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2018

Open-File Report 2018-01

Contents:

- Report (27 p.)

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Preliminary Bedrock Geology of Southern Trempealeau County, Wisconsin

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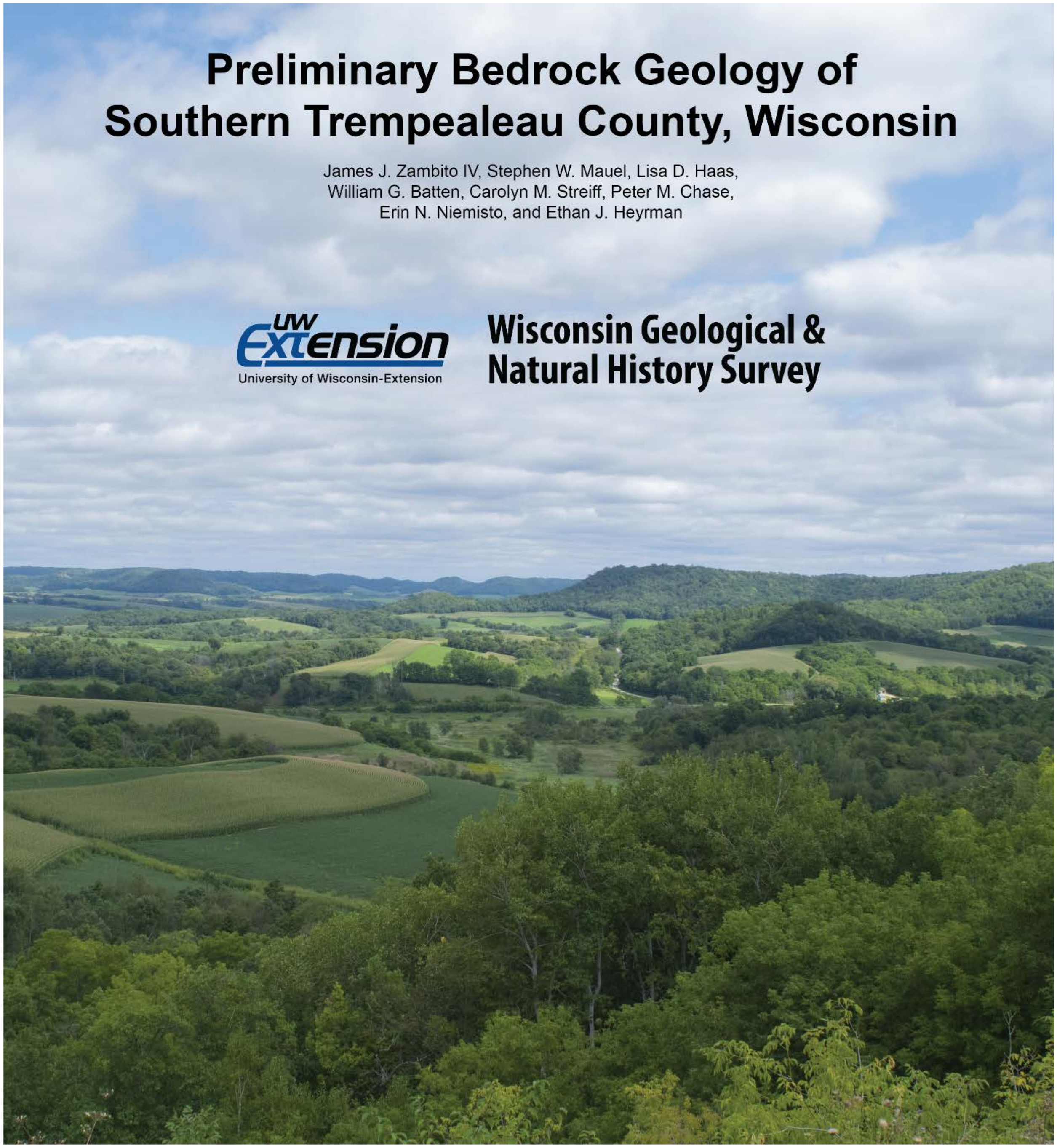


View from Arcadia Ridge, Tamarack quadrangle, looking east across central Trempealeau County.

Abstract

Trempealeau County, in west-central Wisconsin, is at the center of the nation's frac sand resources. However, the current state of knowledge concerning the abundance, quality, and distribution of this natural resource is generalized; industry, government, and citizens in Wisconsin demand detailed information regarding the distribution of this resource and the potential effects of sand mining on surface and groundwater quality. The authors of this report are currently engaged in a two-year bedrock geology mapping project of Trempealeau County at the 1:100,000 scale; this report represents the results of the first year of mapping. Year 1 is focused on developing a mapping methodology for the study area, and Year 2 on sandstone mineralogy and trace metal geochemistry. In this report, we focus on the southern portion of Trempealeau County, specifically the parts of the county within the following 7.5-minute quadrangles: Blair, Dodge, Ettrick, Galesville, Hegg, Holmen, Pickwick, Stevenstown, Tamarack, Trempealeau, Whitehall, and Winona East. The purpose of producing this report mid-project is to allow potential users of the final map, including industry, government, and private citizens, to have a chance to provide input into the mapping methods and map product so that the final product can be as useful as possible. This includes members of the Wisconsin Geological Mapping Advisory Committee, the Trempealeau County Board of Supervisors, the Wisconsin Department of Natural Resources, and industrial sand mining companies in the map area.

Map units that were used to create the preliminary bedrock map include, from oldest to youngest: the Mount Simon Formation, Eau Claire Formation, Wonewoc Formation, Lone Rock Formation, Trempealeau Group (St. Lawrence and Jordan Formations), Prairie du Chien Group, and St. Peter Formation. Large extraction operations studied to date include aggregate quarries that extract dolostone from the Prairie du Chien Group and industrial sand mines that extract sand from the Wonewoc Formation. Smaller extraction operations, presumably for local use, include sandstone pits in the Wonewoc and Eau Claire Formations, shale pits in the Eau Claire and Lone Rock Formations, and small quarries in the St. Lawrence Formation.

One key result of Year 1 mapping is the recognition that the acquisition of drill core is necessary for: (1) accurately determining the elevation of map unit contacts because these contacts rarely outcrop in the study area; (2) constraining thickness changes in map units, which is difficult with outcrops alone because map unit contacts are rarely exposed; and (3) understanding how redox, and therefore rock color and cementation, differ within map units. Furthermore, a consideration for finalizing a map of the county is the observation that large differences exist in depth to bedrock in closely spaced wells as recorded in well construction reports (WCRs) located at the base of hillslopes at the edge of river valleys. At the end of the second year of mapping, we aim to have a better constraint on the bedrock topography and potential models for its genesis. Another consideration for the second year of this project is that more data from neighboring counties is required in order to carry map unit layers accurately to the edge of the counties; currently, data at the border of the map is relatively sparse.

Introduction

Trempealeau County, in west-central Wisconsin, is at the center of the nation's frac sand resources. Advances in extracting domestic unconventional oil and gas using hydraulic fracturing have increased the demand for industrial (frac) sand. Many of the Paleozoic sandstone formations in Wisconsin meet hydraulic fracturing proppant specifications, are widespread, at the surface, and along transportation corridors for shipment to unconventional plays in other states (Parsen and Zambito, 2014a, b). While the current state of knowledge concerning the abundance, quality, and distribution of this natural resource is fairly generalized, industry, government, and citizens in Wisconsin demand detailed information regarding the distribution of this resource and the potential effects of sand mining on surface and groundwater quality.

The authors of this report are currently engaged in a two-year bedrock geology mapping project of Trempealeau County at the 1:100,000 scale; this report represents the results of the first year of mapping (fig. 1). Year 1 is focused on developing a mapping methodology for the study area, and Year 2 on sandstone mineralogy and trace metal geochemistry. The purpose of producing this report mid-project is to allow potential users of the final map, including industry, government, and private citizens, to have a chance to provide input into the mapping methods and preliminary map so that the final product can be as useful as possible. The Wisconsin Geological and Natural History Survey (WGNHS), in consultation with the Trempealeau County Board of Supervisors, have identified nonmetallic mineral resource distribution and surface/groundwater quality as areas of importance to communities in this county. The existing geologic map for Trempealeau County was constructed at the 1:250,000 scale (fig. 2; Brown, 1988) and is inadequate for answering current questions and concerns. Paleozoic frac sand and aggregate represent Trempealeau County's main nonmetallic resources, and detailed knowledge of bedrock stratigraphy in the region is essential for environmentally responsible extraction.

Prevention of potential mining impacts on surface and groundwater quality will benefit from a better understanding of the presence, abundance, and geochemistry of trace metal-bearing sulfides found within the bedrock. A preliminary WGNHS study of Cambrian siliciclastics throughout west-central Wisconsin has documented the presence of sulfide minerals in some Cambrian sandstones, which also serve as aquifers at depth (fig. 2; Zambito, Parsen, and others, 2016; Haas and others, 2016). A more-detailed understanding of the presence/absence, mineralogy, and trace metal composition of sulfides will allow industry and regulators to make informed decisions regarding resource extraction/reclamation and water well construction. This map will inform county officials as they make land-use decisions with immediate and long-term impacts.

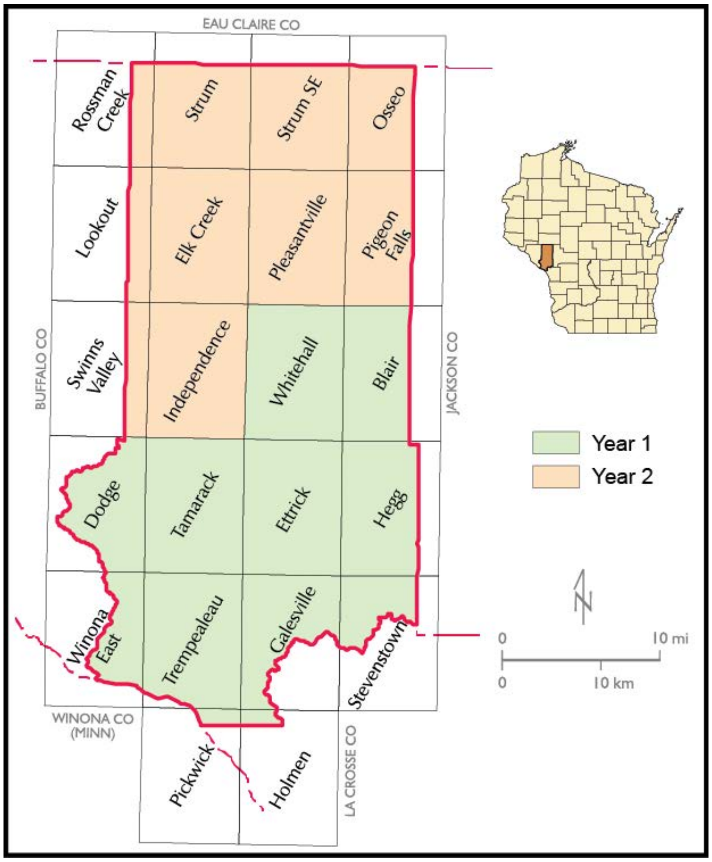
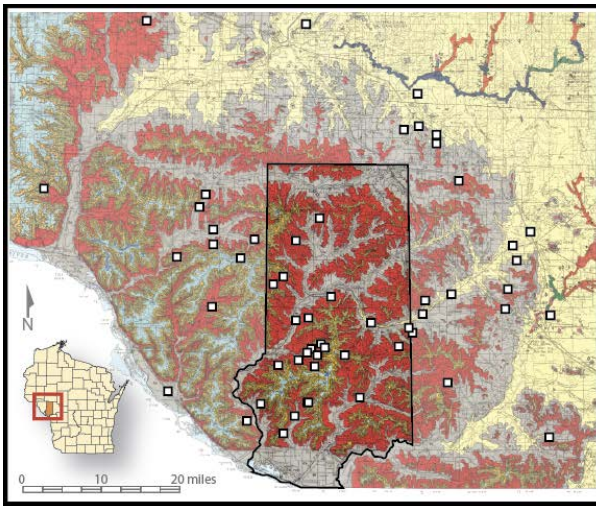


Figure 1: Two-year mapping plan for Trempealeau County.



Correlation of map units in Trempealeau County

	Unit		Aggregate	Frac sand	Other sand uses	Aquifer
ORDOVICIAN	Oa	Ancell Group				
	— Sauk-Tippecanoe Sequence Boundary —					
	Op	Prairie du Chien Gp.	X			
	— major unconformity —					
CAMBRIAN	€t	Trempealeau Gp.	X	X	X	
	€tc	Tunnel City Group		X	X	X
	€w	Wonewoc Fm.		X	X	X
	€e	Eau Claire Fm.		X	X	
	€m	Mount Simon Fm.				X

(Column heading: Resource Uses)

□ Frac sand mines and processing plants (active/permitted as of Oct. 2012)

Figure 2: Trempealeau County is at the center of large-scale industrial (frac) sand mining in west-central Wisconsin. Prior to the current project, the most recent mapping of Trempealeau County was done at the 1:250,000 scale as part of a regional bedrock geology map (Brown, 1998). Trempealeau County has abundant industrial sand and ample aggregate resources; black X's indicate common uses and high extraction rates for the designated purposes, gray X's indicate less common uses and lower rates of extraction.

Geologic setting and prior work

Trempealeau County is located in west-central Wisconsin (fig. 1). Its dissected topography is a ubiquitous feature of the Driftless Area, a region with no evidence of subglacial sedimentary deposits. Proglacial meltwater, modern and ancient fluvial (alluvium), eroded hillslope-derived (colluvium, potentially deposited over millions of years), and windblown (loess, also potentially deposited over millions of years) deposits are all present in the map area but were not investigated in the present study (Thwaites, 1964; Muldoon and Craven, 1998; Cates, 2001). In river valleys, particularly in the southwestern part of the county, deep channels cut through bedrock and unconsolidated fluvial sediment (alluvium) consisting of sand and gravel is up to 225 feet thick according to Wisconsin Department of Natural Resources well construction reports (WCRs) and WGNHS well logs.

The county's bedrock geology is comprised of a buried Precambrian surface overlain by upper Cambrian siliciclastics and, at the highest elevations, Ordovician carbonates and siliciclastics (fig. 2). Wisconsin's Precambrian surface forms regional highs, the Wisconsin Dome and Arch in northern and central Wisconsin, respectively, that were onlapped by Paleozoic strata (Ostrom, 1964; Hinze and Braile 1988; Runkel and others, 1998). Across the study area, Cambro-Ordovician units were deposited on the western slope of the Wisconsin Arch with a facies transition from shallow submarine settings in the northeast to deeper water settings in the southwest toward the Hollandale Embayment depocenter (Runkel and others, 2007).

Bedrock mapping in Trempealeau County was previously done at the 1:250,000 scale (Brown, 1988). Neighboring counties that have been mapped recently at the 1:100,000 scale include La Crosse, Wisconsin (Evans, 2003), and Winona, Minnesota (Steenberg, 2014). A depth-to-bedrock model of the county exists (Cates, 2001), but it does not take into account new, higher quality data from wells drilled since 1987 and would not provide a high-resolution bedrock topography base layer appropriate for current mapping. The number of new wells, spatial distribution of those wells informs and improves our work over previous years.

The Precambrian basement in the map area consists of the Archean continental crust of the Marshfield terrane, with the Spirit Lake Tectonic Zone, separating the Marshfield terrane from the Yavapai Province, presumably running through the southernmost part of the county (NICE working group, 2007; Van Schmus and others, 2007). The Cambro-Ordovician litho- and sequence stratigraphy and depositional environments have been described by Runkel and others (1998, 2007) as part of regional synthesis of Upper Mississippi River Valley. A soon-to-be-completed regional study has identified trace metal-bearing sulfides in the map area that warrant further detailed investigation (Zambito, Parsen, and others, 2016; Haas and others, 2016).

The map area contains the type sections for both the Trempealeau Group and the Galesville Member of the Wonewoc Formation. The Trempealeau Group was originally described by Thwaites (1923) and Ulrich (1924) for exposures of sandy dolomitic shales, dolostone (Black Earth Member of St. Lawrence Formation), yellow and purple thin-bedded sandy dolostone (Lodi Member of St. Lawrence Formation), and dolomitic sandstone (Norwalk Member of

Jordan Formation) along "Trempealeau Bluff" on the Mississippi River, a geographic name that is not found on current maps. (Twenhofel and others, 1935, included other members of the Jordan Formation in the Trempealeau Group; see also Nelson, 1956, for discussion of unit nomenclature). Twenhofel and others (1935) state that Ulrich applied the name to strata exposed on a large bedrock outlier in the otherwise flat Mississippi River Valley adjacent to the Village of Trempealeau, Wisconsin. Ostrom (1966) noted that the Trempealeau Group type section was concealed by vegetative overgrowth and slumping, and designated nearby Bradys Bluff in Perrot State Park as a reference section; it is currently poorly exposed at this location as well. The Galesville Member of the Wonewoc Formation was first described by Trowbridge and Atwater (1934), and is named for the coarse-grained unfossiliferous sandstone exposed along the bluff of Beaver Creek at the mill dam at Galesville, Wisconsin, now called High Cliff Park (fig. 3). Ostrom (1966, 1970) and Ostrom and others (1970) observed relief of about 15 feet at the contact between the Galesville Member and the underlying Eau Claire Formation at this locality.

Figure 3: Type section of the Galesville Member of the Wonewoc Formation, High Cliff Park along Beaver Creek in Galesville, Wisconsin. Picture was taken in early spring. The contact between the Wonewoc Formation and the underlying Eau Claire Formation can be difficult to recognize because the bluff is highly weathered and the outcrop surface case-hardened. Ostrom's observation of about 15 feet of relief on this contact is based on exposures to the left of the area shown.

Materials and methods

The overall goal of this project is to produce a 1:100,000 scale bedrock geology map of the entire county. In this report, we focus on the southern portion of Trempealeau County, specifically the parts of the county within the following 7.5-minute quadrangles: Blair, Dodge, Ettrick, Galesville, Hegg, Holmen, Pickwick, Stevenstown, Tamarack, Trempealeau, Whitehall, and Winona East (fig. 1; plate 1). For Year 2 we will map the remaining quadrangles: Elk Creek, Independence, Lookout, Osseo, Pigeon Falls, Pleasantville, Rossman Creek, Strum, Strum SE, and Swinns Valley.

Geologic data that was used to define map units and determine their distribution comes from cores, outcrops, active and inactive quarries/mines/pits, well cuttings, well geophysical logs, and geochemical analyses of core and well cutting samples. With a few exceptions, the data used to construct this preliminary map comes from within the county boundary, and some data is from the Year 2 map area. In Year 1 of 2 we drilled three cores (62000213–Lockington, 62000216–Weltzien Quarry, and 62000218–Thompson Valley) and analyzed a fourth core (62000166–Arcadia Quarry) that we had drilled as part of a previous groundwater quality study (fig. 4a, plate 2); these cores are all housed at the WGNHS core repository in Mount Horeb.

To locate and study outcrops and quarries/mines/pits, we drove along roads in the map area and noted the location of bedrock exposures and the map units present, and, if observed, map unit contacts; at the time this preliminary map was constructed, we had studied 575 bedrock exposures (fig. 4b). We also studied area well cuttings at the WGNHS core repository in order to define subsurface stratigraphy. For the entire county, we have identified 36 high-quality and stratigraphically useful well cutting sample sets and have studied a majority of those within the map area for Year 1 (fig. 4c). We collected geophysical logs from core holes that we drilled (with the exception of 62000218–Thompson Valley in which well construction prohibited geophysical logging), from wells associated with a sand mining operation near Blair, and from a municipal drinking water well at Arcadia (fig. 4d).

We studied the geology of large extraction operations for construction of this map such as aggregate quarries that extract dolostone from the Prairie du Chien Group (17 total, 7 active) and industrial sand mines (12 total and active) that extract sand from the Wonewoc Formation. Smaller extraction operations, presumably for local use, include sandstone pits in the Wonewoc and Eau Claire Formations (15 total, 6 active), shale pits in the Eau Claire and Lone Rock Formations (45 total, 5 active), and small quarries in the St. Lawrence Formation (12 total, 3 active). A quarry/mine/pit was determined to be active if there appeared to be land disturbance within the last 5 years based on site visits and/or aerial photography and lidar-derived digital elevation model (5 foot; DEM); therefore “active” herein does not necessarily indicate extraction.

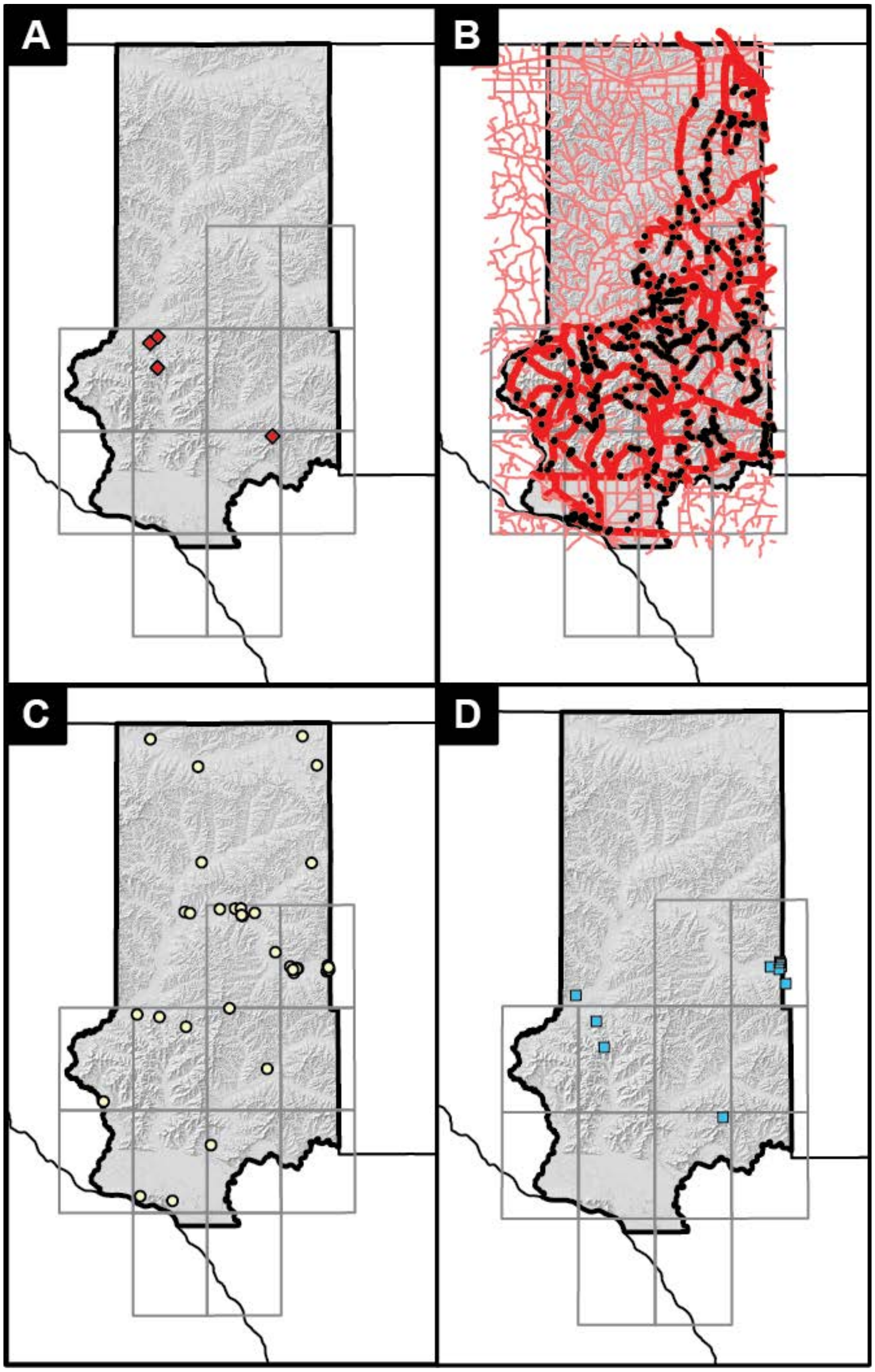


Figure 4: Distribution of geologic datasets used to construct the preliminary bedrock geology map. Base map is a digital elevation model, gray rectangles denote quadrangle boundaries (see fig. 1). A) Location of drill cores studied (red diamonds, n = 4). B) Location of outcrops studied to date (black dots, n = 575). Thin red lines represent roads in the area; bolder red lines indicate roads driven while searching for bedrock outcroppings. C) Location of well cutting sample sets that are being utilized as part of this study (n = 36). D) Location of geophysical logs (the most useful for this study being natural gamma) used to aid subsurface correlations (n = 11).

Geochemical analyses were undertaken using a portable x-ray fluorescence (pXRF) analyzer at WGNHS (see Zambito, McLaughlin, and others, 2016, for methodological details). Cores were analyzed at <0.5-foot intervals for elemental concentrations to aid in unit description; herein we present data on calcium, aluminum, and silicon, using these elemental concentrations as proxies for carbonate cement, aluminum silicate content (as well as gamma), and quartz sand, respectively (see Zambito and others, 2017, for further details on pXRF chemostratigraphy).

Map units were determined based on the spatial resolution, quality, and confidence in the available data to differentiate and trace/correlate units at the 1:100,000 scale. To develop the preliminary map, we used the software program Petrel (E&P Software Platform 2016) to create a three-dimensional model of the map unit layers. This was undertaken as an iterative process: initial map unit layers were constructed using map unit contacts based on subsurface records (cores, cuttings, and geophysical logs) and map unit contacts in outcrop, and then manually adjusted to accommodate outcrop and quarry/mine/pit observations. For example, a three-dimensional layer was created for the top of the Wonewoc Formation (contact of the Wonewoc Formation with the overlying Lone Rock Formation) by correlating across the map area the occurrences of this horizon observed in cores, cuttings, geophysical logs and outcrops. Next, we plotted all the occurrences of Wonewoc Formation outcrops and Lone Rock Formation outcrops in this same three-dimensional space. Lastly, we adjusted the top of Wonewoc Formation layer so that it was above (at a higher elevation than) any Wonewoc Formation outcrops and below (at a lower elevation than) any Lone Rock Group outcrops. Our final top of Wonewoc surface was therefore constrained not only by subsurface correlations but also all available surface data. This process was repeated for the tops of the Mount Simon Formation, Eau Claire Formation, Lone Rock Group, Trempealeau Group, and Prairie du Chien Group using available subsurface and outcrop data to create additional three-dimensional layers. We used the Smooth function in Petrel (iterations = 20, filter width = 5 to 20) to reduce local distortions in the surface that resulted from manual manipulation while adjusting these map unit layers to accommodate outcrop and quarry/mine/pit observations. Map unit layers were then intersected with the bedrock topography surface base layer and exported to ArcGIS where polygon editing and cartographic construction was undertaken. The distribution of the Wonewoc Formation on the map (plate 1), for example, is therefore the area between the top of Wonewoc Formation and the top of Eau Claire Formation layer intersections with the bedrock topography base layer.

The bedrock topography base layer, which is the base map for plate 1, was constructed using a combination of landform analysis, field observations, and depth to bedrock data available from well construction reports. First, we applied the Topographic Position Index method of Weiss (2001) and Jenness (2006) to derive a basic landform map from a 5-foot resolution DEM of the map area. Topographic Position Index (TPI) is the difference between the elevation of a cell and the mean elevation of neighboring cells; this forms the basis of a landform classification system and has been used in previous geologic mapping studies (Ilia and others, 2013). The goal of using TPI for constructing a bedrock topography model in this study was to use an algorithm to identify the spatial extent of three basic landforms (valley floors, hillslopes, and ridgetops;

quarries were also identified by the algorithm because they are flat areas on top of ridges), or bedrock elevation interpolation components, rather than trace them out by hand in ArcGIS. Modelling bedrock topography in the Driftless Area saves a considerable amount of time given the dendritic incision of the map area (plate 1), and provides a high-resolution bedrock topography model. We successfully derived these three basic landforms (plus quarries) using a combined window (analysis grid) size of 1000 by 1000 meters and 2000 by 2000 meters in TPI analysis. This provided the most generalized landform classification for the geomorphology of the study area, which we feel is appropriate for the final map product at 1:100,000 scale (fig. 5). We visually inspected the results of the TPI classification and manually corrected areas that had been mischaracterized (for example, piles of sand on valley floors identified as hillslopes/ridgetops, and floors of aggregate quarries on ridgetops identified as plains).

The second step in making the bedrock topography base layer was to apply a depth-to-bedrock estimate for each landform. Based on our field observations while mapping (fig. 6) and our study of well construction reports in the study area, we determined that the depth to bedrock was probably at most 15 feet on ridgetops and 8 feet on hillslopes, but deeper in valleys. With the exception of large quarries and mines, where the depth to bedrock equals zero, we subtracted 5 feet from the DEM in order to make sure the bedrock topographic layer always occurs below land surface; 5 feet was chosen because it is negligible at the scale mapped (1:100,000). We then subtracted an additional 15 feet from landforms classified as ridgetops and 8 feet from hillslopes. For valley floors we interpolated depth to bedrock from geo-referenced WCRs and feathered, over two cells (10 meters), where different landform classifications met. Lastly, to model the top of bedrock surface, we manually contoured the valleys in Petrel, paying particular attention to the large valley that runs between Trempealeau and Centerville in the southern tip of the county. In the valley floor zone, a number of peaks and pits resulting from the poor spatial resolution of depth to bedrock measurements available from WCRs; these were smoothed (removed) manually in Petrel.

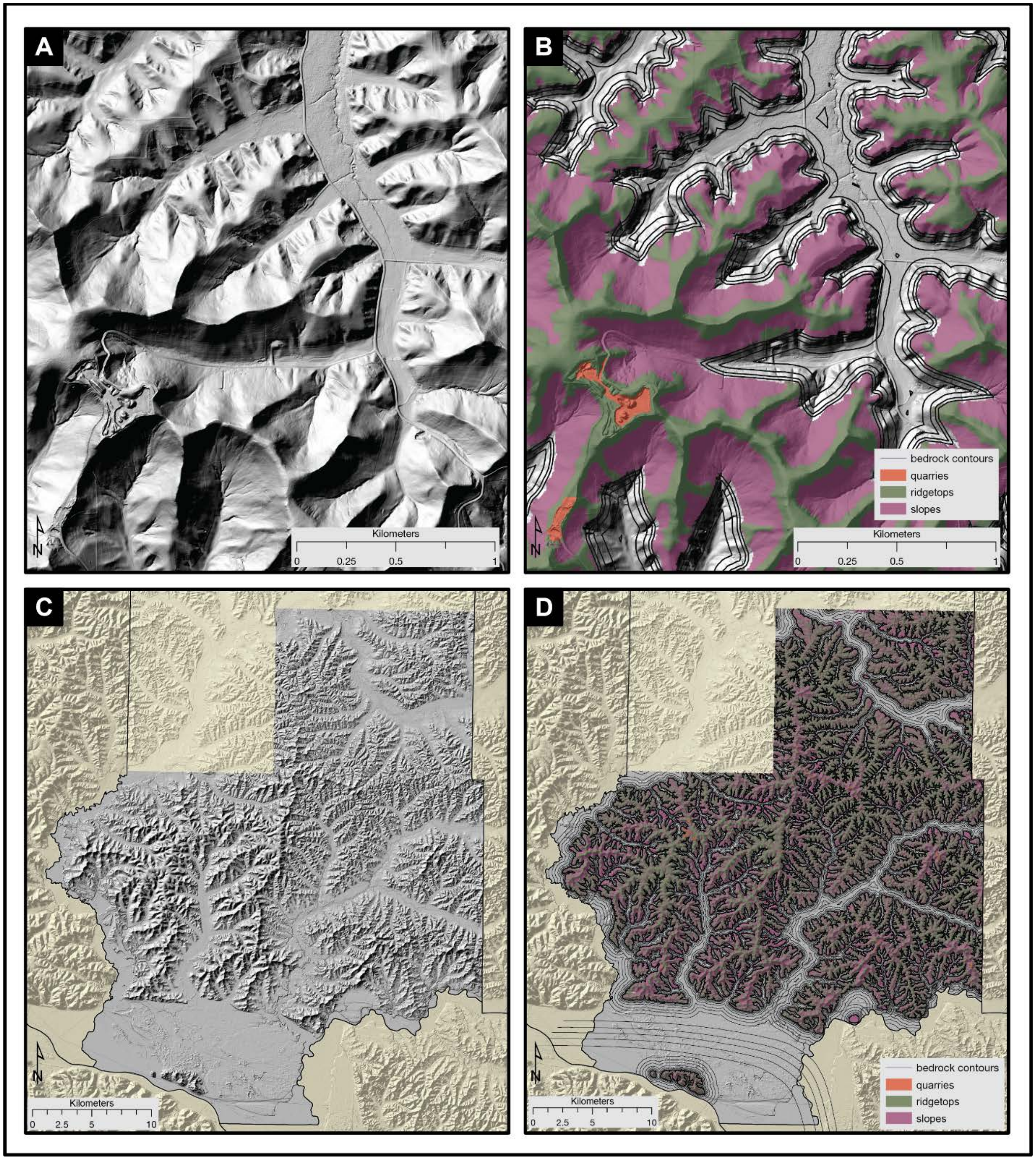


Figure 5: Examples of landform classification using the Topographic Position Index (TPI) method. A) Shaded relief of topography for a portion of the map area. B) Distribution of landform classes determined by TPI (valley floors, hillslopes, and ridgetops, plus quarries) and estimated bedrock depth contours used to create bedrock interpolation components. C) Shaded relief of the Year 1 of 2 map area, southern Trempealeau County D) Distribution of landform classes determined by TPI and the estimated bedrock depth contours used to create bedrock interpolation components within the Year 1 map area.

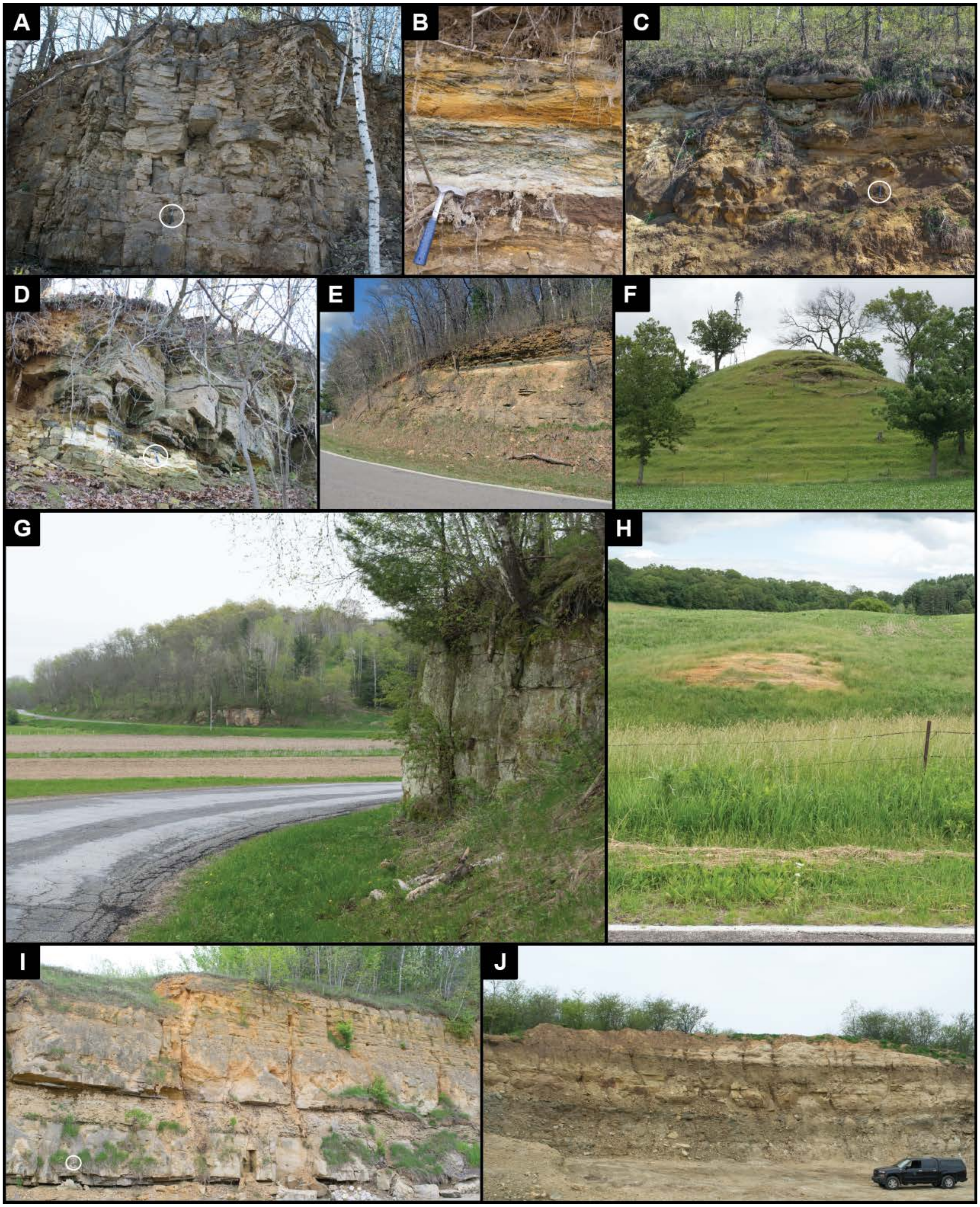

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Figure 6: (previous page): Pictures showing depth to bedrock observations in the field. Note that regardless of lithology, the depth to bedrock is very shallow in the map area. In pictures A, C, D, and I, a white circle identifies the location of a hammer placed for scale. A) Prairie du Chien Group, aggregate quarry wall, Town of Arcadia, Whitehall quadrangle. B) Stockton Hill Member of the Oneota Formation, Prairie du Chien Group, roadcut showing soil at top of picture and roots extending into bedrock, Town of Arcadia, Independence quadrangle; hammer for scale. C) Jordan Formation, roadcut, Town of Arcadia, Dodge quadrangle. D) St. Lawrence Formation, roadcut, Town of Arcadia, Whitehall quadrangle. E) Lone Rock Formation, roadcut, Town of Arcadia, Whitehall quadrangle; outcrop is ~6 meters tall. F) Wonewoc Formation, natural outcropping in pasture, Town of Sumner, Strum SE quadrangle; windmill water pump for scale. G) Wonewoc Formation, natural outcropping along valley-wall in foreground and distance, Town of Arcadia, Independence quadrangle; road for scale. H) Wonewoc Formation, natural outcropping in farm field, Town of Hale, Whitehall quadrangle; barbed wire fence for scale. I) Contact intervals of the Wonewoc and Eau Claire Formations, outcrop in parking lot, Town of Arcadia, Swinns Valley quadrangle. J) Eau Claire Formation, active shale pit, Town of Chimney Rock, Elk Creek quadrangle; pick-up truck for scale.

Results

Map units that were used to create the preliminary bedrock map include, from oldest to youngest: the Mount Simon Formation, Eau Claire Formation, Wonewoc Formation, Lone Rock Formation, Trempealeau Group, Prairie du Chien Group, and St. Peter Formation. This nomenclature conforms with Ostrom (1967) and Ostrom and others (1970), which is the current WGNHS standard (WGNHS, 2011); the reader is referred to these references and plate 1 for further details of the lithostratigraphic framework. Bedrock units in Trempealeau County are nearly flat-lying, with a shallow dip to the southeast that likely reflects depositional dip. Bedrock was at or near the land surface everywhere except on valley floors. In the largest river valleys, bedrock commonly outcropped where valley walls met flat valley floors. In smaller valleys, bedrock was observed at or near the surface along hillslopes and near ridgetops. This suggests that the 15 and 8 feet subtracted from the countywide digital elevation model for ridgetops and hillslopes (valley walls), respectively, is likely an overestimate for depth to bedrock in much of the map area. Precambrian rocks do not outcrop in Trempealeau County, were not penetrated by core holes studied, and are rarely encountered at depth in well-cutting sets; the Precambrian is not addressed further.

The distribution of the data types used to construct the three-dimensional map unit layers is spatially variable (fig. 4). The most accurate information on map unit thickness and the elevation of map unit contacts comes from drill core (fig. 4a, plate 2). The locations of core holes were selected to maximize the number of map units (rock formations) that would be penetrated. As such, in the area just south of Arcadia we drilled three cores that start in the Prairie du Chien Group, and proceed through the Trempealeau Group, Lone Rock Group, Wonewoc Formation, Eau Claire Formation, and penetrate the uppermost Mount Simon Formation (plate 2). These cores constrain the elevation of all map unit contacts, which is the underpinning of our three-dimensional map unit layers (see methods above). Additionally, they provide unparalleled samples of map units with both oxidized and reduced cements (most notably the Wonewoc Formation, plate 2); these samples will be analyzed for mineralogy and elemental composition in year 2 of the project. Whereas the cores provide a continuous vertical succession of map unit "data points" from which to construct our three-dimensional map unit layers, outcrops only provide a single data point. Additionally, outcrop data is constrained to the roads driven while searching for outcrops (fig. 4b). Of the 575 outcrops observed, none were of the Mount Simon Formation, about half were of the Wonewoc Formation, and the remainder divided about evenly among the remaining 6 map units. Well cutting sample sets, which are primarily from municipal wells, are restricted to valleys where population centers are located (fig. 4c). While these sets represent quasi-continuous samples similar to cores as described above, they are almost entirely in the Eau Claire and Mount Simon map units. Geophysical logs are also spatially variable with three collected from boreholes drilled by WGNHS for rock core, one collected from a recently drilled municipal well in Arcadia, and eight logs collected from a series of monitoring wells at an industrial sand mine near Blair (fig. 4d; one log is located just outside Trempealeau County and therefore not shown in fig. 4d).

Unit descriptions

Elk Mound Group (Cambrian)

Mount Simon Formation. In Trempealeau County, the sandstone and shale of the Mount Simon Formation was only observed in subsurface well cutting and core samples; for this reason, we had to infer the location of the contact of the Mount Simon with the overlying Eau Claire Formation (see plate 1). The Mount Simon is the primary aquifer for municipalities (located within valleys) in the map area. The Mount Simon Formation is composed of interbedded quartz sandstone and gray shale; the lower portion of the formation is shalier based on inspection of well-cutting sets and gamma logs (plate 2). The uppermost portion, seen in drill core, is bioturbated, indicating a marine origin for at least that part of the unit. Conglomerates sometimes occur near the base of the Mount Simon Formation where it sits unconformably on Precambrian crystalline basement rocks (WGNHS geologic logs). The formation is up to 375 feet thick in the map area, though thickness is variable due to relief on the top of the Precambrian basement surface. Limited elemental data (with calcium, aluminum, and silicon used as proxies for carbonate cement, aluminum silicate content/natural gamma, and quartz sand, respectively) are shown in plate 2, and suggest that the upper Mount Simon is lithologically similar to the Wonewoc Formation.

Eau Claire Formation. The Eau Claire Formation shows an overall coarsening upward sequence of interbedded green to gray shale and fine-grained thin- to medium-bedded glauconitic quartz sandstone (figs. 3 and 7, plate 2). Phosphatic brachiopod shells, disarticulated trilobites, and bioturbation (*Palaeophycus*) are common. Tool marks (a sedimentary structure cause by a solid object being dragged along a muddy substrate typically by current action), cross-stratification bounded by horizontal bedding surfaces, and hummocky cross-stratification were observed. The Eau Claire Formation appears to sit unconformably on the underlying Mount Simon Formation, though this contact is only observed in two cores (plate 2). The formation is poorly exposed in the map area, with the top of this unit forming valley floors and outcropping only near valley (coulee) mouths along hillsides and in sandstone and shale pits. The Eau Claire

Formation is approximately 120 feet thick in the southeast and approximately 150 feet thick in the northwest of the map area (plate 2). Elemental data are shown in plate 2. These data indicate that the unit is lithologically variable, with a higher aluminum silicate and carbonate-cement content than the underlying Mount Simon Formation or the overlying Wonewoc Formation; for this reason, this unit serves as a regional aquitard.

Wonewoc Formation. The Wonewoc Formation is a medium- to coarse-grained quartz sandstone with thin gray and green shale partings; it is orange-colored where cemented by iron oxides, but can be gray in the subsurface where cemented by iron in reduced mineral phases (figs. 3, 7, and 8, plate 2). Phosphatic brachiopod shells occur, as do burrows, primarily *Skolithos*. Large sets of swaley and trough cross-stratification are ubiquitous; cross-stratification bounded by horizontal bedding surfaces also occurs. The Galesville (lower) and Ironton (upper) Members of the Wonewoc Formation, representing the Sauk II–III subsequence boundary (Runkel and others, 1998) can be identified in complete successions, though they are not shown at the scale mapped (plate 1). The Tunnel City Group unconformably overlies the Wonewoc Formation, with the Wonewoc Formation reworked into the lowest beds of the overlying unit. The lower Wonewoc Formation commonly outcrops along the lower portion of coulees forming the base of bluffs, and is well exposed in sand mines where it is the primary target for industrial sand extraction. The Wonewoc Formation ranges from 125 to 150 feet thick in the map area; it is thicker in the southeast than in the northwest (plate 2). Elemental data are shown in plate 2. These data indicate that this unit is a relatively clean quartz sandstone with only minor carbonate cements; minor aluminum silicate content and poor cementation is one of the reasons it is a suitable industrial sand resource.

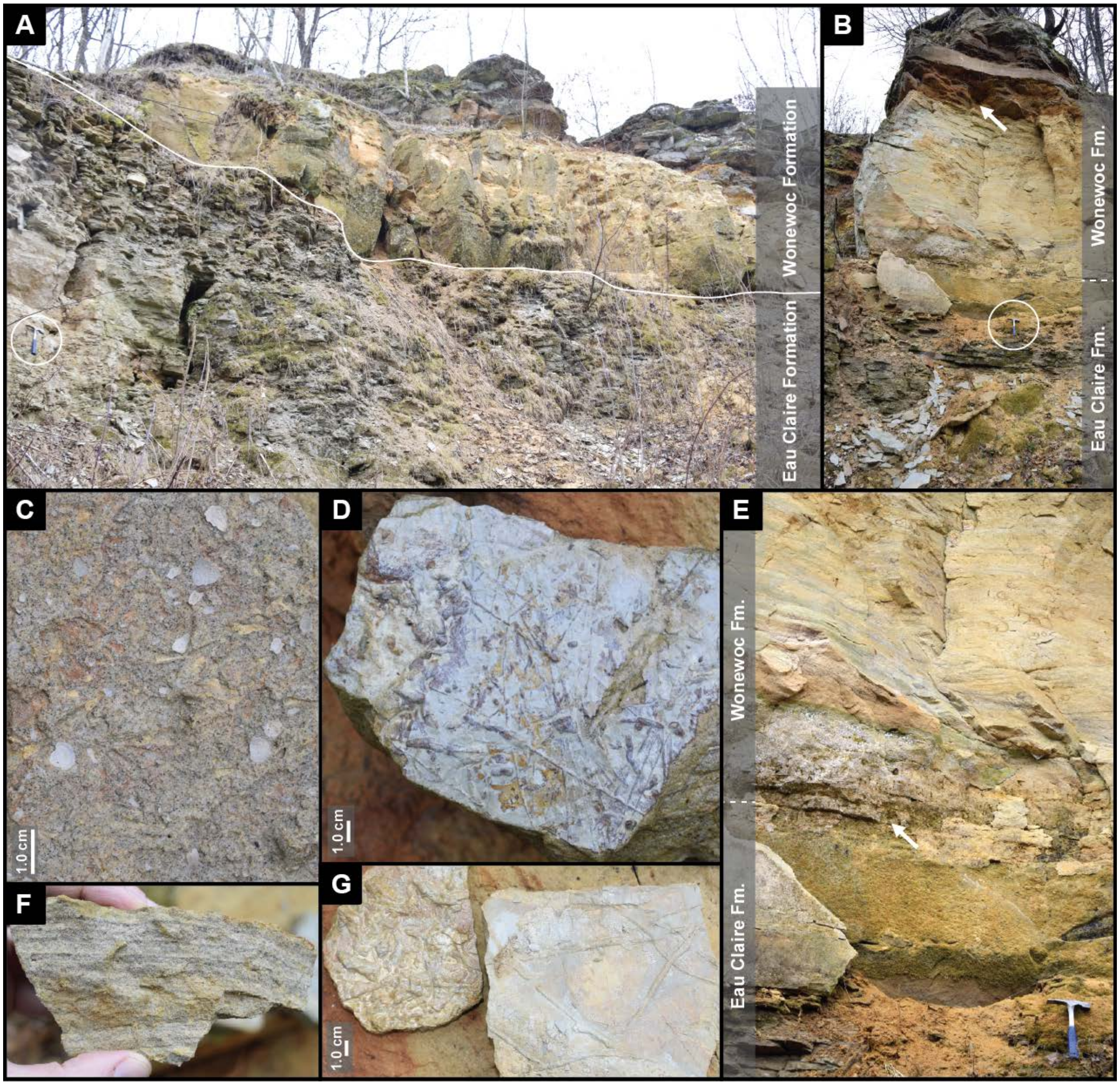

Figure 7: Eau Claire and Wonewoc Formations exposed in an inactive shale/sand pit northwest of Hegg, Wisconsin, Hegg quadrangle. A) Overview photo showing shale-dominated Eau Claire Formation and sandstone-dominated Wonewoc Formation (hammer in white circle for scale). B) View of same interval shown in part A from another part of the locality (hammer in white circle for scale). Note iron oxide-rich interval near top of outcrop (white arrow), a common feature of the Wonewoc sandstone when near overlying regolith/soil. C) Phosphatic brachiopods in glauconitic quartz sandstone (float), Eau Claire Formation. D) Tool marks and burrows on the underside of shaly sandstone of the Eau Claire Formation (float). E) Close-up picture of the contact between the Eau Claire and Wonewoc Formations (hammer for scale). The uppermost Eau Claire Formation is a quartz sandstone with rare glauconite grains; we tentatively place the contact at the base of a *Skolithos* burrowed quartz sandstone (white arrow). F) Cross-bedded glauconitic quartz sandstone typical of the Eau Claire Formation (float). G) *Palaeophycus* traces on the base of shaly sandstone-siltstone of the Eau Claire Formation (float).

Tunnel City Group (Cambrian)

The Tunnel City Group is comprised of the Lone Rock and Mazomanie Formations. Similar to neighboring La Crosse County (Evans, 2003), the Mazomanie Formation was not recognized in Trempealeau County.

Lone Rock Formation. The Lone Rock Formation and its members are identifiable in the map area. The members, from oldest to youngest, are Birkmose, Tomah, and Reno; these are not differentiated at the map scale (plate 1). The Birkmose Member is a dolomite-cemented, coarse-grained, glauconitic sandstone to sandy dolostone with flat-pebble conglomerates; the Tomah Member is a tan to white-colored, medium-grained, glauconitic quartz sandstone; and the Reno Member is a glauconitic medium- to coarse-grained quartz sandstone with flat-pebble conglomerates (figs. 8 and 9, plate 2). *Palaeophycus* and *Skolithos* are common, as is hummocky cross-stratification and cross-stratification bounded by horizontal bedding surfaces. The contact with the overlying St. Lawrence Formation is sharp and unconformable. The Lone Rock Formation is commonly exposed in shale pits, along roads leading to ridgetops, and at the top of sand mine high walls where the Wonewoc Formation is extracted and the Birkmose Member forms the caprock. The formation is approximately 150 feet thick in the map area. Elemental data for part of the Lone Rock Formation is shown in plate 2. These data show the formation's lithologic variability, in particular the distinct upper carbonate-cemented and lower sandstone-dominated intervals in the Birkmose; the lower interval consists of reworked quartz grains from the underlying Wonewoc with interspersed, rare glauconite grains and phosphatic brachiopods.

Trempealeau Group (Cambrian)

The Trempealeau Group is comprised, from oldest to youngest, of the St. Lawrence and the Jordan Formations; it has a combined thickness of approximately 125 feet in the map area.

St. Lawrence Formation. The St. Lawrence Formation is subdivided into green and buff to tan glauconitic and thrombolitic dolostone of the Black Earth Member and buff to tan thin planar-bedded siltstone and sandy dolostone of the Lodi Member; these lithostratigraphic members interfinger (fig. 9B, plate 2). The formation is poorly exposed in the map area, limited to small aggregate quarries extracting the dolostone of the Black Earth Member. Because these are few in number, and natural outcrops and roadcuts in this formation are rare, we did not map this unit separately from the Jordan Formation (see Evans, 2003, for a similar approach). The contact between the two formations is somewhat gradational; further study is needed.

Jordan Formation. The Jordan Formation is an orange coarse-grained quartz sandstone (Van Oser Member; figs. 9 and 10, plate 2); we did not recognize the Norwalk Member of the Jordan Formation due to difficulty in identifying the contact between the Jordan and the St. Lawrence Formations in core and because the contact was not seen in outcrop. Trough cross-stratification is observed, and silica cements are common near the top of this unit as are calcite-cemented concretions ranging from centimeters to decimeters (fig. 10). The uppermost Jordan Formation outcrops along roads leading to ridgetops capped by, as well as within aggregate quarries extracting, the Prairie du Chien Group. The Jordan Formation is unconformably overlain by the Stockton Hill Member (lowest Prairie du Chien Group; see discussion in Evans, 2003).

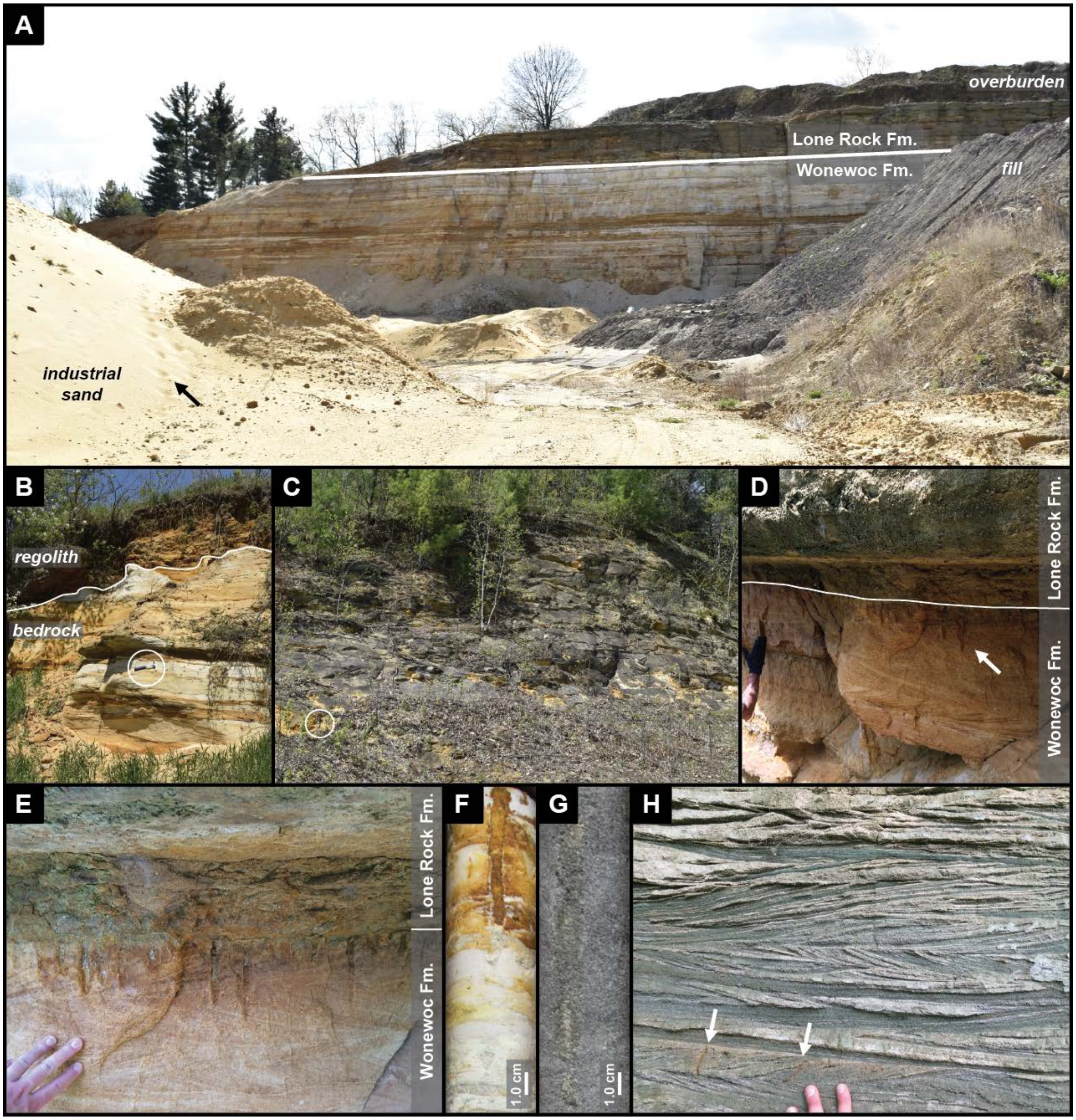

Figure 8: Wonewoc and Lone Rock Formations exposed in an active sand pit west of Arcadia, Wisconsin, Tamarack quadrangle. A) Contact between the quartz sandstone of the Wonewoc Formation and dolomitic glauconitic sandstone of the Lone Rock Formation, Birkmose Member (footprints in industrial sand pile, indicated by black arrow, referenced for scale). B) Wonewoc Formation northeast of Chapultepec, Wisconsin, Ettrick quadrangle; note thin regolith horizon overlying bedrock (hammer in white circle for scale). C) Wonewoc Formation north of Hegg, Wisconsin, Hegg quadrangle; note case hardening of outcrop obscuring underlying orange sandstone (hammer in white circle for scale). D) Contact between the Wonewoc and Lone Rock Formations exposed in Perrot State Park, Trempealeau quadrangle (hand for scale). White arrow points to *Skolithos* burrows in the upper Wonewoc Formation. E) Close-up of contact shown in part D showing iron oxide-filled *Skolithos* burrows (fingers for scale). F) Wonewoc Formation in the Weltzien Quarry core (62000218, ~168-ft depth) showing an iron oxide-filled *Skolithos* burrow. G) Basal Lone Rock Formation in the Arcadia Quarry core (62000166, ~348-ft depth) showing an iron sulfide-filled *Skolithos* burrow. H) Hummocky cross-stratification in glauconitic quartz sandstone typical of the Lone Rock Formation at Perrot State Park, Trempealeau quadrangle (fingers for scale). White arrows point to small oxidized burrows, presumably originally filled with iron sulfides.

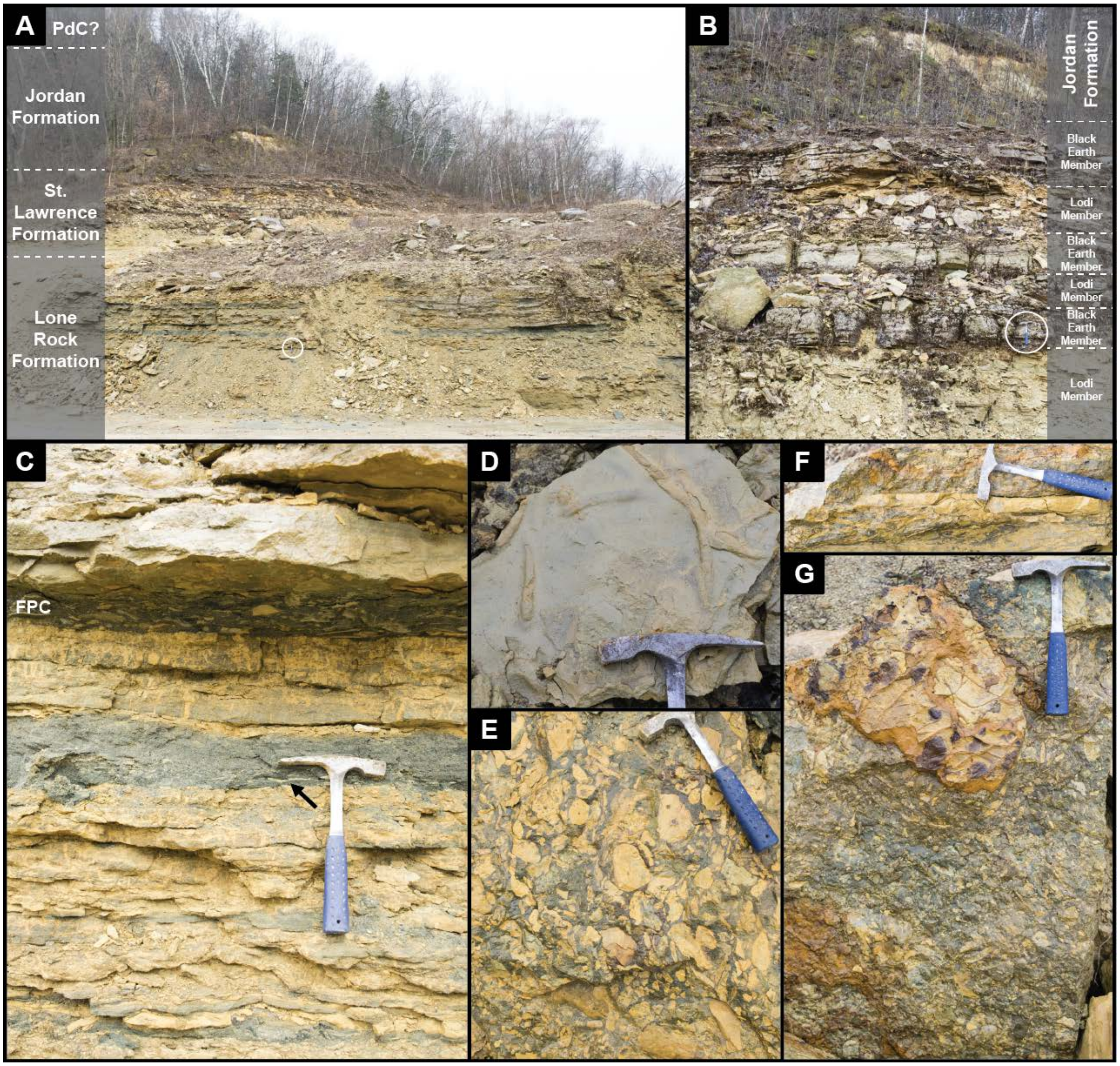

Figure 9: Lone Rock, St. Lawrence, and Jordan Formations, as well as possibly the Prairie du Chien Group (inaccessible) exposed in an active shale pit and hillside northeast of Galesville, Wisconsin, Galesville quadrangle. A) Overview photo (hammer in white circle for scale). B) Picture of the St. Lawrence Formation showing interbedded dolostone of the Black Earth member and dolomitic silty sandstone of the Lodi Member (hammer in white circle for scale). C) Typical Lone Rock Formation lithologies (hammer for scale) including bioturbated glauconitic sandstone (throughout; abundant immediately above hammer), flat pebble conglomerate (FPC), and rip-up clasts (black arrow). D) *Palaeophycus* burrows on the base of a piece of shaly glauconitic sandstone of the Lone Rock Formation found in float (hammer for scale). E) Fresh, bedding-parallel face of a flat pebble conglomerate (float) showing tan-colored mudstone chips within a matrix of glauconitic sandstone (hammer for scale). F, G) Flat pebble conglomerate (float) shown perpendicular to bedding (F) and parallel to bedding (G); presence of large re-worked clasts suggest high-energy (storm) conditions during deposition (hammer for scale).

Prairie du Chien Group (Ordovician)

Oneota and Shakopee Formations (not differentiated). The Ordovician Prairie du Chien Group is present at the highest elevations within the map area, forming the caprock on many of the ridges and serving as the primary source of aggregate material. We do not differentiate between the Oneota (lower) and Shakopee (upper) Formations that comprise the Prairie du Chien Group because these strata are relatively inaccessible in quarry highwalls and could not be investigated in detail; it is possible only the Oneota Formation is present in map area. The Oneota Formation is a buff to tan-colored stromatolitic thin- to thick-bedded sandy dolostone with white to cream-colored silica nodules (dolostone facies, Hager City Member) and interbedded dolostone and friable white quartz sandstone and green mudstone of the Stockton Hill Member (figs. 10 and 11, plate 2). This unit is poorly exposed along roads that traverse ridge tops, and is well exposed in active and abandoned aggregate quarries. The Prairie du Chien Group is more than 125 feet thick in the map area.

Ancell Group (Ordovician)

St. Peter Formation. The St. Peter Formation was tentatively observed at one locality, in a small portion of an aggregate quarry at the top of the high wall (the Ancell Group was also mapped at the highest elevations of the map area by Brown, 1998, albeit at a different map-scale). In this locality quartz sandstone (Tonti Member) and red and green shale (Readstown Member) of the St. Peter Formation appear to occur within a channel eroded into the underlying Prairie du Chien Group dolostone, on an unconformity with an observed relief of up to about 35 feet formed during the Sauk–Tippecanoe Sequence Boundary (fig. 11; Runkel and others, 2007). Alternatively, this may be altered (terra rossa and/or “pre-karst”) Prairie du Chien and the dolomite cement has been removed, leaving sandstone and red mudstone that superficially resembles the Tonti and Readstown Members, respectively. This close association of terra rossa and karst is similar to that described by Merino and Banerjee (2008), and previous work on terra rossa in the Driftless Area of Wisconsin has noted that it is associated with dolostone, highly variable in thickness, and only partly related to topography (Evans and Hartemink, 2014). Further study is necessary to better understand these lithologies and stratigraphic relations, as well as the possible relationship of our observations to the Rountree Formation of southwestern Wisconsin (see Knox and others, 1990, for description of the Rountree Formation).

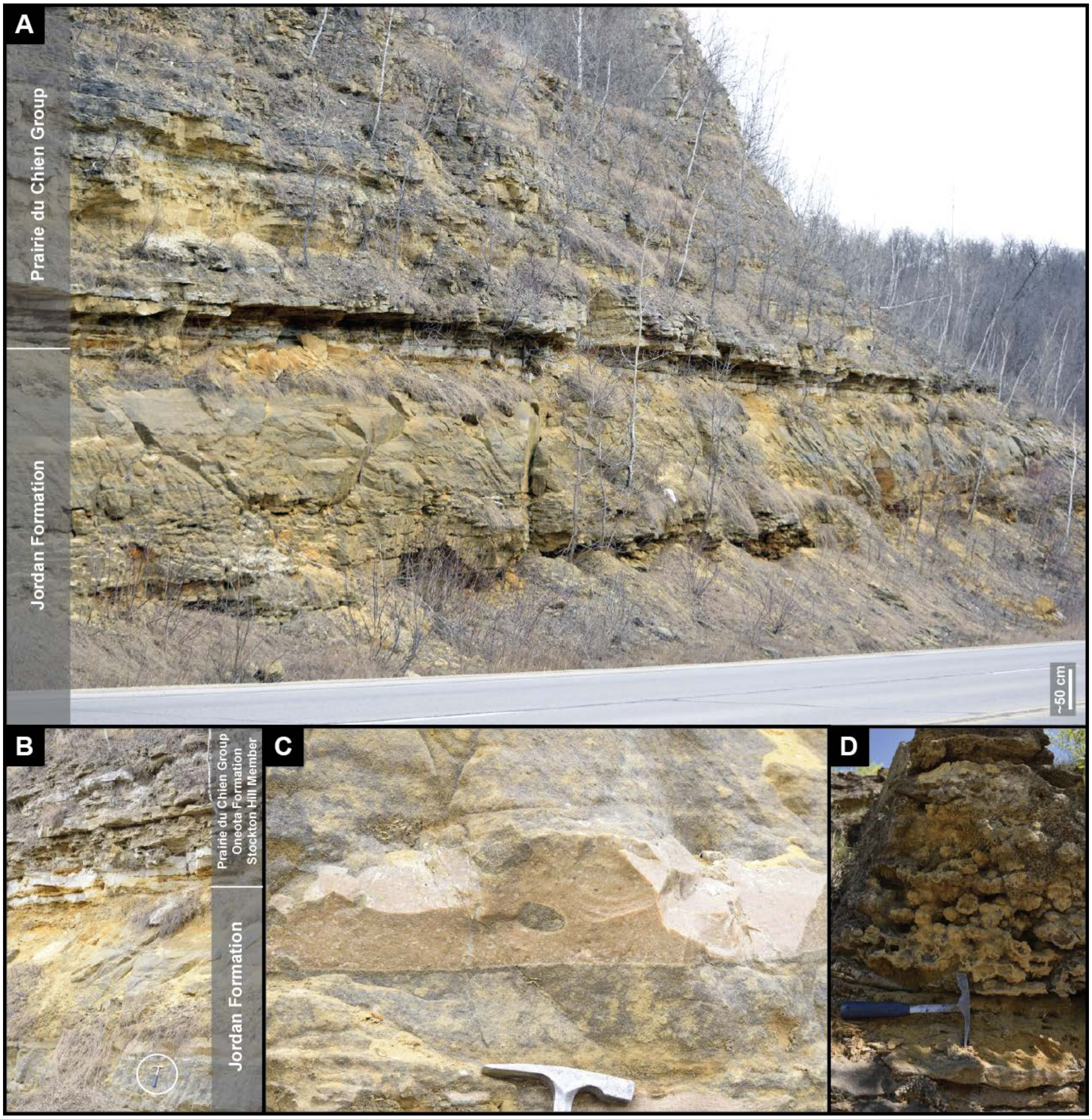

Figure 10: A, B, C) Outcrop of the contact between the Jordan Formation and the Prairie du Chien Group along Wisconsin Route 93 south of Arcadia, Wisconsin, Tamarack quadrangle. A) Overview photo. B) Close-up of contact showing orange quartz sandstone of the Jordan Formation overlain by interbedded white quartz sandstone and buff dolostone of the Stockton Hill Member, Oneota Formation, Prairie du Chien Group (hammer in white circle for scale). C) Photo of silica nodule (chert, note conchoidal fracturing) cementing quartz sand grains in the Jordan Formation (hammer for scale). D) Calcite concretions in the Jordan Formation, south of Hegg, Wisconsin, Hegg quadrangle (hammer for scale).

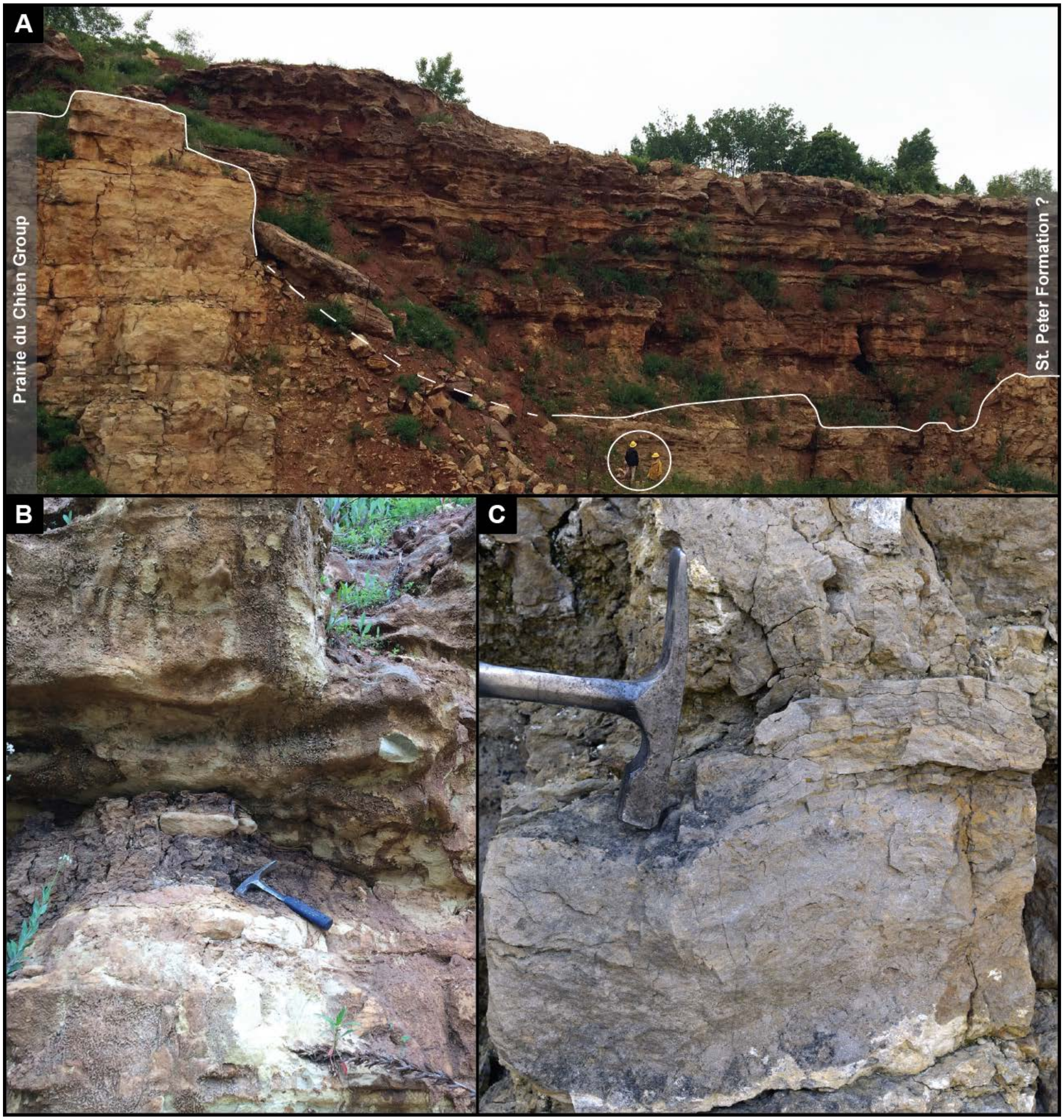

Figure 11: A) Tentatively mapped unconformable contact between Prairie du Chien Group dolostone and overlying shale and sandstone of the St. Peter Formation, south of Arcadia, Wisconsin, Tamarack quadrangle (people in white circle for scale). An alternative interpretation is that this is altered Prairie du Chien with the dolomite cement removed (terra rossa and/or "pre-karst"). B) Close-up of the tentatively identified St. Peter Formation pictured in part A, showing interbedded red and green shales of the Readstown Member and white quartz sandstone of the Tonti Member (hammer for scale). C) Stromatolitic dolostone typical of the Prairie du Chien Group (hammer for scale), approximately equidistant east of Arcadia and south of Whitehall, Wisconsin, Whitehall quadrangle.

Discussion and conclusions

This preliminary report provides a basis for potential users of the final map, including industry, government, and private citizens, to have a chance to provide input into the mapping methods and map product so that the final product can be as useful as possible. This includes members of the Wisconsin Geological Mapping Advisory Committee, the Trempealeau County Board of Supervisors, the Wisconsin Department of Natural Resources, and industrial sand mining companies in the map area. These potential users will be sent a link to the online version of this Open-File Report upon publication.

One key result of Year 1 mapping is the recognition that the acquisition of drill core is necessary for accurately mapping unit contacts, which rarely outcrop in the map area. The continuous nature of drill core, and the fact that the drill core collected penetrates all of the map units, make core samples the most useful of all data used for mapping the bedrock geology (plates 1 and 2). Recognition of changes in unit thickness, for example in the Wonewoc and Eau Claire Formations, was possible because of the acquisition of core (plate 2). Additionally, understanding the redox state of sandstone cements, specifically in the Wonewoc Formation, is dependent upon obtaining core samples from hills and ridges of various sizes and therefore variable oxidation histories (plate 2); drill cuttings do not provide the sedimentary context for determining reduced versus oxidized cement origin. Outcrops, because of their sheer number and spatial distribution, were the second most useful dataset collected. Although map unit contacts rarely outcropped, we observed all map units in outcrop with the exception of the Mount Simon. Over half of the outcrops observed were of the Wonewoc Formation; this unit consistently outcropped along roads leading up valleys (see fig. 6G). Well cuttings samples, constrained to valleys and primarily through the Eau Claire and Mount Simon Formations, were of use for mapping these formations but not for other map units. Geophysical logs were useful when other datasets were not available.

One consideration for finalizing a map of the county was the observation that in the field area, soil profiles and colluvium were relatively thin (figs. 6, 8B, and 9A, B). Additionally, with closely spaced wells, we observed large differences in depth to bedrock as recorded in well construction reports (WCRs). These differences may be attributable to human error—WCRs are processed by the driller, the Wisconsin Department of Natural Resources, and the WGNHS in both paper and digital formats. During digitization, some WCRs may have been given the wrong geographic location or been miscoded. Additionally, we observed that it is difficult while drilling to distinguish between unconsolidated colluvium/alluvium and the friable sandstones of the bedrock; this error would be amplified if the underlying bedrock is the Jordan, Wonewoc, or Mount Simon Formations. However, we interpret the large differences in depth to bedrock in closely spaced wells (as recorded in WCRs) to represent a deeply incised topography that formed as tributary streams eroded into friable sandstone. Another consideration for the second year of this project is that more data from neighboring counties is required to carry map unit layers accurately to the edge of Trempealeau County; currently, data at the border of the map area is relatively sparse (see fig. 4) and can be supplemented by existing maps (Evans, 2003; Steenberg, 2014). Also, further study of the tentatively identified St. Peter Formation is needed.

In addition to mapping the northern portion of the county, Year 2 will focus on acquiring sample material for pXRF analysis from the Mount Simon Formation; the principal investigator (Zambito) is currently analyzing cuttings samples from this unit as part of a collaborative project with Trempealeau County. Ideally, drilling in Year 2 will result in the collection of core samples through the entire unit and into the Precambrian basement. Additionally, in Year 2 we plan to undertake detailed elemental analysis (ICP-MS, inductively coupled plasma mass spectrometry) and mineralogical analysis (XRD, x-ray diffraction) to better characterize what minerals are present in the rock succession mapped, as well as their trace metal geochemistry in order to better evaluate potential environmental impacts of industrial sand mining. Finally, we will attempt to edge-map, when appropriate, our final map with those for La Crosse (Evans, 2003) and Winona (Steenberg, 2014) Counties.

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Acknowledgements

The authors thank Ken Bradbury and Tom Evans for reviewing this report and providing useful comments that improved it. Val Stanley and Pete Schoephoester provided a georeferenced map of the field area on a Trimble Juno for documenting outcrop data and assisted with downloading the data for use in ArcGIS and Petrel.

A draft of this report was prepared for the U.S. Geological Survey National Cooperative Geologic Mapping Program. The geologic map was funded in part by the USGS National Cooperative Geologic Mapping Program under StateMap award G16AC00143. The views and conclusions contained in this document are those of the authors and should not be interpreted as necessarily representing the official policies, either expressed or implied, of the U.S. Government.

Additional funding for this work was provided by the Wisconsin Geological and Natural History Survey (UW–Extension) and the University of Wisconsin Water Resources Institute under award WR15R004.

View from Oak Ridge, Ettrick quadrangle, looking east from on top of an overburden pile on top of a highwall at an aggregate quarry in the Prairie du Chien Group.