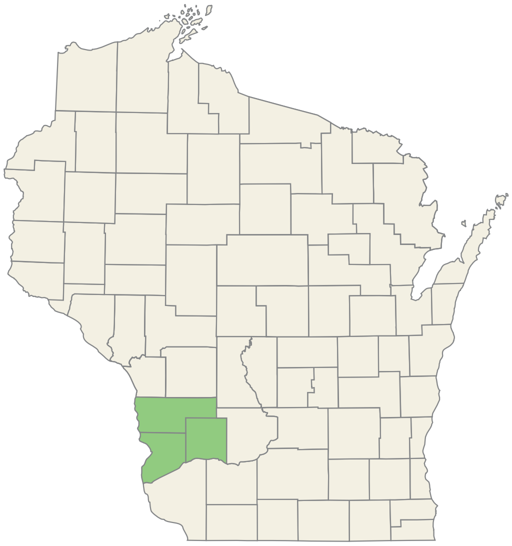

CRAWFORD, RICHLAND, & VERNON COUNTIES

Quaternary Geology of Crawford, Richland & Vernon Counties, Wisconsin

MAP 513–SUPPLEMENT • 2025

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Contents

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Introduction

This supplementary report is intended to provide insight into the mapping decisions and map units that were developed for 1:100,000-scale surficial geologic mapping in the Driftless Area of southwestern Wisconsin, focusing on features represented in Crawford, Richland, and Vernon counties. The so-called 'Driftless Area' represents a region of slightly less than 26,000 sq. km (~10,000 sq. mi.) in southwest Wisconsin and northwestern-most Illinois that was never covered by ice during any of the Quaternary glaciations of the last 2.58 million years (Carson and others, 2023). While this supplementary report is published as part of the *Quaternary Geology of Vernon County* 1:100,000-scale map, the observations and examples herein apply to and are drawn from Crawford (Carson and Christensen, 2025a) and Richland counties (Carson and Christensen, 2025b) as well due to their similar geomorphology.

Crawford, Richland, and Vernon counties represent a single contiguous area in the Driftless Area immediately to the north of the lower Wisconsin River and to the east of the Mississippi River (fig. 1). Since 2009, the Driftless Area has been the focus of a concerted surficial geologic mapping program at the Wisconsin Geological and Natural History Survey (WGNHS) that will produce new 1:100,000-scale maps that will represent this unglaciated terrain using a holistic set of geologic map units; a unified mapping philosophy and level of mapping detail; and seamless mapping from county to county.

As with the entirety of the Driftless Area, the dominant landscape-forming process in the study area is fluvial incision in the nearly flat-lying Paleozoic sedimentary bedrock (fig. 2). The single defining characteristic of the three-county study area is deep fluvial incision in a dendritic, or branching, pattern. Local relief from floodplain to ridgetop is as much as 115 m (375 ft) on both the main stem streams and the lower reaches of tributaries. The reaches of the Mississippi and lower Wisconsin Rivers immediately bordering the study area are incised as much as 60 m (200 ft) below modern floodplain level, with the valleys subsequently filled with sand and gravel to reach the modern morphology. The collection of both shallow (direct-push) and deep (rotosonic) sediment cores in the study area has demonstrated that the lower reaches of tributary streams are similarly incised and filled with alluvial (meaning, they are deposited by running water) sediments. The deep valley of the Kickapoo River extends north-northeast to south-southwest across Vernon and Crawford counties and extends north in Monroe County. Notably, compared to all other tributary streams in the study area and most other such streams in the Driftless Area, the lower portion of the Kickapoo River exhibits a distinct meandering pattern of the valley that is incised into the bedrock. Streams in the western portion of the study area are notoriously steep and narrow, often locally referred to as 'coulees'.

In the western portion of the study area (western Crawford and Vernon counties, principally west of the Kickapoo River), expansive flat upland areas exist supported by resistant bedrock units. Headwaters of tributaries extend onto the upland surfaces but do not completely bisect the uplands. Farther to the east (east of the Kickapoo River), the entire landscape is emplaced lower in the bedrock stratigraphic section. This results in greater dissection of the landscape, and fewer and less extensive flat uplands. Headwater incision into the uplands is more profound, thus forming a series of relatively narrow ridges in the eastern portion of the study area as the highest topographic features.

Figure 1. Study area of Crawford, Richland, and Vernon counties in southwest Wisconsin and surrounding counties. The eastern boundary of the Driftless Area is marked in dark green (Carson and others, 2023).

Methods

All mapping was conducted digitally in a Geographic Information System (GIS) setting. Preliminary interpretations were based on examination of infrared aerial photographs, water well records (WGNHS, unpub. data, 2017), available county soil surveys, digital elevation models, and hillshade maps derived from high-resolution (1.5-m grid square) lidar data (State Cartographer's Office, 2017). Initial mapping interpretations were further refined by field observation and verification of landscapes and mapping. Subsurface data were collected by direct-push and rotosonic coring.

Sediment coring

Sediment core collection and interpretation are integral components of surficial geologic mapping by providing information regarding sediment at depth. Sediment cores validate mapping decisions made based on surface morphology, help to refine map unit descriptions, and provide material for radiocarbon dating. Two methods of sediment coring have been employed in this mapping: direct-push (Geoprobe Systems, Salina, Kan.) and rotosonic coring.

Direct-push coring retrieves a 4.5-cm (1.75-inch) diameter sediment core in a clear polycarbonate liner. Coring is accomplished with direct percussion and hydraulic retrieval of cores 152 cm (5 ft) in length, with subsequent cores retrieved from the same hole as the initial core. Maximum depth achieved with this coring method in the Driftless Area is approximately 27.4 m (90 ft), although typically the quality of core retrieval declines deeper than ~15 m (50 ft). Cores often penetrate to the bedrock surface, although in settings with weathered and/or friable sandstones coring has penetrated 1 to 2 m (3.3 to 6.6 ft) into the bedrock.

Figure 2. Basic physical geography and geomorphology of Crawford, Richland, and Vernon counties highlighting the deep fluvial dissection of the landscape.

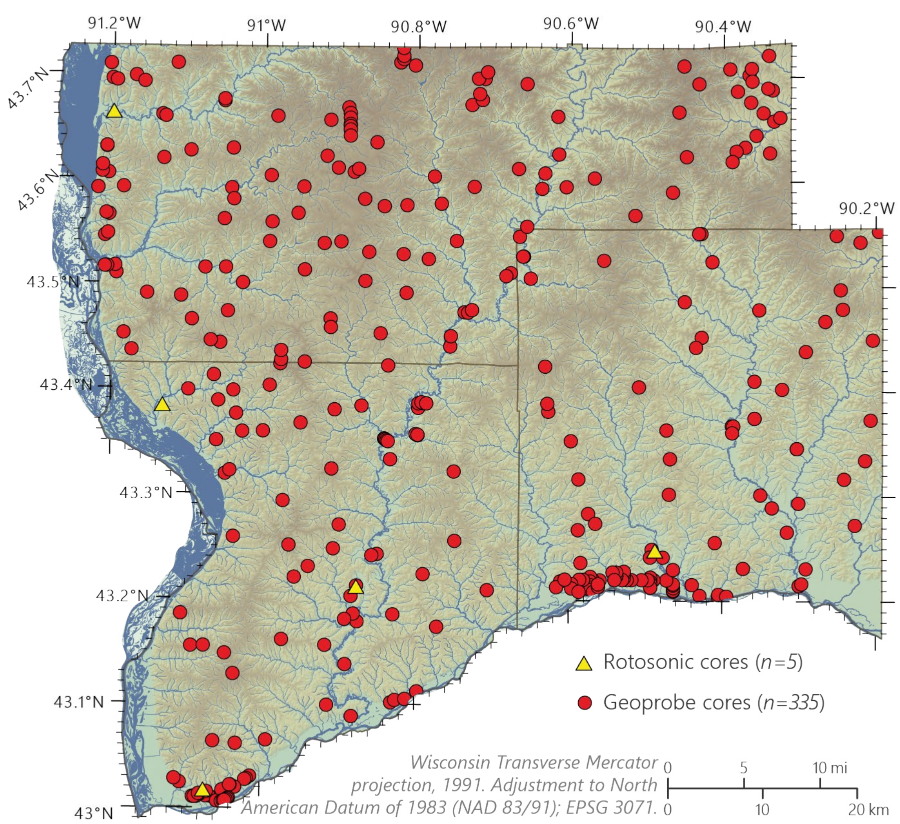
Wisconsin Transverse Mercator projection, 1991. Adjustment to North American Datum of 1983 (NAD 83/91); EPSG 3071.

Rotosonic coring retrieves a 10.2-cm (4-in) diameter sediment core. Continuous steel casing is inserted into the ground, and cores are collected via rotary drilling in approximately 3 m (10 ft) or approximately 6 m (20 ft) increments. Cores are extruded hydraulically and placed in liner bags in approximately 1.5 m (5 ft) increments. Rotosonic coring can penetrate sediment in excess of 120 m (400 ft), although in the Driftless Area the maximum depth encountered was 47.1 m (155 ft) in deeply incised and filled valleys.

Direct-push coring is significantly less expensive than rotosonic coring and thus has been used far more frequently in support of this mapping. Rotosonic cores have been collected only in targeted areas of special interest, typically valley settings with deep sediment fill. This is the only setting with sufficient sediment depth to require rotosonic as opposed to direct-push coring. A total of 335 unique direct-push core locations and 5 rotosonic cores were collected in Crawford, Richland, and Vernon counties in support of this mapping (fig. 3). Core locations are provided in dataset 2.

All cores were split, described, photographed and sampled in the Quaternary Sediments Laboratory at the WGNHS Mount Horeb Core Repository and Education Center in Mount Horeb, Wisc. Representative grain-size analysis of core sediments was conducted on a Malvern Mastersizer 2000E located at the University of Wisconsin–Milwaukee. Plant macrofossils were submitted to Beta Analytic, Inc., for AMS radiocarbon dating to provide absolute chronologic control where possible.

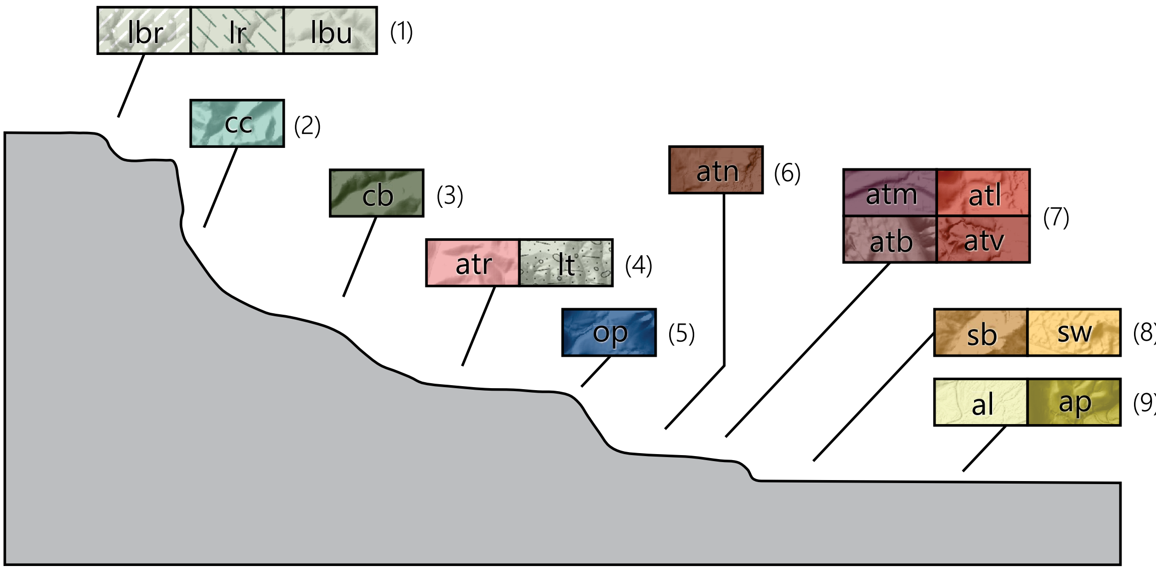
Figure 3. Distribution of cores collected in Crawford, Richland, and Vernon Counties, showing locations of direct-push cores (red circles) and rotosonic cores (yellow triangles).



Classification of geologic map units

Glacial sediments in Wisconsin are formally identified based on lithostratigraphy (Syverson and others, 2011). With limited exceptions discussed later in the text, no such formal designation of sediments—and therefore map units—exists in the unglaciated Driftless Area. Recent and current WGNHS mapping in the Driftless Area has developed a suite of map units that are defined based on landscape position, sediment, and depositional process (fig. 4). The topography throughout the study repeats a sequence (from highest areas to lowest) of uplands, steep slope, shallow toe slope, a descending sequence of terraces, and floodplain. The upland surfaces are uniformly blanketed with windblown silt, which is differentiated into several map units based on the underlying material. Steep slopes are solely mapped as coarse colluvium (sediment moving downslope under the effect of gravity). Shallow toe slopes, where present, are mapped with fine-grained colluvium on bedrock. Numerous terrace units with varying elevations relative to the floodplain have been mapped, and in one isolated area in southern Crawford County, loess (windblown silt) mantles an early to middle Quaternary till deposit. Windblown sand and thin sand on bedrock are found in areas low on the landscape: on floodplains and immediately adjacent terraces or shallow toe slopes. Floodplains are the lowest point on the landscape and are mapped as modern or pre-Holocene alluvium (Holocene being the most recent 11,700 years of Earth's history, generally denoting time since the last major global glaciation).

Figure 4. **Hypothetical topographic cross section from upland surface to floodplain showing where various map units in the study area occur in relation to the topography.**



(1) *Loess on undifferentiated bedrock (lbu), loess on residuum (lr), and loess on the Readstown Member of the St. Peter Formation (lbr):* found on relatively flat upland surfaces that are the highest points on the landscape.
(2) Coarse *colluvium (cc):* found on steep slopes supported by resistant sandstone and dolomite bedrock formations.
(3) *Fine grained colluvium on bedrock (cb)*: found on gentle toe slopes, generally underlain by the poorly indurated Tunnel City Group sandstone.
(4) *Alluvium of the Bridgeport terrace (atr)* and *loess on till (lt):* found on the bedrock strath that forms the Bridgeport terrace, *atr* beyond the pre-Illinoian glacial limit and lt behind the pre-Illinoian glacial limit.
(5) *Offshore sediment in bedrock paleomeanders (op):* found in abandoned bedrock meander loops, generally coincident with the highest level of Pleistocene aggradation in the adjacent mainstem valley.
(6) *Sediment of non-glacial terraces (atn):* found on tributaries to the Mississippi and Wisconsin Rivers, generally farther upstream than other depositional terraces.
(7) *Meltwater stream sediment in terraces (atm) and lacustrine sediment in terraces (atl):* found at the mouths of tributaries to the Wisconsin River. *Sediment of the Savanna Terrace (atv)*: found in the mouths of tributaries to the Mississippi River. *Sediment of the Bagley Terrace (atb):* found along the mainstem Mississippi River. All units found near floodplain level.
(8) *Thin sand on bedrock (sb) and windblown sand (sw):* found near the lowest points on the landscape.
(9) *Alluvium (al) and pre-Holocene alluvium (ap):* found at or near the lowest points on the landscape.

Description of map units

Influence of bedrock on surface morphology

The bedrock units at and near the surface in southwestern Wisconsin are primarily late Cambrian to late Ordovician sandstones and dolomites with lesser amounts of shales (Bremmer and others, 2025; Fitzpatrick and others, 2025), as depicted in the displayed portion of the Wisconsin stratigraphic column (fig. 5). The bars to the left of the column represents the portion of the late Cambrian–Ordovician succession that is expressed at or near the surface in Crawford, Richland, and Vernon counties. At a landscape scale, the flat-lying sedimentary bedrock layers in the region control the morphology of the land surface and allow for a predictable occurrence of resistant, ridge-forming units on uplands that protect underlying more erodible layers on steep slopes that are in some places buried by coarse colluvium.

With the notable exception of alluvial fill in deeply incised bedrock valleys, the sediment cover in the study area is generally thin, between 1 and 10 m (3.3 and 32.8 ft). As such, many of the bedrock units are expressed in various ways throughout the map area. Depending on the situation, bedrock-related features such as scarps, exposed vertical faces of bedrock, and joints/faults are mapped as line features or incorporated into map units.

Scarp of Tonti Member of St. Peter Formation on upland surfaces

The Tonti Member is the upper of two members of the St. Peter Formation. It is described as a fine-grained, well sorted, friable sandstone (Templeton and Willman, 1963). It varies in thickness in response to pre-existing topography associated with the unconformable contact between the St. Peter Formation and the underlying Prairie du Chien Group. It forms a prominent scarp where a particularly well indurated horizon crops out. Throughout much of Crawford and

Figure 5. Portion of the bedrock stratigraphic column for Wisconsin (WGNHS, 2011), with vertical bars on the left showing the portion of the bedrock stratigraphy encountered near the surface in each county.

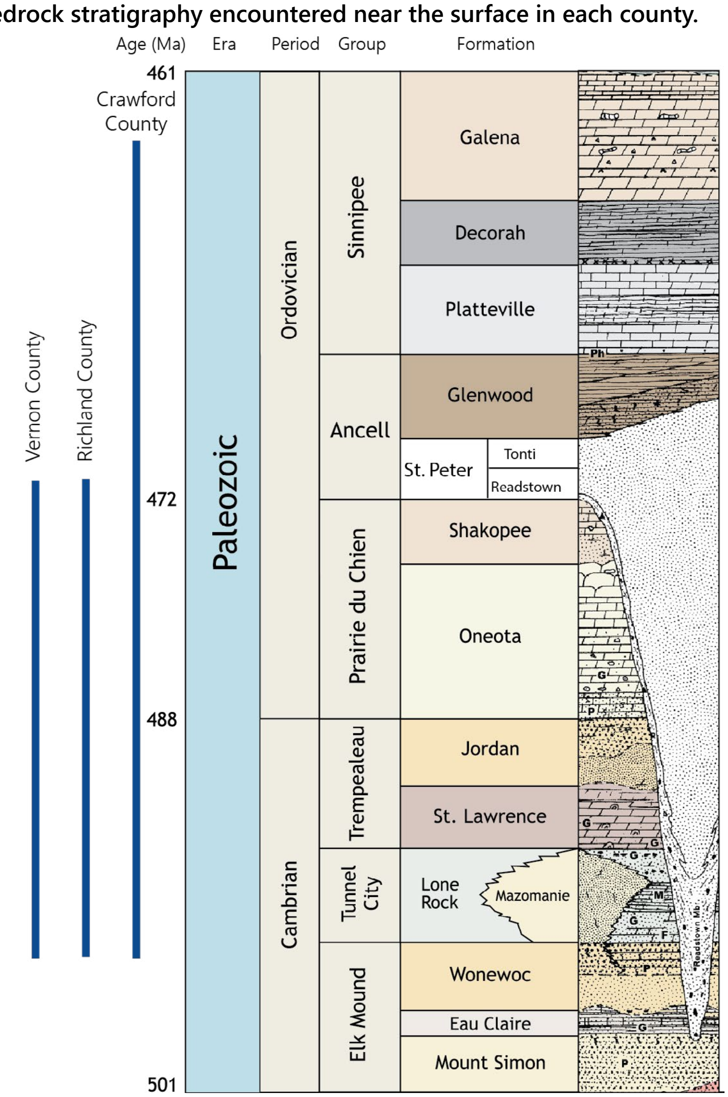


Figure 6. Distribution of mappable topographic scarps of the Tonti Member of the St. Peter Formation (red lines).

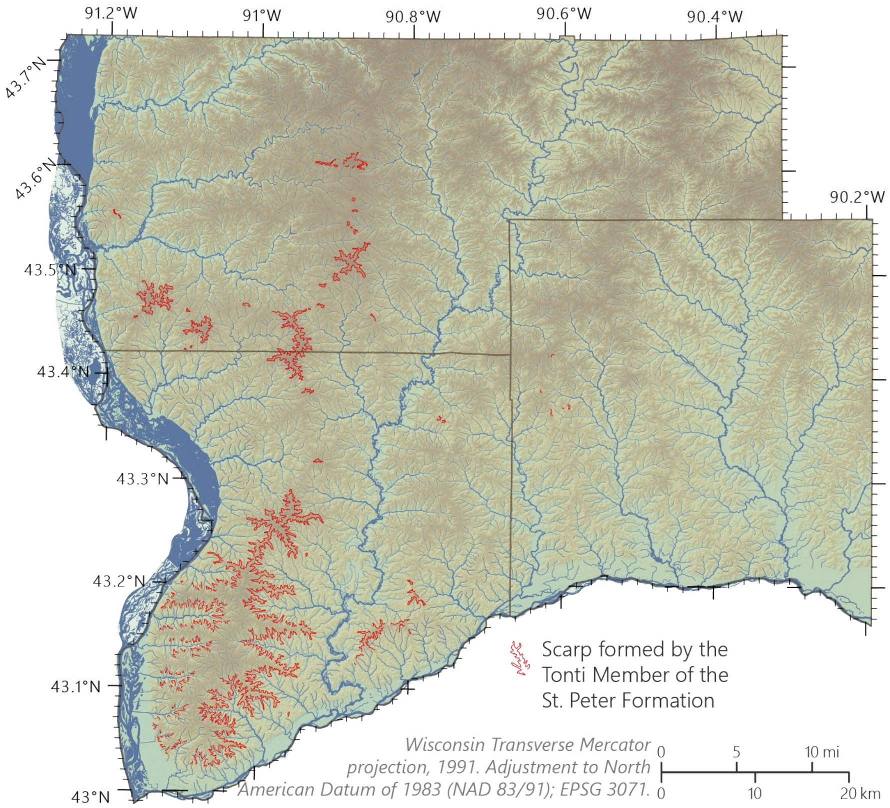
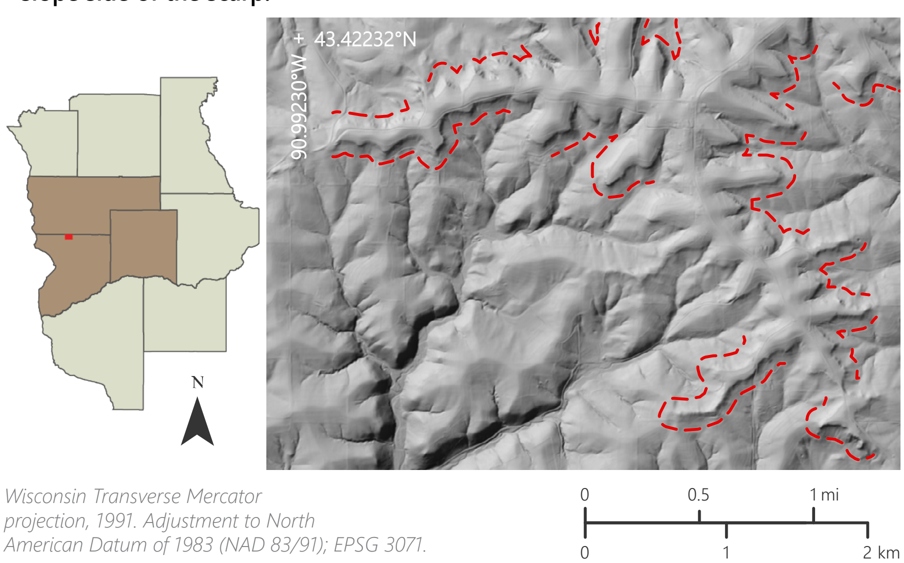


Figure 7. Example from northern Crawford County showing a typical topographic expression of the scarp of the Tonti Member of the St. Peter Formation as seen in high-resolution lidar, red dashed line outlining the down-slope side of the scarp.



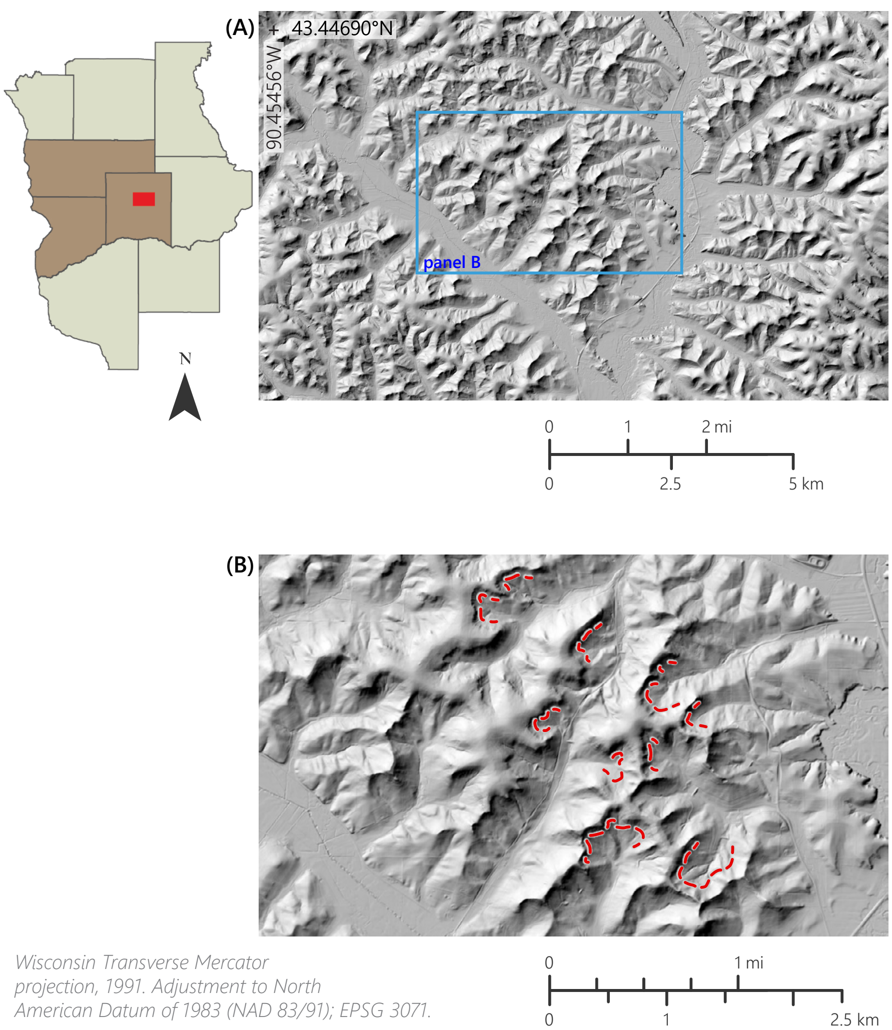
Vernon counties, the Tonti Member crops out on the highest upland surfaces (fig. 6); the ground surface in Richland County is too far down-section in the Paleozoic sequence to contain significant areas of the Tonti Member. Where it expresses as a topographic feature on the landscape, the scarp forms an abrupt, sometimes discontinuous, steep slope often 5 to 8 m (16.5 to 26.3 ft) tall (fig. 7). It was mapped as a discontinuous line feature where evident on lidar. In isolated cases, what appears to be particularly well indurated portions of the Tonti Member is resistant enough to crop out along the scarp or even present as free-standing spires (fig. 8).

Nature of the Prairie du Chien Group on upland surfaces

Resistant dolomite of the Prairie du Chien Group underlies many upland surfaces in the study area. Rock of this group is as thick as 25 m (82 ft) (Clayton and Attig, 1990), although subsequent erosion associated with the development of the unconformity that caps these rocks imparted significant topography into the surface. The largest areas of continuous, nearly flat, upland surfaces are underlain by the Prairie du Chien Group. Direct-push coring in these areas encounters continuous loess from the surface to the impenetrable dolomite surface, or both loess and residual clay. In many portions of the study area where upland surfaces are formed by Prairie du Chien Group, there is a very pronounced break in slope on the surface between the upland and the steep colluvial slope below, and the edge of that break in slope often has a distinctive 'scallop' shape when seen in lidar (fig. 9). Where the Prairie du Chien Group is the bedrock cap of uplands, it is almost uniformly covered by loess. It is mapped along with other bedrock units that may cap uplands as Loess on Undifferentiated Paleozoic Bedrock, map unit **lbu**.

Figure 8. The 'Three Chimneys' outcrop north of Viroqua, Wisc., is an example of particularly well-cemented sandstone of the Tonti Member of the St. Peter Formation.

Figure 9. Panel A, example of topography with 'scallop' shaped break in slope between upland surface and colluvial slopes formed where resistant Prairie du Chien Group dolomite caps the landscape. Panel B, showing the feature in greater detail.

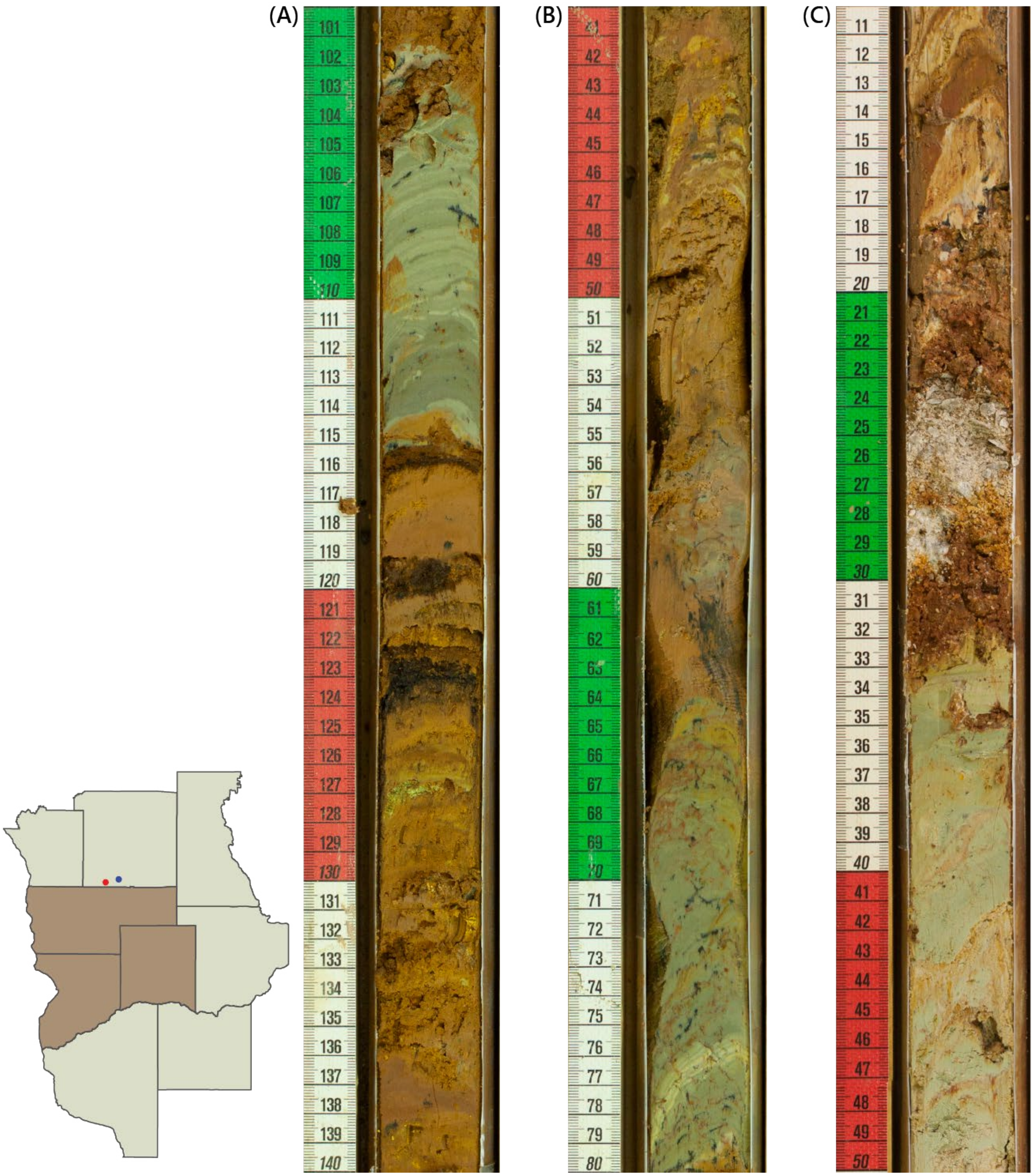


Readstown Member of St. Peter Formation on upland surfaces

The Readstown is the lower member of the St. Peter Formation. As with the upper member, the Tonti, the thickness of the Readstown varies considerably as the material originally filled the topography that had been carved into the underlying Prairie du Chien Group (Willman and Templeton, 1951; Ostrom, 1967). Where it has been encountered in numerous direct-push cores, the Readstown Member is a mixture of varied sands and clays. The sands occur in shades of white, yellow, tan, orange, and red. The clays occur in shades of white, yellow, tan, orange, red, gray, black, and pale green, the last of which is most diagnostic (fig. 10). It is not uncommon for direct-push coring to be able to penetrate through three or more meters of this material because it is heavily weathered. In the study area, the Readstown Member is only encountered in cores beneath loess. It is mapped as Loess on Paleozoic Bedrock of the Readstown Member, map unit **lbr**.

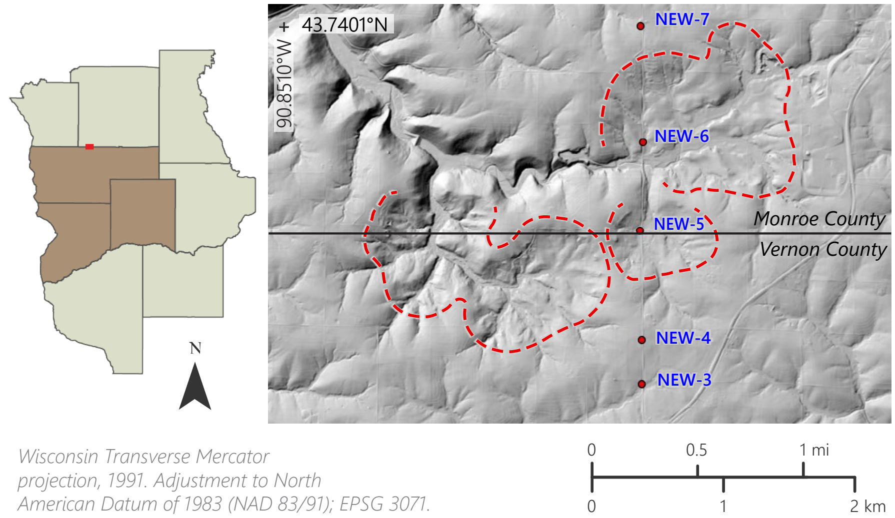
There is a distinct surface morphology associated with upland areas where loess is underlain by the Readstown Member

Figure 10. Examples of weathered clay and sand of the Readstown Member present in the subsurface as encountered in cores from southern Monroe County near the study area; each shows a 40-cm segment of core. Panel A, section of core SAM-2, starting at 4.7 m (15.5 ft) depth. Panel B, section of core SAM-2 starting at 5.3 m (17.4 ft) depth. Panel C, section of core NEW-6 starting at 7.7 m (25.3 ft) depth. Location of cores SAM-2 and NEW-6 shown by blue and red circles, respectively.



that is evident when comparing direct-push core and lidar data. In these areas, headwater tributary streams tend to form a peculiar ‘head of cauliflower’ shape (fig. 11). This morphology is too subtle to be noticed without lidar data. Direct-push coring has demonstrated that the presence of this morphology indicates the presence of the Readstown Member in the subsurface not only within the shape of the depression but in the adjacent landscape. We have recognized the correlation between this subtle surface morphology and the presence of subsurface Readstown Member throughout this study area as well as in Dane, Iowa, and Monroe counties. However, coring also documents that the Readstown Member occurs in areas where this distinctive surface morphology does not occur. The St. Peter Formation—with the Readstown as its bottom member—lies unconformably on the Prairie du Chien Group dolomite (Wooster, 1882; Smith and others, 1993); the surface which separates those two units contains considerable topography that is in-filled by the St. Peter Formation. It seems plausible that this ‘head of cauliflower’ morphology occurs where the headwaters of surface drainage systems coincides with the thickest locations of the heavily weathered and mobile Readstown Member.

Figure 11. **Example of distinctive ‘head of cauliflower’ valley-head morphology associated with the presence of weathered sediment of the Readstown Member in the subsurface (underlying loess and on top of solid bedrock). Red dashed lines trace outline of the distinctive shape. Red circles indicate direct-push cores, including NEW-6 core (identified) which is shown in figure 10. Information about cores located in Monroe County is available upon request.**



Rountree Formation on upland surfaces

The Rountree Formation is a reddish-brown clay that is often silty in its upper portions, is rich in manganese concretions and soil pedon coatings, and contains frequent chert clasts. It is derived from weathering dolomites of the Galena Formation (Sinnipee Group) or the Prairie du Chien Group (Frolking, 1978; Knox and others, 1990; Syverson and others, 2011). In outcrop (fig. 12), a weathered reddish-brown color is readily apparent; this coloration is most often observed as part of the overburden in quarry faces within the Prairie du Chien Group dolomite. Direct-push core samples of the Rountree Formation exhibit a uniform bright reddish-brown colored clay with chert clasts clearly visible. The chert often shatters during sample collection (fig. 13). Knox and others (1990)

Figure 12. **Field exposures of the Rountree Formation in quarry excavations. Panel A (blue circle), photo of quarry wall and overlying Roundtree Formation along County Highway M northeast of Norwalk, Wisc. For scale, the bedrock wall is estimated to be 12 m (40 ft) tall, date unknown. Photo © Jim Knox. Panel B (red circle), excavators removing Rountree Formation as overburden while opening a new quarry along County Highway AA northwest of Norwalk, Wisc. in November 2019.**

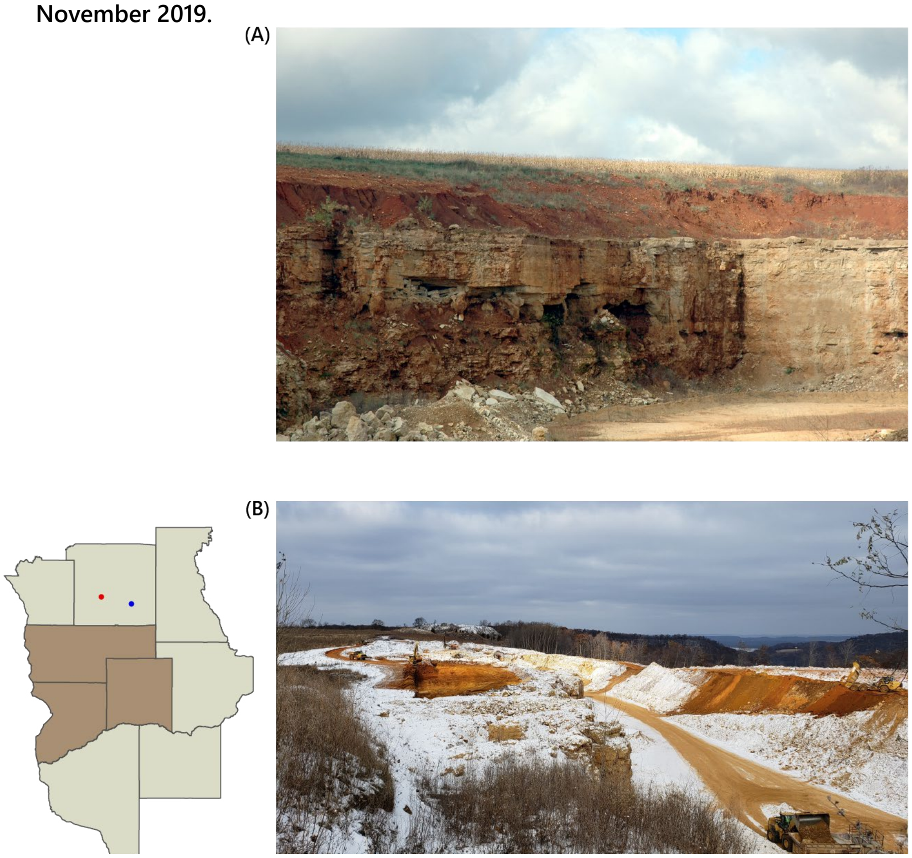
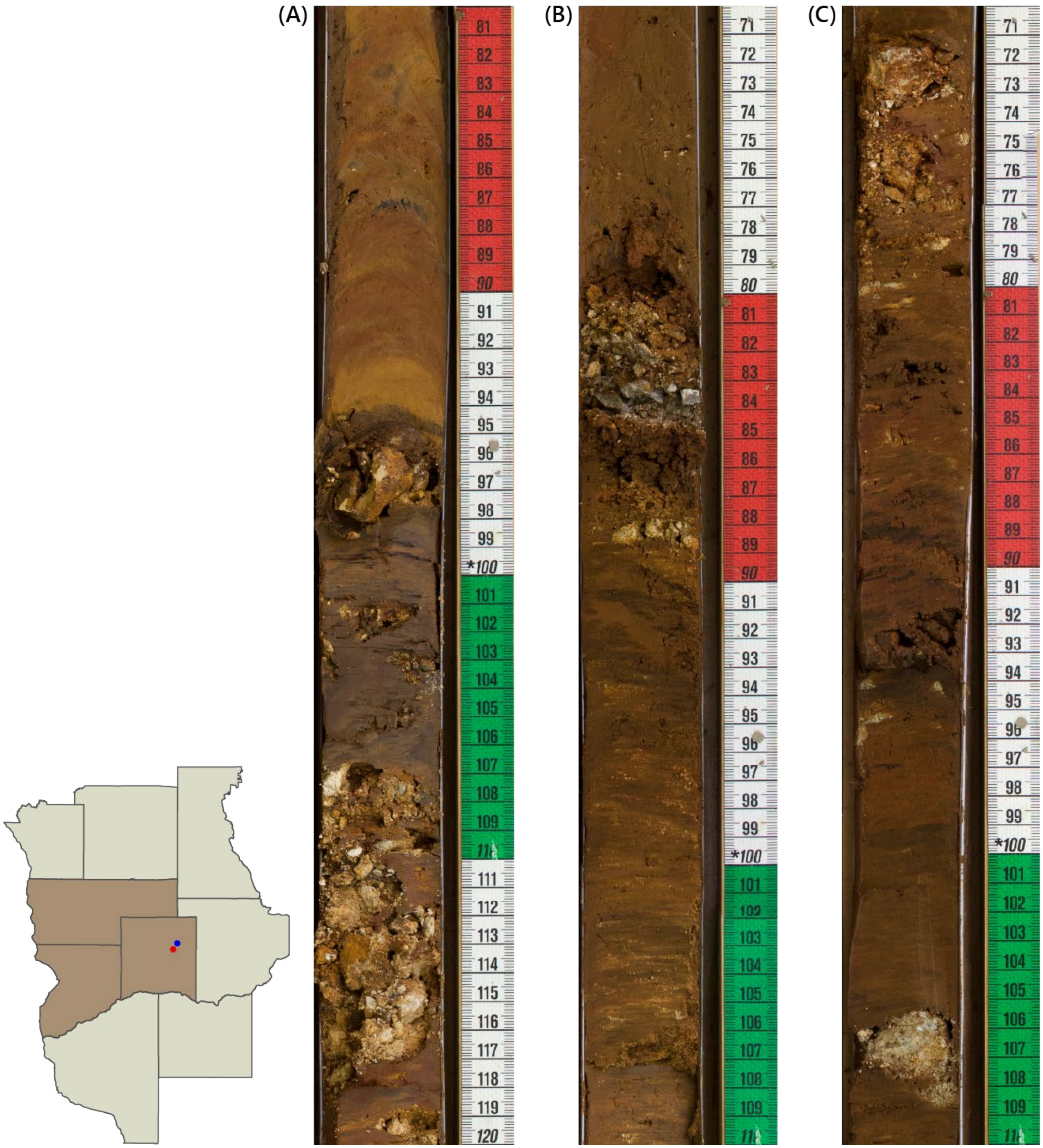


Figure 13. Examples of reddish-brown clay with chert fragments characteristic of the Rountree Formation present in the subsurface as encountered in cores from central Richland County in the study area; each shows a 40-cm segment of core. Panel A, section of core PLR-3, starting at 8.4 m depth. Panel B, section of core PLR-4 starting at 5.3 m depth. Panel C, section of core PLR-4 starting at 6.8 m depth. Location of cores PLR-3 and PLR-4 shown by blue and red circles, respectively.



and Syverson and others (2011) noted that the Rountree Formation seems to occur in greater thicknesses where forming on the Prairie du Chien Group dolomites (in the study area and in Monroe County) as compared to where it forms on the Sinnipee Group (south of the Wisconsin River in Grant, Iowa, and Lafayette counties, see fig. 1). In the study area, the Rountree Formation is only encountered in cores beneath loess. It is mapped as Loess on Weathered Residuum of the Rountree Formation, map unit **lr** (residuum being sediment chemically weathered in place).

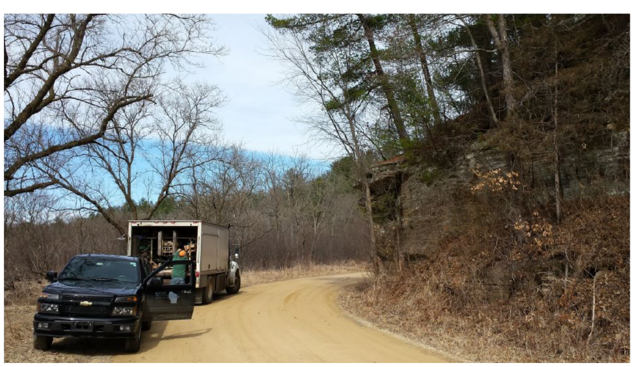
Surface expression of the Wonewoc Sandstone

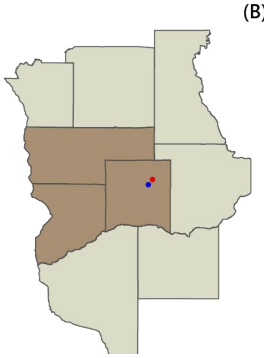
The uppermost portion of the Wonewoc Formation is known as the Ironton Member. Particularly in Vernon and Richland Counties, but also in adjacent counties, the Ironton Member includes a dolomitic, glauconitic horizon and tends to express as vertical cliffs up to approximately 8 m (26 ft) high where exposed (fig. 14). In the study area, this only occurs where larger streams have incised through the Tunnel City Group to expose the Ironton Member near floodplain level. The vertical face of the Wonewoc Formation was mapped as a line feature where it occurs in the study area (fig. 15).

Figure 14. **Verticals cliff formed by the Ironton Member of the Wonewoc Formation. Panel A (blue circle), exposure at Pier County Park near Rockbridge, Wisc. Floodplain of the Pine River is at the extreme right edge of the image. Panel B (red circle), exposure north of Rockbridge, Wisc. Road and vehicles are at floodplain level. The vertical cliff of the Wonewoc Formation continues into the subsurface documented by direct-push core PNR-10, which was collected where drill rig is parked that encountered bedrock at a depth of 7 m (23 ft).**

(A)

(B)





Windblown sediment

Windblown sediment in the study area is divided into loess and sand. Loess is ubiquitous on the landscape, particularly on upland surfaces where it is widely mapped. It occurs exclusively on upland surfaces that are predominantly used for row-crop agriculture, with lesser areas managed as agriculture or left in mature forest. Sand is much less abundant, largely found in terraces along the lower Wisconsin River and immediately downwind of localized sources such as the Kickapoo and Pine rivers. These terraces on the lower Wisconsin River and its tributaries are often developed for row-crop and pastureland.

Loess

Loess is identified in Wisconsin as the Kieler Formation; it is divided from youngest to oldest into the Peoria, Roxana, Loveland, and Wyalusing members (Syverson and others, 2011). The Peoria Member is the thickest and most extensive of the four throughout the Driftless Area (Mason and others, 2019). On upland surfaces where most of the direct-push coring occurred for this study, the Peoria Member was found ubiquitously. The Roxana Member was found in few cores and the Loveland and Wyalusing Members were only found in a few direct-push and rotosonic cores on protected surfaces near local base level. Mason and others (2019) suggest that this distribution reflects periglacial erosion from upland surfaces during glaciations that removed older loess units before a younger one was deposited.

Loess is ubiquitous across the study area and is here further differentiated based on underlying sediment or bedrock units. **lbr** Loess on Paleozoic Bedrock of the Readstown Member. **lr** Loess on Residuum of the Rountree Formation. **lbu** Loess on Undifferentiated Paleozoic Bedrock (to capture areas underlain by units that could not be easily distinguished). Cartographically, the loess has been displayed using a single map color with distinct patterns for each map unit.

Figure 15. **Distribution of the vertical face of the Wonewoc Formation where mapped as a line feature in Richland and Vernon counties, identifying the two reaches that the Pine and Kickapoo rivers incised that deeply into the Paleozoic sedimentary sequence.**

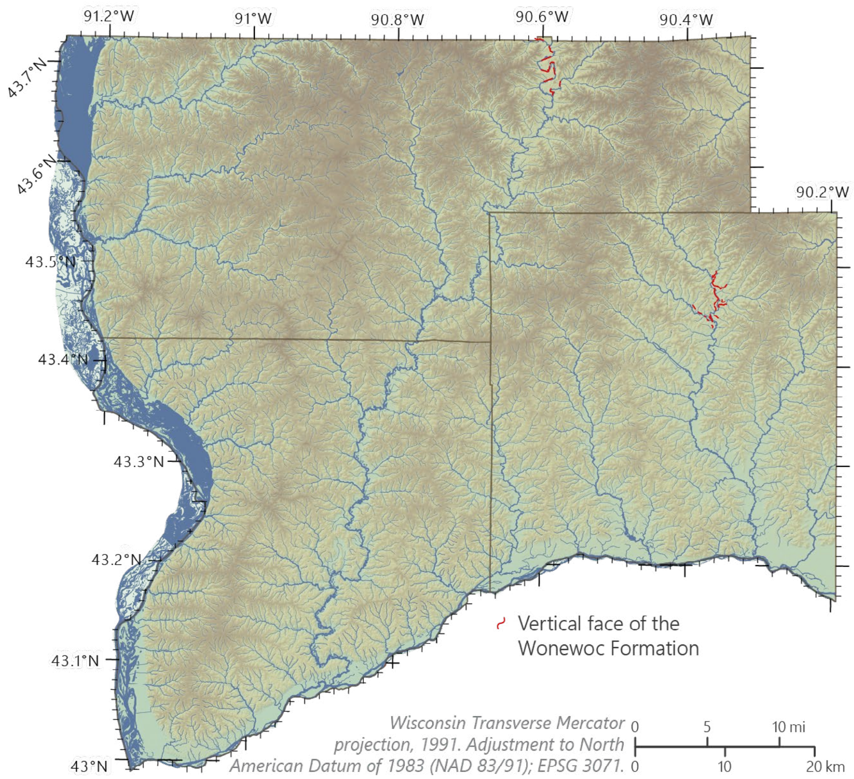
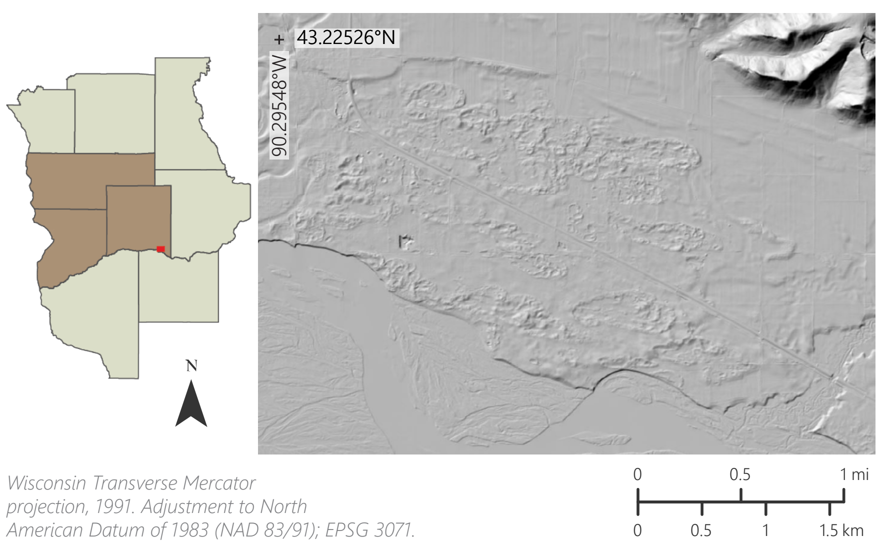


Figure 16. **Stabilized parabolic dunes and blowouts on an alluvial terrace surface adjacent to the Wisconsin River near Gotham, Wisc. Duneforms are 1- to 1.5-m high, and are generally not easily visible while on the landscape.**



There is a limited area in southernmost Crawford County that contains loess on a low elevation surface (the strath terrace as described below). This loess overlies pre-late Wisconsin till sourced from the northwest (Carson and others, 2019a). This isolated area has been mapped as **lt** Loess on Till.

Windblown sand

Windblown sand, map unit **sw**, is locally derived and transported. It occurs in relative abundance along the lower Wisconsin River valley where it mantles alluvial terraces discontinuously. Duneforms in this area are common but not universal (fig. 16). Smaller, more isolated deposits of windblown sand can be found near the mouth of the Pine River and especially along much of the length of the Kickapoo River. Duneforms are generally not present with these deposits; rather they occur as 'sand ramps' on the downwind (east) side of the valleys (Knox, 2019). They often fill west-facing alcoves in the valley walls with 10 m (32.8 ft.) or more of sand (fig. 17). In limited areas, windblown sand occurs as thinner deposits that reveal the form of the underlying sandstone bedrock. These areas have been mapped as Sand on Bedrock, map unit **sb**.

Colluvial sediments

Resistant bedrock on steep slopes

Dolomites of the upper portions of the Prairie du Chien Group or sandstone of the Tonti Member of the St. Peter Formation underlie most of the upland surfaces throughout the study area. A pronounced break in slope separates these upland surfaces from steep colluvial surfaces descending to near base level (the local stream level). The bedrock exposed in steep colluvial slopes is a combination of generally resistant dolomites of the lower portions of the Prairie du Chien Group, sandstone of the Jordan Formation, and dolomite of the St. Lawrence Formation.

The coarse-grained colluvium, map unit **cc**, is an unsorted matrix-supported slope sediment derived from erosion of these Paleozoic bedrock units. Bedrock blocks are generally angular and can be larger than 2 m (6.5 ft) in intermediate axis diameter and are dispersed in a silty matrix that is presumably derived from windblown sediment moving downslope. Total thickness on steep slopes is generally less than 2 m (6.5 ft) and can be locally absent due to slope failure (landslide) events. Accumulation occurs at the base of steep slopes and can locally be up to 20 m (65 ft) thick (fig. 18).

Low-relief surfaces underlain by Tunnel City Group

The upstream reaches of several streams—notably the Kickapoo River, Pine River, and upstream portions of the Upper Baraboo River in eastern Vernon County—have incised lower than the base of the St. Lawrence Formation and into weakly cemented sandstones of the Tunnel City Group. A marked decrease in surface slope accompanies this transition in near-surface bedrock geology, associated with the fine-grained colluvial map unit **cb**. It has been observed that large, coarse, colluvial blocks accumulate at the base of the steeper slope, and the shallower slope contains only fine-grained material that can continue to wash downslope. Coring into this surface indicates that sediment is as much as 10 m thick. Direct-push cores uniformly penetrate into Tunnel City Group sandstone, easily recognizable due to the high content of green glauconite (fig. 19).

The break in slope associated with the transition from coarse colluvium above and fine colluvium below on the toeslope also often corresponds to a systematic shift in land use. The more gently sloping surfaces of map unit **cb** are often pastureland and the steeper surfaces of map unit **cc** above are left wooded, commonly with a fence line at or very near to the break in slope (fig. 20).

Figure 17. Example of a 'sand ramp' north of Gays Mills, Wisc. View is looking northeast into the mouth of a valley that has been filled with windblown sand and is now being mined. For scale, the exposed sand face on the right side of the image is approximately 18 m (60 ft) high.

Figure 18. Example of coarse colluvium, map unit cc, showing angular and subangular boulders in a matrix of silt.

Terraces

Alluvial terraces are flat, step-like landforms adjacent to and higher than active river floodplains; fundamentally, they represent former floodplains that have been abandoned as a result of stream incision. Mappable terraces are abundant in the study area along the Mississippi and lower Wisconsin rivers and their major tributaries, the majority of them reflecting the impacts of late Pleistocene glaciations in the affected watersheds. During glaciations, the volume of sand and gravel produced by glaciers exceeds the ability of the meltwater streams to transport it; thus, sand and gravel accumulate on the valley floor and fill the valley over time. During interglacial periods, the sediment supply is much smaller and therefore allows the stream to incise into the sand and gravel deposited during the previous glaciation.

Strath terrace—the Bridgeport terrace

There are three discrete segments of a bedrock-cored, or strath, terrace along the lower Wisconsin River valley. The three segments of this bedrock terrace, map unit **atr**, occur on the north side of the valley: one opposite the town of Muscoda, Wisc. (fig. 21); one bisecting the mouth of the Kickapoo River near Wauzeka, Wisc.; and one near the confluence of the Wisconsin and Mississippi Rivers just east of Prairie du Chien, Wisc. Bedrock within the terrace is exposed in no fewer than six places by natural gullies or roadcuts. The bedrock core of the terrace is covered by 2 to 15 m (6 to 50 ft) of mixed alluvium, colluvium, loess, windblown sand and glacio-lacustrine sediment. Knox and Attig (1988) applied the name of Bridgeport terrace to the surface and interpreted it to represent remnants of pre- and early Quaternary bedrock floor of the valley. Carson and

Figure 19. Examples of weathered material of the Tunnel City Group displaying the characteristic green color derived from high glauconite content in direct-push cores from the study area. All images depict 40-cm intervals from cores and all images are from the basal ~1 m of each core. Panels A and B correspond to the red circle, panel C corresponds to the blue circle.

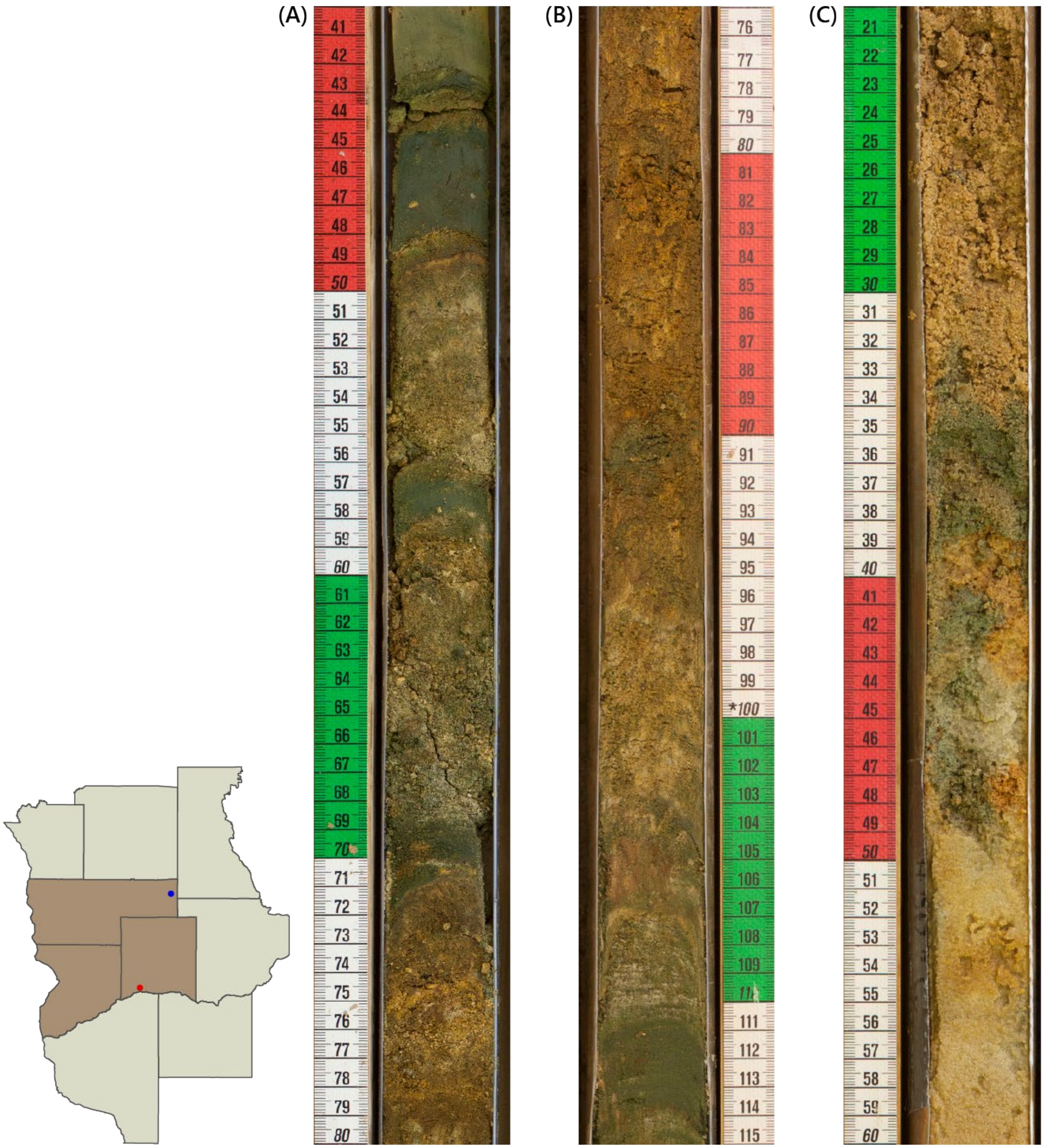
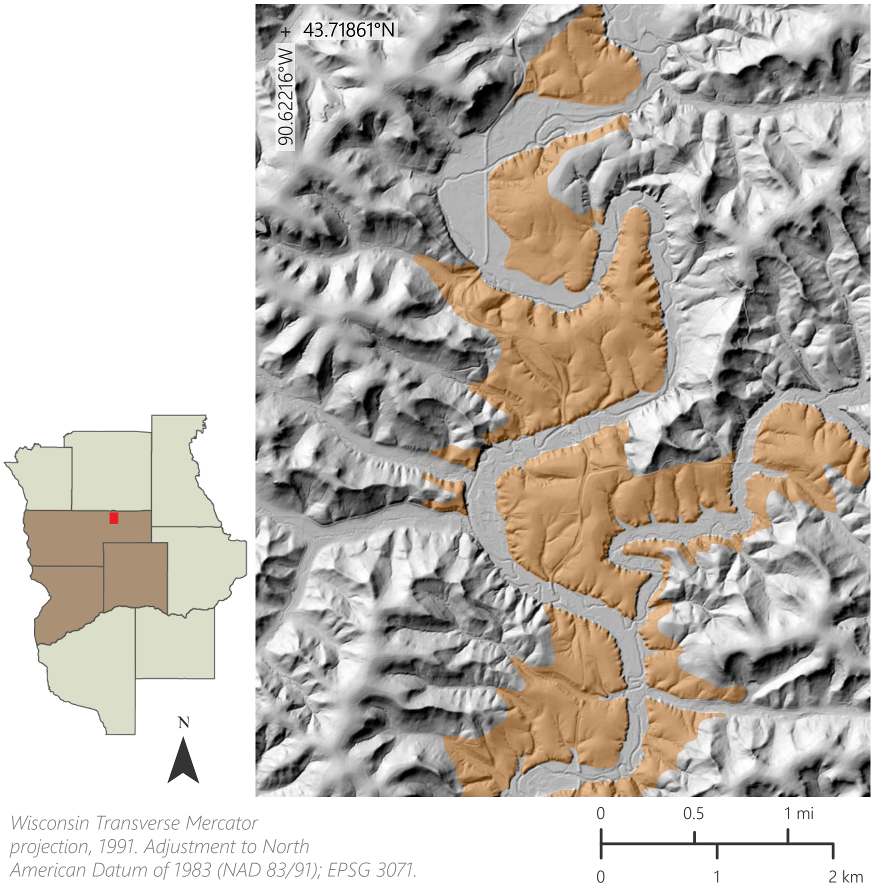


Figure 20. Examples of fine-grained colluvium surfaces underlain by weathered material of the Tunnel City Group along the Kickapoo River south of Ontario, Wisc.; map unit cf shown by orange shading. Note the decrease in slope compared to areas of coarse colluvium, map unit cc, upslope as well as the decreased amount of gullying.



others (2018) attribute its abandonment to downcutting in response to large-scale reorganization of midcontinent river systems, likely in the early Quaternary. This terrace is the highest, and therefore the oldest along the lower Wisconsin River.

Meltwater terraces, including the Bagley terrace

Significant meltwater sediment, primarily sand and gravel, aggraded on the Mississippi and lower Wisconsin River valleys during late Pleistocene glaciation. Railroad and highway borings record that aggradation exceeded 45 m (150 ft) along these river corridors.

Along the lower Wisconsin River, aggradation and subsequent incremental incision has produced several terrace surfaces generally 2 to 6 m (6.5 to 19.5 ft) above adjacent modern floodplain elevation (fig. 22). Along the Mississippi River, meltwater sediment that had aggraded in the main stem valley was subsequently significantly impacted by episodes of down-cutting, possibly associated with bursts of sediment-poor water released from ice-marginal lakes upstream (Knox, 1999). Fluvial incision during the retreat of the Laurentide Ice Sheet (the ice sheet that covered most of Canada and the northern United States during the last major global glaciation) eroded meltwater sediment within the Mississippi River

Figure 21. Sediment of the Bridgeport Terrace in southern Richland County just north of Muscoda, Wisc., shown by yellow shading. For comparison of Bridgeport Terrace to aggradational terraces, dashed white box in western portion of the image identifies the area depicted in figure 22; dashed white box in eastern portion of the image identifies the area depicted in figure 24.

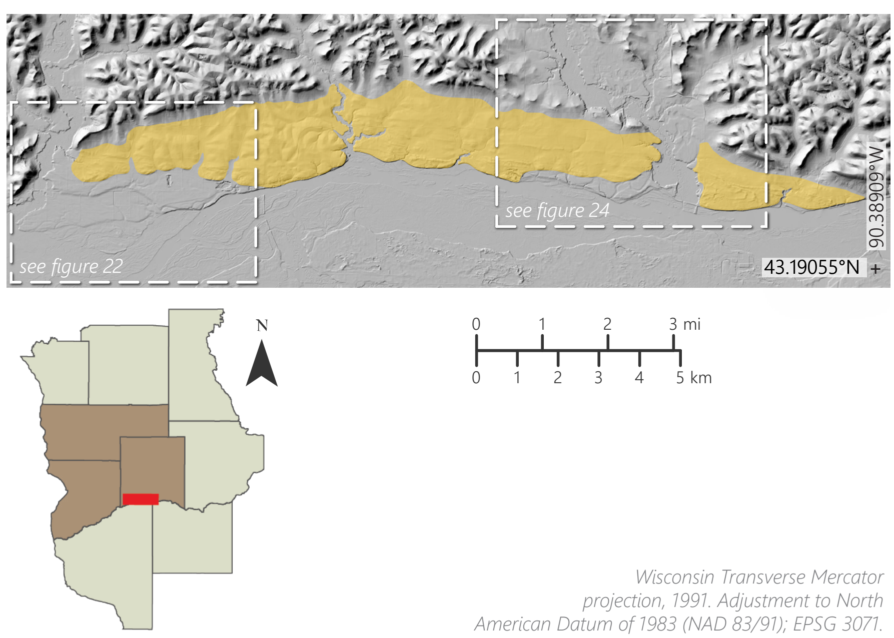


Figure 22. **Aggradational terraces, map unit atm, along the lower Wisconsin River immediately downstream of Blue River, Wisc. (the trace of the County Highway T bridge across the Wisconsin River immediately north of Blue River, Wisc., is visible on the extreme east margin of the image). Aggradational terraces at several elevations are delineated in this image with higher terraces as increasing dark shades of green. The visible scars of sand and gravel mines (shown by arrows) on the highest of them attests to them being constructed of meltwater sediment. Slackwater terrace map unit atl also shown in tributary mouth in blue.**

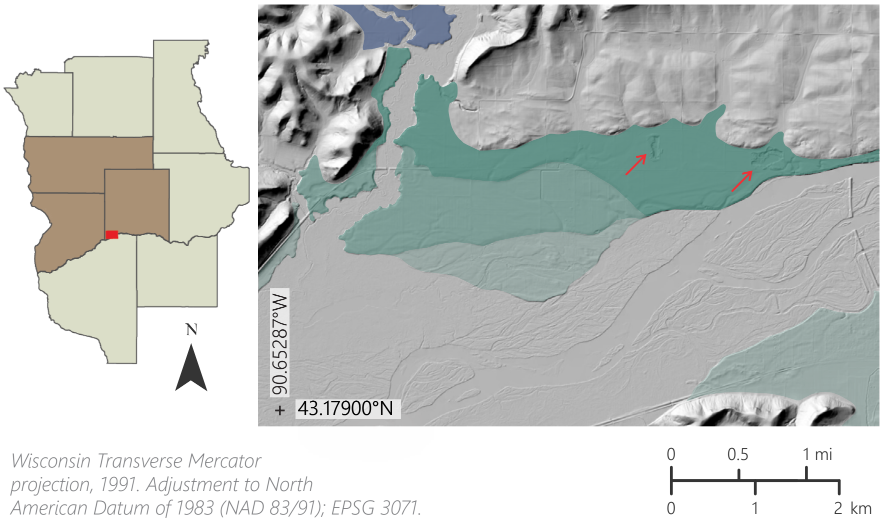
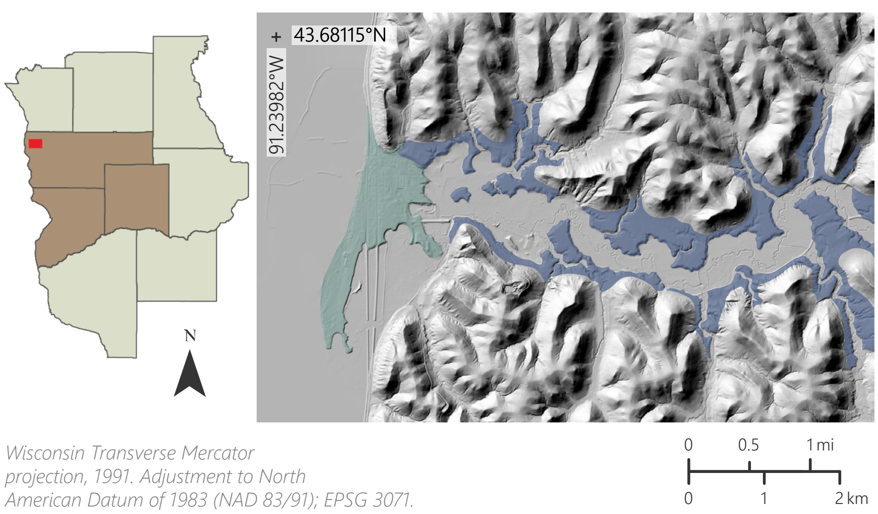


Figure 23. **Aggradational meltwater terrace sediment known as the Bagley terrace, map unit atb, shown by green shading, along the Mississippi River at the mouth of Coon Creek at Stoddard, Wisc. Notice that the town of Stoddard is built upon that lower terrace surface. Slackwater terrace sediment known as the Savanna terrace, map unt atv, shown by blue shading in the tributary valley.**



corridor, producing an erosional surface known as the Bagley terrace that occurs 7 to 10 m (23 to 33 ft) above adjacent pool elevation (fig. 23). This erosion likely occurred between 14,000 to 9,000 years before present (Knox, 1999).

The terraces along both the lower Wisconsin and Mississippi Rivers are fluvio-glaciogenic and the sediment associated with each was deposited contemporaneously. However, the surface associated with the Bagley terrace along the Mississippi was subsequently modified by fluvial incision in a manner that did not occur along the lower Wisconsin. Thus, these have been mapped as two separate units, map unit **atm** along the lower Wisconsin River and map unit **atb** along the Mississippi River, which are mapped separately as the Mississippi River was subsequently scoured while the terrace on the lower Wisconsin River was not. Other than the post-depositional scouring of map unit **atb**, these two terraces are correlative and are the lowest (youngest) terraces in the study area.

Slackwater terraces, including the Savanna terrace

Aggrading meltwater sediment on the lower Wisconsin and Mississippi Rivers during the late Pleistocene glaciation impounded the mouths of unglaciated tributary streams, causing them to become slackwater lake settings where generally fine-grained sediment accumulated between 25,000 and 14,000 years before present (Flock, 1983; Knox, 1996). The lacustrine nature of the sediment that comprises the Savanna terrace was confirmed by numerous direct-push and rotosonic cores as part of this mapping. Typically, this sediment is laminated silt and clay, commonly found with thin horizons of plant macrofossils. Numerous AMS radiocarbon ages from four slackwater sites in the study area plus additional AMS radiocarbon ages from similar sites in Grant, Iowa, Dane, and Sauk counties indicate slackwater aggradation commenced at some sites by 34,500 years before present and continued through at least 17,500 years before present (Carson and others, 2012; 2019b).

The sediment associated with this slackwater setting is only preserved as a terrace in the mouths of unglaciated tributaries. Because the surface represents the floor of a slackwater lake rather than a former floodplain surface, it generally slopes at a much shallower angle than the adjacent modern tributary stream and floodplain. This results in the terraces being evident typically for a few kilometers upstream from the mouths of the tributary valleys.

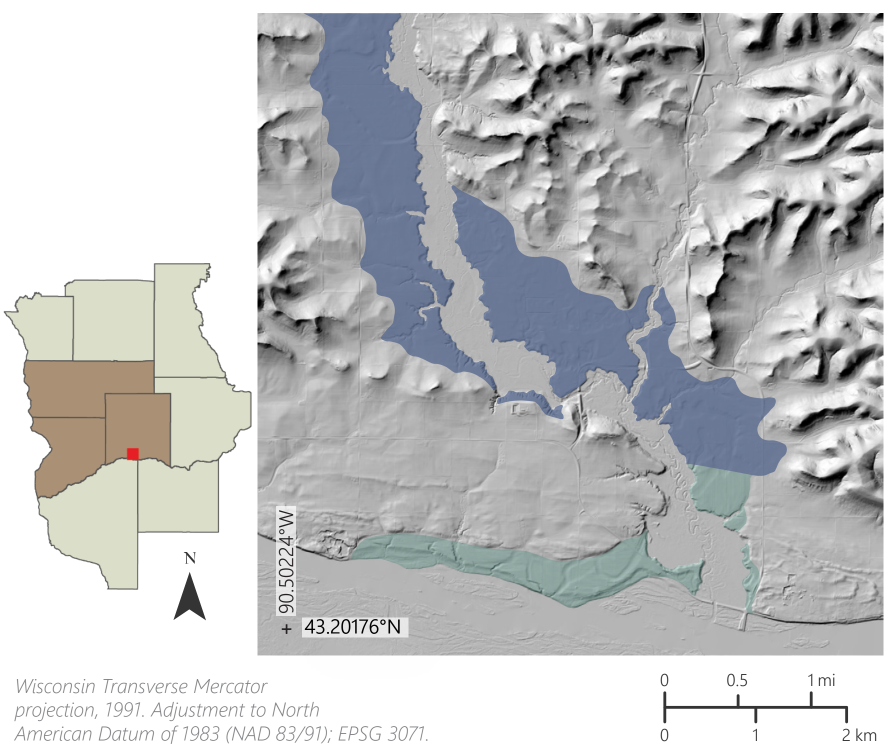
Along the Mississippi River, this terrace is known as Savanna terrace, map unit **atv**. Because of the outburst flooding following the peak of the most recent glaciation that scoured meltwater deposits along the main stem Mississippi River corridor (Flock, 1983), the Savanna terrace is 15 to 20 m (50 to 65 ft) above adjacent pool elevation on the Mississippi River and often 10 to 12 m (33 to 40 ft) above the Bagley meltwater terrace (fig. 23). Along the lower Wisconsin River, where no similar late-glacial scouring occurred in the main stem valley, the topographic surface of the slackwater terraces (only found in tributary mouths), map unit **atl**, grades to the elevation of the meltwater terraces (only found on the main stem lower Wisconsin River), map unit **atm** (figs. 22 and 24). These terraces along the Mississippi River and lower Wisconsin River are correlative and were deposited coevally with the meltwater terraces, map units **atm** and **atb**. Along the lower Wisconsin River, map units **atm** and **atl** have been mapped separately to emphasize the difference in meltwater sand and gravel versus laminated fine-grained slackwater sediment in the two map units, respectively.

Non-glacial terrace

In a limited setting within the three-county study area (although not unique across the greater Driftless Area), a terrace occurs along a substantial extent of the Kickapoo River and along more limited reaches of the Pine River and one of its tributaries, Willow Creek. Coring has demonstrated that the terrace is constructed of fine-grained, well sorted sand, as opposed to laminated silt and clay found in slackwater terraces and in other unglaciated tributaries in the study area. This terrace grades at a slope very close to the slope of the modern floodplain and thus can be mapped approximately 85 km (53 miles) upstream along the Kickapoo River from its mouth (fig. 25); slackwater terraces, which have almost no surface slope moving up-valley, can only be mapped approximately 10 km (6 miles) upstream from the mouths of tributary valleys.

We interpret this terrace, map unit **atn**, to represent Cambrian sand that was excavated in the upper reaches of the Kickapoo River and transported downstream when sediment flux was at a maximum during permafrost conditions in the late Pleistocene (Batchelor and others, 2019). AMS radiocarbon ages indicate aggradation of this terrace sediment had started by 26,700 years before present and continued through at least 19,800 years before present (Carson and others, 2018). This terrace was deposited coevally with the previously discussed meltwater and slackwater terraces. It does not grade similarly to any other terrace unit because its source was sand from the headwaters of the Kickapoo River rather than glaciogenic sediment from the main stem stream.

Figure 24. **Slackwater terrace sediment, map unit atl, shown by blue shading, at the mouth of the Pine River in southern Richland County. Meltwater terrace sediment, map unit atm, is shown by green shading along the lower Wisconsin River in the southern portion of the image.**



Lacustrine sediments

Many streams in the Driftless Area, and in adjacent areas in southeast Minnesota and northeast Iowa, have a meandering planform that is significantly incised into the Paleozoic bedrock. Numerous tributaries to the lower Wisconsin and Mississippi Rivers that exhibit this morphology—including the Kickapoo, Grant, and Platte rivers in Wisconsin; the Turkey and Upper Iowa rivers in Iowa; and the Root and Zumbro Rivers in Minnesota—also preserve meander loops carved into the Paleozoic strata that have been abandoned by those streams. Numerous of these abandoned bedrock meanders are found along the lower reaches of the Kickapoo River in southern Crawford County (fig. 26). These areas have been mapped as Offshore Sediment in Bedrock Paleomeanders, map unit **op**. Direct-

Figure 25. Non-glacial terrace sediment, map unit atn, along the Kickapoo River in northeast Crawford County.

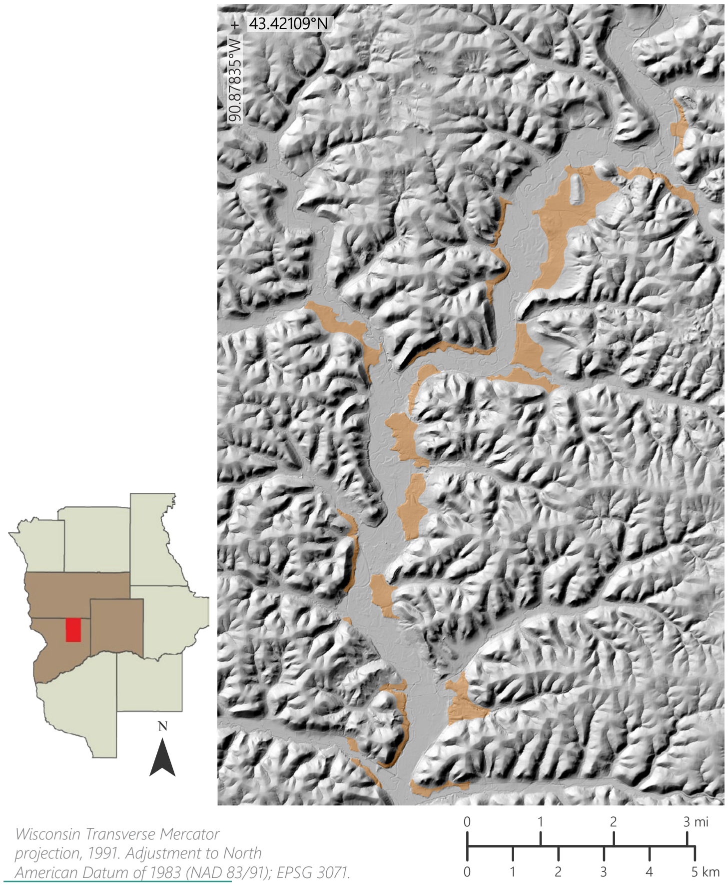
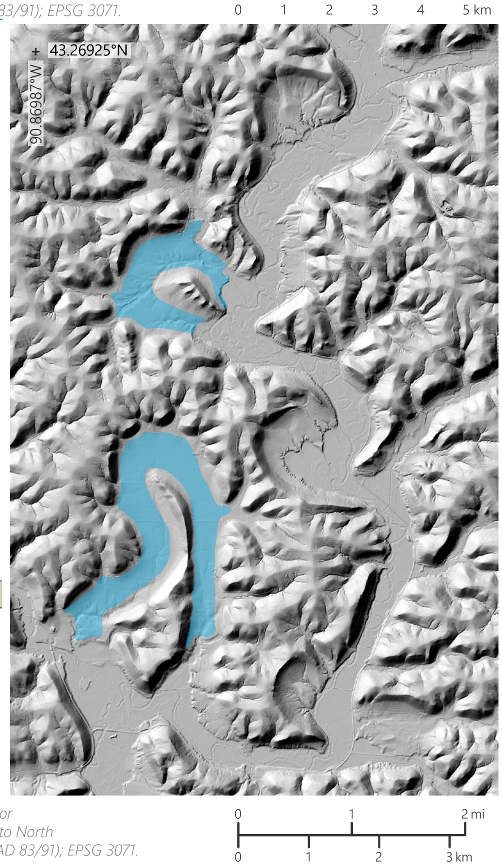


Figure 26. Slackwater paleomeanders filled with lacustrine sediment, map unit op, along the lower Kickapoo River in southern Crawford County.



push and rotosonic coring into sediment preserved in the abandoned bedrock meanders in Crawford County reveals that the features are filled with material consistent with slackwater lacustrine sedimentation in response to sand aggradation on the main stem Kickapoo during the latest Pleistocene. AMS radiocarbon ages returned from riparian plant macrofossils constrain both aggradation of sand on the Kickapoo River and deposition of lacustrine sediment in the abandoned bedrock paleomeanders to have started by 26,700 years before present and continued through at least 19,800 years before present (Carson and others, 2018).

Alluvium

Streams in the Driftless Area largely exhibit a dendritic, or branching pattern, reflecting incision into bedrock that has occurred over millions of years; the same pattern of bedrock incision likely occurs over much of the Midwest, but is obscured by younger glacial sediment everywhere except in the Driftless Area (Knox, 2019). Most tributary streams in the Driftless Area exhibit a meandering pattern to the channel, although the lower Wisconsin River and Mississippi River are braid-bar systems (though this is largely obscured on the Mississippi River by the locks and dams built for navigation). Alluvium, map unit **al**, is typically sand and gravel on the main stem streams with fine-grained sediment deposited in sloughs and backwater areas; it is a mix of lateral accretion point bar sands and fine-grained overbank sediment along tributary valleys. This represents stream sediment deposited during the Holocene. Pre-Holocene alluvium, map unit **ap**, is confined to tributary streams and occurs higher on the landscape than map unit **al**, suggesting that it was deposited at the end of the last glaciation (~19,000 years before present).

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Supplemental material

The following materials are available for download at https://doi.org/10.54915/jpzs9081:

Map: Geologic map
A map (.pdf format) of the Quaternary geology of Vernon County.

Dataset 1: GIS data
GeMS Level 3 file geodatabase (.gdb format) including map unit contacts and core locations.

Dataset 2: Core data
Table (.csv format) of locations (latitude, longitude), identification numbers, and depths of sediment cores collected in Vernon County. See Map 514 (https://doi.org/10.54915/uddu2475) and Map 515 (https://doi.org/10.54915/ptqi5841) for data tables associated with Crawford and Richland counties, respectively.

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