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Late Cenozoic evolution of the lower Wisconsin River valley

Evidence for the reversal of the river

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Contents

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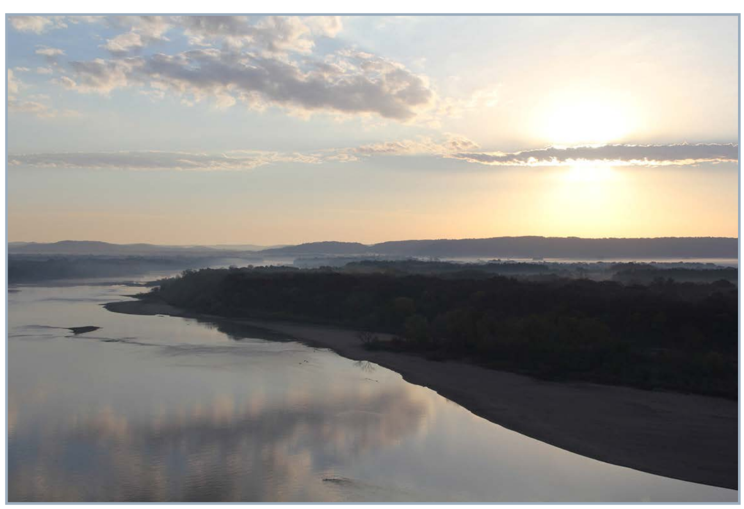
Introduction

The global-scale geomorphic impact of the succession of Quaternary glaciations is manifest, particularly in the high- and mid-latitude regions of northern hemisphere continents. In North America, landforms and landscapes that formed during the last glaciation (Marine Isotope Stage 2) extend into northern United States; deposits associated with older glaciations extend even farther south. As such, Quaternary glaciations have played a significant role in reconfiguring drainage patterns in these regions that evolved earlier in the Cenozoic. It has long been hypothesized that the modern Missouri River was rerouted—and today closely following the MIS 2 ice margin toward the southeast—from streams that initially flowed in a northerly direction toward the Arctic (e.g., Warren, 1868; Todd, 1902, 1914; Flint, 1949). Similarly, it has long been recognized that the modern Ohio River is a relatively recent construct, formed by diversion and piracy of streams that once flowed north into the St. Lawrence drainage into a southwesterly flowing tributary of the Mississippi drainage (e.g., Wright, 1890; Chamberlin and Leverett, 1894; White, 1896; Fowke, 1898; Tight, 1903; Leverett, 1934; Wayne, 1952). While many of these studies were based on the geomorphological record of drainage reorganization, additional studies can look at longer-timescale records of drainage diversion based on down-stream sedimentation. For example, the ancestral Bell River has been recognized as a late Oligocene and early Miocene conduit from the American Cordillera to the Labrador Sea near Baffin Island, in part based on pollen deposited in the Labrador Sea (Sears, 2013); and the sedimentary package in the Gulf of Mexico has been studied to evaluate continental-scale shifts in sediment supply—and therefore drainage organization—through the Cenozoic (Galloway and others, 2011).

The upper Mississippi watershed (upstream of the confluence of the modern Mississippi and Wisconsin Rivers) represents a major sub-basin of the greater Mississippi River system that has been significantly altered by Quaternary glaciations. The upper Mississippi and its major tributaries (fig. 1A) all cross the MIS 2 glacial margin, and exhibit the effects of multiple Quaternary glaciations on their geomorphology, planform (contours), and course (Warren, 1884; MacClintock, 1922; Hobbs, 1950). Buried bedrock valleys, modern streams underfit to the bedrock channels in which they flow, and river courses aligned to former ice margin positions are common features. Furthermore,



late Quaternary glaciations drove sequences of aggradation and incision, producing multiple depositional terraces throughout the basin (Flock, 1983; Knox, 1996). Most prominently, the Savanna and Bagley Terraces along the Mississippi River were graded to a higher elevation than the modern floodplain surface during MIS 2. While it has long been hypothesized that Quaternary glaciations have resulted in wholesale modifications of upper Mississippi basin drainage patterns (e.g., Martin, 1932; Baker and others, 1998), such discussions have previously lacked direct field-based evidence and have thus been largely conjectural. Much of this reflects that large portions of the upper Mississippi drainage were glaciated during the Quaternary.

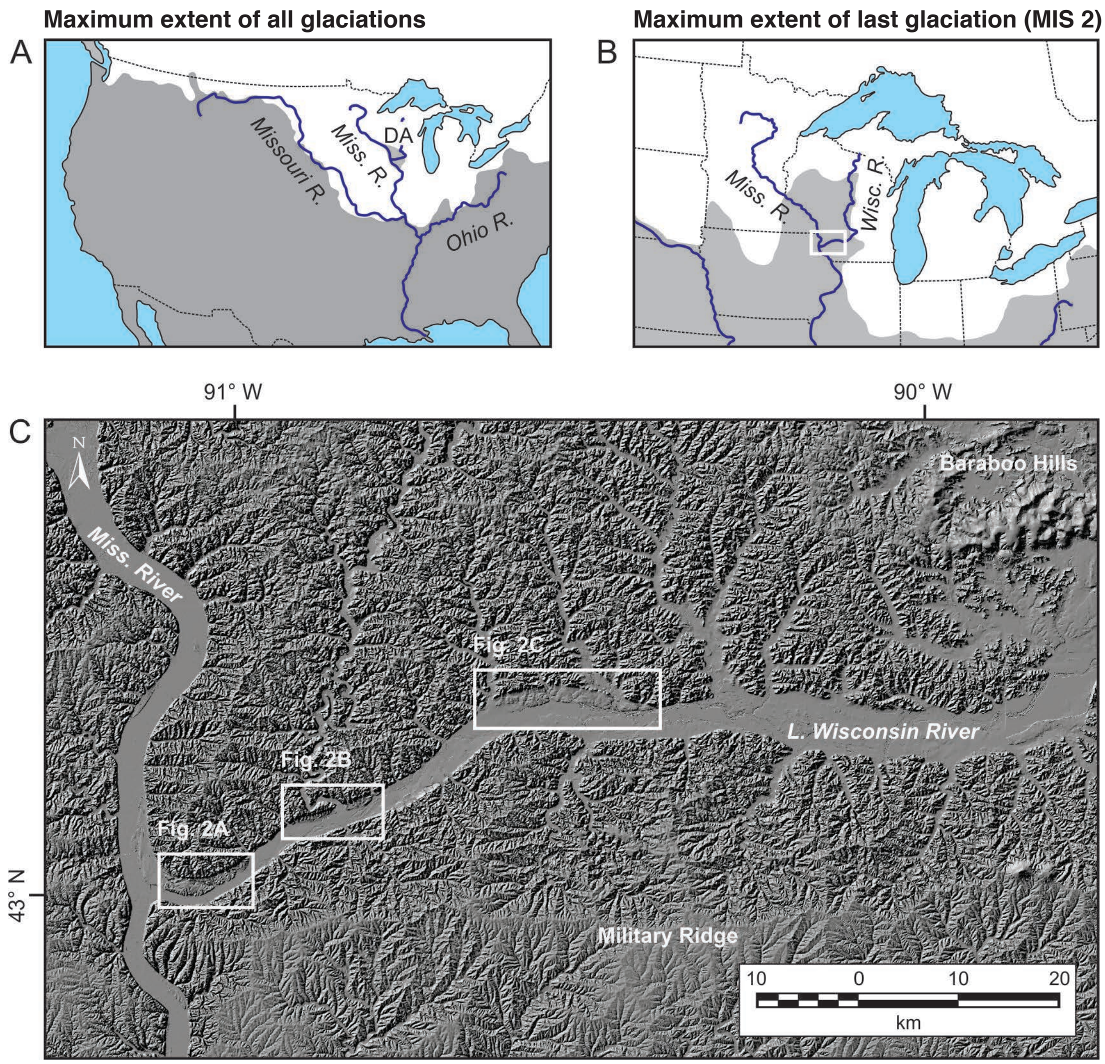


Figure 1. Location maps of study area. **A—Major tributaries** of the Mississippi River system in relation to the maximum extent of all Quaternary glaciations, shown in white. The unglaciated Driftless Area (DA) shown in upper Midwest. **B—Location** of the upper Mississippi River and Wisconsin River in relation to the maximum extent of MIS 2 glaciation, shown in white. **C—LiDAR-derived hillshade** image of the lower Wisconsin River valley and confluence with the Mississippi River. The three remnant segments of the Bridgeport strath are located within the white boxes, which identify areas of detailed maps in figure 2.

As opposed to the Missouri and Ohio Rivers, which occupy ice-marginal positions and flow sub-parallel to the MIS 2 ice margin, the Mississippi River and its major tributaries flow across a recently glaciated landscape. A notable exception is the lower Wisconsin River, which flows west across the unglaciated Driftless Area of southwestern Wisconsin to the confluence with the Mississippi River. Many of the geomorphological features that have been used to recognize drainage reorganization in unglaciated tributaries and reaches along the Missouri and Ohio Rivers can be applied along the lower Wisconsin River in the Driftless Area (fig. 1A).

Because it was not glaciated at any time during the Quaternary (Chamberlin, 1883; Alden, 1918; Martin, 1932; Mickelson and others, 1982), the Driftless Area contains a longer record of landscape evolution than any other portion of the upper Mississippi valley. This is underscored by the presence of the Bridgeport strath (bedrock) terrace, the sole example of a well-preserved strath terrace along a major river in the North American mid-continent. The lack of similar widespread features along other major unglaciated rivers in the mid-continent suggest that the lower Wisconsin River valley bears evidence of a unique geologic history with profound implications for understanding long-term drainage evolution of North America.

The Wisconsin River and lower Wisconsin River valley

The modern Wisconsin River is a tributary of the Mississippi River that drains approximately 32,000 km^2 in central Wisconsin (fig. 1B). The river originates in Lac Vieux Desert on the Wisconsin-Michigan state line, and flows south across previously glaciated northern Wisconsin and the Central Sand Plains. In south-central Wisconsin, the Wisconsin River flows around the east end of the Baraboo Hills, where it was dammed by MIS 2 ice of the Green Bay Lobe to form Glacial Lake Wisconsin (Clayton and Attig, 1989), and possibly also by earlier glaciations. Downstream of the Baraboo Hills, the Wisconsin River flows west through the unglaciated Driftless Area to its confluence with the Mississippi River; this portion of the river is informally referred to as the lower Wisconsin River.

No credible evidence indicates that the Driftless Area of southwestern Wisconsin was ever glaciated during the Quaternary (Chamberlin, 1883; Alden, 1918; Martin, 1932; Mickelson and others, 1982), dating to observations that were noted by several scientists and naturalists as early as the 1810s (p. 106–119 of Martin, 1932). The Driftless Area is bounded on the east by MIS 2 glacial deposits; on the south by MIS 6 glacial deposits; and on the north and west by older (middle to early Quaternary) glacial deposits. Because of the lack of Quaternary glaciation, the geomorphology of the Driftless Area is dominated by deep incision into the Paleozoic sedimentary strata, providing a record of fluvial landscape evolution in a mid-latitude cratonic setting that dates to pre-Quaternary time.

Bridgeport strath terrace

Reflecting the long record of landscape evolution preserved in the Driftless Area, the lower Wisconsin River is distinctive among major rivers in the North American mid-continent for containing remnants of a strath (bedrock) terrace (Knox and Attig, 1988). This surface, known as the Bridgeport terrace, is incised into Cambrian sandstone and is generally covered by 5–15 m of Quaternary sediment; the ground surface of the Bridgeport terrace ranges between 25 and 40 m higher than adjacent floodplains and depositional terraces. Three isolated remnants of the Bridgeport terrace occur along the lower Wisconsin River valley within about 70 km upstream (east) of the confluence of the Wisconsin and Mississippi Rivers (figs. 1C and 2), with a limited number of outcrops of the local bedrock demonstrating that the feature is, in fact, a strath terrace. Today, more than 50 m of late Quaternary sand and gravel fill the lower Wisconsin River valley. The bedrock surface of Bridgeport strath is as much as 70 m higher than the bedrock floor of the valley, testifying to the amount of incision that has occurred since the Bridgeport surface was abandoned as the active valley floor.

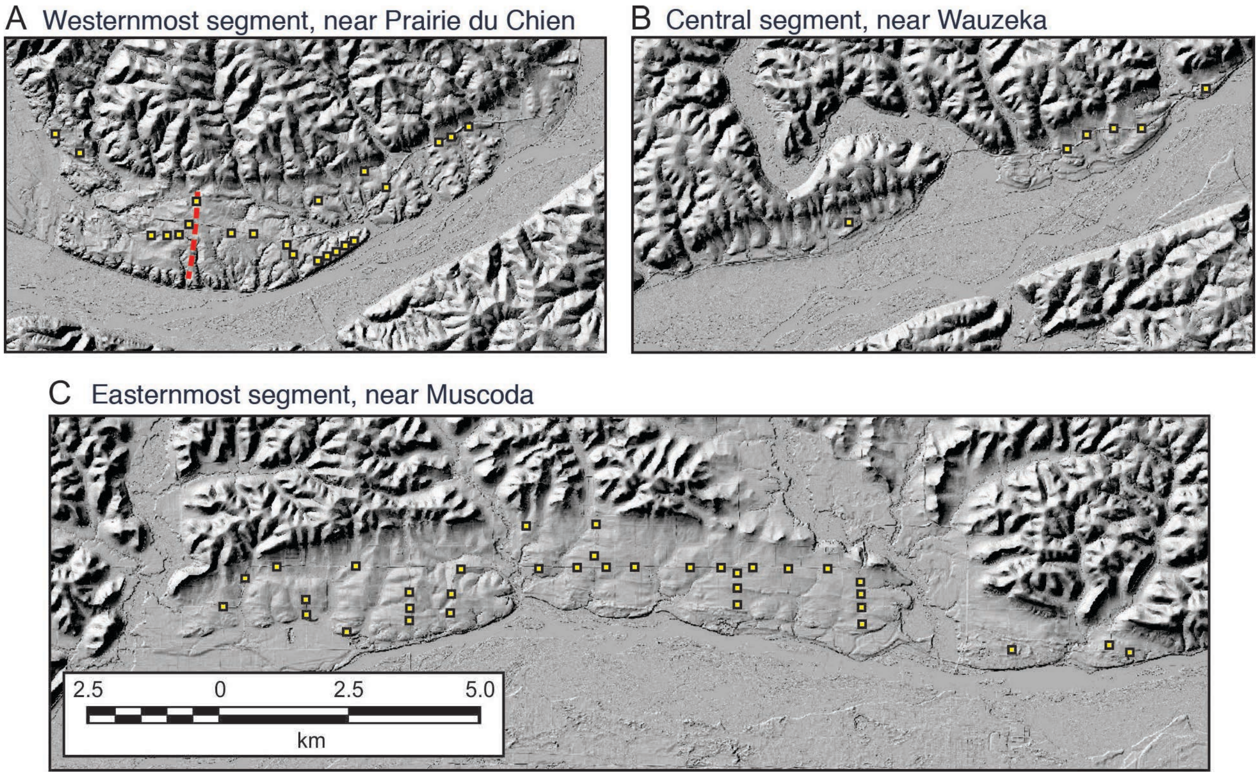


Figure 2. Detailed LiDAR-derived hillshade maps of the three remnant segments of the Bridgeport strath (map locations shown in fig. 1C). Yellow squares identify locations of Geoprobe coring to determine bedrock surface elevations. The Bridgeport moraine is marked by the red dashed line in A. All images are at the same scale.

Previous study of the Bridgeport strath has been limited. Knox and Attig (1988) identified a moraine approximately 5 km east of the confluence of the modern Mississippi and Wisconsin Rivers (fig. 2A), and sand and gravel on the Bridgeport strath that they interpreted to be outwash. The sand and gravel contains east-dipping foreset beds and a reversed remanent paleomagnetism; these deposits were interpreted to represent an advance from the west prior to about 760,000 years ago that blocked the mouth of the Wisconsin River and resulted in a temporary reversal of flow direction along the lower Wisconsin valley. Presumably, water would have spilled over a low point at some location behind the MIS 2 ice margin farther to the east to continue flowing to the Gulf of Mexico, although review of well records in south-central Wisconsin were unable to identify a buried bedrock valley of sufficient size and elevation to allow flow of Wisconsin River water to the south.

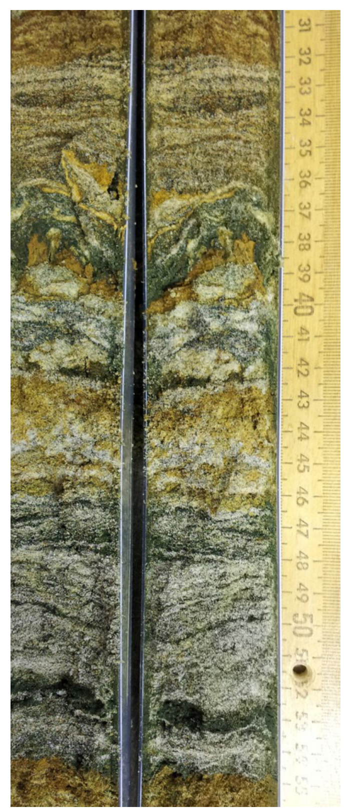
The interpretation that pre-Illinoian ice caused a temporary reversal of flow along the lower Wisconsin River valley was based upon the a priori assumption that the modern drainage pattern reflects the drainage system that carved the lower Wisconsin River valley (i.e., a westward-flowing river in the lower Wisconsin River valley) throughout the late Cenozoic. Alternatively, it is possible that modern drainage pattern does not reflect the drainage system that prevailed through the late Cenozoic. Numerous hypotheses for the organization of pre-Quaternary drainage of the mid-continent have been proposed. Martin (1932) suggested that drainage across the Driftless Area of southwestern Wisconsin was arranged with streams flowing to the southeast toward the modern Rock River of Illinois; Hobbs (1997) proposed that the entire upper Mississippi River system flowed north to the Arctic Ocean prior to the Quaternary; Baker and others (1998) hypothesized that the upper Mississippi River always flowed across several positions high on the modern landscape prior to major incision in its current position; and Cupples and Van Arsdale (2014) and Cox and others (2014) also argued that the upper Mississippi River has always flowed south, and included a drainage basin that extended as far north as the Arctic Circle during the Pliocene.

An intriguing, testable hypothesis for the pre-Quaternary incision of the lower Wisconsin River (and, by association, the upper Mississippi River) is that the initial incision of the modern lower Wisconsin River valley was accomplished by an eastward-flowing river that subsequently experienced a stream piracy event that permanently reversed flow to the westward direction of the modern lower Wisconsin River. The presence of the Bridgeport strath allows this hypothesis to be tested against all prior assumptions that the valley was carved by a westward-flowing river: since the strath surface represents a relict valley floor profile, it necessarily dips in the direction of flow at the time that the valley was incised to that level. A westward dip to the Bridgeport strath would indicate that the valley was carved under conditions similar to, and by a drainage network like, the modern Wisconsin River; an eastward dip to the Bridgeport strath would indicate that early incision of the lower Wisconsin River valley was accomplished at a time when the prevailing drainage network was radically different than that of today.

Reversal of the lower Wisconsin River

Identification of bedrock elevation at individual coring locations was completed using a combination of high-resolution LiDAR coverage of the study area to precisely identify ground-surface elevation and Geoprobe direct-push coring to precisely identify depth to bedrock. High-resolution LiDAR (Light Detection and Ranging) topographic imagery for Crawford, Grant, Iowa, Monroe, Richland, and Vernon Counties, Wisconsin, was collected in 2010 and 2011 using a matching grant provided by the Federal Emergency Management Agency. The data was processed to produce digital elevation models and shaded-relief imagery with 1.5 m grid squares. Elevation data for individual grid squares is estimated to be accurate to within about 5 cm (in the z-axis). Geoprobe coring drives a 1.75-in. (4.5-cm) sampling tube into the ground with direct hydraulic force. Samples are collected in successive 5-foot (152-cm) lengths. Total below-ground depth of coring can be measured to an accuracy of within about 2 cm.

A total of 59 Geoprobe cores were sited on the three segments of the Bridgeport strath (fig. 2). Core samples were split and described at



Geoprobe core
Cambrian sandstone

the Wisconsin Geological and Natural History Survey's Mt. Horeb Research Collection and Educational Center. The transition from unconsolidated Quaternary sediment to Cambrian bedrock was clearly identifiable due to the glauconite content of the local Tunnel City Group sandstone that forms the bedrock of the Bridgeport strath. In many cases, the Geoprobe coring penetrated 1 m or more into the Cambrian sandstone, allowing a precise measurement of depth from the ground surface to the bedrock strath surface. The combination of precise data for ground surface elevation and depth to bedrock allow estimation of elevation of the buried bedrock surface to within about 5 cm at each coring site. Experimentation at individual sites confirmed the ability to identify bedrock surface with a closed sampling tip (no sample collection, but quicker and less expensive drilling time) as well as with an open sampling tip; coring included a mix of the two sampling strategies. Eight cores did not penetrate to the bedrock surface, in most cases because the coring equipment was stopped by fine sand or compact clay. Bedrock elevation data was collected at the 51 remaining locations from the three remnant segments of the Bridgeport strath; the core locations span roughly 65 km along the length of the lower Wisconsin River valley.

As expected, individual coring sites reveal considerable variability below the trend line of the original strath surface owing to localized erosion of the strath following its abandonment. However, the general trend of the strath as resolved from the coring is that the surface dips to the east, in the opposite direction of flow of the modern Wisconsin River, with an estimated gradient of 0.15 m/km (fig. 3A). The gradient of the strath surface estimated from coring is consistent over a broad scale with many other mid-continent streams, and close to the gradients of the modern lower Wisconsin River floodplain and associated MIS 2 glacial outwash terraces. The inescapable conclusion to be drawn from the orientation of the strath is that the lower Wisconsin River valley was carved to the level of the Bridgeport strath by a river flowing to the east. Within the context of the westward-dipping late Quaternary surfaces in the lower Wisconsin River valley, the eastward dip of the Bridgeport strath stands in stark contrast (fig. 3B).

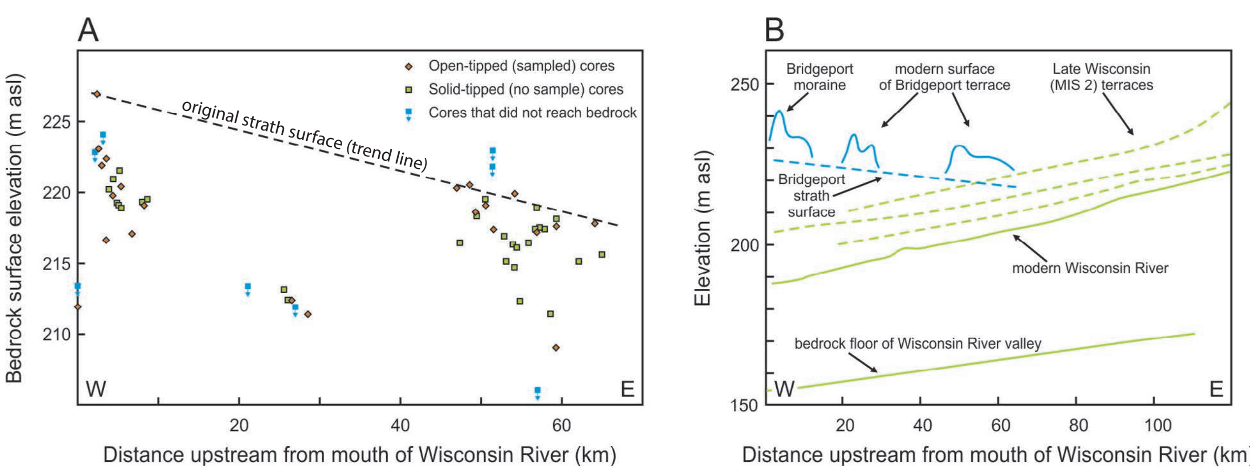


Figure 3. Results of Geoprobe coring to determine orientation of strath surface. **A—Elevation of strath surface** at each coring site as a function of distance upstream from the mouth of the Wisconsin River. The black dashed trend line represents the original strath surface, dipping to the east with an estimated slope of 0.15 m/km. **B—Bridgeport strath surface** (eastward-dipping dashed line) in relation to other major westward-dipping surfaces in the lower Wisconsin River valley. Early to middle Quaternary surfaces shown in blue; late Quaternary surfaces shown in green.

Geomorphology of the lower Wisconsin and Mississippi River valleys

Transformative events to the landscape should—and often do—leave indications of the previous conditions, and the geomorphology of the lower Wisconsin River valley contains several indications of having been formed by an eastward-flowing river. The following details, visible in figure 4, are etched in the landscape:

1. **Tributaries angle to the east.** The lower Wisconsin River valley, between the modern confluence with the Mississippi River and the MIS 2 glacial margin, has a large number of barbed tributaries—valleys that join the lower Wisconsin River valley angling to the east—as would be expected if they formed over time as tributaries to an eastward-flowing river (fig. 4A). Lacking an over-riding structural control, the presence of barbed tributary valleys has long been held as primary evidence of reversal of flow on the mainstem stream (e.g., Chamberlin and Leverett, 1894, p. 265).
2. **Tight curve of valley wall at confluence.** The curve of the valley wall at the inside (i.e., to the immediate northeast) of the confluence of the modern Mississippi and Wisconsin Rivers is inconsistent with having been incised as the confluence of two rivers (fig. 4B). Rather, it is consistent with being at the inside of a tight bend of a single river; numerous similar forms can be found along the insides of curves along the upper Mississippi and lower Wisconsin Rivers. In contrast, the valley wall on the inside of the confluence of two rivers much more typically comes to a point.
3. **Wisconsin River valley narrows from east to west.** The lower Wisconsin River valley narrows from east to west; this is incongruous for a westward-flowing river, as most river valleys broaden in the downstream direction (fig. 4B). While this could be attributed a control exerted by the local Paleozoic

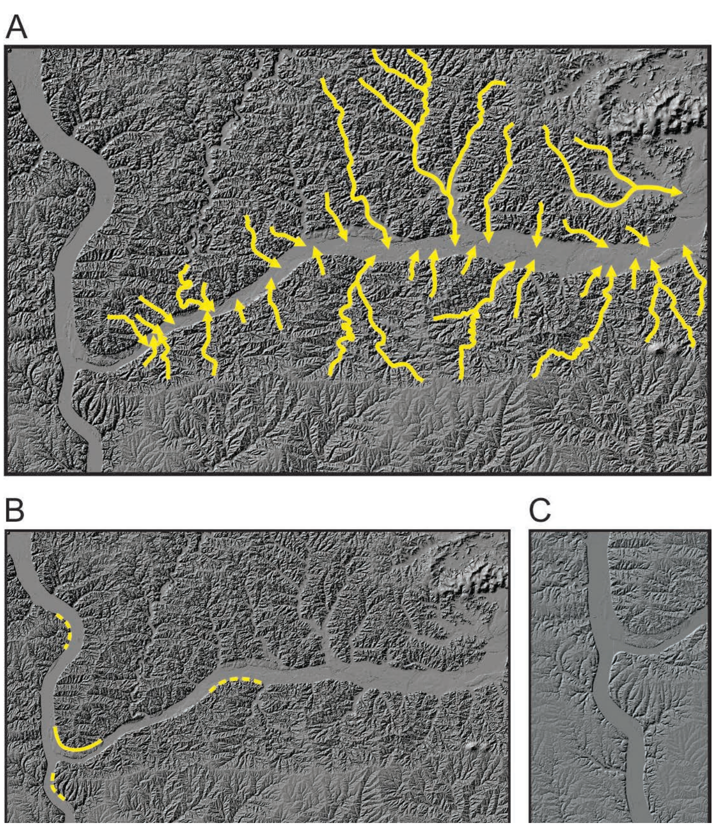


Figure 4. Geomorphological features of the lower Wisconsin River valley that indicate drainage reorganization has occurred.
A—Barbed tributaries. The Wisconsin River flows west, yet the majority of tributaries angle to the east where they join the river.
B—Curve of valley wall at confluence. The northeast wall at the confluence of the rivers has a smooth curved radius (solid yellow line) more similar to the inside of a bend on a single river (examples identified by dashed yellow lines) than a feature that evolved by bedrock incision at a confluence of two rivers. The narrowing of the river valley from east to west is another indicator that the Wisconsin River has changed direction.
C—Steep tributaries, narrowing river. Immediately downstream from its confluence with the Wisconsin River, the Mississippi River narrows and a series of unusually steep tributaries (locally known as "coulees") feed in, suggesting formation of this reach of the river during a period of intense, relatively recent incision.

strata, it also lends additional credence to the argument for a valley that was incised by an eastward-flowing river and subsequently reversed.

4. **Steep tributaries and narrow river after confluence.** The Mississippi River also contains a hallmark feature of stream piracy. The reach of the Mississippi River valley immediately south of its confluence with the Wisconsin River is distinctly narrow with short, steep tributaries (fig. 4C). The dissimilarity of these tributaries to other valleys throughout the region is so striking, in fact, that they are locally referred to by the etymologically distinct term 'coulee'. While these characteristics can be attributed to incision through the bedrock escarpment formed by Ordovician dolomites in the area, they are consistent with a stream that has experienced recent and pronounced down-cutting. Within the context of recognizing a major reversal on the nearby lower Wisconsin River valley, it should not be surprising that the Mississippi River valley contains geomorphic features that reflect such a significant reorganization of drainage patterns.

The ancestral Wyalusing River

Recognition of an eastward-flowing river occupying the modern lower Wisconsin River valley necessitates consideration of the larger drainage pattern required to achieve this configuration. We propose that a river we herein refer to as the 'Wyalusing River' developed through the late Cenozoic that followed the course of the

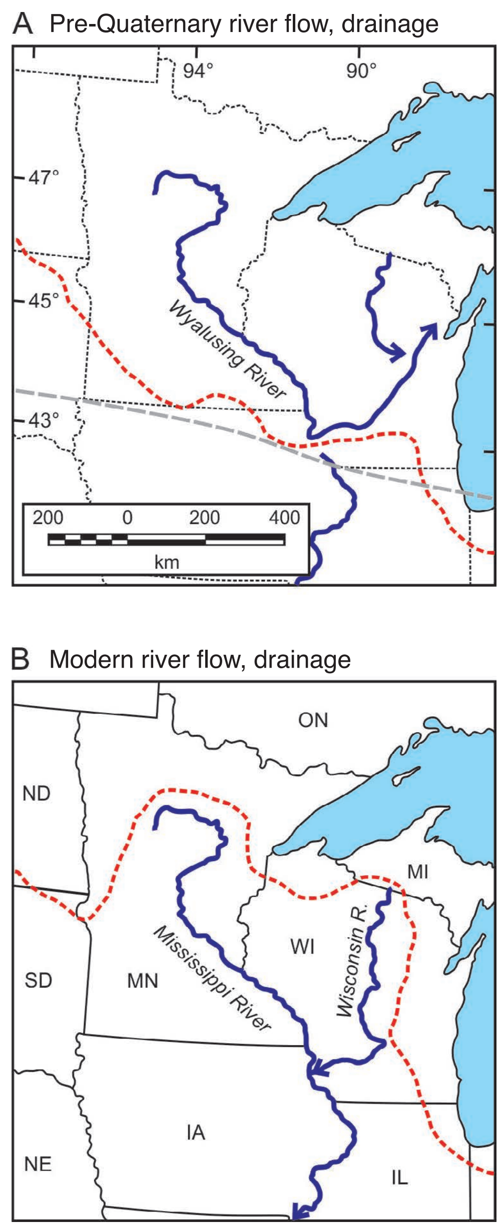


Figure 5. Organization of mid-continent drainage systems showing: **A—pre-Quaternary** ancestral Wyalusing River and **B—modern** upper Mississippi and Wisconsin Rivers. In both images, red dashed lines represent the continental drainage divide separating Gulf of St. Lawrence drainage from Gulf of Mexico drainage. The heavy gray dashed line in A represents continental drainage divide during the Pliocene as inferred from alluvial sedimentary packages in the Gulf of Mexico (Galloway and others, 2011).

modern uppermost Mississippi River to the point of its confluence with the Wisconsin River. At that location near Wyalusing State Park and the town of Wylausing, Wisconsin, rather than being joined by the Wisconsin River and continuing south as the modern Mississippi River does, the Wyalusing River turned to the east to flow along the modern lower Wisconsin River valley (fig. 5). The high, east-west trending ridge to the south of the lower Wisconsin River valley, known locally as Military Ridge (fig. 1C), is formed by the resistant Ordovician-age Galena and Platteville Formation dolomites; this bedrock structure forms a natural drainage impediment that would have preferentially directed the Wyalusing River in this direction rather than to the south. In such a configuration, the numerous barbed tributaries along the modern lower Wisconsin River are explained; the curve of the valley wall at the modern confluence of the Mississippi and Wisconsin Rivers is simply the inside of a bend in the Wyalusing River; and the width of the valley along this reach broadens in the downstream direction as would typically be expected. East of the MIS 2 glacial margin the buried valley formerly occupied by the Wyalusing River has been traced in well records as far northeast as Green Bay (Bates and Carson, 2014).

Late Cenozoic history of the Wyalusing River valley

The long-documented understanding of the evolution of the Ohio River system provides a consistent, unified framework for the Quaternary evolution of the Wyalusing River (draining to the Gulf of St. Lawrence) to the upper Mississippi River (draining to the Gulf of Mexico). The bedrock strath coring data and associated geomorphological features from the lower Wisconsin River valley presented in this research support the interpretation that the ancestral Wyalusing River evolved the late Cenozoic (prior to Quaternary glaciations) as a tributary of the St. Lawrence drainage (fig. 6A). At this point in time, the downstream continuation of the modern Mississippi River had not yet been incised; Military Ridge represents the continental drainage divide separating run-off to the north and east from run-off to the south.

The early Quaternary glaciers that advanced into the area were flowing in a southeasterly direction from the Canadian Cordillera, as confirmed both by local mapping (Knox and Attig, 1988; Carson and Knox, 2011) and by regional studies that have identified clasts in early Quaternary tills that are derived from Minnesota and the Dakotas (Baker and others, 1983; Johnson, 1986; Attig and Muldoon, 1989; Attig, 1993; Ham and Attig, 1997; Syverson, 2007). A glacial advance from the northwest (fig. 6B) would be associated with the deposition of the Bridgeport moraine and associated sand and gravel deposits in the lower Wisconsin River valley that contain eastward-dipping foreset beds (Knox and Attig, 1988). Knox and Attig (1988) originally hypothesized that the eastward-dipping beds represent a temporary reversal of flow along the lower Wisconsin River; the scenario presented here simply represents outwash being carried eastward along the course of the eastward-flowing Wyalusing River. The significance of this distinction is that eastward-dipping sand and gravel foresets have been described as much as 60 km east of the Bridgeport moraine. The transport and deposition of sand and gravel that distance is difficult to reconcile with ponded water and a flow reversal as had originally been hypothesized; however, it is consistent with the Wyalusing River being a braided outwash stream as a result of having its headwaters glaciated.

During the multiple interglacials during the early and middle Quaternary, the Wyalusing River valley would have reverted to its pre-Quaternary organization as an eastward-flowing tributary of the St. Lawrence drainage basin (fig. 6C). However the distribution of glacial deposits across North America indicates that glaciations during the middle and late Quaternary featured an increasing component of ice derived from Hudson Bay lowlands. Certainly, MIS 6 (Illinoian) and MIS 2 (Wisconsin) glacial deposits in Wisconsin are derived from the northeast, rather than from the west or northwest as is

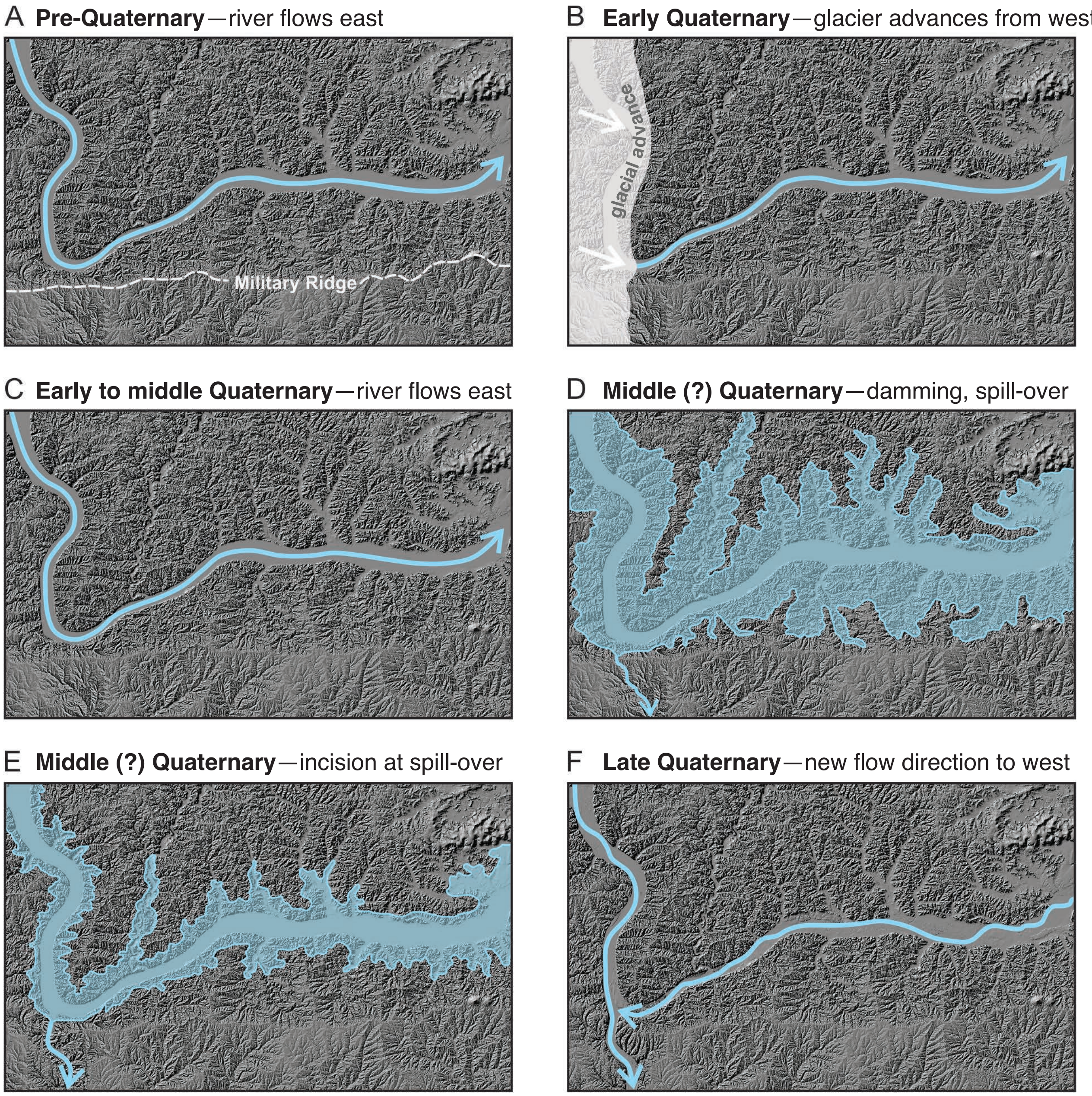


Figure 6. Proposed time series for the processes that drove stream piracy and conversion of the ancestral Wyalusing River to become the modern upper Mississippi River (all images show same area). **A—Pre-Quaternary,** proposed configuration of the ancestral Wyalusing River with the river flowing to the east. **B—Early Quaternary,** glaciers advance into area from the west, depositing the Bridgeport moraine and associated outwash sediments (Knox and Attig, 1988). **C—Early to middle Quaternary,** the Wyalusing River continues to flow eastward during this interglacial period. **D—Middle (?) Quaternary,** glaciation causes damming of the St. Lawrence River valley, driving formation of a lake in the Wyalusing River valley; the lake would have filled until it spilled over the lowest point at the drainage divide and initiated southward flow of water. **E—Middle (?) Quaternary,** dammed water in the Wyalusing River valley would have created an incision at the spill-over point; once a channel had cut through the resistant Ordovician carbonates that form Military Ridge, the underlying relatively weak Cambrian sandstones would have been eroded to establish a permanent drainage pattern to the south as part of the Mississippi River drainage to the Gulf of Mexico. **F—Late Quaternary,** incision adjusted to new base level would have left the Wyalusing River surface stranded as the Bridgeport strath terrace; the modern Wisconsin River finally occupies the valley flowing to the west as a tributary of the Mississippi River.

the case with early Quaternary glacial deposits (Frye and others, 1969; Fricke and Johnson, 1983; Need, 1985; Clayton and Attig, 1997; Mickelson and Syverson, 1997; Clayton, 2001; Hooyer and Mode, 2008; Carlson and others, 2011; Clayton, 2013). As a result, likely by the middle Quaternary glacial episodes, glacial ice derived from the Hudson Bay region had begun to advance far enough south to block the lower portions of the St. Lawrence drainage, advancing as far south as southern Illinois, Indiana, and Ohio by MIS 6. Glaciation of the lower St. Lawrence valley would have dammed any of the northward flowing tributaries of that drainage, including the Wyalusing River (fig. 6D). During this time interval, the ancestral Pittsburgh River was dammed to form Glacial Lake Monongahela in western Pennsylvania and West Virginia (White, 1883, 1896; Chamberlin and Leverett, 1894; Leverett, 1934; Gillespie and Clendening, 1968), which eventually spilled over a drainage divide near New Martinsville, West Virginia. Subsequent incision and stream piracy rerouted the river to the southwest as the upper Ohio River portion of the greater Mississippi River drainage. The ancestral Teays River was likewise dammed to form Glacial Lake Tight in southern Ohio and West Virginia (Wright, 1890; Tight, 1903; Happ, 1934; Stout and others, 1943; Norris and Spicer, 1958; Rhodehamel and Carlston, 1963). The ancestral Teays River system was quite possibly diverted earlier in the Quaternary to occupy the now-buried Teays-Mahomet valley in Indiana and Illinois (Gray, 1991), but was certainly diverted by spill-overs at drainage divides near Manchester, Ohio, and Madison, Indiana. Subsequent incision and stream piracy rerouted the river to southwest to become the central Ohio River portion of the greater Mississippi River drainage. Slackwater sediments from both glacial Lake Monongahela and glacial Lake Tight have a reversed paleomagnetism, demonstrating that the damming which drove the stream piracy events along the modern Ohio River occurred prior to about 760,000 years ago. Similarly, blockage of the St. Lawrence drainage impounded a lake along the Wyalusing River valley which would have filled until it spilled over the lowest drainage divide (fig. 6D). The tight bend in the Wyalusing River depicted in figs. 6A–D represent a reasonable location for the lowest drainage divide from the combined result of incision along the outside of the bend on the Wyalusing River to the north of the drainage divide and headward erosion of a south-flowing stream to the south of the drainage divide.

Once the new flow path toward the south had eroded through the resistant Ordovician dolomites, the relatively poorly lithified sandstones of the Cambrian-age Trempealeau, Tunnel City, and Elk Mound Groups would have permitted rapid incision to permanently establish southward flow (fig. 6E). Formation of this stretch of the modern Mississippi River immediately south of its confluence with the modern Wisconsin River pirated all upstream water toward the Gulf of Mexico, and caused a reversal of flow to a westward direction along the lower Wisconsin River valley. At some time following establishment of the southward flow toward the Gulf of Mexico, the modern westward-flowing Wisconsin River would have occupied the valley originally incised by the eastward-flowing Wyalusing River (fig. 6F). Subsequent incision along the upper Mississippi and lower Wisconsin River valleys during adjustment to the new base level left remnants of the Bridgeport erosion surface stranded as a terrace along the lower Wisconsin River valley, and provided the accommodation for the thick late-Quaternary alluvial fill now found in the upper Mississippi and lower Wisconsin River valleys.

Larger implications

While the conversion of the ancestral Wyalusing River basin (draining to the Gulf of St. Lawrence) into the upper Mississippi and Wisconsin River basin (draining to the Gulf of Mexico) is a new interpretation for the region, it is not unique in North America (fig. 7). It has long been recognized that the upper Ohio River was created by glacially driven piracy of the north-flowing ancestral Pittsburgh River (e.g., Chamberlin and Leverett, 1894; Leverett, 1934; Stout and others, 1943). Similarly, the middle Ohio River was created by diversion of the ancestral Teays River (e.g., Tight, 1903; Stout and others, 1943; Horberg, 1945). While some would argue that the Teays River developed prior to Quaternary glaciations as a tributary of the Mississippi River system via the Mahomet River valley, circumstantial evidence suggests that it is more likely that the Teays River drained to the Gulf of St. Lawrence in pre-Quaternary time (Bleuer, 1991; Gray, 1991). Combined, the ancestral Wyalusing, Pittsburgh, and Teays River basins represent 14.7 percent of the drainage area of the modern Mississippi River basin, and those areas contribute 26.7 percent of the mean annual discharge of the Mississippi River (Carson and others, 2014). This suggests the magnitude of the discharge delivered to the Gulf of St. Lawrence in pre-Quaternary time that has been diverted to the Gulf of Mexico by the effects of Quaternary glaciations in North America.

Acknowledgments

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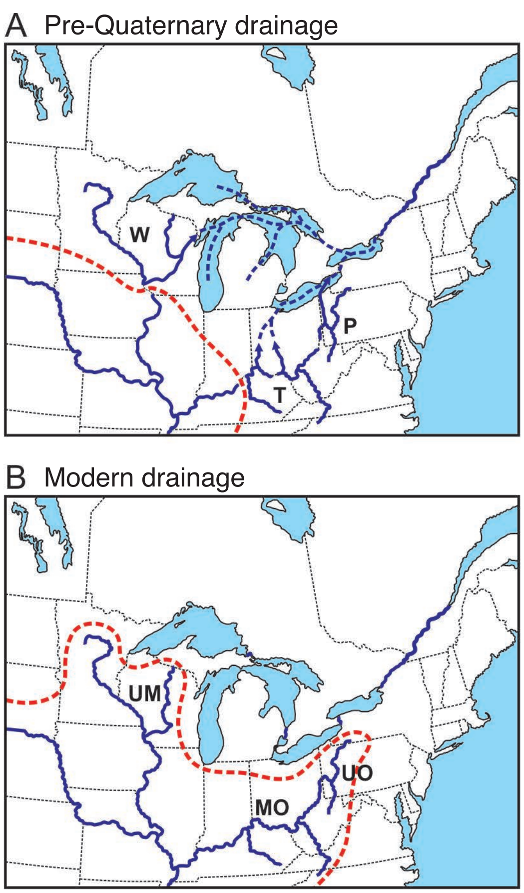
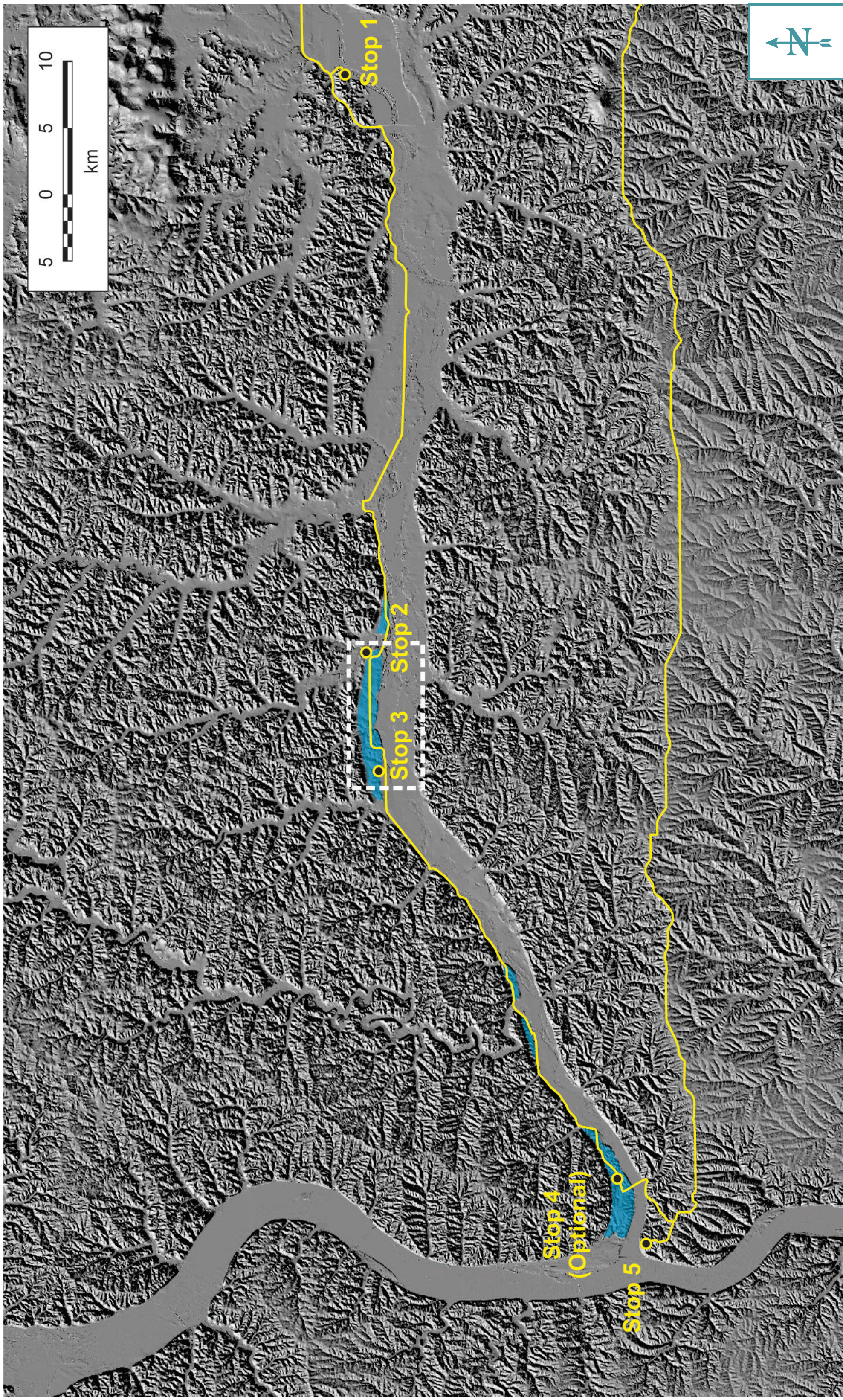


Figure 7. Organization on North American mid-continent rivers. **A**—**Pre-Quaternary** drainage systems showing the ancestral Wyalusing (W), Teays (T) and Pittsburgh (P) Rivers as tributaries of the St. Lawrence drainage system.
B—**Modern** drainage systems showing the Upper Mississippi (UM), Middle Ohio (MO) and Upper Ohio (UO) Rivers as tributaries of the Mississippi River. In both images, red dashed lines represent the continental drainage divide separating Gulf of St. Lawrence drainage from Gulf of Mexico drainage.



ROAD LOG

The **starting point** for the road log is the Wisconsin Geological and Natural History Survey, 3817 Mineral Point Road, Madison, Wisconsin, 53705. This map shows general locations of the field trip stops.

Figure 8. Field trip route, showing same areas as figures 1C, 4, and 6. Field trip stops are labeled as black dots, the driving route is shown by the yellow line, Bridgeport strath terraces are shown in blue, and the area shown in figure 10 is indicated by the white dashed box.

STOP 1 Ferry Bluff overlook and the Wisconsin River valley

Ferry Bluff State Natural Area spans the entirety of the Cambrian succession of sandstones. The Wonewoc Sandstone outcrops near river level, the less-resistant Tunnel City Group does not prominently outcrop, and the Jordan Sandstone caps the local bluffs. The Paleozoic bedrock in southwest Wisconsin dips gently to the southwest as it comes off the Wisconsin Arch; because of this, the Wonewoc Sandstone and Tunnel City Group sandstones are at or near river level the entire length of the Wisconsin River from Ferry Bluff to Pairie du Chien, Wisconsin. From the parking area near river level, follow the marked trail that leads up the hill to Cactus Bluff for an overlook of the lower Wisconsin River valley.

Getting to **STOP 1 / FERRY BLUFF**

DISTANCE	TRIP TOTAL	DIRECTIONS
0.0	0.0	Drive west on Mineral Point Road
4.2	4.2	Turn right (westbound) onto Hwy 12, Beltline
21.9	26.1	Turn left (westbound) onto Hwy 60
4.3	30.4	Turn left onto Ferry Bluff Road
1.1	31.5	Drive to end of Ferry Bluff Road, parking area for Ferry Bluff S.N.A.

From the MIS 2 ice margin just east of Sauk City, Wisconsin, to the confluence with the Mississippi River, the Wisconsin River flows west across the Driftless Area in the deeply incised lower Wisconsin River valley. From valley wall to valley wall, the lower Wisconsin River valley is as much as 6 km wide near Ferry Bluff (Stop 1), and progressively narrows downstream to as little as 2 km wide near the confluence with the Mississippi River at Prairie du Chien (Stop 4). The river channel averages 1,000 to 2,000 m wide and meanders irregularly from one side of the valley to the other. The channel splits and rejoins to form both temporary sandbars and semi-permanent wooded islands. Numerous late Wisconsin depositional outwash surfaces have been mapped along the lower Wisconsin River valley (Clayton and Attig, 1990, 1997; Carson, 2012). The bedrock floor of the lower Wisconsin River valley is incised as much as 100 m below the modern floodplain surface; the valley has been filled with sand and gravel associated with presumably late Wisconsin glaciations (Carson and others, 2015; Ceperley and others, 2015).

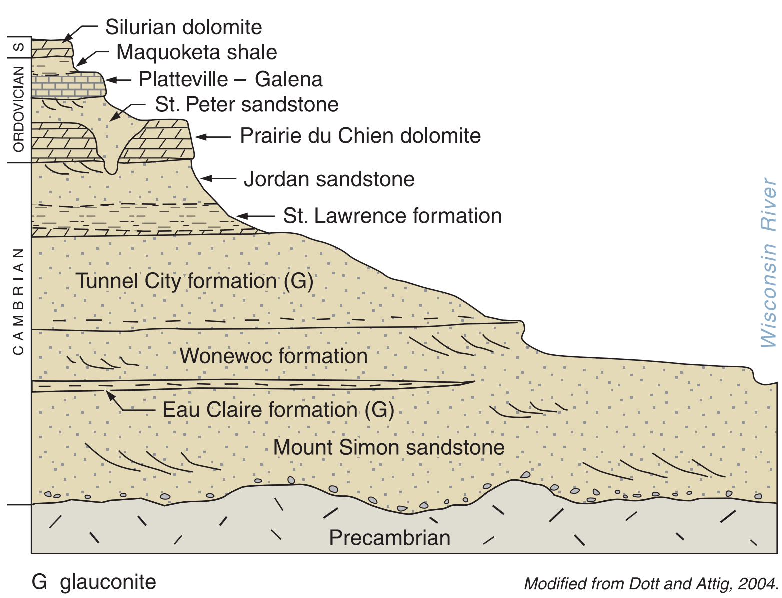


Figure 9. Paleozoic strata exposed in the Driftless Area in southwestern Wisconsin, showing general outcrop appearance of various formations. The contact between the Cambrian Wonewoc sandstone and Tunnel City Group sandstone is near the modern level of the Wisconsin River for the entire distance between Ferry Bluff (Stop 1) and the confluence with the Mississippi River (near Stop 4). Military Ridge to the south of the lower Wisconsin River valley is capped by the Ordovician Platteville and Galena dolomites.

STOP 2 Shadewald Mounds and overlook of Muscoda segment of Bridgeport strath terrace

Shadewald Mound Group (also known as the Elder Group) is a series of pre-historic effigy mounds on hilltops immediately on either side of Highway 193. On the hill to the east of Highway 193 are several animal effigies, including an eagle and a bison; the hill to the west of Highway 193 has 12 conical mounds arrayed in a line. The land was purchased, managed, and preserved by the late Frank Shadewald.

Looking west from the mounds will give a view along the length of the easternmost of the three preserved segments of the Bridgeport strath terrace. Highway 60 can be seen running east–west along the length of the terrace. During the summer of 2013, a total of 31 Geoprobe cores were collected from this segment of the terrace to identify depth to the bedrock strath. Unconsolidated Quaternary sediment ranged between 2.7 and 15.0 m thick on top of the glauconitic Tunnel City Group sandstone that forms the bedrock surface of the strath. Geoprobe cores from this segment of the strath terrace include a mix of aeolian, fluvial, and possibly lacustrine sediment.

Approximately 3 km southwest of Shadewald Mounds is the Bock site described in Knox and Attig (1988). While heavily overgrown now, this site formerly was a sand and gravel quarry in the MIS 2 depositional terrace immediately south of the Bridgeport terrace. Excavation in the quarry extended far enough north to expose the face of the Tunnel City Group sandstone that forms the strath surface and the overlying Quaternary sediment. Knox and Attig (1988) documented sedimentary structures at various scale (ripple marks to foreset beds) consistent with eastward flow of water during time of deposition.

Getting to **STOP 2 / SHADEWALD MOUNDS**

DISTANCE	TRIP TOTAL	DIRECTIONS
0.0	31.5	Drive north on Ferry Bluff Road
1.1	32.6	Turn left (westbound) onto Hwy 60
14.9	47.5	Turn right (westbound) onto Hwy 14/60 at Spring Green
11.9	59.4	Turn left (westbound) onto Hwy 60 at Gotham
9.9	69.3	Turn right (northbound) onto Hwy 193
0.1	69.4	Park at Shadewald Mounds

STOP 3 Bridgeport strath core and Prairie Sand and Gravel Blue Mound Pit

The Coumbe Cemetery site is one of the locations that has been cored to identify bedrock surface for the strath. The site is located at the extreme southern edge of the Bridgeport strath. The approaching road traverses the MIS 2 depositional terrace between Highway 60 and the base of the strath terrace scarp, then curves up onto the strath terrace surface; the Prairie Sand and Gravel Blue Mound Pit is located in the MIS 2 depositional terrace immediately at the base of the strath terrace scarp.

Getting to **STOP 3 / BRIDGEPORT STRATH**

DISTANCE	TRIP TOTAL	DIRECTIONS
0.0	69.4	Drive south on Hwy 193
0.1	69.5	Turn right (westbound) onto Hwy 60
6.8	76.3	Turn right (north) onto Coumbe Cemetery Lane
0.2	76.5	Park at Coumbe Cemetery

The surface of the strath terrace is 8.5 m above the surface of the adjacent depositional terrace. Coring at the site (including the core displayed) documents that the bedrock surface of the strath is 3.7 m below ground surface (4.8 m above the surface of the adjacent MIS 2 depositional terrace). Visual inspection of the sand and gravel quarry shows that material has been excavated to at least 10 m depth on the depositional terrace.

This core also demonstrates the ability of the Geoprobe cores to penetrate into the friable, glauconitic sandstone of the Tunnel City Group. The glauconitic mineralogy of the Tunnel City Group allows for precise documentation of the contact between Cambrian sandstone and overlying unconsolidated Quaternary sediment.

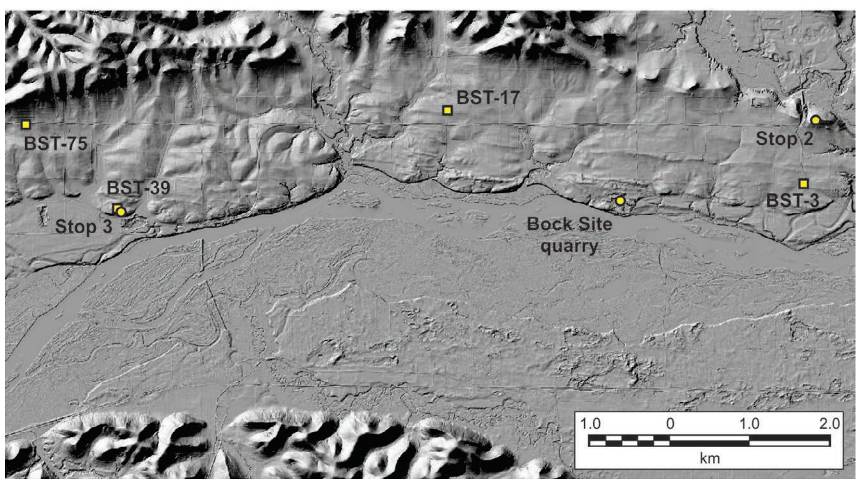


Figure 10. General area of Stops 2 and 3. Bridgeport strath terrace near Muscoda, Wisconsin, showing stop locations, the Bock Site quarry, and locations of core samples displayed at Stop 3.

STOP 4 Outcrop of Tunnel City Group sandstone (optional stop)

This optional stop is one of at least four locations where the Tunnel City Group sandstone is exposed in roadcuts along Highway 60. On the north shoulder of the highway is an outcrop exposed by excavation for the road bed. While significantly overgrown, the bedrock is still easily visible. The exposure occurs immediately west of where a small creek (draining from Tucker Hollow) has incised deeply into the strath terrace. At this location, near the mouth of the Wisconsin River, the exposure of bedrock is approximately 23 m above adjacent river level.

Getting to **STOP 4 / TUNNEL CITY OUTCROP**

DISTANCE	TRIP TOTAL	DIRECTIONS
0.0	76.5	Drive south on Coumbe Cemetery Lane
0.2	76.7	Turn right (westbound) onto Hwy 60
7.0	83.7	Turn left (westbound) onto Hwy 60/61
1.2	84.9	Continue straight (westbound) on Hwy 60
10.2	95.1	Turn right onto N. Business St. in Wauzeka to continue on Hwy 60
0.1	95.2	Turn left onto Guard St. in Wauzeka to continue on Hwy 60
9.2	104.4	North shoulder of Hwy 60

Geoprobe tip / Tunnel City Group sandstone

STOP 5 Wyalusing State Park and overlook of Wisconsin and Mississippi River valleys

The overlook area at Wyalusing State Park provides a view of the confluence of the Wisconsin and Mississippi Rivers. Looking north provides an upstream view of the Mississippi River and the town of Prairie du Chien, Wisconsin. Prairie du Chien is sited next to the Mississippi River on the Savanna terrace (Flock, 1983; Knox, 2003). Looking northeast and east provides an upstream view of the Wisconsin River and Bridgeport strath terrace. The significant elevation difference between the Savanna terrace and Bridgeport terrace is easily seen. Less easily identified, but still present is the (pre-Illinoian) Bridgeport moraine, located west of the intersection of Highway 60 and Highway 18/35.

A total of 21 Geoprobe cores and one rotosonic core were collected from this segment of strath to identify depth to bedrock; six of the cores collected on this segment of the strath are higher than the highest bedrock elevation from the segment of the strath near Muscoda.

This site is also near several salient features associated with the interpretation of the course of the ancestral Wyalusing River and reversal of flow (see fig. 4 and related discussion in the text of the guidebook). Primarily, the curve of the valley wall visible opposite Wyalusing State Park (north of the Bridgeport strath and east of the town of Prairie du Chien) is inconsistent with the confluence of two rivers; rather, we interpret it to have formed as the inside of a tight bend on the Wyalusing River, which flowed south along the modern Mississippi River valley (toward the overlook at Wyalusing State Park) and then made a tight turn to the left and flowed east along the lower Wisconsin River valley (away from the overlook at Wyalusing State Park).

Getting to **STOP 5 / WYALUSING STATE PARK**

DISTANCE	TRIP TOTAL	DIRECTIONS
0.0	104.4	Continue west on Hwy 60
1.8	106.2	Turn left (southbound) onto Hwy 18/35
1.3	107.5	Turn right (westbound) onto Cty C
3.1	110.6	Turn right (westbound) onto Cty X
1.0	111.6	Turn right onto State Park Lane at Wyalusing State Park
1.8	113.4	Drive to parking lot at Wisconsin Ridge Campground area

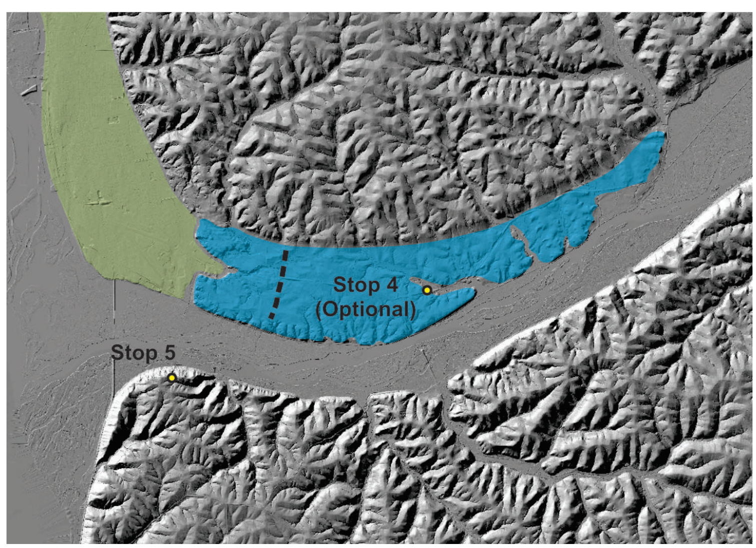


Figure 11. General area of the final two stops. Stop 5 overlooks confluence of Wisconsin and Mississippi Rivers at Wyalusing State Park. Bridgeport strath terrace shown in blue shading (Stop 4); Savanna terrace (MIS 2, depositional) shown in green shading. Dashed black line shows location of pre-Illinoian Bridgeport moraine (Knox and Attig, 1988).

Returning to **MADISON / WISCONSIN GEOLOGICAL SURVEY**

DISTANCE	TRIP TOTAL	DIRECTIONS
0.0	113.4	Drive south on State Park Lane
1.8	115.2	Turn left (eastbound) onto Cty X
2.7	117.9	Turn left (eastbound) onto Cty P
4.9	122.8	Turn right (eastbound) onto Hwy 18/35
0.2	123.0	Continue straight (eastbound) on Hwy 18 near Patch Grove
17.0	140.0	Turn right onto Lincoln St. in Fennimore to continue on Hwy 18
0.5	140.5	Turn left onto 12th St. in Fennimore to continue on Hwy 18
11.7	152.2	Continue straight (eastbound) on Hwy 18/80 in Montfort
5.0	157.2	Continue straight (eastbound) on Hwy 18 in Cobb
11.6	168.8	Take eastbound on-ramp to Hwy 18/151
38.0	206.8	Continue straight as Hwy 18/151 turns into S. Midvale Blvd. at Beltline
1.7	208.5	Turn right onto Mineral Point Road
0.6	209.1	Wisconsin Geological and Natural History Survey on right

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