

Bedrock Geology of Grant County, Wisconsin



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Eric D. Stewart
Stephen W. Mauel
Sarah E. Bremmer
William A. Fitzpatrick



Wisconsin Geological
and Natural History Survey
DIVISION OF EXTENSION
UNIVERSITY OF WISCONSIN-MADISON



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Cover photos

Front: Outcrop of the St. Peter Formation, southeast of Mount Hope, WI

Back: View from Wilson Hill Rd, southwest of Mount Hope, WI



Contents

Abstract	1	Description of map structures.	14
Introduction	1	Fractures	14
Methods	2	Orthogonal joint sets. . .	14
Description of map units . .	4	Conjugate shear fractures .	16
Silurian	4	Complex fracture pattern. .	16
Silurian undivided	4	Folds	16
Ordovician	4	Mineral Point anticline and Annaton syncline	16
Maquoketa Group	4	Beetown syncline	16
Galena Formation	5	Meekers Grove anticline and Georgetown syncline .	18
Decorah Formation.	6	Discussion	21
Platteville Formation	8	Orogenic stress transmission and the origin of fractures. .	21
Ancell Group	9	Conceptual model for development of fractures and folds	22
Prairie du Chien Group . . .	11	Hydrogeology map applications	23
Cambrian	11	Impact of folds and faults on groundwater flow . . .	24
Jordan Formation.	11	Impact of stratigraphy on springs and hydrogeology .	25
St. Lawrence Formation. . .	12	Cross-connecting groundwater wells in Grant County	27
Tunnel City Group	13	Acknowledgments	28
Elk Mound Group.	13	References	28



Bedrock geology of Grant County, Wisconsin

Figures

1. Geologic map sources used to construct the bedrock surfaces and county-wide bedrock geologic map. 2
2. Depth-to-bedrock map of Grant County 3
3. Histogram of openings found in the Galena and Decorah formations in Grant County . . . 5
4. Isopach map of the Decorah Formation in the Platteville area of southeast Grant County . . . 7
5. Isopach map of the Spechts Ferry Member of the Decorah Formation 8
6. Whole-rock geochemical results for Fe_2O_3 , S, As, and P_2O_5 plotted as abundance versus elevation relative to the base of the Glenwood Formation . . .10
7. Isopach map of the combined Prairie du Chien (Opc) and Ancell (Oa) groups12
8. Half rose diagrams showing the distribution of fracture orientations for different domains in Grant County . . .15
9. Examples of fractures and deformation bands in Grant County17
10. Structure contour map of the base of the Platteville Formation 18
11. Structure contours of the base of the Platteville Formation . . .19
12. Geologic cross section and electromagnetic sections. . . 20
13. Aeromagnetic anomaly map of Grant County with aeromagnetic contours21
14. A. Conceptual model for major folds in Grant County 24
15. Histograms of the location within the stratigraphic section of springs and seeps 26
16. Location of wells open to the Galena Formation and the Ancell Group 27

Supplemental material

The following materials are available for download at: <https://doi.org/10.54915/xdjk3760>.

Plate 1: Geologic map

A map (.pdf format) of the bedrock geology of Grant County.

Dataset 1: GIS data

A file geodatabase (.gdb) in the Geologic Map Schema (GeMS) Level 3 format, including map units, folds, faults, observations, measurements, and other geologic map features.

Dataset 2: Geochemical data

Data (.csv format) of whole-rock geochemical measurements.

Dataset 3: Bedrock contact rasters

A file geodatabase (.gdb) including raster datasets of the elevation of the base of all bedrock formations (18 m resolution), and of the bedrock surface (10 m resolution), and a depth to bedrock (10 m resolution) dataset.



Wisconsin Geological and Natural History Survey

Abstract

Three-dimensional bedrock mapping of Grant County at a scale of 1:100,000 provides new baseline information on the distribution of geologic units. Grant County contains Paleozoic bedrock units ranging in age from Silurian to Cambrian. Strata typically dip to the southwest between 14 and 30 ft per mile. Older rocks are typically found at low elevations in the northern portion of the County. Silurian rocks are only exposed at Sinsinawa Mound in southern Grant County.

Gentle folds and small faults deform the Paleozoic sequence. Folds were mapped based on structure contours of the base of the Platteville Formation and Prairie du Chien Group. The northwest trending Mineral Point anticline is the largest fold in Grant County, where it reaches around 200 ft in structural relief. Fracture patterns vary across the county, but can be interpreted in the context of local folds. Paleozoic folding is interpreted to have resulted from reactivation of Precambrian faults, and the accompanying strain in the Paleozoic section induced differential stresses resulting in fracture sets. Modeled finite strain at the fault tipline near the base of the Cambrian section is significant despite the small displacements inferred along basement faults.

Introduction

Grant County lies along the border with Illinois and Iowa in southwestern Wisconsin. The County is divided into two physiographic regions separated by the east-west trending Military Ridge. In the north, the landscape is dissected by streams and contains approximately 300 ft of topographic relief. In the south, the landscape is flatter and is composed of rolling uplands. Several large drainages, including the Grant and Platte Rivers, cut through the topography. Also interrupting the topography is Sinsinawa Mound, a monadnock in southern Grant County composed of Silurian-aged rocks.

Southern and much of central Grant County is part of the historic Upper Mississippi Valley Zn-Pb mining district. The district is the namesake for Mississippi Valley-type base metal deposits, which form from hydrothermal brines migrating upwards and precipitating Zn, Pb, Fe, and minor Cu sulfides, usually in carbonate rocks (Leach and others, 2010). Due to the economic significance of the mining district, studies on the geology began early with Owen and others (1844), Percival (1856), Strong (1877), and Chamberlin (1882). These early authors identified the basic stratigraphic framework of Grant County and recognized the role of folds in localizing sulfide

mineralization. Mapping to support mineral exploration continued into the 20th century. Of note was the work of Grant (1906) and numerous USGS workers in the 1950s and 1960s (e.g. Mullens, 1964; Taylor, 1964; Whitlow and West, 1966a; Whitlow and West, 1966b). Mining ended in the Wisconsin portion of the mining district in 1979.

Bedrock mapping was reinitiated in Grant County to support the results of the southwest Wisconsin groundwater and geology project (SWIGG). SWIGG was designed to study nitrate and bacteria contamination in groundwater wells in Grant, Iowa, and Lafayette counties. SWIGG found that in addition to land use and well site characteristics, bedrock geology and well construction practices impact the probability of a groundwater well containing high levels of nitrate and bacteria (Stokdyk and others, 2023).

This report and the accompanying map (plate 1) build on the surface mapping of early workers by describing and mapping geologic units and structures in three dimensions across all of Grant County. Field work from historic and recent mapping produced extensive field observations that are used to revise unit nomenclature. Compilation of structure data are used to interpret the origins of fractures, folds, and the regional tectonic history. Structural interpretations and the accompanying GIS datasets can be used to support the results of the SWIGG study because nitrate and bacteria issues are three-dimensional problems involving both well construction practices and bedrock geology. The results can also be used to improve understanding of the structural setting of mineral deposits.



Pecatonica member in an abandoned quarry northeast of Fennimore, WI

Bedrock geology of Grant County, Wisconsin

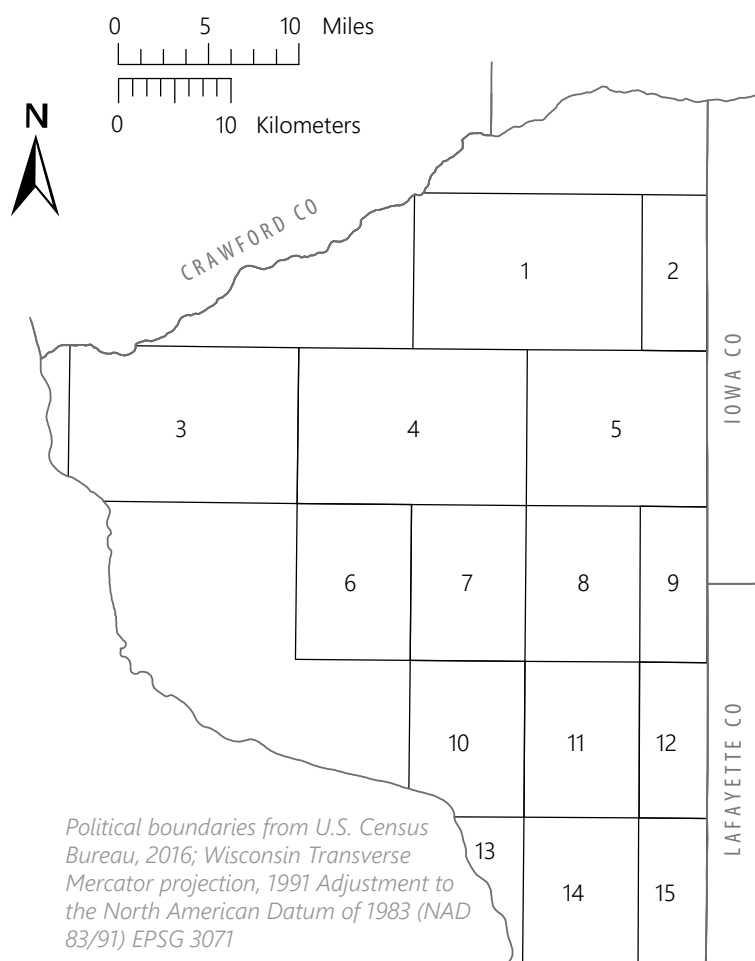
Methods

Contacts on the bedrock map were constructed by intersecting rasters consisting of a specific contact between bedrock formations and groups with a raster of the bedrock surface. The elevation of the bedrock surface is land surface minus the thickness of overlying unconsolidated Quaternary sediment. Bedrock contact rasters (dataset 3) were constructed from new mapping and previously published maps. Figure 1 shows the locations of datasets used to construct bedrock rasters. Structure contours, unit thickness estimates, and elevation data extracted from surface contacts were compiled from published 1:24,000-scale maps (Agnew, 1963; Whitlow and Brown, 1963; Mullens, 1964; Taylor, 1964; Whitlow and West, 1966a, 1966b, 1966c; West

and others, 1971; West and Blacet, 1971; West and Heyl, 1985; Stewart and others, 2022a, 2022b; Bremmer and others, 2023; Stewart and others, 2023; Fitzpatrick and Stewart, 2024) and used to construct contact rasters. Field contact lines from mapping were converted into a series of points in ArcGIS Pro, and surface elevation values were calculated for each point. The spacing between points ranged from less than 65 ft to approximately 650 ft. Field data were supplemented by interpretations from geologic logs of the Mineral Development Atlas (Tweedy and Heyl, 1952; Pepp and others, 2019), and interpretations from select water well construction reports (WGNHS, unpub. data, 2025). Airborne electromagnetic data from southwest Wisconsin (Crosbie and others, 2023) were used in areas with little surface control. Airborne electromagnetic

data provide a two-dimensional resistivity model along measured flight paths. Certain stratigraphic intervals, such as the combined Glenwood, Platteville, and Decorah formations, tend to be less resistive than overlying and underlying units, and can be used to approximate the base of the Platteville Formation in some locations. All compiled data for each unit contact were used to construct interpolated raster contact surfaces using the TopoToRaster tool in ArcGIS Pro. Some smoothing of the interpolated surface was introduced to reduce the importance of datasets with higher uncertainty, such as well construction reports. Smoothing has little effect on high density data sources, such as field contact points. The result is a constructed raster surface that tracks

Figure 1. Geologic map sources used to construct the bedrock surfaces and county-wide bedrock geologic map. 1–Stewart and others (2022a) 2–Fitzpatrick and Stewart (2024) 3–Stewart and others (2022b) 4–Bremmer and others (2023) 5–Stewart and others (2023) 6–West and Heyl (1985) 7–West and Blacet (1971) 8–West and others (1971) 9–Taylor (1964) 10–Whitlow and West (1966a) 11–Whitlow and West (1966b) 12–Agnew (1963) 13–Whitlow and Brown (1963) 14–Whitlow and West (1966c) 15–Mullens (1964). Areas outside of boxed areas are new mapping.





Wisconsin Geological and Natural History Survey

field contacts closely and smooths out some of the unevenness of well construction report data.

Map contacts on the plate are generally close to contacts on geologic maps from adjacent counties. 1:24,000-scale data sources straddle the boundary of Grant County with all of Lafayette County (Agnew, 1963; Mullens, 1964; Taylor, 1964), much of Iowa County (Carlson, 1961; Taylor, 1964; Fitzpatrick and Stewart, 2024), and all of Jo Daviess County, Illinois (Whitlow and Brown, 1963; Mullens, 1964; Whitlow and West, 1966c). In those cases, the map is continuous with the existing maps across the county boundaries. Slight variation exists in the base Maquoketa contact between this map and the 1:62,500-scale bedrock map of Jo Daviess County by McGarry (2000), probably due to different data sources. Contacts at the boundary between this map and the adjacent 1:100,000-scale map of Iowa County (Batten and Attig, 2010) are similar, though less Ancell Group is generally mapped on ridge crests in the Iowa County geologic map.

Uncertainty in the accuracy of the rasters varies by location, data sources, and geologic unit. Most contacts derived from previously published 1:24,000-scale maps (fig. 1) are probably accurate to within 20 vertical feet. Rasters in these areas have a similar accuracy. However, raster surfaces beneath flat upland areas far from mapped contacts have higher uncertainty. Additionally, field observation density varies in published 1:24,000-scale maps, and areas with low data density will tend to have higher uncertainty. Areas of rasters not previously mapped at 1:24,000-scale (fig. 1) have higher uncertainty, perhaps approaching 50 ft. Units progressively deeper in the subsurface have progressively higher uncertainty. Finally, the unconformable surface at the base of the St. Peter Formation is difficult to predict in the subsurface. The base St. Peter surface constructed as part of this

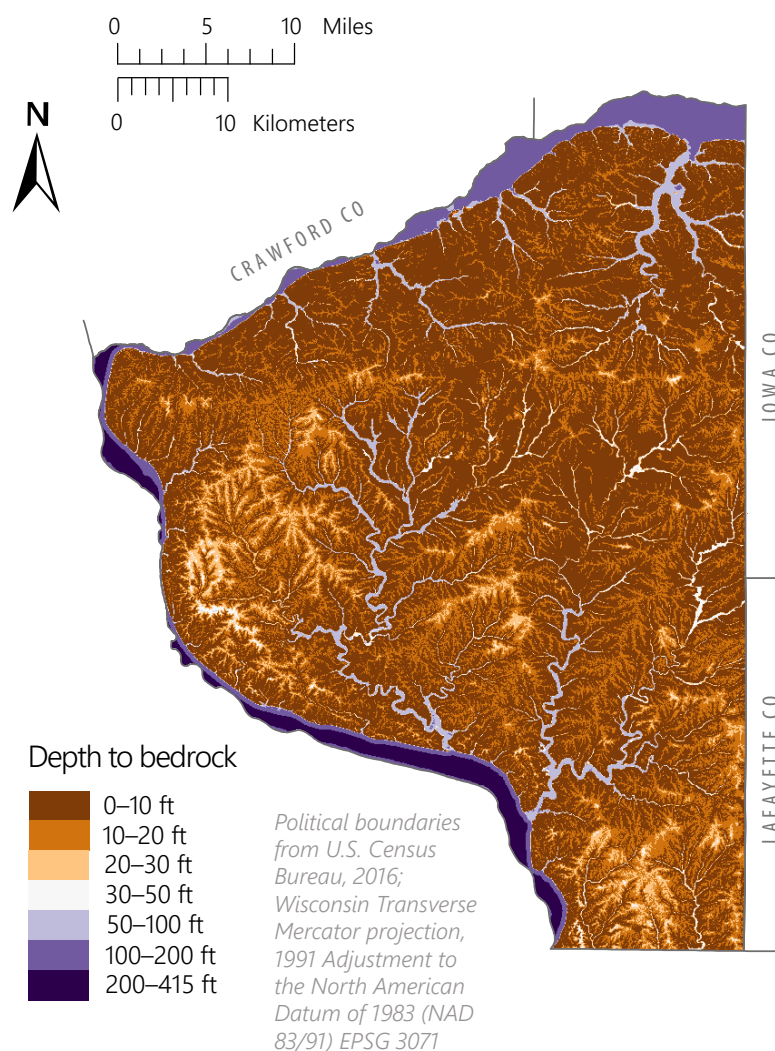
map is a geologically plausible surface depicting paleochannels, but it is likely highly inaccurate locally (uncertainty is greater than 100 ft). Users interested in understanding areas with better and poorer constrained contacts are referred to the maps referenced in figure 1.

Folds were mapped using structure contours of the base of the Platteville Formation and base of the Prairie du Chien Group and were assumed to continue into underlying and overlying units. To include folding in subsurface units with little surface or well control, isopach rasters were constructed for

these units and added to or subtracted from the elevation rasters of well constrained contacts. This approach allowed thickness changes in map units to be accounted for in elevation rasters of subsurface contacts with poor control. Following the intersection of contact rasters and the bedrock surface, some map contacts were hand edited to remove intersection effects. All rasters are included in the supplementary data (dataset 3).

The bedrock surface was constructed by subtracting a depth-to-bedrock map of Grant County (fig. 2) from the 2017 NED DEM (United States

Figure 2. Depth-to-bedrock map of Grant County. Data sources used to construct the depth-to-bedrock map include outcrop locations, geologic logs from the Mineral Development Atlas, logs from water well construction reports, and lidar.





Bedrock geology of Grant County, Wisconsin

Geological Survey, 2017) with a 10 m (32.8 ft) land surface resolution. The depth-to-bedrock map was constructed using outcrop locations from new and previously published geologic maps (Agnew, 1963; Whitlow and Brown, 1963; Mullens, 1964; Taylor, 1964; Whitlow and West, 1966a, 1966b, 1966c; West and Blacet, 1971; West and others, 1971; West and Heyl, 1985; Stewart and others, 2022a, 2022b; Bremmer and others, 2023; Stewart and others, 2023; Fitzpatrick and Stewart, 2024), depth-to-bedrock interpretations from geologic logs of the Mineral Development Atlas, depth-to-bedrock interpretations from water well construction reports, and lidar. Figure 2 shows a generalized depth-to-bedrock map for Grant County.

Whole-rock geochemistry was analyzed by ALS in Vancouver, Canada. Hand-size samples were crushed to chips, then a selection of each sample was ground so that at least 85 percent had a grain size diameter smaller than 75 microns. Major elements were analyzed by ICP-AES following a lithium borate fusion. Most trace elements were analyzed with ICP-MS using an acid dissolution of the fused bead. Volatile trace elements (As, Bi, Hg, In, Re, Sb, Se, Te, Tl) were analyzed by ICP-MS using the ALS aqua regia two-acid (nitric and hydrochloric) digestion. This is effective at dissolving sulfides, carbonates, and phosphates. Sulfur and carbon were analyzed with IR spectroscopy following induction furnace heating. Whole-rock geochemical results are available in the supplemental materials (dataset 2).

Description of map units

Each unit description is divided into two sections: a brief historical background followed by a description. Many historical maps and geologic logs in Grant County and across southern Wisconsin used nomenclature that predates divisions established by Ostrom (1969). The historical background is meant to serve as a bridge between historic data and current nomenclature. Carbonate units are described using the terminology of Dunham (1962).

Silurian

Silurian undivided

Background

Silurian-aged rocks in Grant County are part of the Edgewood, Kankakee, and Hopkinton formations (Heyl and others, 1959). In Grant County, exposure of these rocks is restricted to the far southern portion of the county at Sinsinawa Mound. Whitlow and West (1966c) divided Silurian-aged rocks into separate formations, but this map does not attempt to subdivide Silurian units.

Description

Silurian strata are generally yellowish-gray to olive-gray, fine- to medium-grained crystalline dolomite. Agnew and others (1956) note Silurian dolomites are yellower than the underlying Galena Formation and contain far fewer vugs. Chert nodules and chert beds are present in most of the exposed section at Sinsinawa Mound (Whitlow and West, 1966c). The basal 20 ft of the Silurian dolomite is laminated and argillaceous (Agnew and others, 1956), but becomes massively bedded and less argillaceous above (Whitlow and West, 1966c). Tabulate corals are present at Sinsinawa Mound in southern Grant County (Whitlow and West, 1966c), where approximately 140 ft of section is exposed.

Ordovician

Maquoketa Group

Background

The Maquoketa Shale was first named by White (1870) for exposures in eastern Iowa. Ostrom (1969) followed nomenclature used in Iowa by treating the Maquoketa Shale as a formation. For several decades, Wisconsin maps and survey publications treated the Maquoketa as a formation (Evans and others, 2004; Batten and Attig, 2010; WGNHS, 2011). However, Stewart (2021) followed the nomenclature of Illinois (Templeton and Willman, 1963) and treated the Maquoketa as a group. The Neda, Brainard, Fort Atkinson, and Scales were treated as formations within the Maquoketa Group. This shift was done in part because in eastern Wisconsin the Brainard and Scales are thick enough to map separately at a scale of 1:100,000. This map follows Stewart (2021) and treats the Maquoketa at the group level. However, exposure of the Maquoketa is poor in southwestern Wisconsin, and no attempt was made to subdivide the unit.

Description

The Maquoketa Shale is a dark-blue, gray, to brown shale with lesser interbedded dolomite. The proportion of dolomite increases to the south, west, and east of Grant County (Agnew and others, 1956). A hematitic shale and flat pebble conglomerate probably equivalent to the Neda Formation is found at the top of the unit and is 8 to 17 ft thick (Agnew, 1955). The base of the unit, marking an increase in siliciclastic content compared to the upper Galena Formation, is interpreted to represent a sequence boundary (Choi and others, 1999). The base contains phosphate clasts and multiple hardground surfaces (McLaughlin and others, 2011). Graptolites and cephalopods are found in the Maquoketa (Whitlow and West, 1966a). The thickness of the unit varies regionally. At Sinsinawa Mound in southern Grant County, the Maquoketa



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is around 135 ft thick. To the south near Galena, Illinois, the Maquoketa is 108 ft thick, but north of Grant County near Blue Mounds, it increases to 240 ft thick (Agnew and others, 1956).

Galena Formation

Background

The Galena Formation was first described by Hall (1851). The most recent subdivisions in Wisconsin subdivide the Galena into an upper Dubuque Member, a middle Wise Lake Member, and a lower Dunleith Member (Templeton and Willman, 1963; Ostrom, 1969). However, the base of the Galena Formation has been inconsistently defined (see Decorah Formation discussion below). This map follows previous mapping in southwest Wisconsin and places the base of the Galena Formation above the Ion Member of the Decorah Formation (e.g. Agnew and others, 1956; Heyl and others, 1959). The description of the Galena below follows Agnew and others (1956) and is broken into informal upper (non-cherty) and lower (cherty) members. The informal upper member described below corresponds to the Dubuque and Wise Lake members of Ostrom (1969), while the informal

lower (cherty) member corresponds to the upper two-thirds of the Dunleith Member of Ostrom (1969).

Description

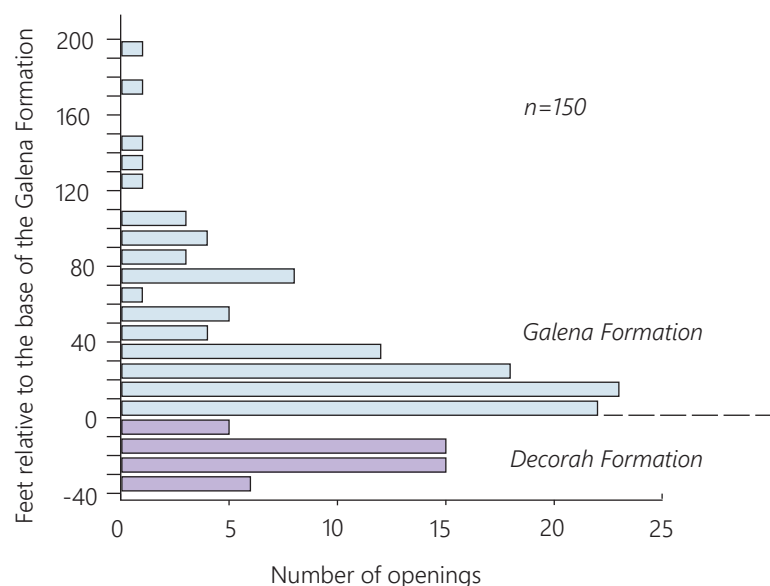
Upper (non-cherty) member.

Generally light-yellowish-brown dolomitic mudstone to wackestone (Choi and others, 1999). Near the top of the Galena Formation (Dubuque Member), thin-bedded dolomitic shale becomes interbedded with dolomite (Agnew and others, 1956). The non-cherty upper Galena Formation is generally medium- to massively-bedded but becomes thin- to medium-bedded at the top (Agnew and others, 1956). The lower part of the non-cherty Galena Formation (Wise Lake Member) has a honeycomb weathering appearance (Agnew and others, 1956). *Receptaculites* and invertebrate fauna such as brachiopods and gastropods occur in the upper member (e.g. Whitlow and Brown, 1963). The upper (non-cherty) member has a total thickness of around 115 to 120 ft (Agnew, 1963).

Lower (cherty) member. Generally tan to light-brown, mudstone and wackestone (Choi and others, 1999). Tan to light-brown skeletal wackestone and packstone with minor shale partings occur roughly 50 ft above the base of the Galena Formation above

a discontinuity surface interpreted by Choi and others (1999) as a sequence boundary. Gray chert nodules and beds are common in the lower Galena Formation. Fine- to medium-grained dolomitic sand often fills vugs and solution enlarged joints. Shale partings become much more prevalent in the Ion Member below the Galena Formation. The unit is dolomitized in southwestern Wisconsin. Beds are medium- to massively-bedded. Hardgrounds are common (Beyer and others, 2008). *Receptaculites* is common in parts of the lower Galena Formation. *Thalassinoides* also occur in parts of the lower Galena Formation (Beyer and others, 2008; Stewart and others, 2022b), though the high density of burrows often make exact identification difficult. The burrows and surrounding matrix have different porosity and permeability values (Dockal, 2021), which probably gives rise to differential weathering and the characteristic honeycomb weathering of the Galena Formation. Geologic logs from the Mineral Development Atlas (Pepp and others, 2019), drilled in areas of prospective sulfide mineralization, show “openings” in the rock that are concentrated near the base of the unit (fig. 3). Openings in the historic literature can represent both open space in the rock and open space subsequently

Figure 3. Histogram of openings, or open space elongate parallel to bedding, found in the Galena and Decorah formations in Grant County. Data come from geologic logs that are part of the Mineral Development Atlas (Pepp and others, 2019). Frequency measures the number of openings recorded over 10-ft intervals in the geologic logs relative to the base Galena Formation. Vertical fractures and fissures have been removed. Only logs with the base of the Galena Formation are included. Logs come from areas with mineralization potential, so the distribution of openings may not be similar in unmineralized areas.





Bedrock geology of Grant County, Wisconsin

filled with clay. Most exploration holes represented by figure 3 were started within the upper Galena Formation, so the data are biased against recording openings near the very top of the unit. The thickness of the cherty portion of the Galena Formation is around 100 to 107 ft (Agnew and others, 1956; Agnew, 1963).

Decorah Formation

Background

The nomenclature and upper contact of the Decorah Formation has been inconsistently defined and used in Wisconsin. This inconsistency has led to considerable confusion in the literature. In this map, we follow the usage of Kay (1928) and include the upper Ion Member, the Guttenberg Member, and the basal Spechts Ferry Member as part of the Decorah Formation. All southwestern Wisconsin geologic maps from the second half of the 20th century onwards, as well as many research articles, have included the Ion as a member of the Decorah Formation (Carlson, 1961; Allingham, 1963; Agnew, 1963; Whitlow and West, 1966a; West and Blacet, 1971; West and Heyl, 1985; Emerson and others, 2004; McLaughlin and others, 2011; Callen and Herrmann, 2019; Stewart and others, 2022a; Stewart and others, 2023; Fitzpatrick and Stewart, 2024). However, when Ostrom (1969) defined the Sinnipee Group in Wisconsin, the Ion was moved into the Galena Formation. No rationale was provided for this move. This stratigraphic shift was used by WGNHS (2006; 2011) and was picked up in numerous journal articles (e.g. Choi and others, 1999; Swanson and others, 2014). The placement of the Ion into the stratigraphically higher Galena Formation was likely the result of carrying nomenclature used in northern Illinois (Templeton and Willman, 1963) into Wisconsin. In northern Illinois, the equivalent units to the Ion are the Buckhorn and St. James members of the Dunleith Formation, which are included stratigraphically

above the Decorah (see Templeton and Willman, 1963). Relative to Grant County, the percentage of shale in the Ion-equivalent units of the section decreases southward into Illinois and eastward into central Wisconsin and is probably the cause of the nomenclature confusion. Placing the Ion within the Decorah Formation is favored here due to its lithostratigraphic similarity to the Guttenberg and Spechts Ferry Members of the Decorah Formation in southwestern Wisconsin, its historic placement within the Decorah Formation in geologic maps of southwestern Wisconsin, and its lithologic differences from the Galena Formation.

Description

Ion Member. The Ion Member of the Decorah Formation is a gray to grayish-blue wackestone with interbedded skeletal packstone (Bremmer and others, 2023). Green shale laminations that demarcate beds are common and can locally reach approximately 0.5 ft thick. The Ion varies from dominantly a limestone in the west to a dolomite in the east (Heyl and others, 1959). The base of the Ion contains more siliciclastics and clay than the top (Agnew and others, 1956). The Ion contains tabular, thin to medium beds. Brachiopods, bryozoans, crinoids, and trilobites occur in the unit (Agnew and others, 1956; Choi and others, 1999). Agnew and others (1956) considered the contact between the Ion and Guttenberg to be conformable, but Choi and others (1999) revised this interpretation, showing the base of the Ion is a sequence boundary representing a sharp discontinuity, hardground, and omission surface. The Ion is typically 20 to 22 ft thick.

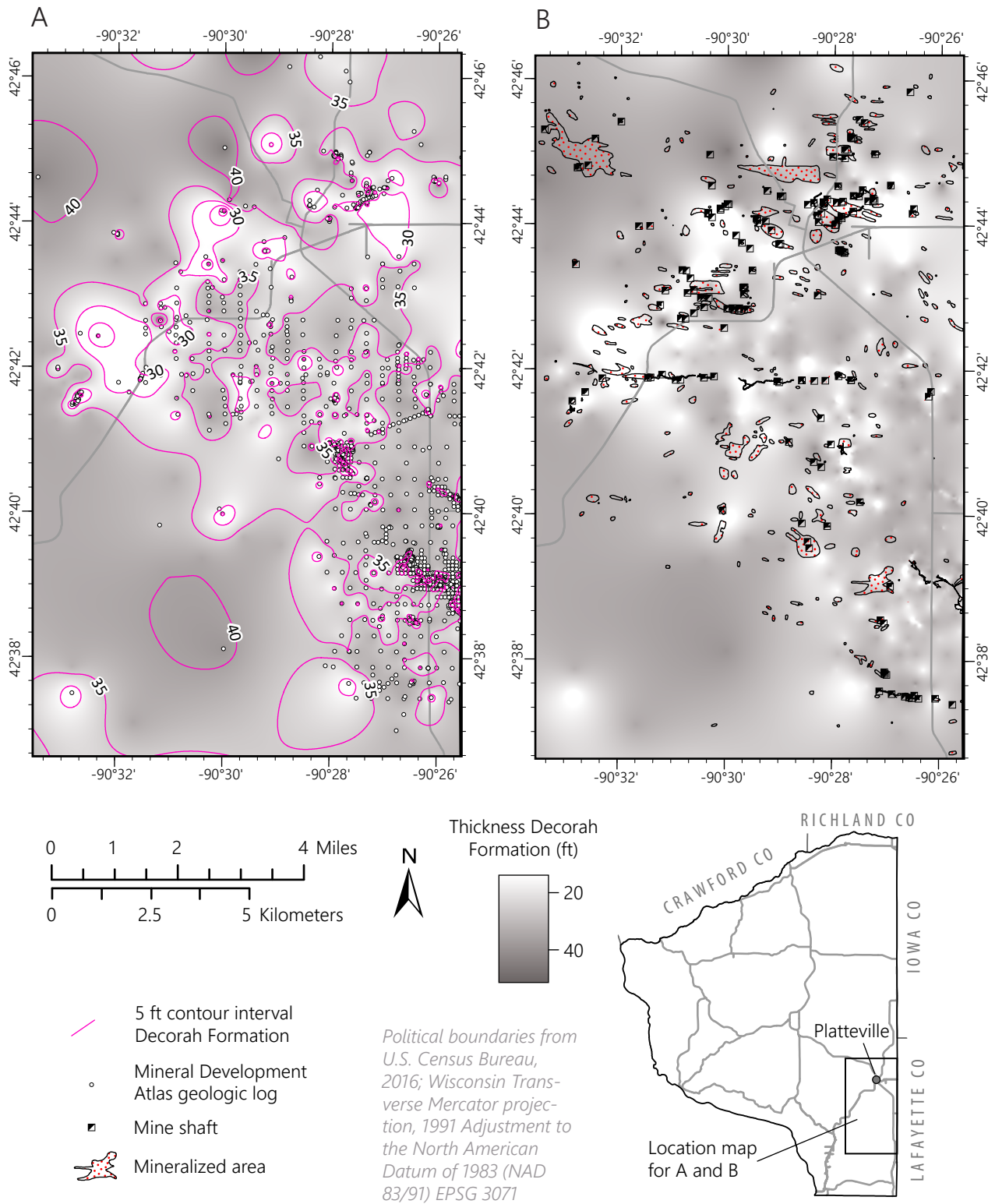
Guttenberg Member. The Guttenberg Member is a gray mudstone to skeletal wackestone and packstone with interbedded brown organic-rich shale. The Guttenberg is a limestone in Grant County but becomes progressively dolomitized eastward. Bedding is typically thin and wavy. The Member contains brachiopods, mollusks,

trilobites, and bryozoans (Agnew and others, 1956). The thickness of the Guttenberg varies. Where unaltered, it is typically 12 to 17 ft thick in Grant County. Around areas of mineralization, however, much of the carbonate has been dissolved by passing fluids, leaving a shaly residuum. Thicknesses less than 2 ft for the Guttenberg are reported in exploration holes in the Mineral Development Atlas. Figure 4 shows how the Decorah Formation thickness in the Platteville area is highly irregular (fig. 4a) in areas of Mississippi Valley-type mineralization (fig. 4b). Most of the thinning of the Decorah Formation results from dissolution of the Guttenberg Member from passing fluids.

Spechts Ferry Member. The Spechts Ferry Member is a green to greenish-blue shale with interbedded light-gray skeletal packstone and grainstone (Choi and others, 1999). Bentonite typically occurs near the base of the shale, and phosphatic pebbles occur in several beds near the top (Agnew and others, 1956). Locally, several feet of micrite with interlaminated shale and minor packstone can underlie more typical shale-rich Spechts Ferry, but overlie the bentonite (Bremmer and others, 2023). This can give the Spechts Ferry an anomalously large local thickness. Brachiopods, bryozoans, crinoids and trilobites occur in the unit, as well as *Chondrites* (Choi and others, 1999). The base of the Spechts Ferry Member is interpreted to be an unconformity and sequence boundary (Choi and others, 1999). In Grant County, the shaly portion of the Spechts Ferry Member ranges from around 7 ft thick in the far west to 2 ft thick in the east (fig. 5). In mineralized areas, most of the carbonate has been dissolved, leaving a thin shaly residuum (Agnew and others, 1956).

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Figure 4. Isopach map (thickness) of the Decorah Formation in the Platteville area of southeast Grant County (see inset panel for location). Panel A shows the thickness of the Decorah Formation with 5 ft contour lines overlaid. Panel B shows the thickness of the Decorah Formation with areas of mining activity and surface workings.



Bedrock geology of Grant County, Wisconsin

Platteville Formation

Background

The Platteville as a formation name was first used by Bain (1906). Prior workers had included both the Platteville and Decorah formations within the Trenton limestone (e.g. Strong, 1877; Chamberlin, 1882). The Platteville Formation includes the upper Quimbys Mill Member, the middle McGregor Member, and the basal Pecatonica Member. The Quimbys Mill Member was named by Agnew and Heyl (1946) for exposures roughly two miles north of New

Diggings in Lafayette County, officially replacing the earlier colloquial mining term of "glass rock." The McGregor Member was named by Kay (1935) for exposure in Clayton County, Iowa. The Pecatonica Member was first named by Hershey (1894) for exposure along the Pecatonica River in northern Illinois.

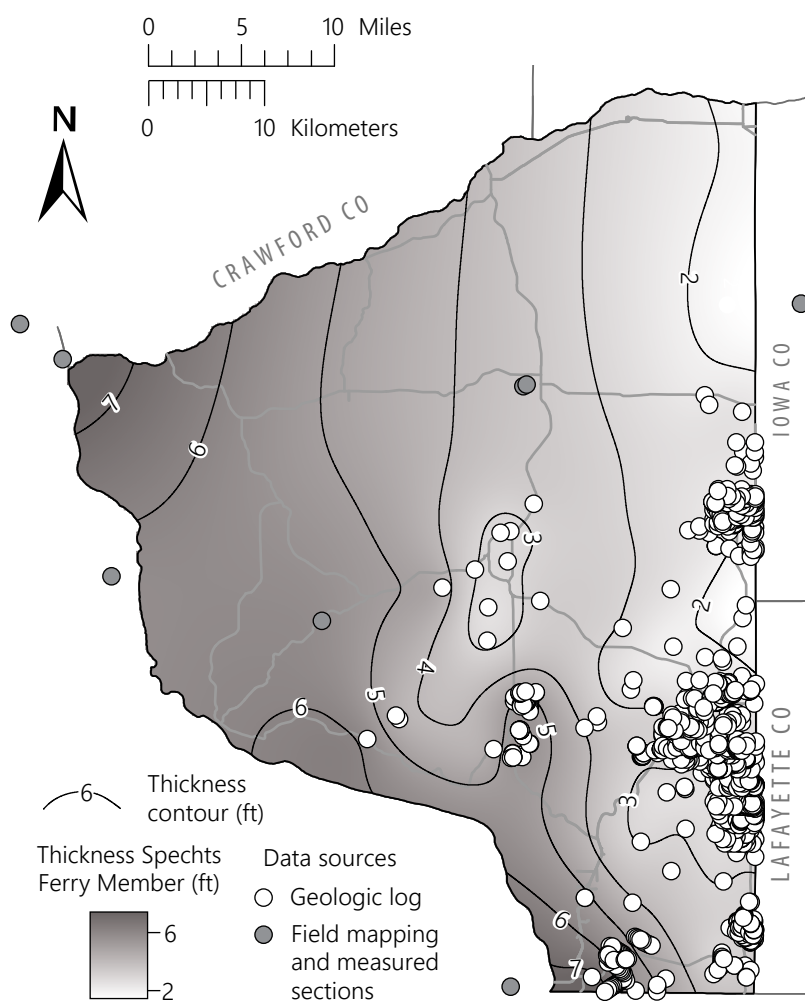
Description

Quimbys Mill Member. The Quimbys Mill Member is a light-gray to light-pinkish-brown very fine-grained carbonate mudstone with thin interbedded chocolatey-brown organic-rich laminae. The unit consists of

both limestone and dolomite and is extremely well lithified such that the unit breaks conchoidally when fractured. It is thin- to medium-bedded. Horizontal and vertical burrow networks are present along discrete beds which probably represent omission surfaces. Brachiopods and trilobites are also common, particularly in the limestone intervals (Agnew and Heyl, 1946). The Quimbys Mill Member thickens eastward and thins westward. In western Grant County, it is less than 1 foot thick, but in eastern Lafayette County the unit is 13 to 14 ft thick (Agnew and others, 1956). The unit also becomes increasingly dolomitized eastward and was locally thinned by Mississippi Valley-type mineralizing fluids.

McGregor Member. The McGregor Member is a bluish-grey to light-grey silty mudstone to wackestone with interbedded thin skeletal packstone to grainstone beds (Choi and Simo, 1998). Agnew and others (1956) note a green to blue, calcareous shale up to 1 foot thick occurs at the base of the McGregor in places. Limestone is typical of the unit in western Grant County, but it becomes increasingly dolomitized eastward. It is typically thin bedded. The McGregor Member has distinctive wavy bedding, interpreted by Byers and Stasko (1978) as a diagenetic effect. The base of the unit contains *Trypanites* (Byers and Stasko, 1978). *Trypanites* is characterized by vertical or high angle, isolated burrows excavated into a hardground surface. Above the base of the McGregor, *Chondrites* is common (Byers and Stasko, 1978). The hardground at the base of the McGregor is interpreted as a sequence boundary (Choi and Simo, 1998). The McGregor Member is 28 to 31 ft thick in southwest Wisconsin (Agnew and others, 1956).

Figure 5. Isopach (thickness) map of the Spechts Ferry Member of the Decorah Formation.



Political boundaries from U.S. Census Bureau, 2016; Wisconsin Transverse Mercator projection, 1991 Adjustment to the North American Datum of 1983 (NAD 83/91) EPSG 3071



Wisconsin Geological and Natural History Survey

Pecatonica Member. The basal Pecatonica Member is a gray to tanish-brown mudstone to skeletal wackestone. Sandy dolomite is common at the base of the Pecatonica Member. Quartz grains are medium- to coarse-grained (Agnew and others, 1956). The base of the Pecatonica also contains phosphatic pebbles (Agnew and others, 1956). The Pecatonica is dolomitic in composition. It is typically medium- to thick-bedded, and beds are typically planar. Brachiopods and gastropods are common, as are *Chondrites* and *Thalassinoides* trace fossil assemblages (Choi and Simo, 1998). Carbonate mud is often heavily bioturbated. The Pecatonica is 18 to 24 ft thick (Agnew and others, 1956; Carlson, 1961).

Ancell Group

Background

Like most Ordovician units in Wisconsin, the Ansell Group has not avoided nomenclature disputes. The Ansell Group includes the upper Glenwood Formation and the lower St. Peter Formation and was defined for Wisconsin by Ostrom (1969). Other authors have placed the Glenwood as a member of the overlying Platteville Formation (Strong, 1877; Agnew and others, 1956; West and Blacet, 1971; West and Heyl, 1985). Still others have placed the Glenwood as a member of the St. Peter Formation rather than a separate formation (Ostrom, 1967; Mai and Dott, 1985; Dott and others, 1986; Batten and Attig, 2010).

Authors have also debated about the exact contact between the St. Peter Formation and the Glenwood unit. Most geologic maps have followed the initial description of Calvin (1906) and limited the Glenwood to only a shaly and dolomitic zone beneath the Platteville Formation (Agnew and others, 1956; West and Blacet, 1971; West and Heyl, 1985; Stewart and others, 2022a; Stewart and others 2022b; Bremmer and others, 2023; Fitzpatrick and Stewart, 2024). Sedimentologists, however, have argued that the underlying 5 to 10 ft of sandstone is

depositionally related to the overlying shale rather than the underlying sandstone, and so have placed the base of the Glenwood within the sandstone package (Thiel, 1937; Templeton and Willman, 1963; Ostrom, 1969). The descriptions below place the base of the Glenwood above the sandstone, but recognize that the upper St. Peter Formation may be closely related to the shales of the Glenwood Formation.

Description

Glenwood Formation. The Glenwood Formation is a green sandy shale to dolomitic shale (Agnew and others, 1956). Dark-brown to black phosphate pebbles occur near the top of the Glenwood (Agnew and others, 1956). Pyrite cement is common (Agnew and others, 1956). Sand grains within the shale vary from fine- to coarse-grained. The shale is generally laminated. Horizontal and vertical burrows are found in the Glenwood

Formation (Bremmer and others, 2023). The thickness of the Glenwood varies depending on where the base of the unit is mapped. Limited to only the shaly beds, the Glenwood is typically 1 to 3 ft thick in Grant County, though it may be close to 6 ft near Beetown in western Grant County (Ostrom, 1969).

St. Peter Formation. The St. Peter Formation contains an upper Tonti Member and a lower Readstown Member. Ostrom (1967) defined the Readstown Member for exposures in Vernon County and established the Tonti as a member of the St. Peter Formation.

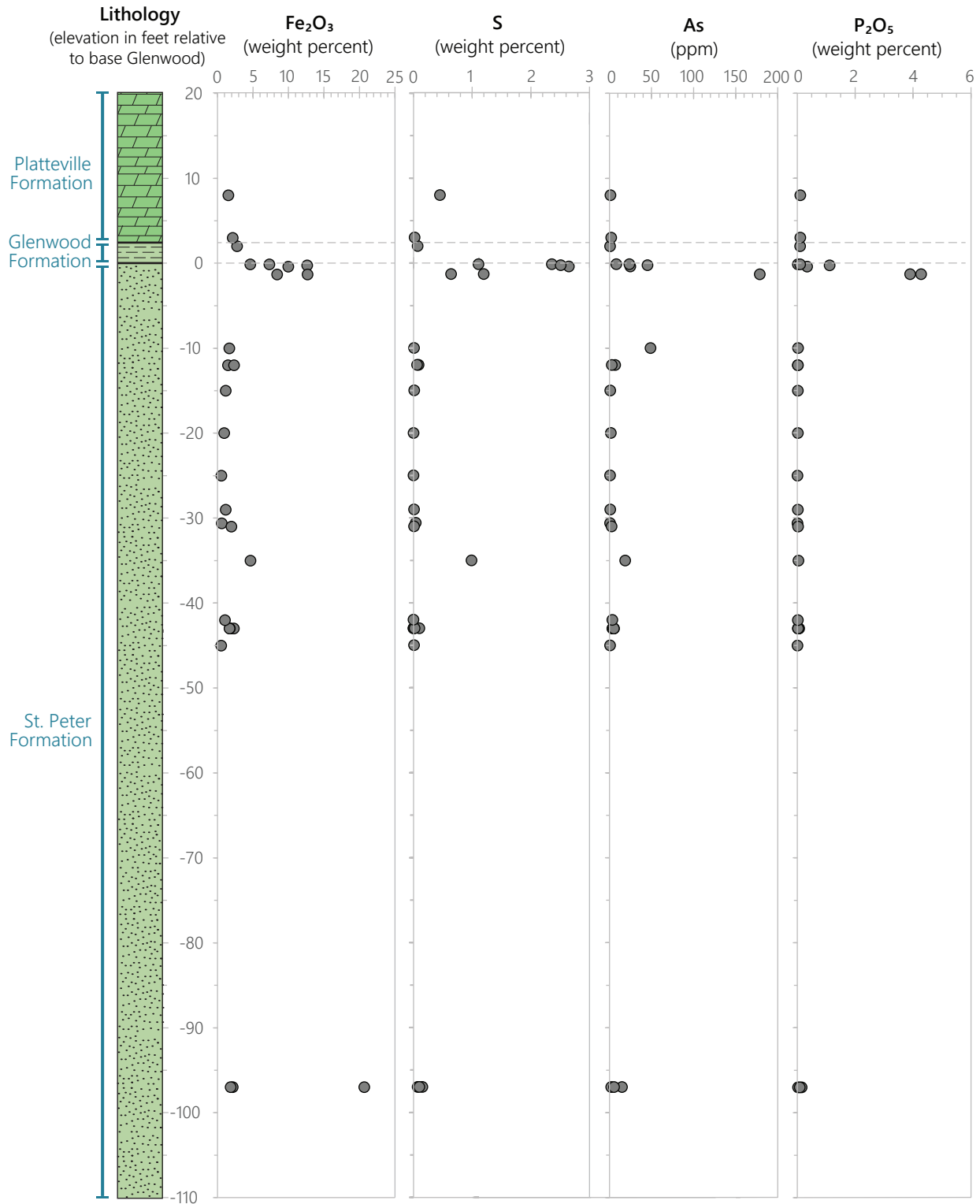
The upper 5 to 10 ft of the Tonti Member is fine- to coarse-grained sandstone, with some green shale laminations. Iron sulfide cements, weathering to iron-hydroxides at the surface, are abundant near the contact with the Glenwood Formation. Geochemical patterns at the top of the St. Peter

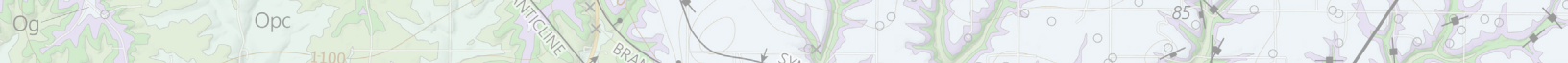




Bedrock geology of Grant County, Wisconsin

Figure 6. Whole-rock (n=28) geochemical results for Fe_2O_3 , S, As, and P_2O_5 plotted as abundance versus elevation relative to the base of the Glenwood Formation. Dataset 2 contains results from the full range of analyzed elements and includes one additional sample with a poorly controlled elevation relative to the Glenwood Formation.





Wisconsin Geological and Natural History Survey

immediately below the Glenwood contact show spikes in Fe_2O_3 , S, As, and P_2O_5 related to sulfide mineralization (fig. 6). Sandstone near the top of the St. Peter is poorly sorted, and occurs in medium- to thin-beds (Ostrom, 1969). Horizontal and vertical burrows have been observed in core from northern Grant County (Bremmer and others, 2023).

The rest of the Tonti Member of the St. Peter Formation is a white, tan, or reddish-brown, fine- to coarse-grained, supermature quartz arenite. Most of the Tonti is weakly cemented, but locally, the Tonti Member can contain iron oxide, dolomite, calcite, or silica cement (Chamberlin, 1882; Agnew and others, 1956). Sand grains are subangular to round (Agnew and others, 1956) and are well sorted. Bedding varies from thin to massive-bedded (Agnew and others, 1956). Cross-beds are common.

The basal Readstown Member is a white, green, to red-brown sandstone, conglomerate, and shale. The composition of conglomerate clasts includes sandstone, chert, shale, and dolomite (Mai and Dott, 1985). Bedding thickness is variable. Many shale beds are wavy. Soft sediment deformation is common in the unit.

The basal contact of the St. Peter Formation with the underlying Prairie du Chien Group forms an undulatory (or possibly pitted) surface with scattered sharply incised paleovalleys. Chamberlin (1882) was the first to recognize that the variability in thickness of the St. Peter Formation was due to its unconformable contact with the underlying Prairie du Chien Group. Much of the St. Peter Formation has a thickness between 40 and 80 ft, but thicknesses less than 20 ft and greater than 200 ft occur. Paleovalleys cutting through the Prairie du Chien Group are best exposed in the Highland area in northeastern Grant County. Some paleovalleys near Highland contain the base of the St. Peter Formation in contact with the Jordan Formation or

St. Lawrence Formation (Fitzpatrick and Stewart, 2024). The maximum thickness of the St. Peter Formation in the Highland area is around 330 ft. Elsewhere, paleovalleys appear to be present but can only be inferred from subsurface well data.

Prairie du Chien Group

Background

Bain (1906) named the Prairie du Chien Group for section near the town of Prairie du Chien in Crawford County, Wisconsin, replacing the earlier “Lower Magnesian” unit used in the upper Mississippi Valley. Bain (1906) subdivided the Prairie du Chien into an upper Shakopee Formation, a middle New Richmond Formation (sandstone), and a lower Oneota Formation. This nomenclature was used by Heyl and others (1959) and a large number of quadrangle maps published by the USGS in southwest Wisconsin during the 1960s and 1970s (fig. 1 and references therein). Davis (1966) and Ostrom (1967), however, disagreed and changed the New Richmond into a member of the Shakopee Formation near the end of the USGS mapping campaign in southwestern Wisconsin. The timing of this change was unfortunate because the large body of USGS mapping from the 1960s and 1970s did not use the new naming scheme. The Ostrom (1967) nomenclature was used in WGNHS (2011). In addition to discrepancies about the stratigraphic level of the New Richmond, many mappers have mentioned trouble identifying the New Richmond in the field (e.g. Deal, 1947; Heyl and others, 1959; Carlson, 1961; Fitzpatrick and Stewart, 2024). Many maps did not discuss the problem but simply left the Prairie du Chien Group as an undivided unit (e.g. Taylor, 1964; West and Blacet, 1971; West and others, 1971; West and Heyl, 1985). The New Richmond sandstone is likely absent in many areas, and its utility as either a formation or member is questionable. This map does not attempt to break the Prairie du Chien

Group into separate formations, and instead keeps the Prairie du Chien as an undivided group.

Description

The Prairie du Chien Group is a gray to tan, dolomitic mudstone to wackestone to crystalline dolomite. Chert is common. Green shale partings are common near the top of the unit (Agnew and others, 1956). Oolitic beds, sandy dolomite, and minor glauconite are common near the base (Deal, 1947). Bedding varies from laminated to massive. Vugs are common. The lower 150 ft of the Prairie du Chien Group contains scattered beds of laminated, silicified dolomite with stromatolite domes reaching up to 3 to 4 ft in diameter (Fitzpatrick and Stewart, 2024). Davis (1966) and Ostrom (1967) interpreted the base of the New Richmond member as an unconformity over the Oneota Formation. The top of the Prairie du Chien is a karsted unconformity overlain by the Readstown Member of the St. Peter Formation. The thickness of the Prairie du Chien Group varies locally due to the unconformity. The combined thickness of the Prairie du Chien Group and Ancell Group progressively increases from around 270 ft in northeastern Grant County to approximately 380 ft near Cassville in southwestern Grant County (fig. 7).

Cambrian

Jordan Formation

Background

The Jordan Formation was first named by Winchell (1874) for sandstone outcrops in southeastern Minnesota near the town of Jordan. At about the same time in Wisconsin, Irving (1875) named stratigraphically similar strata the Madison Sandstone, and speculated there might be a connection to Winchell’s section. Despite the simplicity of this correlation, a dizzying number of names, correlations, and basal contacts for units near the stratigraphic level of the Jordan were proposed over the next

Bedrock geology of Grant County, Wisconsin

nearly 60 years. Finally, Trowbridge and Atwater (1934, p. 26) decided that “order should be brought out of this chaos” and they established the Jordan Formation as the sandstone beds in both Minnesota and Wisconsin below the carbonate of the Prairie du Chien Group and above the carbonate and siltstone of the St. Lawrence Formation. The early establishment of this nomenclature by Trowbridge and Atwater (1934) helped stabilize the terminology of the Jordan Formation, and made all recent maps consistent in usage.

Description

The Jordan Formation is a tan, pink, orange or white, fine- to coarse-grained quartz arenite. The uppermost 5 ft of the Jordan Formation locally contains green shale partings (Stewart and others, 2022a). The upper 15 to 20 ft of the unit can also locally contain 6–12 in thick beds composed of sand grains with optically continuous quartz overgrowths with a dense interlocking fabric (Fitzpatrick and Stewart, 2024). The quartzite at the top of the unit is commonly interbedded with a fine- to medium grained friable sandstone and flat pebble conglomerate. Locally,

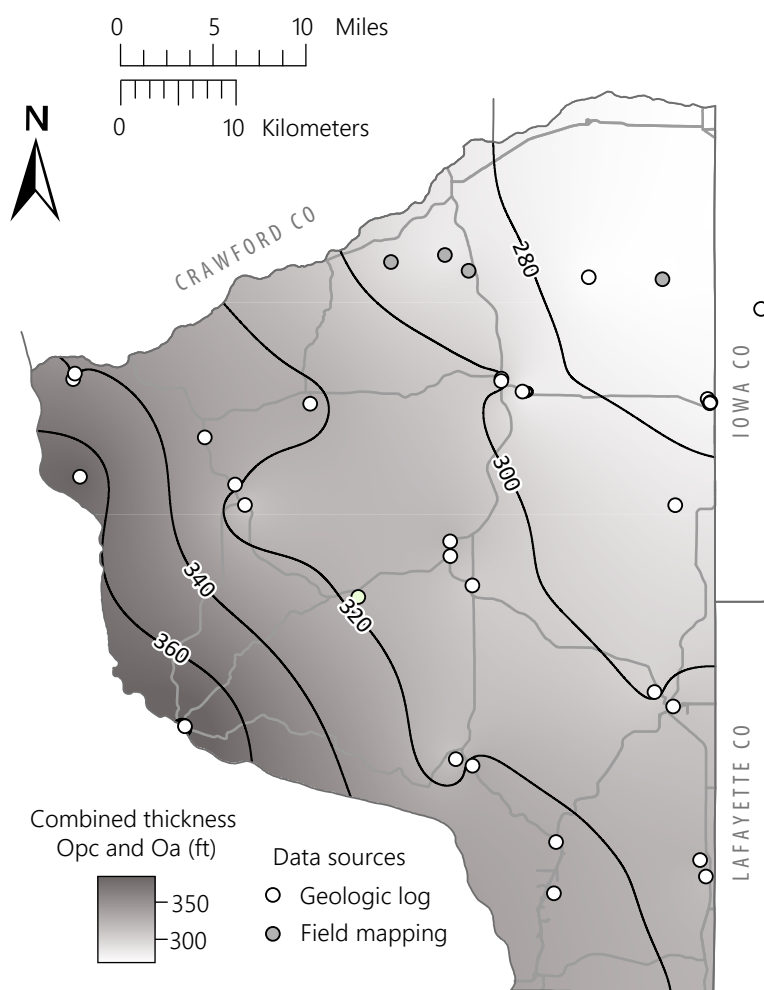
the upper 40 ft of the Jordan can also contain a very fine- to coarse-grained dolomite-cemented sandstone and sandy dolomite (Fitzpatrick and Stewart, 2024). Grains vary from subangular to round (Agnew and others, 1956). The Jordan is thin- to thick-bedded. Cross-beds are common and reach 3 ft in amplitude (Stewart and others, 2022a). Fitzpatrick and Stewart (2024) found the base of the Jordan grades into the underlying St. Lawrence Formation. Bed thickness and grain size decrease towards the contact. Ostrom (1964), however, reported an erosive contact at the base of the Jordan. The Jordan is typically 35 to 80 ft thick, but geologic logs in Grant County suggest thicknesses as small as 25 ft and as large as 130 ft. Thicker sections of Jordan Formation generally correspond to thinner sections of the St. Lawrence Formation, though the combined thicknesses are not consistent across Grant County and variations do not show systematic patterns. Byers and Dott (1995) found the base of the Jordan was generally gradational with the St. Lawrence Formation, but in places the base of the Jordan was sharp and represented an erosional truncation of the underlying St. Lawrence. As a result, both deposition and erosion may play a role in thickness changes in the Jordan Formation.

St. Lawrence Formation

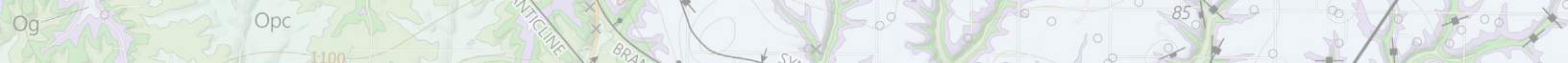
Background

The St. Lawrence Formation was described by Winchell (1874) for exposures in Scott County, Minnesota. Near Madison, Wisconsin, Irving (1875) named the Mendota limestone for rocks at a similar stratigraphic level. Like the nomenclature for the Jordan Formation, it took until Trowbridge and Atwater (1934) to definitively correlate the Mendota to the St. Lawrence Formation. They further subdivided the St. Lawrence into an upper Lodi Member and a lower Black Earth Member. This nomenclature has been relatively stable since the 1930s.

Figure 7. Isopach (thickness) map of the combined Prairie du Chien (Opc) and Ancell (Oa) groups.



Political boundaries from U.S. Census Bureau, 2016; Wisconsin Transverse Mercator projection, 1991 Adjustment to the North American Datum of 1983 (NAD 83/91) EPSG 3071



Wisconsin Geological and Natural History Survey

Description

Lodi Member. The Lodi Member is the upper portion of the St. Lawrence Formation and is composed of a green to tan siltstone with interbedded white to tan, very fine- to fine-grained sandstone (Fitzpatrick and Stewart, 2024). Medium-grained sandstone is less common. Calcareous cement is common in the unit, particularly in the finer grained intervals. The upper St. Lawrence is laminated to thin-bedded. Fine- to medium-grained sandstone is often cross-bedded. Bioturbation is common and *skolithos* burrows are present.

Black Earth Member. The Black Earth Member is the lower portion of the St. Lawrence Formation, and is composed of a light-tan to gray, silty to sandy crystalline dolomite. Sand and silt grains are typically composed of quartz. Isolated vugs are common, though less abundant than in the Prairie du Chien Group or Galena Formation. Bedding varies from laminated to massive. Laminated beds probably represent algal deposits. Trilobites and brachiopods have been reported in the dolomitic portion of the St. Lawrence Formation elsewhere (Twenhofel and Thwaites, 1919), but were not observed in Grant County. The thickness of the combined Lodi and Black Earth members of the St. Lawrence Formation is estimated to range from 75 to 135 ft.

Tunnel City Group

Background

Ostrom (1967) established the Tunnel City Group in Wisconsin by renaming and shifting the base of the older Franconia Formation. The base of the Tunnel City was placed above the Ironton Member, and the Ironton Member was shifted into the Wonewoc Formation of the Elk Mound Group. Ostrom established the Lone Rock Formation as the glauconitic facies of the Tunnel City, and the Mazomanie Formation as the non-glauconitic facies. However, Ostrom (1967) also noted that in places the Lone Rock

Formation “encloses” the Mazomanie Formation, and stratigraphic columns imply the Lone Rock Formation can be both stratigraphically above and below the Mazomanie Formation. Though the stratigraphic code forbids a formation to be both above and below another formation, this arrangement remains in use in Wisconsin (i.e. WGNHS, 2011). To avoid this complication, this map does not break the Tunnel City into separate formations. Most of the Tunnel City in Grant County is part of the Lone Rock Formation.

Description

The Tunnel City Group in Grant County is typically a white, tan, or green very fine- to medium-grained sandstone with common tan to green shale partings. Very-fine grained, micaceous white to tan, friable sandstone beds are poorly cemented, while more resistant sandstone beds contain dolomite cement. Glauconite-rich beds are characteristic of the unit. These beds commonly have basal scours with overlying flat pebble conglomerate (Fitzpatrick and Stewart, 2024). Most of the Tunnel City Group is thin-bedded. Cross-bedding is particularly common in glauconite-rich beds (Fitzpatrick and Stewart, 2024). Bioturbation and *skolithos* burrows are common in the Tunnel City. Trilobites and brachiopods also occur here (Deal, 1947). The thickness of the Tunnel City Group in Grant County, based on lithologic descriptions from geologic logs, ranges from 80 ft to 130 ft. Most logs, however, indicate a thickness of close to 100 ft.

Elk Mound Group

Background

Ostrom (1967) established the Elk Mound Group in Wisconsin by renaming and shifting the top of the roughly equivalent Dresbach Formation (i.e. Twenhofel and others, 1935). Ostrom (1967) noted that the older Franconia and Dresbach stratigraphic nomenclature also had usage as biostratigraphic stages, but these stages were not coincident with the lithologic contacts

mapped in the field. This confusion led him to establish the new Elk Mound Group, which included the Wonewoc, Eau Claire, and Mt. Simon formations. The Ironton Member of the Franconia Formation was moved to the top of the Wonewoc Formation as part of this revision.

Description

The Elk Mound Group does not crop out in Grant County, but is interpreted to occur at the buried bedrock surface in the Wisconsin and Mississippi River valleys beneath Quaternary sediment. Descriptions of the Elk Mound Group are based on cuttings sets and geologic logs of deep-water wells, and descriptions of the Elk Mound Group in nearby counties.

Wonewoc Formation. The Wonewoc Formation is a white to light-gray fine- to coarse-grained sandstone. It locally contains dolomitic and limonitic cement. Light-green shale partings, silcrete nodules, and rip-up clasts are present in the Wonewoc Formation in neighboring Lafayette County. The Wonewoc Formation in Grant County typically ranges in thickness from 150 to 165 ft.

Eau Claire Formation. The Eau Claire Formation is a gray to light- gray, fine- to medium-grained sandstone, siltstone and green, gray, or red shale. Shale often occurs as partings or laminae within very thin bedded sandstone. Dolomite cement is common. Sandstones can be glauconitic. The Eau Claire Formation typically ranges in thickness between 110 and 165 ft.

Mt. Simon Formation. The Mt. Simon Formation is a gray to pink, fine- to coarse-grained sandstone. Shale interbeds are common in parts of the unit. Interbedded sandstone and minor conglomerate occur in the lower-most several hundred ft of the unit. Dolomite cement is locally present in some beds. The thickness of the unit is poorly constrained. It is 675 ft thick at Lancaster, but may be thicker elsewhere.



Bedrock geology of Grant County, Wisconsin

Description of map structures

Fractures

Fractures form when differential stresses exceed the failure criteria of a rock. In southwestern Wisconsin, ancient tectonic events, recent unloading, and dissolution, karsting, and collapse could all produce differential stresses that lead to fracturing.

Fractures are divided into shear fractures and joints. Each type forms under different conditions. Shear fractures have a transport direction that lies within the plane of the fracture, while joints, or opening-mode fractures, have fracture walls that open away or perpendicular from the plane of the fracture. Shear fractures form under higher differential stresses than joints, and often form conjugate sets. Each set forms around ~20–30 degrees from the maximum principal stress (Handin and Hager, 1957; many others). Joints strike in the direction of the maximum principal stress, and open in the direction of the minimum principal stress. In the field, shear fractures often contain slickenlines and show offset of planar or linear markers. Joints do not contain slickenlines.

The fracture pattern and types of fractures in a region can give insight into the cause of the fracturing, as well as the stress state in the crust. Fractures forming from unloading are related to the near surface stress state of the Earth. Fractures caused by karsting and collapse will create chaotic and random fracture orientations. Shear fractures and joints from a tectonic source have preferred orientations related to tectonic events. If tectonic shear fractures and joints exist in a rock, these fractures may be reactivated during unloading, not leading to a new set of fractures.

New and published fracture orientations (Heyl and others, 1959; Whitlow and Brown, 1963; Mullens, 1964; Taylor, 1964; Stewart and others, 2022a, b; Stewart and others, 2023; Bremmer and others, 2023) were compiled and divided into domains based on similar patterns (fig. 8). Fractures on the map plate come from the sources listed above, but represent a small sub-set of the total fractures compiled on figure 8. Only fractures with dips of greater than or equal to 70 degrees were included on figure 8 to facilitate the use of rose diagrams, and because most fractures in the district are sub-vertical. Fractures were measured in all geologic map units. Fracture length tended to vary with bed thickness, and so a wide range of fracture lengths were measured (less than 1 ft to greater than 10 ft). Fracture morphology varied from closed to open. Some were solution-enhanced with enough open space that they could be termed fissures. Some fractures contained evidence for sulfide mineralization. Three population types were identified and are described below.

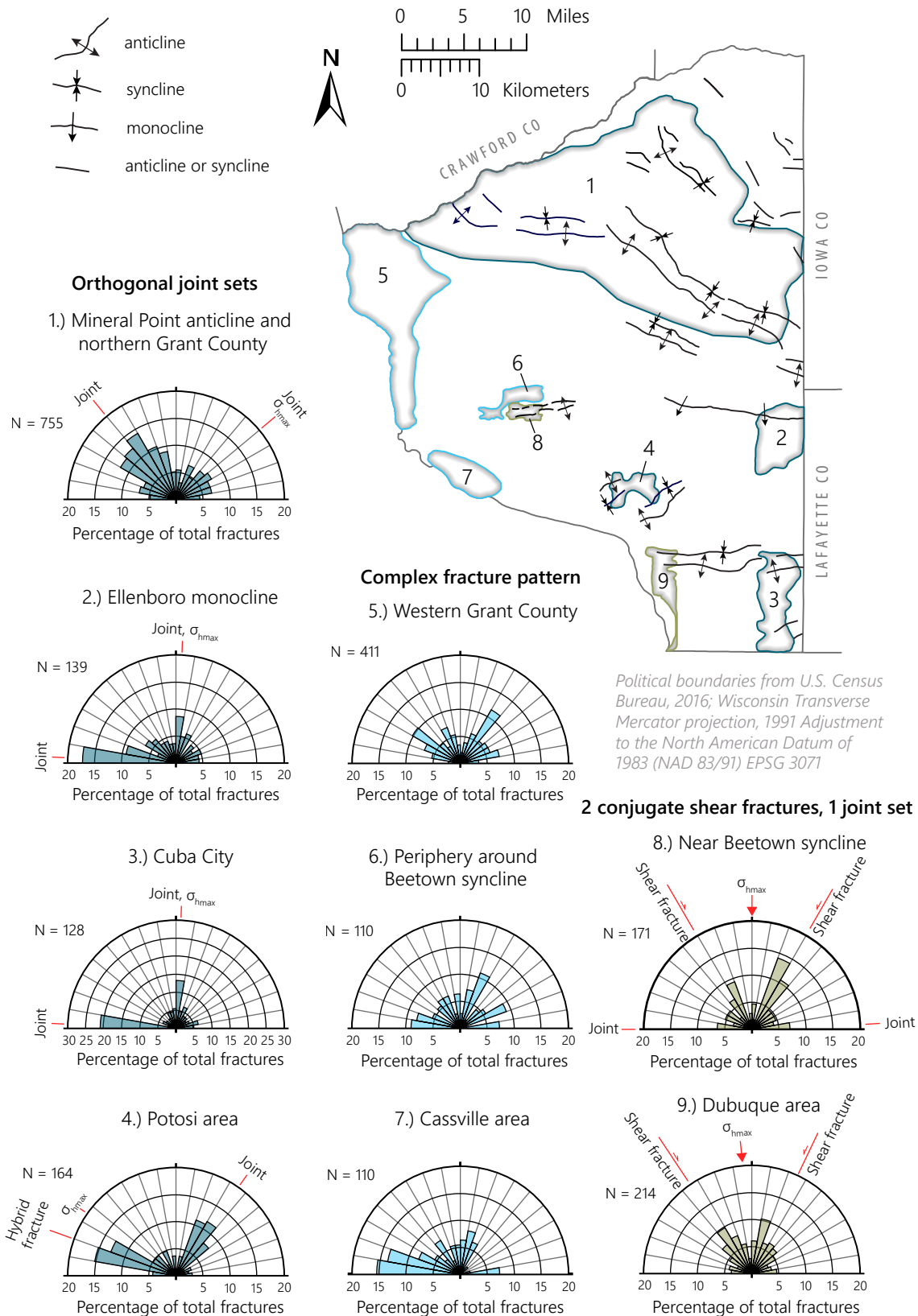
Orthogonal joint sets

Near the Mineral Point anticline, the Ellenboro monocline, and in the Cuba City and Potosi areas, fractures are orthogonal. One fracture set is perpendicular and the other parallel to the adjacent folds (fig. 8). Larger datasets, such as along the Mineral Point anticline and northern Grant County (n=755), have a larger spread of fracture and fold axis orientations, though nearly all fractures strike either northwest or northeast. Very few fractures in northern Grant County or along the Mineral Point anticline showed evidence for dip-slip or strike-slip movement. Figure 9a shows an example of dominantly orthogonal fractures near the Mineral Point anticline. In the Potosi area, Heyl and others (1959) recognized the northwest-striking fractures were generally open, but a subset contained horizontal lineations.

The bimodal fracture populations in the areas around the Mineral Point anticline, Ellenboro monocline, and Cuba City are interpreted to represent two dominantly opening-mode joint sets that formed as a result of folding. This interpretation is supported by the orthogonal fracture populations at all locations and the lack of slickenlines and evidence for shear fractures near the Mineral Point anticline. Variation in the direction of the joint sets between some of the sites (fig. 8, nos. 1–4) is interpreted to reflect changes in the stress state related to local folding conditions. This implies there was not a consistent regional stress state that controlled jointing, but rather jointing was related to local folding. Joints striking perpendicular to nearby fold axes are interpreted to record a maximum horizontal principal stress direction roughly consistent with the shortening direction inferred from folding (assuming the folds formed from contraction). Joints striking parallel to local fold axes are interpreted to record axis-perpendicular stretching.

Northwest-striking fractures near Potosi, however, are unlikely to be pure opening-mode joints. Some northwest-striking fractures contain horizontal slickenlines (Heyl and others, 1959), and the northwest-striking fracture population is oriented roughly 80 degrees (rather than perpendicular) to the northeast-striking set. The non-orthogonal orientation of the fracture sets combined with field observations suggests the northwest-striking set records hybrid slip (Ramsey and Chester, 2004), or a combination of opening mode and shear fracturing. This forms under somewhat higher differential stresses than pure joints, but lower than end-member shear fractures.

Figure 8. Half rose diagrams showing the distribution of fracture orientations for different domains in Grant County. Interpreted maximum horizontal stress is shown on the rose diagrams (σ_{hmax}), which is often close to perpendicular to fold axes for each respective area.





Bedrock geology of Grant County, Wisconsin

Conjugate shear fractures

In the Dubuque and Beetown areas, fractures form two or three populations (fig. 8, nos. 8–9). The smallest population, mostly observed in the Beetown area, strikes east-west and roughly parallels the nearby fold axes. In the Beetown area, this fracture set is more heavily mineralized and contains an opening mode component (Heyl and others, 1952). The other two fracture sets strike northwest and northeast, and are roughly 60 degrees from the fold axes. Northwest and northeast striking fractures tend to be closed in the Beetown area (Heyl and others, 1952).

The northwest and northeast fracture sets are conjugate shear fractures, and the east-west fractures are joints (Heyl and others, 1952; Whitlow and Brown, 1963). Figure 9b shows an outcrop example of the conjugate shear fractures from the Beetown area. The acute bisector of the shear fractures is interpreted to represent the average maximum compressive principal stress. The acute bisector is defined as the line that evenly splits the smaller acute angle (less than 90 degrees) between the fracture populations. In both Dubuque and Beetown, the inferred maximum horizontal stress was nearly north-south, close to perpendicular to the local fold axis.

Complex fracture pattern

The fracture pattern in parts of western and southwestern Grant County have more complex or irregular patterns. Fracture populations in western Grant County (fig. 8, no. 5), in the periphery around the Beetown syncline (fig. 8, no. 6), and near Cassville (fig. 8, no. 7) show populations that resemble patterns in adjacent domains, but are typically less well defined. The pattern in Cassville resembles the bimodal pattern near the Ellenboro monocline, except for a more diffuse northwest to northeast set of populations. Tectonic control is probably still important in areas with complex fracture patterns,

but unloading, karst, or other factors may be contributing more than in areas much closer to major folds.

Folds

In Grant County and across southwest Wisconsin, bedrock contacts generally dip to the southwest between 14 and 30 ft per mile (fig. 10). Interrupting the average dip are several large folds with amplitudes of 100 ft to greater than 200 ft (Grant, 1906; Heyl and others, 1952; Heyl and others, 1959; Carlson, 1961; Taylor, 1964; Mullens, 1964; Klemic and West, 1964; West and Heyl, 1985; Bremmer and others, 2023; Stewart and others, 2023). Large folds have a wavelength of 1 to 3 miles. Smaller folds and undulations are found across the county and can be nested within the limbs of larger folds. In most of Grant County, folds were interpreted from structure contour mapping of the base of the Platteville Formation (fig. 10). In northern Grant County, folds were interpreted from structure contour mapping of the base of the Prairie du Chien Group. The largest folds are described below.

Mineral Point anticline and Annaton syncline

The Mineral Point anticline and the Annaton syncline are a west to northwest trending, asymmetric, gentle anticline-syncline pair that crosses northern Grant County (fig. 10). The forelimb of the anticline dips 3.5 degrees and the back limb dips less than 1 degree. The folds have a combined amplitude reaching over 200 ft. The Mineral Point anticline is north-vergent and is composed of a series of underlapping to overlapping fold segments. Fractures along the anticline are typically vertical and strike either northwest or northeast. Deformation bands are concentrated along the steeper north-dipping limb of the Mineral Point anticline (Stewart and others, 2023). Deformation band density varies from isolated occurrences to dense webs, and no shear offset was observed in the field or

inferred from petrographic observations. Deformation bands are believed to be compaction bands. Structure contours of the base-Platteville surface align with aeromagnetic anomalies, and several structural highs closely correspond to aeromagnetic highs (fig. 11; Daniels and Snyder, 2002).

The steeper northeast-dipping limb of the Mineral Point anticline is locally displaced by small normal or sub-vertical faults. Faults were mapped when offset between contacts was abrupt (less than 50 ft) and contained evidence for brittle deformation, or when geophysical evidence supported faulting (fig. 12). Due to poor exposure, more small faults with less than 20 ft throw probably exist than are mapped. The Gregory Branch fault (Bremmer and others, 2023), a normal fault with 50 to 60 ft of down-to-the-northeast throw, is present north of Stitzer and is visible in airborne electromagnetic data (fig. 12; Crosbie and others, 2023). A small high-angle fault, named the Croft fault, is also probably present immediately west of Fennimore (Bremmer and others, 2023). Along the rest of the Mineral Point anticline, no other faults were recognized. Heyl and others (1959) mapped a thrust fault along much of the length of the Mineral Point anticline, but no evidence for thrusting was observed in the field or in AEM data.

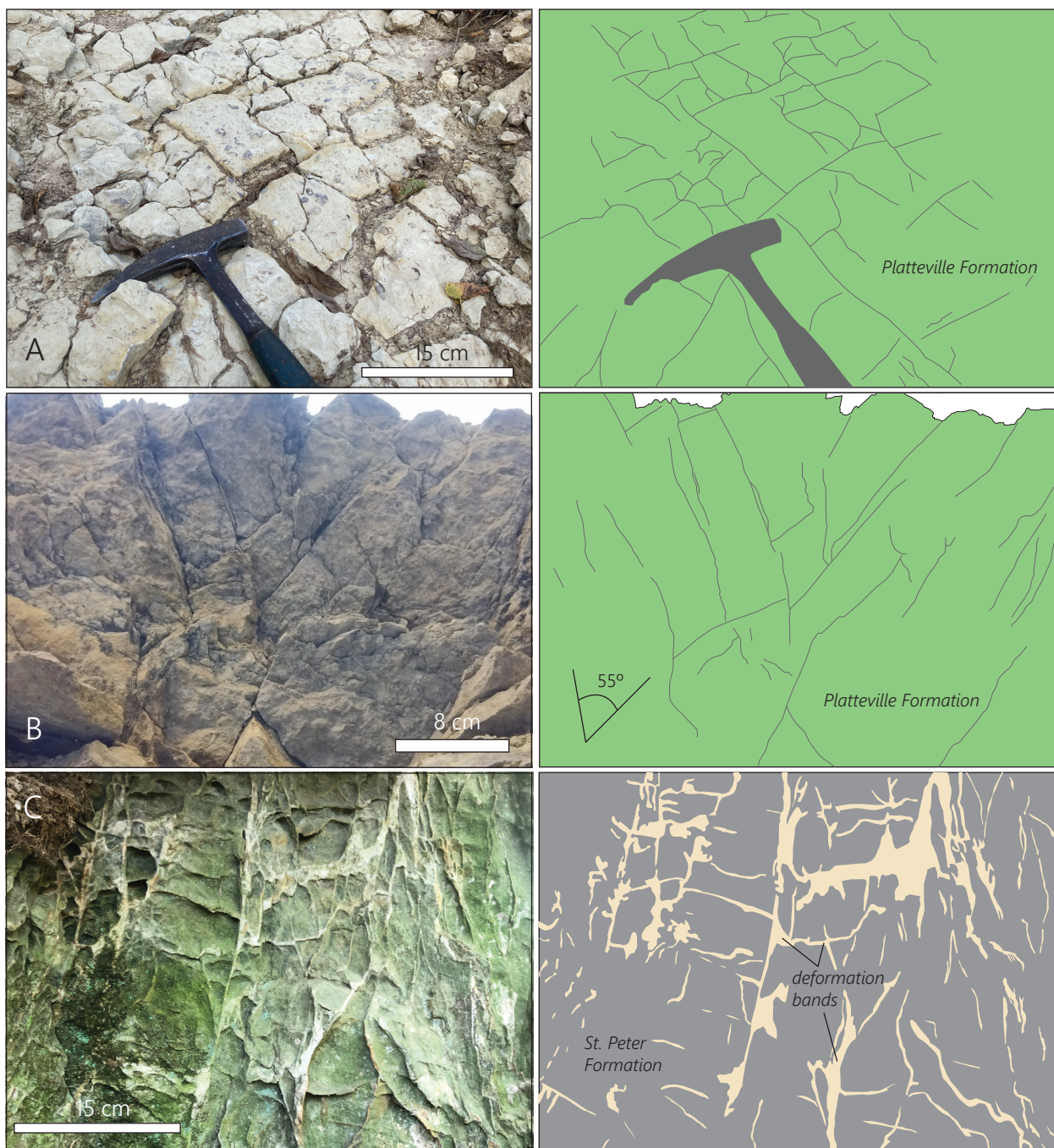
Beetown syncline

The Beetown syncline is an east-northeast trending, asymmetric, gentle syncline in west-central Grant County. The fold has a maximum amplitude of close to 100 ft. The Beetown syncline has a steeper south limb that dips 3 degrees to the north, and a gentler north limb that dips less than a degree south. The syncline is part of a north vergent anticline-syncline pair. The fold is likely composed of several underlapping segments. A 3-mile-wide zone of Pb and Zn mineralization runs parallel with the Beetown syncline and extends beyond to the east-northeast. This zone also contains higher



Wisconsin Geological and Natural History Survey

Figure 9. Examples of fractures and deformation bands in Grant County. Panel A is a field example of largely orthogonal (90°) fracture sets near the Mineral Point anticline. Panel B is a photo with a view looking up at an overhanging outcrop of conjugate shear fractures near the Beetown syncline (42.7942°N, 90.8868°W). Panel C is an example of webs of deformation bands in the St. Peter Formation adjacent to a map-scale syncline, southwestern Highland West quadrangle (43.0109°N, 90.4788°W).



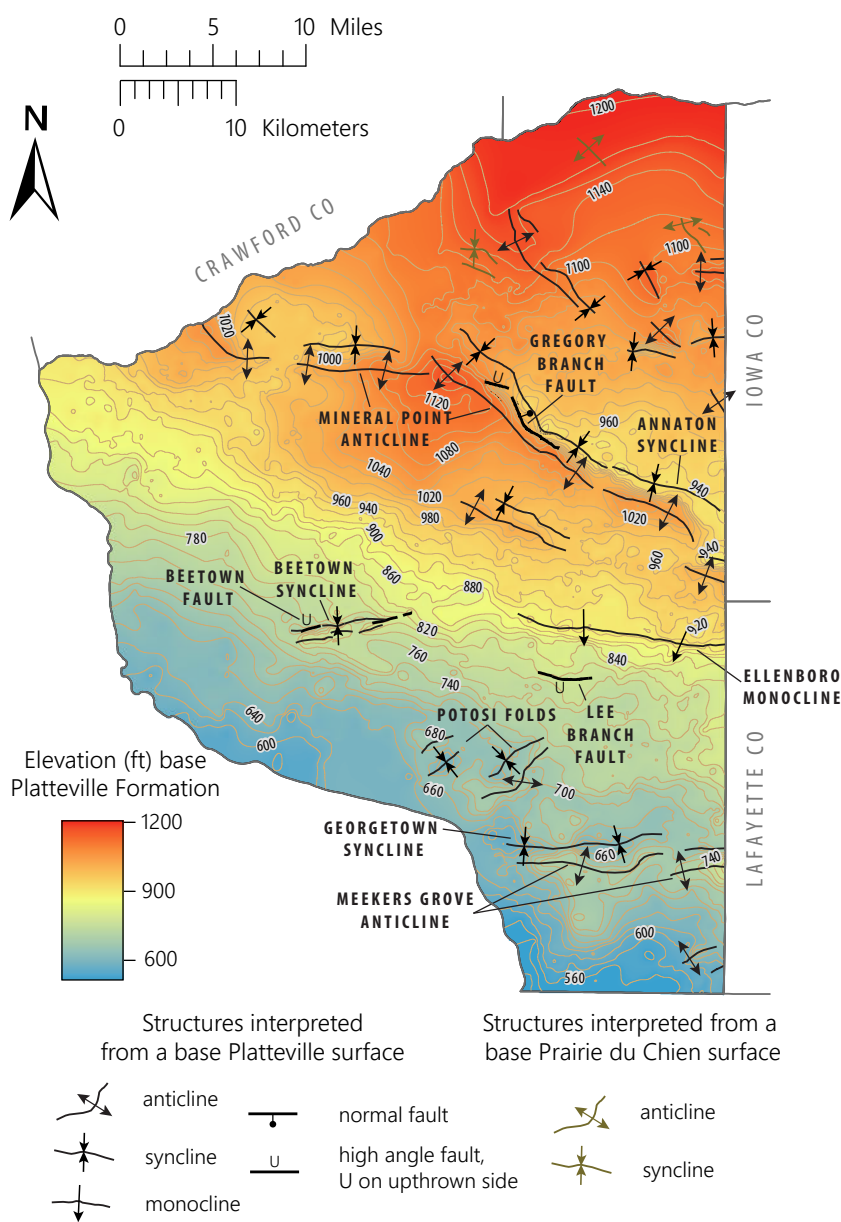
Bedrock geology of Grant County, Wisconsin

zinc concentrations in spring water discharged at the surface (De Geoffroy, 1969). Alteration associated with this zone includes solution thinning, dolomitization, and silicification (West and Heyl, 1985).

The Beetown syncline is locally displaced by several small high-angle faults of unknown dip or type. Displacements were estimated to vary from 10 ft to 50 ft (West and Heyl, 1985). Some faults are down-on-the-north, while others are up-on-the-north. The faults occur along the axis of

the fold rather than along the dipping limbs of the fold. The most prominent and westernmost of the faults is the Beetown fault, which is characterized by fractured, brecciated, and altered wall rock (Heyl and others, 1959). Clastic dikes are reported in the vicinity of the faults (West and Heyl, 1985). The dikes contain sandstone similar to the St. Peter Formation but are strongly cemented with abundant quartz overgrowths (Heyl and others, 1959).

Figure 10. Structure contour map of the base of the Platteville Formation, showing major folds and faults in Grant County.



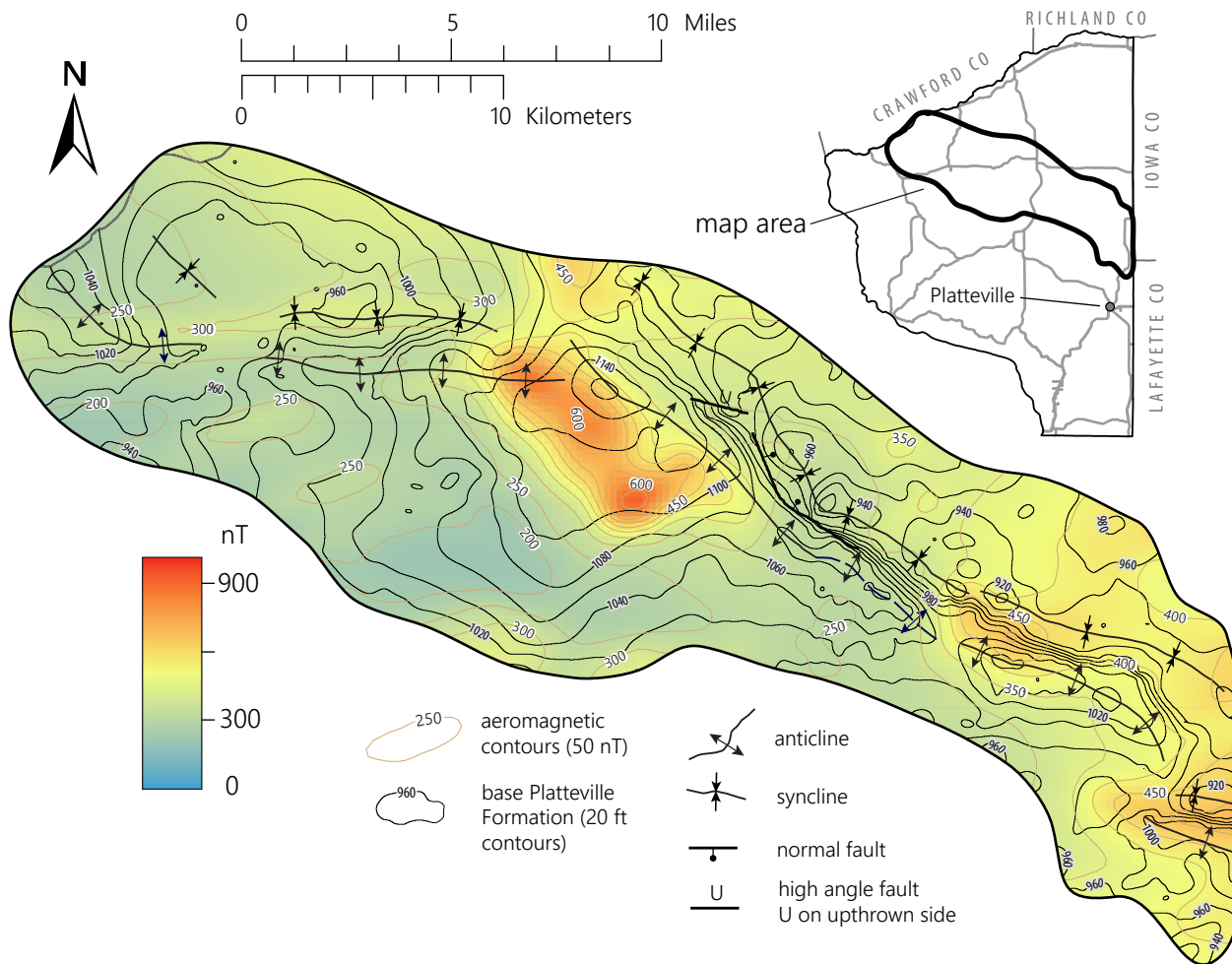
Meekers Grove anticline and Georgetown syncline

The Meekers Grove anticline and Georgetown syncline are an east-west trending, asymmetric, gentle anti-cline-syncline pair that cross southern Grant County. In Grant County, the fold pair have a typical amplitude of around 100 ft, but it reaches 260 ft to the east in Lafayette County (Mullens, 1964). The steeper north limb of the anticline generally dips 1 to 2 degrees to the north, and the south limb dips less than 1 degree to the south. In Grant County, the Meekers Grove anticline is north vergent, and appears to be composed of at least two overlapping segments. Little Zn-Pb mineralization is associated with the fold in Grant County, but some mining activity took place along the Meekers Grove anticline to the east in Lafayette County. Patterns in base Platteville structure contours and the trend of the fold tend to follow aeromagnetic anomaly contours in southern Grant County (fig. 13; Daniels and Snyder, 2002).

Political boundaries from U.S. Census Bureau, 2016; Wisconsin Transverse Mercator projection, 1991 Adjustment to the North American Datum of 1983 (NAD 83/91) EPSG 3071

Wisconsin Geological and Natural History Survey

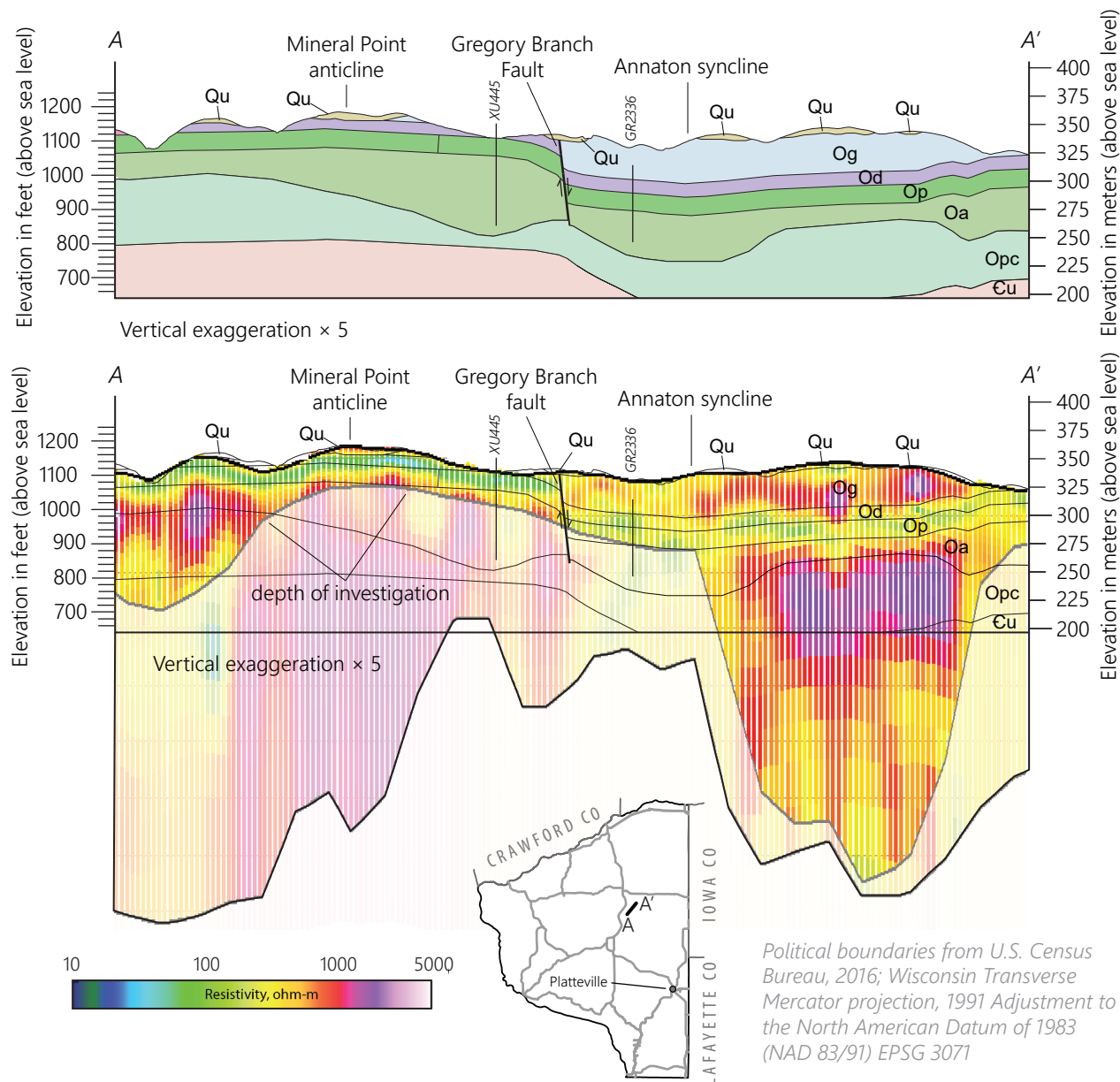
Figure 11. Structure contours of the base Platteville Formation along the Mineral Point anticline, overlaying part of the aeromagnetic anomaly map of Wisconsin. Aeromagnetic contours for the basemap are also included. Aeromagnetic data from Daniels and Snyder (2002).



Political boundaries from U.S. Census Bureau, 2016; Wisconsin Transverse Mercator projection, 1991 Adjustment to the North American Datum of 1983 (NAD 83/91) EPSG 3071

Bedrock geology of Grant County, Wisconsin

Figure 12. Geologic cross section of the Mineral Point anticline, Annaton syncline, and Gregory Branch fault (top), and airborne electromagnetic section across the same location (bottom). Airborne electromagnetic data from Crosbie and others (2023). Green values are more conductive, red and purple colors are more resistive. Results within the partially transparent area below the depth of investigation are not considered reliable. Vertically exaggerated 5 times.





Discussion

Orogenic stress transmission and the origin of fractures

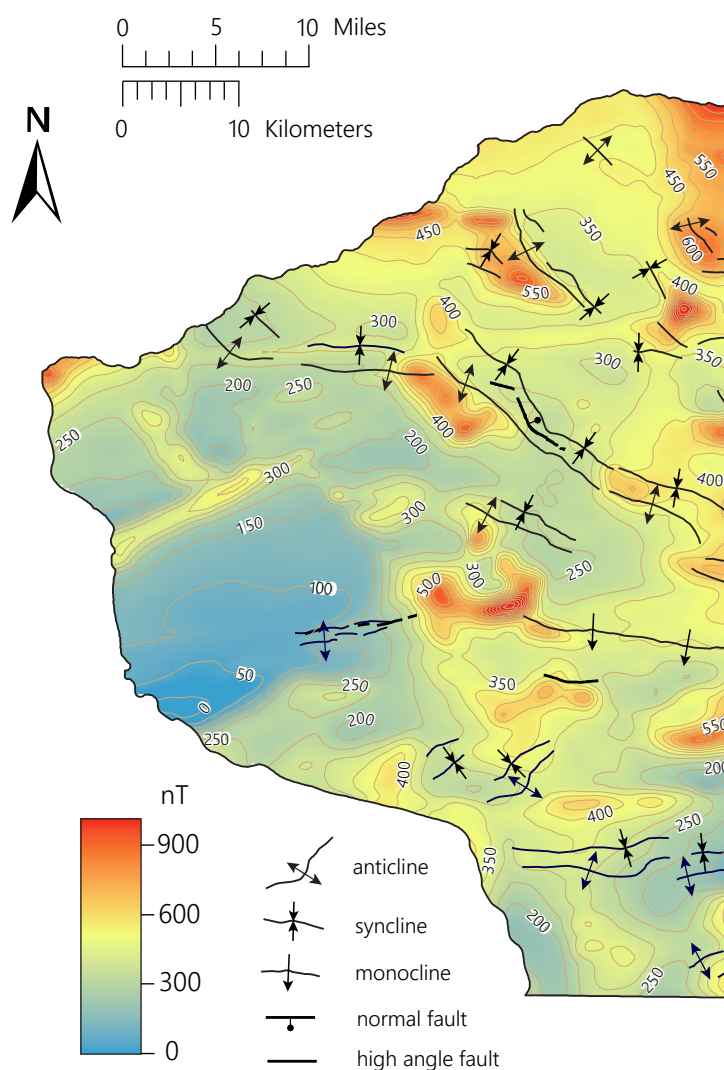
Despite the relatively flat-lying orientation of sedimentary rocks in Grant County, local deformation produced folds, faults, and fractures. Map-based studies in southwest Wisconsin found that larger folds with amplitudes of 100 to 200 ft formed from shortening related to regional tectonic events (Grant, 1906; Heyl and others, 1952; Carlson, 1961; Agnew, 1963; Klemic and West, 1964; Whitlow and West, 1966; Heyl and others, 1978; West and Heyl, 1985). Studies on far-field stresses in the upper Midwest generally support map-based interpretations (Craddock and Van der Pluijm, 1989; Van der Pluijm and others, 1997). Craddock and Van der Pluijm (1989) and Craddock and others (1993; 2017) found that stresses leading to calcite twinning were transmitted as far as Wisconsin and Minnesota, 2000 kilometers inboard from the active Appalachian thrust belt.

How stresses are transmitted deep into continental interiors during contractional tectonic events is less clear, but is important because it has implications for predicting fracture heterogeneity. Deviatoric stresses capable of deforming sedimentary rocks in Grant County may have been transmitted through the Paleozoic section or could have been transmitted through basement Precambrian rocks. Craddock and van der Pluijm (1989) and Craddock and others (1993) noted the shortening directions measured in calcite twins in the continental interior were consistently perpendicular to the nearest foreland thrusts, and they suggested stresses were transmitted deep into the continent within the Paleozoic section. Failure and faulting could occur within any plane of

weakness in the Paleozoic section if stresses were transmitted within the Paleozoic cover section. Elevated rock fracturing associated with faulting would be difficult to predict, because it would depend on where in the section faults developed. Other papers (e.g. Craddock and others, 2017) and maps (Mossler, 2006; Stewart, 2021) have shown that Precambrian basement faults were reactivated during later

Paleozoic events, indicating orogenic stresses were, at a minimum, also transmitted through the underlying basement. Reactivated Precambrian faults may cause forced folding of the overlying Paleozoic succession. Forced folding induces differential stresses in the Paleozoic cover (i.e. strain causes differential stresses), which could cause rock fracturing. In this case, strain and rock fracturing would be concentrated

Figure 13. Aeromagnetic anomaly map of Grant County with aeromagnetic contours (50 nT), derived from data in Daniels and Snyder (2002). The location of major folds and faults are also shown. See figure 10 for fold and fault names.



Political boundaries from U.S. Census Bureau, 2016; Wisconsin Transverse Mercator projection, 1991 Adjustment to the North American Datum of 1983 (NAD 83/91) EPSG 3071



Bedrock geology of Grant County, Wisconsin

in Paleozoic rocks at the base of the section near the Precambrian contact, and would diminish upward.

In Grant County, dominant paleostress directions inferred from fracture sets are interpreted to have occurred in association with folding of Paleozoic sedimentary rocks (fig. 8). Maximum interpreted horizontal stress directions are close to perpendicular to nearby fold axes. Maximum horizontal paleostress directions do not have a consistent azimuth across Grant County (fig. 8), which would be expected if far-field stresses were propagating through the Paleozoic cover sequence. The cause of folding and its relationship to fracturing is discussed in the conceptual model section below.

While the tectonic origin for large folds and faults in Grant County (plate 1) is well established (Grant, 1906; Heyl and others, 1952; Carlson, 1961; Agnew, 1963; Klemic and West, 1964; Whitlow and West, 1966; Heyl and others, 1978; West and Heyl, 1985), more uncertainty exists for the origin of anticlines and synclines with amplitudes of less than 40 ft. Heyl and others (1959) believed folds with amplitudes less than 40 ft were also largely caused by tectonics, and in some cases enhanced by solution thinning and sagging of overlying beds. Mullens (1964) believed solution thinning was the cause of the smaller folds. Whitlow and West (1966a) believed structures less than 20 ft were from solution thinning and collapse. The amount of solution thinning in the Decorah Formation is evident in figure 4 for the Platteville area, where 10 to 15 ft of thinning in a unit otherwise around 40 ft thick is common. If solution thinning also occurred in other stratigraphic units, synclines or basins reaching close to 40 ft are possible. Irregularities in the Precambrian surface may also cause differential compaction, and cause small undulations on the order of 20 to 40 ft in Paleozoic contacts.

Conceptual model for development of fractures and folds

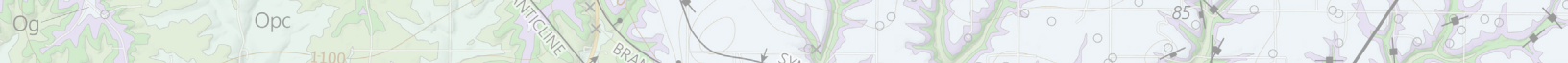
This section proposes a conceptual model for the development of folds and fractures in Grant County. It first describes a tectonic origin for large folds, then interprets paleostress directions and fracturing in the context of folding, and finally discusses evidence for extension and shortening near major folds. Collectively, these lines of evidence are used to constrain the conceptual model for folding and fracturing described at the end of the section.

In the study area, large folds (greater than 100 ft amplitude) in Paleozoic rocks formed from reactivation of underlying Precambrian faults (Carlson, 1961; Klemic and West, 1964; Heyl and others, 1978; Bremmer and others, 2023). Many folds, including the Mineral Point anticline, Meekers Grove anticline, and Beetown syncline, have segments with a similar general trend to underlying aeromagnetic anomaly contours or occur along the boundary to larger aeromagnetic anomalies (fig. 13). Aeromagnetic anomalies are often interpreted to be caused by differences in Precambrian geology in the upper Midwest, even when buried by hundreds of feet of Phanerozoic sediments (e.g. NICE working group, 2007). Several aeromagnetic highs have similar locations to structural highs along the Mineral Point anticline (compare aeromagnetic contours and base Platteville contours on fig. 11). The overall trend of the Beetown syncline, Ellenboro monocline, folds in the Potosi area, and the Meekers Grove anticline also generally follow the trend of nearby aeromagnetic contours. The Beetown syncline and the Ellenboro monocline are separated by a semi-circular aeromagnetic high that may represent an igneous intrusion (fig. 13, see fig. 10 for fold names). It is possible the Beetown syncline and Ellenboro monocline formed from reactivation

of the same Precambrian fault, but the fault was intruded out by a younger igneous event preventing a continuous Paleozoic structure.

Fracture populations suggest paleostress directions are inconsistent across Grant County, but are roughly coaxial with fold axes (fig. 8). If folding resulted from reactivation of Precambrian basement, such a scenario is consistent with stresses being transmitted from an orogenic belt through the Precambrian basement, reactivating variously oriented Precambrian faults. This relationship suggests strain associated with forced folding induced differential stresses in the cover sequence, causing failure and fracturing. Such a scenario is significant because it predicts a different distribution and density of fractures than from regional, far-field stresses transmitted through the Paleozoic section. It also predicts a higher fracture density where finite strain is highest near folds. Stewart and others (2022a) found such a relationship within the study area. Fracture density in the Castle Rock and Long Hollow 7.5-minute quadrangles was generally higher near mapped folds, though with significant scatter. Joint swarms up to 4 ft wide were found to be concentrated near folds (Stewart and others, 2022a; Bremmer and others, 2023), though Fitzpatrick and Stewart (2024) also noted joint swarms in the Highland area but did not find a clear connection to folding. It is possible increased fracturing near folds impacted the distribution of Mississippi Valley-type deposits by providing enhanced secondary porosity for the focused transport of mineralizing fluids (Arnold and others, 1996). It is also possible these same structures could provide high permeability zones for modern groundwater systems, but such a hypothesis is untested.

Major folds also show evidence for axis-normal extension. The Mineral Point Anticline is cut by the down-to-the-northeast Gregory Branch normal fault (Bremmer and others,



Wisconsin Geological and Natural History Survey

2023; fig. 12). Northwest-striking joints parallel the main trend of the Mineral Point anticline, also accommodating axis-normal stretching. Other major folds show similar structures. East-west striking joints near Cuba City parallel the Meekers Grove anticline and accommodate axis normal extension. Populations of axis parallel joints also occur along the Ellenboro monocline and the Beetown syncline. Several high angle faults also cut the trough of the Beetown syncline. All these secondary structures occur approximately 1,500 ft above the Precambrian basement. It is possible they were caused by outer arc stretching related to folding, or alternatively they could be caused by a change in stress state.

Thrust or reverse reactivation of Precambrian faults is tentatively interpreted to be the cause of forced folding in most and possibly all of the major folds in Grant County. Both thrust/reverse and normal reactivation of basement faults can produce asymmetric gentle folds in overlying rocks, but the strain history in the cover sequence differs and can be used to tentatively interpret basement kinematics. Normal reactivation of an underlying basement fault produces consistent horizontal extensional strain perpendicular to the fold axis in the overlying forced fold (Cosgrove and Ameen, 1999). Thrust or reverse reactivation commonly produces contractional and extensional strain in the overlying folded sequence, varying both with respect to location in the fold and potentially overprinting each other through time (Cosgrove and Ameen, 1999). The Mineral Point anticline is a good example of a large fold in Grant County, and it shows evidence for both shortening and extension, most consistent with thrust or reverse reactivation of the underlying basement. Joints striking parallel with the fold and the Gregory Branch fault both indicate extension occurred normal to the fold axis. However, compactional deformation bands in the St. Peter Formation are found

along the north-dipping limb of the anticline. Compactional bands suggest a contractional origin because they are uncommon in extensional settings (Soliva and others, 2013). Additionally, cataclastic shear deformation bands tend to be localized around faults in extensional settings but are more distributed in contractional settings (Solum and others, 2010; Soliva and others, 2016). Deformation bands along the Mineral Point anticline are widely distributed though heterogeneous in density along the approximately 0.5-mile-wide north-dipping limb of the fold, more consistent with a compressive setting. Finally, the Beetown syncline and the Meekers Grove anticline near Dubuque are interpreted to contain shear fractures. These fractures are interpreted to have a maximum compressive stress that is horizontal (see above), similar to the predicted maximum compressive stress for thrust/reverse motion in basement faults.

Figure 14 presents a conceptual model for the geometry and internal strain for major folds in Grant County and is based on field data and subsurface modeling. Near surface constraints are based on field mapping and AEM profiles, while deformation near the Precambrian basement is modeled based on the trishear fault propagation fold model (Erslev, 1991). Trishear is a kinematic model where deformation in advance of the tipline of a fault is accommodated within a triangular zone propagating away from the tipline. Throw on the Precambrian fault was modeled as 130 ft, typical of much of the fold. The thrust was given an arbitrary dip of 30 degrees (vertically exaggerated in fig. 14). Strain ellipses near the tipline and fault propagation fold geometry were calculated using FaultFold v. 7.2.0, a program based on the algorithms of Allmendinger (1998) and Zehnder and Allmendinger (2000). Deformation was forward modeled from an undeformed state to match the mapped geometry of the fold in Ordovician units. The fault propaga-

tion to slip ratio was set at 1.5, and the trishear angle was set at 60 degrees. Varying these parameters does not significantly change the results. The cross section (fig. 14) is vertically exaggerated 5 times to show changes in bedding dip with depth. Finite strain ellipses are not exaggerated.

Several predictions can be derived from figure 14. First, the dip of the bedding on Paleozoic rocks is interpreted to progressively increase with depth, and the width of the fold zone is predicted to decrease with depth. Second, finite strain modeling of Cambrian strata close to the propagating fault tip yields strongly deformed rocks despite the small offset of the fault (fig. 14b). If dense networks of deformation bands accommodated some or most of the shortening in the basal Cambrian section, a significant reduction in bulk rock permeability may result. Finally, higher up near current land surface, modeled strain ellipses show less finite strain (fig. 14b). In this area, field observations suggest some contractional strain was accommodated by deformation bands and shear fractures. Extensional strain, accommodated by both normal faulting and jointing, either overprinted the contractional strain or perhaps occurred over the same time interval. Extension may have resulted from outer arc stretching related to the geometry of the fold, or perhaps due to a change in regional stresses.

Hydrogeology map applications

Three-dimensional bedrock mapping in Grant County can be used for various fundamental and applied research questions relating to nitrate contamination, bacteria contamination, and other applied problems. The map allows surface and/or subsurface features, such as springs or mineralized areas, to be interpreted in three-dimensional space. In the following sections, three examples of hydrogeologic applications are provided. First, the potential impacts of folds and

Bedrock geology of Grant County, Wisconsin

faults on groundwater are described. Second, mapping is used to assess the impact of stratigraphy on springs. Springs form from focused flow below ground surface, and a better understanding of their stratigraphic distribution may help improve conceptual models for groundwater flow. Finally, the mapping is used to assess the number of groundwater wells open to multiple Ordovician aquifer systems, which have the potential to transfer bacteria and nitrates from the more contaminated and fractured Sinnipee carbonate aquifer to underlying less contaminated aquifers.

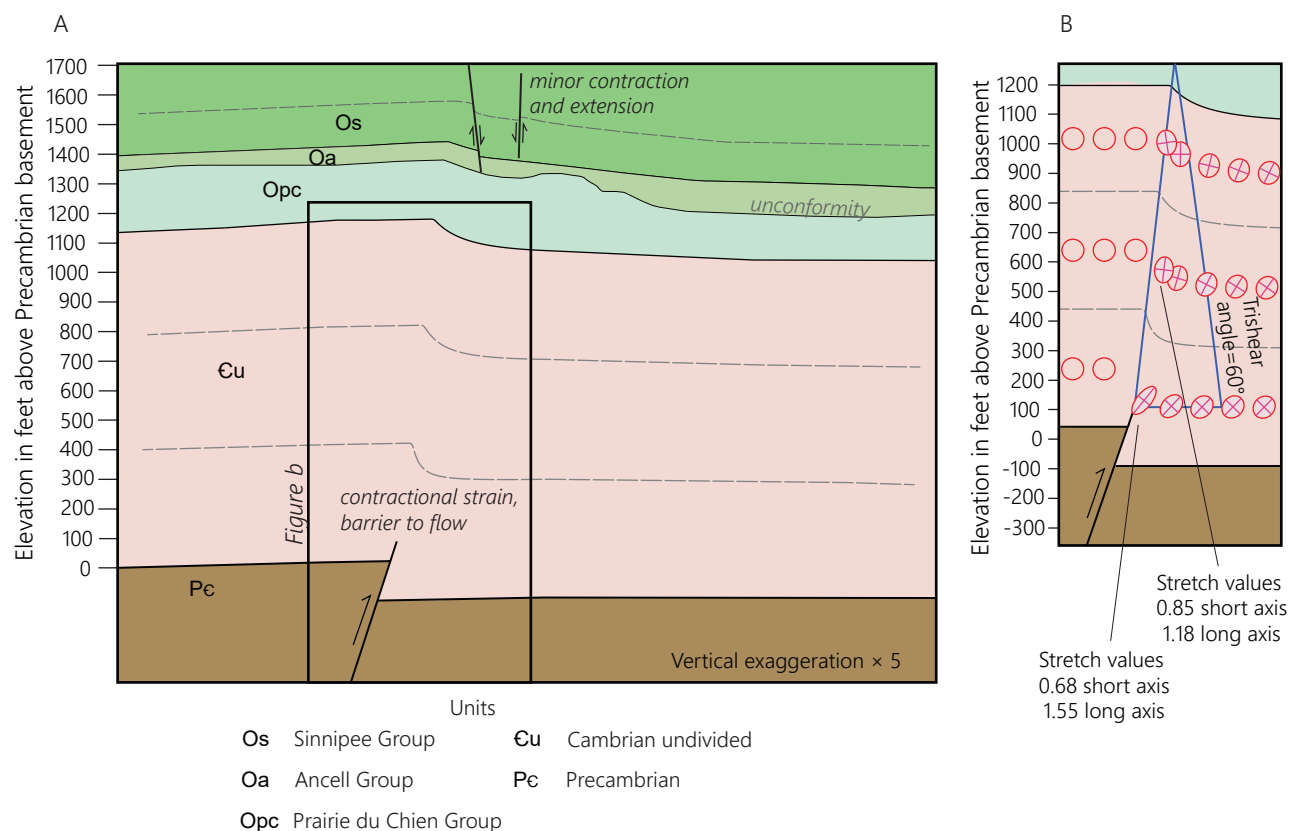
Impact of folds and faults on groundwater flow

Larger folds and faults may impact modern hydrologic systems because they likely focused groundwater flow during mineralization in the Upper Mississippi Valley Zn-Pb district (UMVD). Zn-Pb sulfide deposits are found across much of Grant County. These deposits formed from Permian hydrothermal brines flowing north out of the Illinois Basin through Ordovician carbonates in the UMVD (Brannon and others, 1992). Synclines in the district (see fig. 10), including the Beetown syncline (West and Heyl, 1985) and folds in the Potosi area (Whitlow and

West, 1966a), commonly host Zn-Pb deposits. These observations led many workers to the interpretation that synclines helped focus mineralizing fluids (e.g. Heyl and others, 1959). Groundwater flow modeling by Arnold and others (1996) helped quantify the impact of field observations. They found that elevated vertical hydraulic conductivity in the Maquoketa Group, likely related to fracturing and folding, was an important variable for focusing mineralizing fluids.

Clastic dikes, which are concentrated in areas of folded and faulted rocks (Heyl and others, 1959), provide insight into the scale and heterogeneity of

Figure 14. Panel A is a conceptual model for major folds in Grant County, showing contractional strain near the base of the Cambrian undivided (Cu) section from thrust-sense reactivation of basement Precambrian faults. Networks of deformation bands may act to lower horizontal hydraulic conductivity near the propagating fault tip. Higher up in the Ordovician section (Opc, Oa, Os), minor contractional and extensional strain occur in the same part of the section, and bedding dip decreases. Panel B shows modeled strain ellipses near the propagating tip of the fault. Near surface constraints are based on field mapping and AEM profiles, while deformation near the Precambrian basement is modeled using FaultFold v. 7.2.0 (Allmendinger, 1998; Zehnder and Allmendinger, 2000). Strain ellipses are not exaggerated.





Wisconsin Geological and Natural History Survey

fracture systems and their potential to cross-connect aquifers. The clastic dikes are thought to have formed during tectonic deformation when open fractures formed as a result of folding. The fractures allowed a slurry of sand and wall rock chips to be injected upwards into the Sinnipee Group by overpressured fluids (Heyl and others, 1959; Allingham, 1963). The presence of clastic dikes stratigraphically high in the Galena Formation indicates large fracture systems and faults can be continuous from the St. Peter Formation to the Galena Formation, and these large fractures are likely concentrated in folded and faulted areas (Heyl and others, 1959). It is unknown whether these large fracture systems locally impact groundwater systems today by hydraulically connecting upper and lower aquifers.

Folds and faults may also be capable of acting as barriers to groundwater flow. Stewart and others (2023) noted that historic Pb mines in the Crow Branch area of eastern Grant County were focused along the edge of the Annoton syncline in areas between doubly-plunging segments of the Mineral Point anticline (fig. 10). They interpreted the segments as folds that developed over basement faults,

and the overlap region between folds as the area above a transfer zone between faulted segments of Precambrian basement. Elevated fracturing in the transfer zone could conceivably have provided the mechanism to focus mineralizing fluids upward. The main segments of the folds/faults were thought to have acted as lateral barriers to flow. Notably, modeling of modern groundwater flow in the Sandwich Fault Zone of northern Illinois found that the fault core reduces horizontal hydraulic conductivity by at least an order of magnitude (Hadley and others, 2020), reiterating the important though complex role these structures play in impeding or enhancing groundwater flow.

Impact of stratigraphy on springs and hydrogeology

Stratigraphy was found to be one of the principal controls on spring location in southwest Wisconsin (De Geoffroy, 1969; Swanson and others, 2009). Springs often form along high permeability beds that overlie aquitards. As groundwater moves downward and approaches an aquitard, the aquitard causes groundwater flow to become mostly horizontal. The horizontal flow can intersect valley slopes

and discharge as a spring. The distribution of springs can be indicative of locations of both high flow zones and aquitards in the stratigraphic section and can help improve conceptual models of groundwater flow.

The Decorah–Platteville–Glenwood formations act as an aquitard in southwest Wisconsin (De Geoffroy and others, 1967; Carter and others, 2011). High permeability beds, often near the Decorah Formation, occur above and within the Decorah–Platteville–Glenwood aquitard (Swanson and others, 2014). De Geoffroy (1969) reported spring horizons at the base of the Galena Formation, base of the Ion Member, base of the Guttenberg Member, and base of the Platteville Formation. High permeability zones in carbonate rocks within the Decorah–Platteville–Glenwood occur due to the development of secondary porosity, either through chemical dissolution along bedding planes, or through unloading or solution enhancement of preexisting mechanical fractures.

Small springs and seeps in northwestern Grant County are concentrated near the Glenwood Formation and Spechts Ferry Member of the Decorah Formation (Swanson and others, 2014; Stewart and others, 2022b; fig. 15). Springs presented on figure 15 are from Stewart and others (2022), and were recorded where trickling water was noticed during mapping. Seeps were recorded where certain stratigraphic beds showed evidence of water seepage and minor focused groundwater flow. Spring abundance is plotted on a histogram relative to the base of the Platteville Formation mapped by Stewart and others (2022b). The Glenwood and Spechts Ferry are composed largely of shale, an effective aquitard. A small peak in spring abundance is also present near the base of the Galena Formation. Scattered springs also occur throughout the rest of the Decorah Formation and are sporadic within the Prairie du Chien Group. In general, these results



Spring southwest of Fennimore, WI

Bedrock geology of Grant County, Wisconsin

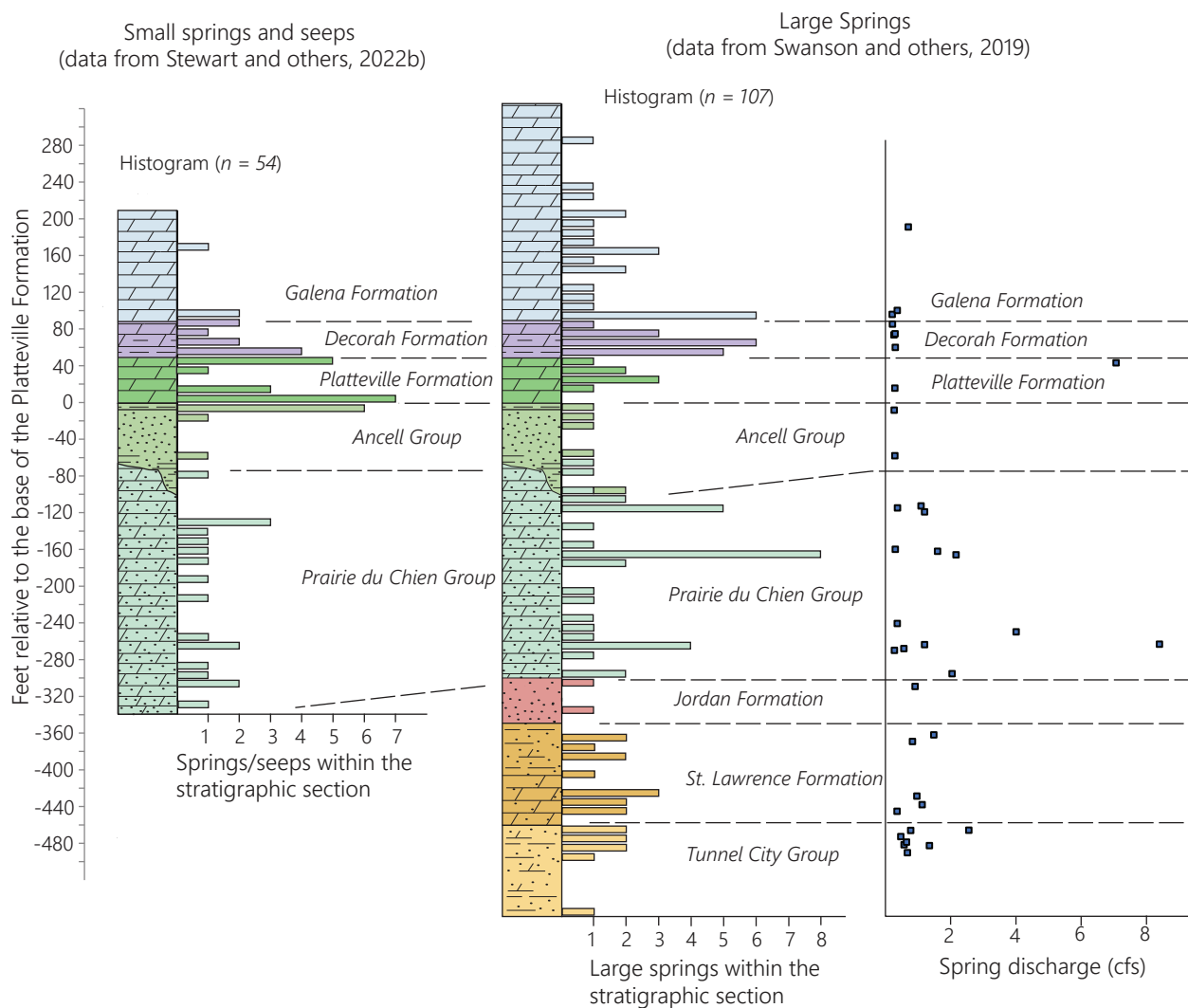
support De Geoffroy (1969) and the idea that stratigraphy is a dominant control on small springs and seeps. It also suggests that the two most continuous aquitards in northwestern Grant County are the Glenwood Formation and the Spechts Ferry Member of the Decorah Formation.

Larger springs also show a dependence on stratigraphy (fig. 15), but spring distribution is complicated by recharge areas. Spring locations and discharge rates are from Swanson and others (2019), and sites represent both sampled springs and springs investigated but not surveyed. These

springs contain much larger flow volumes than springs from Stewart and others (2022b). To account for the change in the combined Ancell–Prairie du Chien thickness across the county (fig. 7), the stratigraphic elevation of springs in the Prairie du Chien Group were normalized to a thickness of 300 ft. Results show springs are concentrated 70–80 ft above the base of the Galena Formation, near the Galena–Decorah contact, the lower 30 ft of the Decorah Formation, and within several horizons in the Prairie du Chien Group. Only 1 spring occurred within 10 ft of the Glenwood Formation, different from a strong peak seen in

the small springs and seeps dataset. The reduction in the number of large springs near the Glenwood Formation is probably related to the Glenwood Formation's place at the base of a series of aquitards, which could prevent groundwater from reaching the Glenwood before it is discharged. Much of Grant County is dissected by stream valleys, and most surface recharge is probably discharged along valley slopes within stratigraphically higher spring horizons, such as the base of the Galena Formation and the base of the Guttenberg Member of the Decorah Formation. Recharge to the Platteville Formation is limited by the

Figure 15. Histograms of the location within the stratigraphic section of small springs and seeps (left) and large springs (right). Spring locations are from Stewart and others (2022b) and Swanson and others (2019). Discharge rates are from Swanson and others (2019).





Wisconsin Geological and Natural History Survey

overlying aquitards and the narrow ridges typical of much of Grant County. Broad uplands are needed to provide recharge to the lower Platteville Formation, and these are characteristic of only parts of southern Grant County, limiting the number of locations in the county where large springs near the Glenwood could form. Seepage along valley slopes from springs discharging in the Decorah and Galena formations may help contribute to the large number of smaller springs and seeps near the Glenwood Formation.

Cross-connecting groundwater wells in Grant County

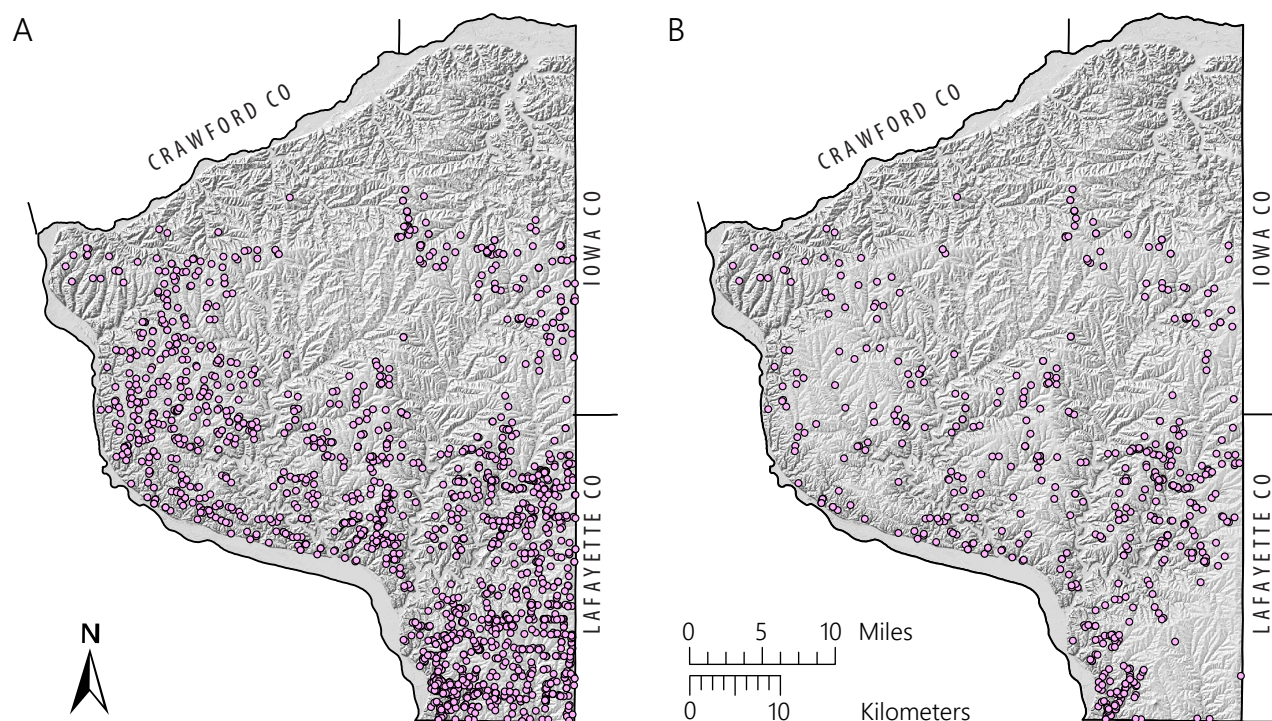
SWIGG identified bedrock geology as one of several risk factors for nitrate contamination in groundwater wells in southwest Wisconsin (Stokdyk and others, 2023). Wells with an open interval in the Sinnipee Group had higher nitrate contamination risk compared to wells only open to underlying

aquifers. Some groundwater wells cross-connect aquifers. These wells have open intervals that span more than one aquifer. If there are differences in hydraulic head between the two aquifers, groundwater will flow down or up the well when pumping is not occurring. When hydraulic head is less in the lower aquifer, there is the potential to transfer contaminants such as nitrate from a contaminated upper aquifer into the lower aquifer. This could adversely impact neighboring wells constructed with an open interval only in the lower aquifer. Wells cross-connecting the Sinnipee Group with lower aquifers, such as sandstones within the Ancell Group, were also found to have a higher contamination risk of nitrate (Stokdyk and others, 2023). Other risk factors include well construction practices and well site characteristics (i.e. slope, elevation, tendency for rainfall to infiltrate into the ground versus runoff).

Bedrock surface rasters (see dataset 3) were used to determine the location and percentage of wells open to the Galena Formation and wells cross-connecting the Galena Formation and the Ancell Group. In total, 6,087 geolocated well construction reports in Grant County contain casing depth and total well depth information. For each of these wells, GIS software was used to calculate the surface elevation, the elevation of the base of the well casing, the elevation of the top and bottom of the Galena Formation, the elevation of the top of the Ancell Group, and the elevation of the bottom of the well. This information was used to identify which wells had open intervals in the Galena Formation, and which wells were open to both the Galena Formation and the Ancell Group.

Understanding the number and locations of wells with elevated risk of nitrate contamination, as well as

Figure 16. Panel A shows the location of wells open to the Galena Formation. Panel B shows the wells open to both.



Political boundaries from U.S. Census Bureau, 2016; Wisconsin Transverse Mercator projection, 1991 Adjustment to the North American Datum of 1983 (NAD 83/91) EPSG 3071



Bedrock geology of Grant County, Wisconsin

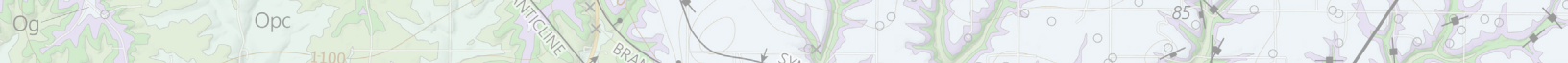
understanding the number and general location of wells that cross-connect aquifers is important for assessing the scope of the nitrate problem in Grant County. A total of 1,855 groundwater wells were estimated to be open to the Galena Formation (30.5 percent). These wells are concentrated in the southern and western portions of the county, as well as along the Annoton syncline near the Iowa County border (fig. 16). 553 groundwater wells are estimated to cross-connect the Galena Formation and the Ancell Group (9.1 percent). The overall geographic distribution is similar to the distribution of wells open to the Galena Formation, except for a lower percentage of cross-connecting wells in the extreme southeast corner of the county (fig. 16). This area is located relatively high in the stratigraphic section, and most wells do not extend deep enough to reach the Ancell Group.

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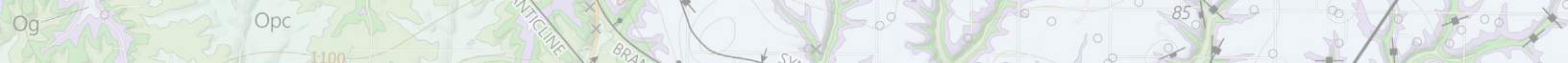
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