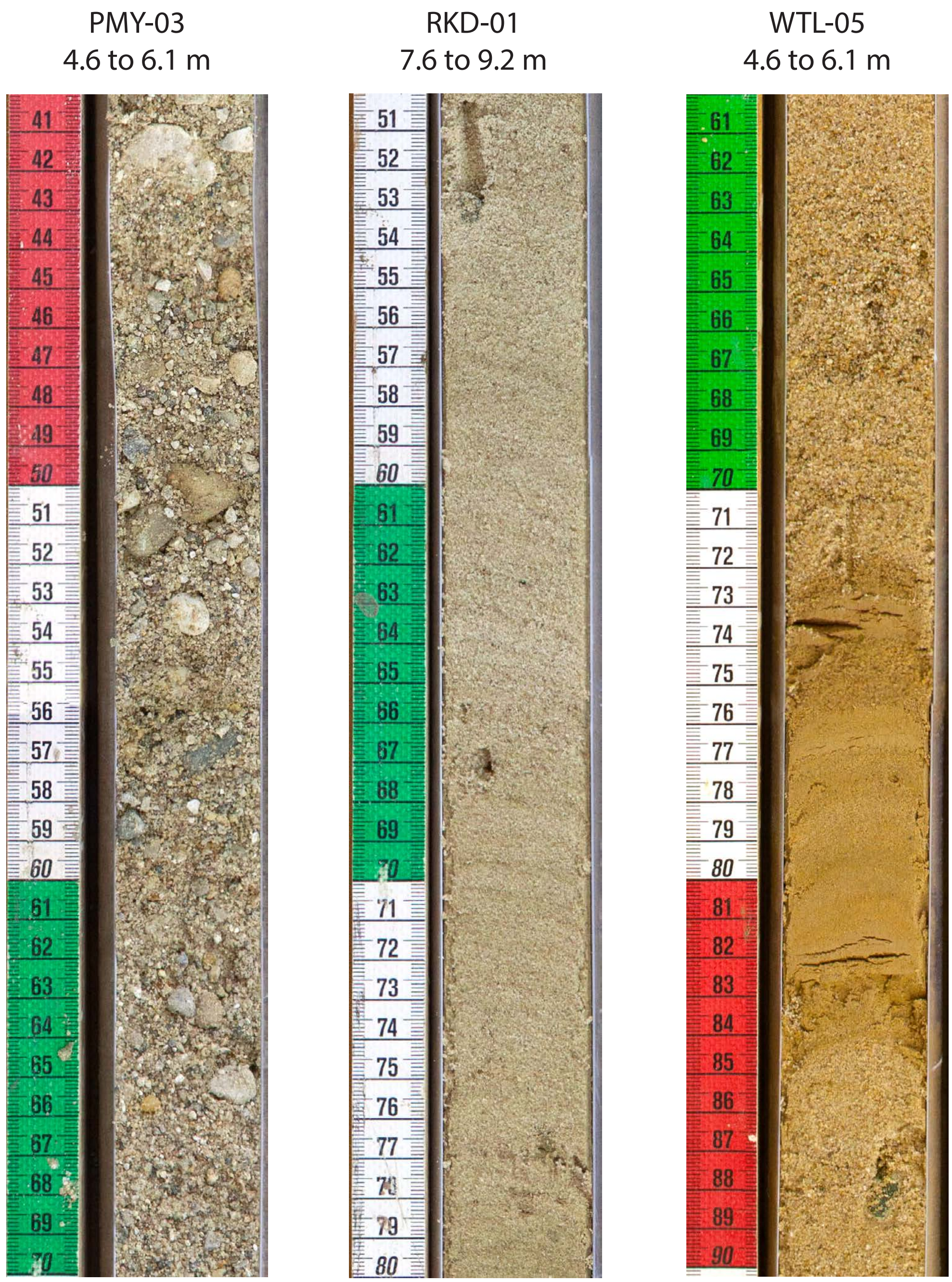
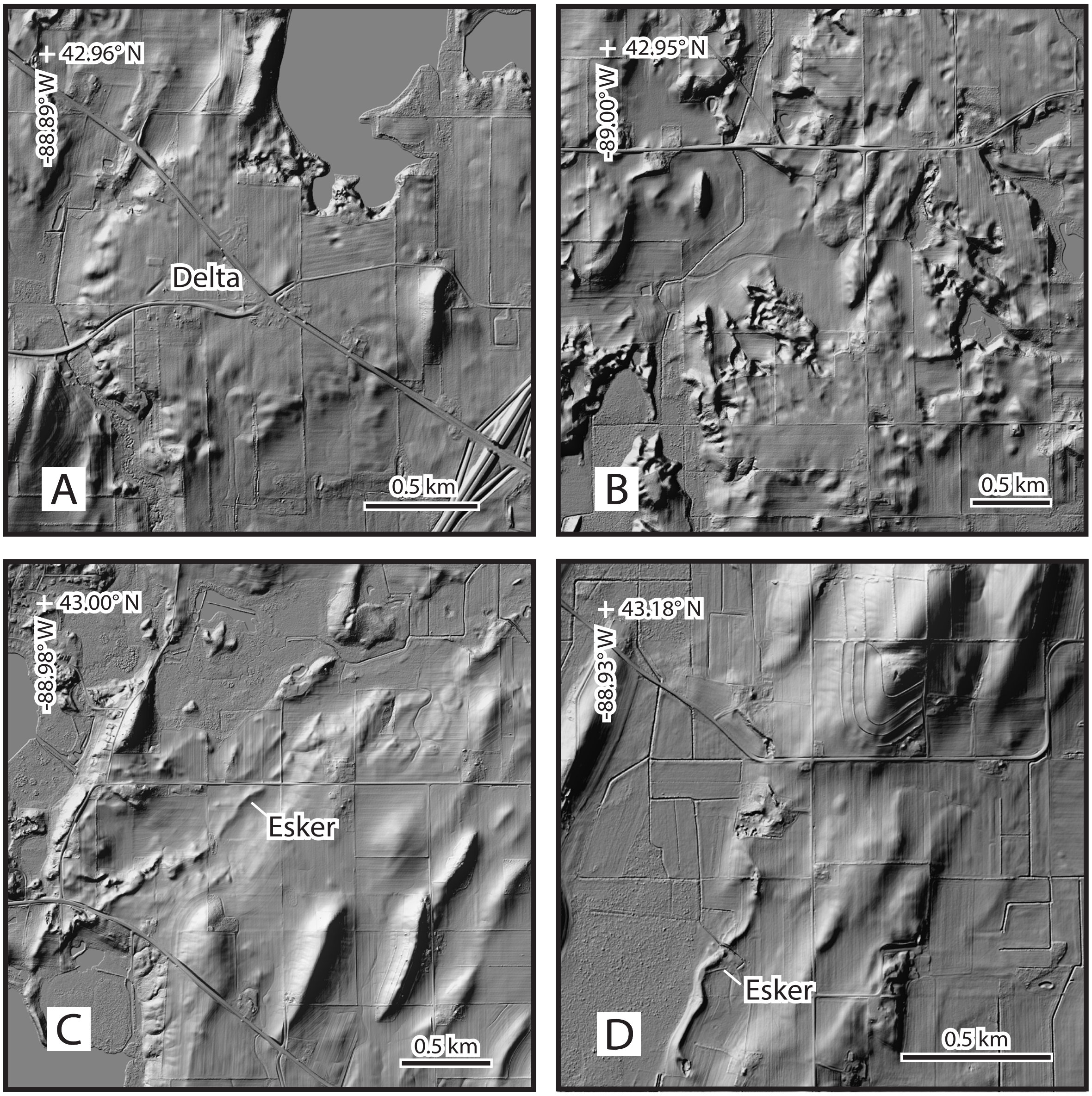


Figure 12. Shaded-relief maps showing landforms resulting from meltwater-streams. (A) Ice-contact delta. (B) Collapsed outwash plain. (C) Large esker. (D) Small, peaked esker in former downglacier direction of a drumlin.



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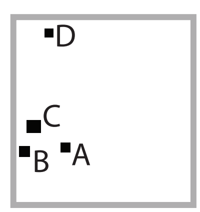

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Meltwater-stream sediment of the Horicon Member

Meltwater-stream sediment deposited by the Green Bay Lobe and not related to the Kettle Moraine primarily occurs in the western part of the county (fig. 4C). Very few outwash surfaces can be traced upstream to ice-margin positions that are marked by end moraines. Outwash in the western part of the county was likely an area of focused meltwater discharge after the Green Bay Lobe retreated from the county. These meltwater streams deposited sand and gravel in outwash plains, outwash terraces, and channels (map unit **su**). In some places, these meltwater streams flowed over stagnant ice, which eventually melted and caused the collapse of the depositional surface, creating kettles and hummocky to pitted topography (fig. 12; map unit **sc**). Thick accumulations (greater than 2 m) of postglacial organic sediment is common in many of the resulting collapse depressions (map unit **os**).

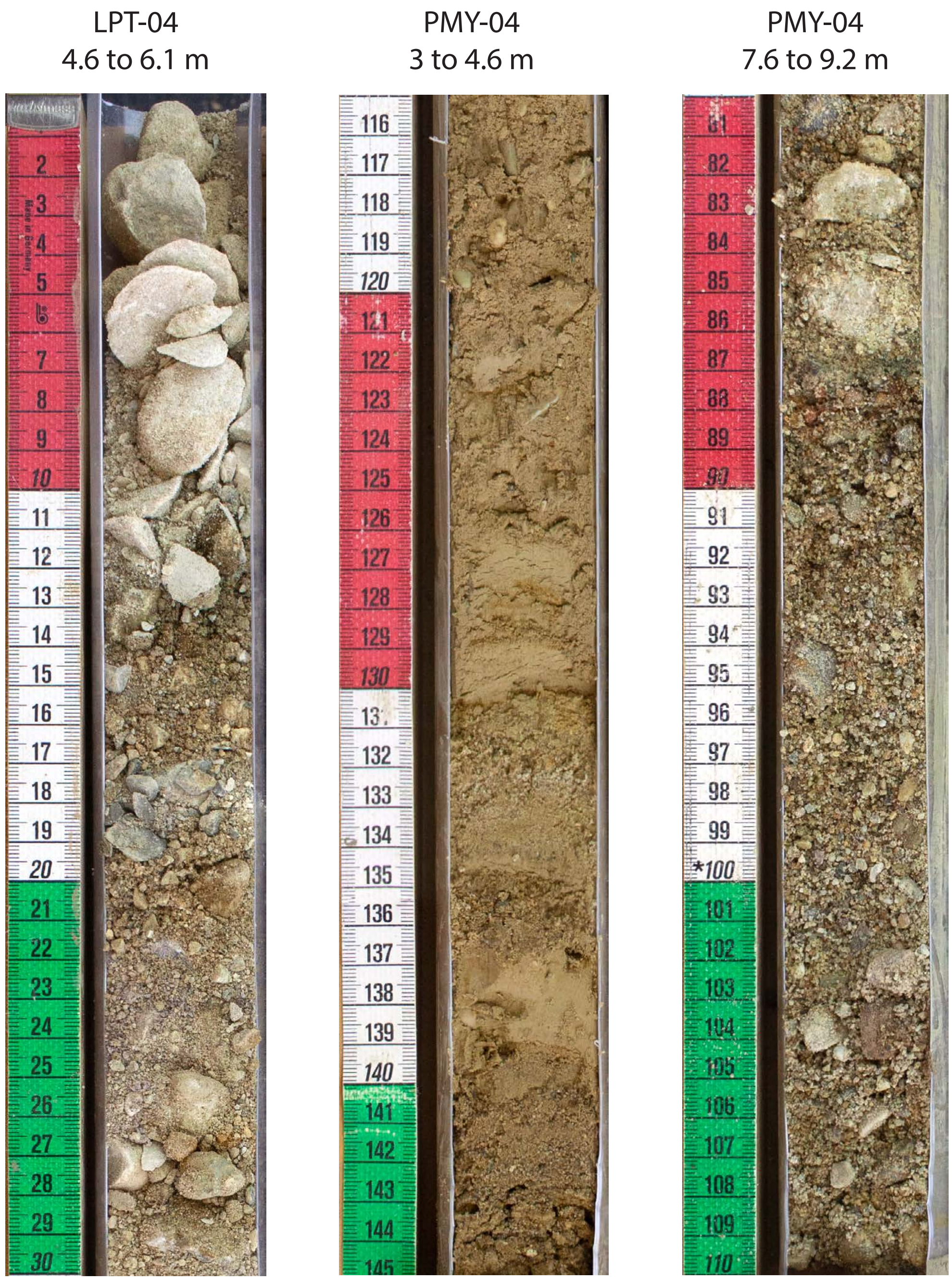
Meltwater-stream sediment of the Horicon Member in Jefferson County includes two uncollapsed ice-contact meltwater-stream features: one ice-contact delta (fig. 12A) and one ice-contact fan. These landforms were created where channelized subglacial (beneath the glacier) and (or) englacial (within the glacier) discharge from the Green Bay Lobe entered glacial Lake Scuppernong. The delta and fan likely formed while in contact with the glacier's front because they have steep upglacier faces. They also occur several meters above other stream sediment depositional surfaces, indicating they were not created by proglacial or nonglacial streams entering a lake. The delta is classified as a Gilbert-type delta because it has gently dipping to flat topset beds that would have been deposited by meltwater streams above base (lake) level and steeply dipping foreset beds that would have been deposited below the lake surface. Ice-contact deltas can be built by meltwater discharge from sources that were subglacial, englacial, and (or) supraglacial (on the surface of the glacier). Supraglacial ice-contact deltas tend to only form at stagnating, dead ice margins (Ashley, 2002); there is no evidence for extensive dead ice in Jefferson County, so this delta most likely was not created by that process. The ice-contact fan differs from the delta by the absence of steeply dipping foreset beds; instead, its surface dips shallowly in the downstream direction, which indicates that the fan was deposited entirely underwater from a subglacial or englacial channel that discharged below the lake's surface (Ashley, 2002).

Meltwater-stream sediment of the Kettle Moraine

The Kettle Moraine (an interlobate moraine that formed between the Green Bay and Lake Michigan Lobes of the Laurentide Ice Sheet; fig. 1) is a prominent part of the landscape of eastern Wisconsin (Chamberlin, 1876; Carlson and others, 2005). We note that the name "Kettle Moraine" is geographic and does not imply any geologic or geomorphic mechanism for the creation of the hills and ridges within the area (Alden, 1904; Clayton, 2001). Although moraines and kettle lakes are present, the origins of the hills, ridges, and water bodies of this region are diverse. The Kettle Moraine consists of an irregular system of ridges and hills that trends south-southwest to north-northeast for about 125 km between Walworth County in the south to Manitowoc County in the north. The Kettle Moraine occupies the southeastern corner of Jefferson County, south of Palmyra. This portion of the Kettle Moraine rises 45 to 60 m above the surrounding landscape, an area of much higher relief than anywhere else in Jefferson County. The area is composed of collapsed (map unit **sck**) and uncollapsed (map unit **suk**) meltwater-stream sediment (fig. 13). The Horicon and New Berlin Members of the Holy Hill Formation were not differentiated within these map units (Syverson and others, 2011).

The sediment in the Kettle Moraine was most likely deposited during the last glacial maximum because the southern Kettle Moraine in Walworth County merges with the large terminal moraines that mark the maximum extent of both the Green Bay Lobe (Johnstown moraine) and Delavan Sublobe of the Lake Michigan Lobe (Darien moraine). Along its western edge, the Green Bay Lobe's margin reached this maximum position between approximately 26.4 and 24.7 ka and had likely started to retreat around 20 ka (Attig and others, 2011; Carson and others, 2012; Carson and others, 2020). These age estimates suggest that the ice margin of the Green Bay Lobe was at or near this position for approximately 5,000 to 6,000 years. The Delavan Sublobe of the Lake Michigan Lobe likely followed similar trends in timing (Curry and others, 2018). During that time, both lobes transported a great deal of sediment and water to their margins. However, unlike the previously discussed moraines, till is very rare in the Kettle Moraine, where the hills mostly consist of sorted sand and gravel (fig. 13; Chamberlin, 1883; Alden, 1918; Black, 1969; Syverson, 1988; Mickelson and Syverson, 1997; Clayton, 2001; Carlson and others, 2005). The geomorphic features of the Kettle Moraine (which include many channels, fans, sand plains, eskers, moulin kames, and kettle basins) suggest that the sediment transported to the lobe margins were reworked and deposited by meltwater. In places, they were deposited on top of buried

Figure 13. Typical Kettle Moraine sediment from direct-push cores in Jefferson County, including very coarse sand and gravel (core LPT-04), the contact (126 cm) between till and stratified meltwater-stream sediment in the relict Kettle Moraine (core PMY-04), and very coarse sand and gravel in the relict Kettle Moraine (core PMY-04). Scale is in centimeters and refers to depth within each 1.5-m-long core segment.



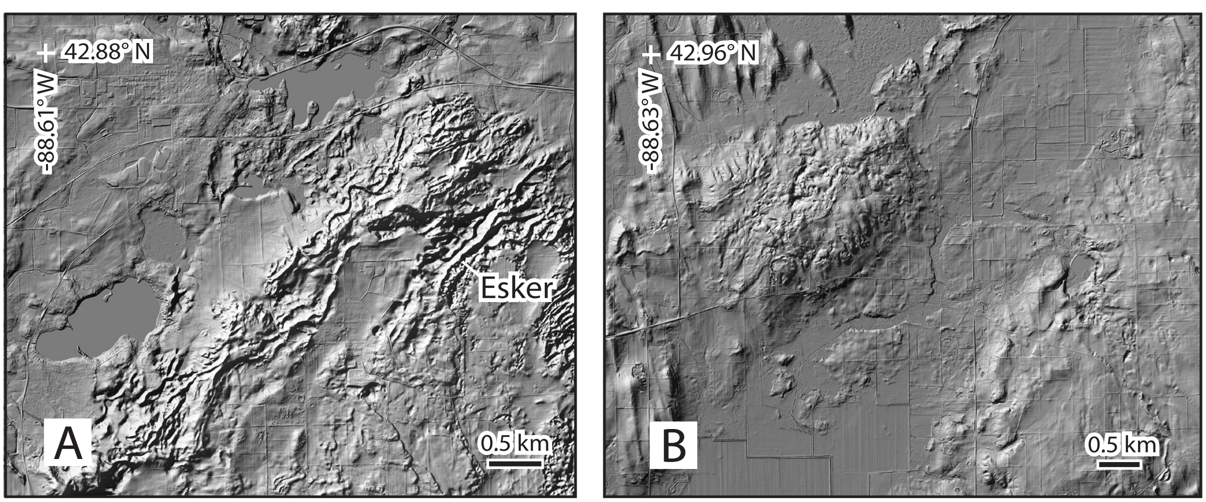
stagnant glacier ice. These processes would have been very similar to those of other meltwater-stream systems, except that the two lobes and the topography they created acted to aggrade (build-up) 45 to 60 m of sand and gravel and funnel the flow of water toward the southwest.

Overridden Kettle Moraine sediment

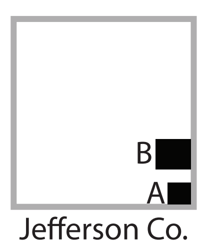
Although the Kettle Moraine developed over several thousand years during the last glacial maximum, the Lake Michigan Lobe and (or) the Green Bay Lobe margin positions likely experienced fluctuations of around 10 km during that time. There is evidence for such fluctuations in the northern portion of the Kettle Moraine (Carlson and others, 2005; Carlson and others, 2011). Additional evidence for a transitory interlobate zone exists in the southern Kettle Moraine of Jefferson County and includes (1) the presence of tall hills consisting of sand and gravel that were later overridden by the Green Bay Lobe and (2) the juxtaposition of the Kettle Moraine and drumlins in southeastern Jefferson County.

Several large hills 2 to 10 km northwest of the mapped Kettle Moraine sediment in Jefferson County (map units **sck** and **suk**) are likely a relict interlobate zone. This interpretation is based on their topography and sedimentary composition. In a manner similar to the mapped Kettle Moraine, these hills rise about 30 to 45 m above the surrounding landscape. In the area formerly occupied by the southern Green Bay Lobe, topographic relief of more than 30 m is only associated with the Kettle Moraine, the Johnstown and Darien terminal moraines, and areas with higher bedrock elevations. Well-construction reports in these hills show that they consist of a thin layer of till underlain by 15 to 55 m of sand and gravel; the thickness of the sand and gravel generally corresponds to the height of the hill. These observations are consistent with descriptions from core PMY-04, which contained 3 m of till overlying meltwater-stream sediment (fig. 13). Because the composition (sand and gravel) and height (more than 30 m) of these hills are consistent with other parts of the Kettle Moraine, we conclude that they were deposited in a manner similar to the mapped Kettle Moraine. Unlike the mapped Kettle Moraine area, these hills show evidence of subglacial and proglacial erosion and deposition, including streamlined bedforms, eskers, and small moraines (fig. 14). These features indicate that the hills were overridden later by the Green Bay Lobe and that they are therefore older than the mapped Kettle Moraine sediment. The presence of overridden interlobate landforms in Jefferson County is additional evidence that the Kettle Moraine interlobate zone was a

Figure 14. Shaded-relief maps showing features of the Kettle Moraine. (A) Eskers in the Kettle Moraine. (B) Older Kettle Moraine deposits that were overridden and streamlined.



Elevation from Jefferson County Elevation Dataset, 2014. Wisconsin Transverse Mercator projection, 1991 Adjustment to the North American Datum of 1983 (NAD 83/91); EPSG 3071.



dynamic system during the last glaciation, and the location of the Green Bay Lobe's margin fluctuated during that time.

Alternatively, these 15- to 55-m-thick hills of meltwater-stream sediment may not have been deposited in the Kettle Moraine interlobate zone but were simply part of end moraines of the Green Bay Lobe. This hypothesis is less likely than an interlobate zone origin for these hills mainly because no similar moraines or moraine remnants rising about 30 m above the surrounding landscape and consisting of meltwater-stream sediment have been found in other areas that were formerly occupied by the southern Green Bay Lobe upglacier from the terminal Johnstown moraine. Although these hills are several miles in the upglacier direction from the mapped Kettle Moraine area in Jefferson County, they do align well with the trajectory of the Kettle Moraine land system in Washington County to the northeast of the study area (Mickelson and Syverson, 1997).

Additional evidence that the interlobate zone between the Lake Michigan and Green Bay Lobes was not static is the relation between the Kettle Moraine and adjacent drumlins. In all observed drumlin fields, including those previously occupied by the Green Bay Lobe, there is a 2- to 25-km-wide drumlin-free gap between the downglacier edge of the drumlin field and the end moraine that was created at the same time as the drumlins (Patterson and Hooke 1995; Colgan and Mickelson, 1997; Jónsson and others, 2014). However, sediment associated with the Kettle Moraine is adjacent to and overlies drumlins. This juxtaposition suggests that the Green Bay and Lake Michigan Lobes each may have, at different times, extended beyond the mapped area of the Kettle Moraine because those drumlins were created several miles upglacier of an interlobate zone.

Eskers

Eskers are elongate, sinuous ridges of glacial meltwater-stream sediment that were deposited in ice-walled tunnels or channels (Benn and Evans, 2010). Eskers form in subglacial, englacial, or supraglacial tunnels and channels.

Three types of eskers occur in Jefferson County:

A. Wide, discontinuous, flow-parallel eskers (mapped by Colgan, 1999; fig. 12C)
B. Narrow, peaked, sinuous, flow-parallel eskers (fig. 12D)
C. Large, peaked, flow-perpendicular eskers (fig. 14A)

Type A eskers are not common, tend to be relatively long (greater than 1 km), and are situated on the lowlands between or winding around the drumlins. They have rounded to peaked crests, are 60 to 120 m wide, 0.5 to 5 m tall, and only occur in Jefferson County where continuous areas of drumlins also are present (**gs**). Many of these larger eskers are somewhat obscured on the landscape and appear to be partially buried.

Type B eskers are more common. They are 2.5 to 6 m high, 30 to 45 m wide, and typically less than or equal to 1 km long. Although they can be highly sinuous, these eskers trend parallel to glacier flow. In some instances, these eskers are located in areas that were immediately downglacier or upglacier of drumlins (fig. 12D); their positions are likely related to subglacial conditions at the time of drumlin and esker formation.


A till exposure in Jefferson County

Type C eskers overlie and (or) are adjacent to meltwater-stream sediment in the Kettle Moraine interlobate zone (fig. 14A). They are 15 to 90 m wide, up to 15 m high, and run parallel to the orientation of the Kettle Moraine and Lake Michigan and Green Bay Lobe margins. The ridges occur as a system of anabranching, discontinuous, sinuous forms. These eskers have complex relations to the adjacent collapsed and uncollapsed outwash plains in the Kettle Moraine. They often overlie both, but sometimes they appear sunk below adjacent outwash plains as part of the collapsed landscape. Eskers sometimes merge with outwash plains at either end of or in the middle of the landform. These same types of eskers were described in the Kettle Moraine of Waukesha County (Clayton, 2001).

The type A and B eskers, which are oriented parallel to the glacier's flow, likely formed in subglacial tunnels beneath the Green Bay Lobe. These tunnels were created by pressurized meltwater carving and melting upward into the ice. The meltwater also carried and deposited sand and gravel through these tunnels, creating the eskers.

The large type C eskers, which are confined to the Kettle Moraine and oriented perpendicular to the glacier's flow, are most likely examples of supraglacial eskers (that is, they formed on the glacier's surface; Clayton, 2001; Benn and Evans, 2010; Perkins and others, 2016). These types of eskers typically formed in stagnating or dead ice at the margins of the glaciers. They were most likely not formed subglacially because there are no subglacial sediment or landforms adjacent to or near them and they are oriented perpendicular to the flow of the Green Bay and Lake Michigan Lobes. The margin-parallel orientation of these eskers indicates that the channels in the stagnant ice were carved by meltwater following the local topography (compared to following a glacier-driven meltwater gradient), which is characteristic of supraglacial meltwater systems. The complex, interwoven relations between these ridges and their positions on the elevated outwash plains in the Kettle Moraine suggest that they are part of the same ice-marginal meltwater system. As the Lake Michigan and (or) Green Bay Lobes retreated from the Kettle Moraine interlobate zone, stagnant ice was left behind. Sometime during the retreat, supraglacial meltwater channels were carved into this ice. Meltwater-stream sediment was deposited in these channels either while the channels were being carved or afterward. The presence of the channels in the ice allowed for thicker successions of meltwater-stream sediment to be deposited in those locations than in adjacent areas so that when the buried ice eventually melted, these filled channels remained on the landscape as eskers. Linear (not sinuous) features are present in the Kettle Moraine area that may have been created in a manner similar to these supraglacial eskers. However, their shape suggests that their origins were as linear crevasses of the glacier margin that filled with meltwater stream sediment.

Modern stream sediment

The stream sediment associated with modern fluvial drainage systems in Jefferson County are included in map unit **sm**. The Rock River is the primary drainage through Jefferson County, exiting in the southwestern part of the county where it flows through the impounded Lake Koshkonong (fig. 3). The Rock, Crawfish, and Scuppernong Rivers are located in the beds of former lakes; their floodplain sediment is therefore typically fine grained, although there is coarser sediment in the active channels. The floodplain may contain organic sediment, although these are not differentiated on plate 1.

Organic sediment and organic-rich sediment

Soil maps indicate Histosols are found throughout Jefferson County where there is standing water and wetlands (Milfred and Hole, 1970; Soil Survey Staff, undated). Small wetlands occupy pits in collapsed outwash and are associated with map unit **os**. Larger wetlands occur in former lake basins and are associated with map unit **ol**. Most large wetlands in Jefferson County have been drained for agricultural purposes. Thin layers of organic sediment are likely in areas such as floodplains.

Quaternary history

The landscape of Jefferson County was mainly formed by processes associated with the most recent advance and retreat of the Green Bay Lobe of the Laurentide Ice Sheet. The far southeastern corner of the county includes portions of the Kettle Moraine interlobate zone, which was created with meltwater and meltwater-stream sediment from both the Green Bay Lobe and the Lake Michigan Lobe. Drumlins in Jefferson County likely formed by the Green Bay Lobe while it was at its maximum extent (Johnstown Phase; Colgan and Mickelson, 1997). The Green Bay Lobe was likely at or near its maximum position from about 26.4 to 20 ka. This is also when the southern Kettle Moraine was likely created. Several moraines and proglacial lakes formed in the footprint of the Green Bay Lobe during its retreat, which began around 20 ka. The Green Bay Lobe had likely retreated north of Jefferson County by approximately 18 ka. Following the deglaciation of Jefferson County, permafrost persisted in the county until 15 ka. Glacial streams and lakes supplied by meltwater from the Green Bay Lobe were extensive in Jefferson County during and immediately following the retreat of the glacier. Although they were less extensive than when the glacier margin was retreating through Jefferson County, glacier-fed lakes and streams likely persisted in Jefferson County until the Green Bay Lobe retreated out of Wisconsin at around 13 ka (Mickelson and others, 2007). Many of these lakes persisted without the influence of glaciers until the middle Holocene (around 6 ka), when many transitioned to wetlands.

Green Bay Lobe

The general flow of the Green Bay Lobe was southward through a lowland bounded to the east by the Niagara Escarpment and the Lake Michigan Lobe and to the west by Precambrian uplands overlain by lower Paleozoic sediment (Colgan, 1999). The lowland that the Green Bay Lobe occupied could have been deepened by subglacial erosion during Pleistocene glacial intervals by either glacial or glacial-meltwater erosion. The lowland was also likely affected by weathering and nonglacial fluvial erosion during Pleistocene interglacial periods.

Four radiocarbon ages were determined from plant material in organic and lake sediment collected from cores in Jefferson County (tables 1 and 2). No attempt was made to identify plant material to separate out aquatic species; therefore, these ages may have experienced a hard-water effect and should be considered maximum ages.

The age of plant material in lake sediment (map unit **ol**) collected from Waterloo Township (core WTL-02; lat. 43.182707 °N, long. 88.960538 °W) in the northwestern part of Jefferson County is 18,180 to 17,850 yr B.P. (sample WTL-02-A, table 2). This sample consisted of bulk plant material recovered from multiple organic-rich laminae collected from the core at 3 to 4.5 m below the land surface. Below the road grade and organic sediment in core WTL-02, the core consisted of laminated silt, clay, and organic material down to 6 m, where the core ended. This core did

Table 2. Radiocarbon age estimates from Jefferson County.

Sample identification	Material dated	Lab identification[a]	Depth below surface (m)	Radiocarbon age (yr B.P., ±2σ)[b]	$\delta^{13}C$ (‰, VPDB)[c]	Calibrated age (yr B.P., 2σ range)[b,d]	Median age (yr B.P.)[b,d]
ROM-1-A	Plant material	563552	3.0	6,010 ± 30	−26.6	6,781–6,942	6,849
ROM-1-B	Plant material	563553	4.5	8,120 ± 30	−17.3	8,993–9,131	9,061
ROM-1-D	Plant material	563554	5.3	12,770 ± 40	−21.4	15,080–15,387	15,229
WTL-02-A	Plant material	548564	4.5	14,680 ± 40	−13.0	17,846–18,176	18,013

[a] Analysis completed by Beta Analytic (Miami, Fla).

[b] The abbreviation "yr B.P." indicates calendar years before present, where present is 1950 C.E.

[c] VPDB refers to isotopic standard Vienna Peedee Belemnite.

[d] Calibrated using Calib v. 8.2 (Stuiver and others, 2021) and IntCal20 (Reimer and others, 2020).

not reach the base of the lacustrine sediment; therefore, the radiocarbon age from sample WTL-02-A represents a point in time when a lake was present at this location, but it does not constrain the beginning or end of lacustrine deposition at this site. However, because there is no evidence for direct glacial influence in this core, this age does indicate that the Green Bay Lobe had retreated out of Jefferson County before 18,180 to 17,850 yr B.P. Because core WTL-02 is located near the northern edge of the county and north (upglacier) of most of the Lake Mills Phase moraines, this age can be used as a maximum age for that phase.

Within the Scuppernong bedrock valley (fig. 2B), three radiocarbon ages were determined from bulk plant material in lake sediment (map unit **ol**) recovered from a core collected northwest of Palmyra (core ROM-1; lat. 42.905834 °N, long. 88.629734 °W). This core contained 3 m of peat overlying a sequence of (top to bottom) laminated silt, clay, fine to medium sand, and organic material that measured up to 10.5 m. The oldest (lowest) peat in this core yielded an age of 6,780 to 6,740 yr B.P. (sample ROM-1-A), indicating that this is when the area now occupied by the Scuppernong River valley transitioned from lake to wetland. Two samples from lake sediment in this core yielded radiocarbon ages of 15,380 to 15,080 yr B.P. (sample ROM-1-D) and 9,130 to 8,990 yr B.P. (sample ROM-1-B). Because the ROM-1 core does not reach the base of the lacustrine sediment, these dates do not constrain when lacustrine sedimentation began at this site but do indicate that a lake occupied the area of the Scuppernong River valley from at least 15,230 to about 6,850 yr B.P.

Once the Green Bay Lobe had retreated from its maximum position, the only outlet for meltwater from its margin in Jefferson County through the Johnstown moraine was by the Rock River. However, there is very little meltwater-stream sediment associated with the Milton or Lake Mills phases of the Green Bay Lobe in Jefferson County. Meltwater-stream sediment that that does exist is isolated with a limited extent. There is no geomorphic evidence (such as underfilled valleys or large outwash plains, for example) for high river discharge from the southern Green Bay Lobe in Jefferson County. The absence of evidence strongly contrasts with adjacent areas in the footprint of the Lake Michigan Lobe, which have numerous large, underfilled valleys. The lower reaches of the Rock River contain evidence of high-discharge events, including those that occurred during the Lake Mills Phase (Anderson, 2005). Additionally, well-construction reports and the results of drilling performed for this study show that the bedrock valleys of Jefferson County are largely filled with up to 100 m of fine-grained sediment (such as fine sand, silt, and clay), which often overlie only several meters of coarse sand and gravel sitting just above the bedrock surface. There is no clear explanation for the limited amount of glacier outwash associated with the Green Bay Lobe in Jefferson County. Possible explanations include the following: (1) meltwater-stream sediment was trapped by ice-marginal lakes and buried by subsequent lake sediment, (2) meltwater-stream sediment was transported down the Rock River and out of the area by meltwater-stream systems, or (3) the Green Bay Lobe in Jefferson County simply did not produce a large amount of meltwater-stream sediment.

Southern Kettle Moraine

At some point before the deposition of the mapped Kettle Moraine, the interlobate zone was located 2 to 10 km to the northwest in Jefferson County. During this time, large hills of sand and gravel were deposited as part of an interlobate meltwater-stream system. Subsequently, the interlobate zone shifted to the east and the Green Bay Lobe advanced over these hills. When the interlobate zone shifted southward, these hills became streamlined by subglacial processes and a veneer of till was deposited over the sand and gravel. The areas mapped as Kettle Moraine sediment (map units **sck** and **suk**) likely mark the youngest interval of this interlobate zone, which was deposited before the final retreat of both lobes.

The final retreat of the Lake Michigan and Green Bay Lobe margins from their last glacial maximum position likely did not occur at the same time. Clayton (2001) suggested that the Green Bay Lobe and Lake Michigan Lobe equally contributed to the interlobate outwash system during their initial retreat, but the Lake Michigan Lobe became the dominant system later. The evidence for these contributions includes outwash fans and terraces in western Waukesha County that slope down towards the west and northwest, suggesting they were deposited by meltwater coming off the Kettle Moraine ridge and Lake Michigan Lobe (Clayton, 2001). The flow from this meltwater system was channeled to the southwest through the Scuppernong bedrock valley. These Lake Michigan Lobe sourced sediment suggest that the Green Bay Lobe retreated to its Lake Mills phase before the Lake Michigan Lobe retreated from its Kettle Moraine margin. Most of the sediment draining through the Scuppernong Valley during this time likely had its source from the Lake Michigan Lobe, possibly largely recycled from the Kettle Moraine.

Glacial Lake Scuppernong

This section discusses the elevation of landforms associated with proglacial lake levels. The elevations reported in this section are the modern elevations of these landforms above sea level. The authors have not attempted to account for the changes in elevation of these landforms due to glacial isostatic adjustment (postglacial rebound of the landscape). Because the landforms discussed here are in a relatively small geographic area and have similar underlying lithospheric conditions and glacial histories (in terms of glacier advance, retreat, thinning, and so on), we assumed that the relative difference in elevation between landforms on the Green Bay Lobe and those on the present landscape has not changed significantly.

There are few constraints on late Pleistocene lake levels in Jefferson County due to the absence of preserved, mappable shoreline features or lake outlets other than the Rock River. The Rock River south of Lake Koshkonong was likely the outlet for meltwater throughout the Green Bay Lobe's retreat because no other outlets have been identified. Therefore, estimates of the maximum extent of the proglacial lake during the retreat of the Green Bay Lobe have been based on the maximum elevation of Pleistocene lakes in neighboring Dane and Waukesha Counties (Clayton and Attig, 1997; Clayton, 2001) and of terraces and sills along the Rock River (Anderson, 2005). Previous workers have proposed a maximum lake elevation of about 270 m that is based on these observations (Clayton, 2001). A lake with this surface elevation would have covered most of Jefferson County and was named glacial Lake Scuppernong (Clayton, 2001). Although proglacial lakes in Jefferson County may have intermittently reached the full proposed extent of glacial Lake Scuppernong, the distribution of lake sediment and the elevation of rare shoreline landforms do not support the hypothesis that glacial Lake Scuppernong was an extensive, long-lived glacial lake. Instead, they suggest that during the retreat of the Green Bay Lobe, the proglacial lake system was much more dynamic. The proglacial lake system in Jefferson County was more likely a series of lake basins with dynamic lake levels that were occasionally connected during high lake levels.

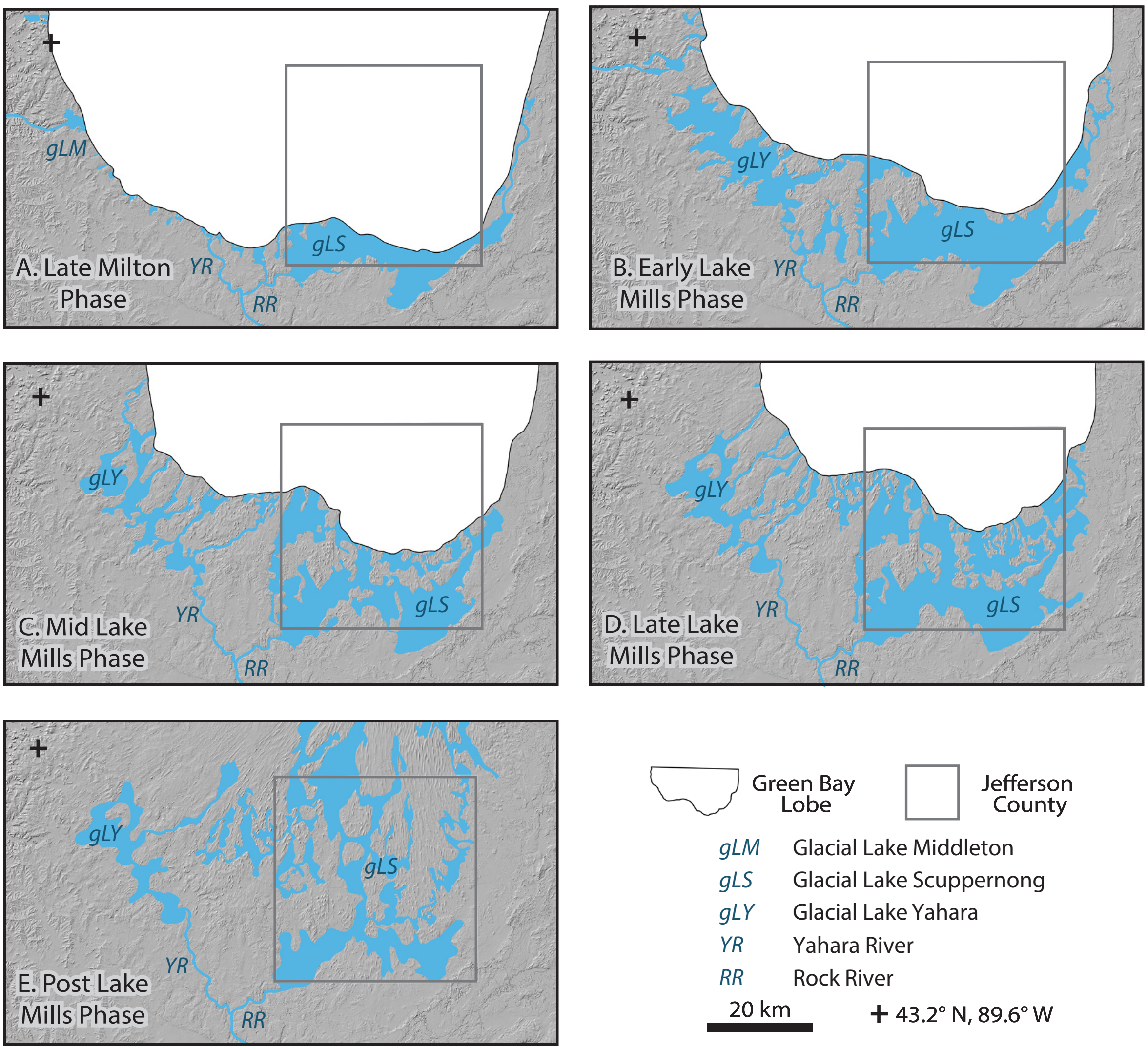
The distribution of lake sediment mapped in this study (plate 1 and fig. 4B) suggests a much more limited extent of proglacial lakes during the retreat of the Green Bay Lobe than has been proposed for glacial Lake Scuppernong. In Jefferson County, lacustrine sediment, including nearshore sediment (map unit **ln**), is notably absent at elevations higher than about 256 m (except where it is associated with meltwater-stream sediment in western Jefferson County), which is 15 m below the glacial Lake Scuppernong level proposed by Clayton (2001). The distribution of lacustrine sediment can only be used to delineate the minimum footprint of ancestral (late Pleistocene) lakes, not their levels. The surface elevation of an ancestral lake can only be inferred from shoreline features such as beach ridges and delta fronts, which indicate water levels during the time of their formation. Although shoreline features are rare in the study area, there is one ice-contact delta in Jefferson County and one in Waukesha County that can be used to infer lake levels at different stages of the Green Bay Lobe's retreat. Ice-contact deltas are useful indicators of lake levels during their formation because the slope break of a delta front approximates this lake level.

An ice-contact delta that formed in front of a late Milton Phase moraine (fig. 15 A) is located 5 km northeast of Palmyra and just south of modern Beaver Dam Lake in Waukesha County (Clayton, 2001; fig. 15). The elevation of the Beaver Dam Lake delta's slope break is 268 m. The ice-contact fan in southern Jefferson County, which formed underwater (see "Meltwater-stream sediment of the Horicon Member," p. 21), is also associated with the late Milton phase and has a maximum elevation of 265 m. The elevation of the fan confirms that proglacial lake levels exceeded 265 m during the late Milton Phase of the Green Bay Lobe's retreat.

The ice-contact delta in Jefferson County formed during the early Lake Mills Phase of the Green Bay Lobe's retreat (fig. 15B). This delta sits just northwest of Fort Atkinson and has a slope break with an elevation of 262 m, which suggests that proglacial lake levels decreased between the Milton and Lake Mills phases of the Green Bay Lobe's retreat.

Despite these limited controls on lake elevation, the Green Bay Lobe's proglacial lake levels likely fluctuated widely. The discharge of water from glaciers can vary by orders of magnitude diurnally, seasonally, and on longer scales. Intervals of warmer temperatures and (or) increased exposure to solar radiation likely drove increases in glacier melting and proglacial discharge, whereas colder temperatures and (or) decreased exposure to solar radiation likely resulted in less melting. The distribution of lakes close to the margins of the Green Bay Lobe was also likely

Figure 15. Generalized maps showing the proposed extents of glacial Lakes Scuppernong, Yahara, and Middleton during phases of the Green Bay Lobe's retreat across southeastern Wisconsin. Maps are arranged oldest to youngest from A to E. Glacial lake extents are based on the distribution of lake sediments and shoreline features in Jefferson, Dane, and Waukesha Counties. This diagram does not assume that lake levels were the same along the Green Bay Lobe margin because there is evidence meltwater was being discharged at different elevations along the glacier's front (higher elevations in Dane County and lower elevations in Jefferson County). Lake levels likely fluctuated widely during retreat due to variations in glacier discharge, opening of new drainage pathways, and isostatic adjustment. Partially based on glacial lake reconstructions from Clayton and Attig (1997) and Clayton (2001).



Elevation from Jefferson County Elevation Dataset, 2014. Political boundaries from Wisconsin Department of Natural Resources, 2011. Wisconsin Transverse Mercator projection, 1991 Adjustment to the North American Datum of 1983 (NAD 83/91); EPSG 3071.

constantly in flux as the margin retreated farther northward. The retreat of the glacier uncovered new low-lying areas that acted as lake basins and new routes for water to pass through. Additionally, isostatic rebound due to the retreat and thinning of the Green Bay Lobe probably resulted in constant changes to topography during this time. Lake levels in glacial Lake Scuppernong may have periodically reached the extent proposed by Clayton (2001), but ice-contact deltas and the distribution of lake sediment in Jefferson County suggest that the lakes more often topped out at lower elevations. There may also have been intervals of water levels lower than the estimated 256 to 268 m when lakes were less extensive.

Landforms in western Waukesha County suggest that the Lake Michigan Lobe was shedding water and meltwater-stream sediment into the glacial Lake Scuppernong–Rock River watershed as the Green Bay Lobe margin retreated northward (Clayton, 2001). Once the Lake Michigan Lobe margin retreated east of the Kettle Moraine interlobate zone, that discharge was likely directed away from the glacial Scuppernong Valley–Rock River watershed and into drainages on the eastern side of the Kettle Moraine, such as the Fox River, or directly into what is now Lake Michigan.

Permafrost

Geomorphic evidence for permafrost conditions in Wisconsin includes relict ice-wedge casts and patterned ground (Mickelson and others, 1983; Attig and others, 1989; Johnson, 1990; Cutler and others, 2000). Recent dating of speleothems at Cave of the Mounds in Dane County, outside the Green Bay Lobe's extent, indicates permafrost conditions existed in southern Wisconsin between 30 and about 15 ka (Batchelor and others, 2019). Similarly, Attig and Rawling (2018) documented evidence for permafrost in the northern highlands of Wisconsin until around 13.5 ka.

Evidence for permafrost in Jefferson County includes ice-wedge polygons (plate 1), which occur in subglacial till (map units **gr** and **gs**) and are common in Pleistocene lake sediment (map units **lf** and **ln**), but do not occur in areas that were likely lakes into the middle Holocene (map unit **lo**). The presence of these features suggests that many lacustrine map unit areas were no longer underwater before 15 ka, when permafrost was still prevalent in southern Wisconsin. Another geomorphic feature not visible until high-resolution lidar-derived digital elevation models became available are parallel gullies common on drumlin slopes. The presence of the gullies suggests that at least discontinuous or perhaps continuous permafrost formed shortly after the deglaciation of Jefferson County.

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