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Supplemental report on the geologic map of Mill Bluff State Park, Monroe and Juneau counties, Wisconsin

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Introduction

This project is the second mapping project performed as a part of an undergraduate Geologic Mapping Internship supported by the Wisconsin chapter of the American Institute of Professional Geologists (AIPG) and by the Wisconsin Geological and Natural History Survey (WGNHS). The internship focused on mapping a selected Wisconsin Department of Natural Resources (DNR) designated state park or protected state natural area, allowing for undergraduate students to develop their skills in performing geologic fieldwork and in the use of GIS resources.

Mill Bluff State Park was chosen as the study site for the 2023 Geologic Mapping Internship (see map). This park is located along the boundary between Juneau and Monroe counties in south-central Wisconsin. The park lies within the Central Sand Plain terrain (Carson and others, 2023) near the margin of glacial Lake Wisconsin and contains spectacular isolated bluffs and pillars of Cambrian sandstone. Many of the bluffs are elongate in the northwest-southeast directions. In addition to mapping the geology of the park, this project tested whether a preferred fracture orientation in the Cambrian sandstones controls the geomorphic characteristics of the bluffs, including their elongation direction.

Mapping within the park builds on previous work in Juneau County by Clayton (1989), which includes parts of the eastern edge of Mill Bluff State Park. In addition, this project provides context for the geology within the park and associated lithological properties. Observations of fractures and deformation structures are utilized to understand the structural properties leading to the bluffs' resistance to erosion. While this study is constrained to the extent of Mill Bluff State Park, the concepts related to bluff structure and reinforcement can be expanded to cover similar features locally and regionally.

Geography and geologic background

Mill Bluff State Park is located near the margin of the Central Sand Plain of Wisconsin (Carson and others, 2023). There is no known evidence of prior glaciation from any of Wisconsin's glacial periods in this region. The most recent glacial advance, the Wisconsin Glaciation, reached its maximum extent approximately 50–60 miles (~90 kilometers) southeastward in the Baraboo Hills. The Green Bay Lobe of the Laurentide ice sheet resulted in the formation of a proglacial lake, glacial Lake Wisconsin (Clayton and Attig, 1989). The modern, low-lying flatlands in the Central Sand Plain are the remnants of the former lake bed of glacial Lake Wisconsin. Glacial Lake Wisconsin's full extent covered the Mill Bluff project area in its entirety, leaving only a few high-elevation sandstone structures exposed above the lake's surface as low islands (Black, 1974; Dott and Attig, 2004). These structures, composed of Cambrian sandstones in the Elk Mound and Tunnel City groups, became the bluffs seen today at the park. Throughout this report, the sandstone structures found within the park boundaries will be referred to as bluffs, regardless of their assigned names.

Throughout the extent of the Central Sand Plain, similar bluffs to those in the park can be recognized standing above from the flat lakebed. Bluffs outside of the park boundaries, but

within the extent of the Central Sand Plain, will be referred to as “outliers” consistent with previous work by Black (1974) and the Department of Natural Resources, to maintain continuity.

Methods

Contextual lithologic information was obtained using previous work by Clayton (1989) and a cross-section generated by Ostrom (1962). Additional cross-sections were hand drawn by the authors using information from well construction reports and from two outcrop descriptions (Ostrom, 1978a; Ostrom, 1978b). Additional context was acquired from unpublished preliminary Quaternary data for Monroe County (E. Carson and C. Rose, WGNHS, unpub. data, 2023).

Fieldwork was done at six locations within Mill Bluff State Park: Wildcat Bluff, Camels Bluff, Ragged Rock, Long Bluff, Mill Bluff, and Round Bluff (see map). Additional fieldwork was performed south of the park neighboring the city of Camp Douglas, where samples were collected for unit descriptions with permission from a local landowner. No sampling occurred within the extent of Mill Bluff State Park.

Traditional field methods were used to generate the geologic map. Orientations of fractures, bedding, and other structures including, but not limited to, deformation bands and iron ribbing were collected. These measurements were analyzed relative to the bluff location of measurement. Orientations were recorded using strike and dip notation. Strike ranges from 000 to 360, where 000/360 is due north and 180 is due south, representing the horizontal direction on the plane of a given feature. The dip measurement is recorded in degrees from 0 (horizontal) to 90 (vertical) and records the angle formed between the plane of a given feature and horizontal, measured perpendicular from the strike. These measurements are accompanied by field notes and images.

In addition, although not the primary focus of the project, field notes and images also detail the sedimentary structures present at Round Bluff and Mill Bluff. These descriptions were used to generate stratigraphic columns of the two bluffs and detailed descriptions of the geologic units (see map).

Analysis of field data was performed using a stereonet program for plotting and figure generation and Excel for data categorization, management, and grouping. Cartography of the map plate was completed using ArcGIS Pro. Contacts were drawn where observed using direct upload of GPS data and inferred using approximated measurements elsewhere. In addition, contacts were interpolated using aerial imagery.

Fractures

Fractures are common and frequently seen within the undifferentiated Elk Mound Group sandstones (EMG, see map for unit descriptions), while the Ironston Member and Tunnel City Group (TCG) display common, but infrequent fractures. Fracture abundance and density in the EMG is highest (approximately 4 to 6 fractures per meter) when the overlying Ironston Member

and Tunnel City Group (TCG) are absent, and the density is reduced to approximately less than 2 fractures per meter when the overlying units are present.

Fracture data collected at several bluffs within the park are presented in Figure 1. Fracture data from Long Bluff were collected but have been omitted from the larger fracture dataset due to the limited number of fracture measurements collected to represent this location.

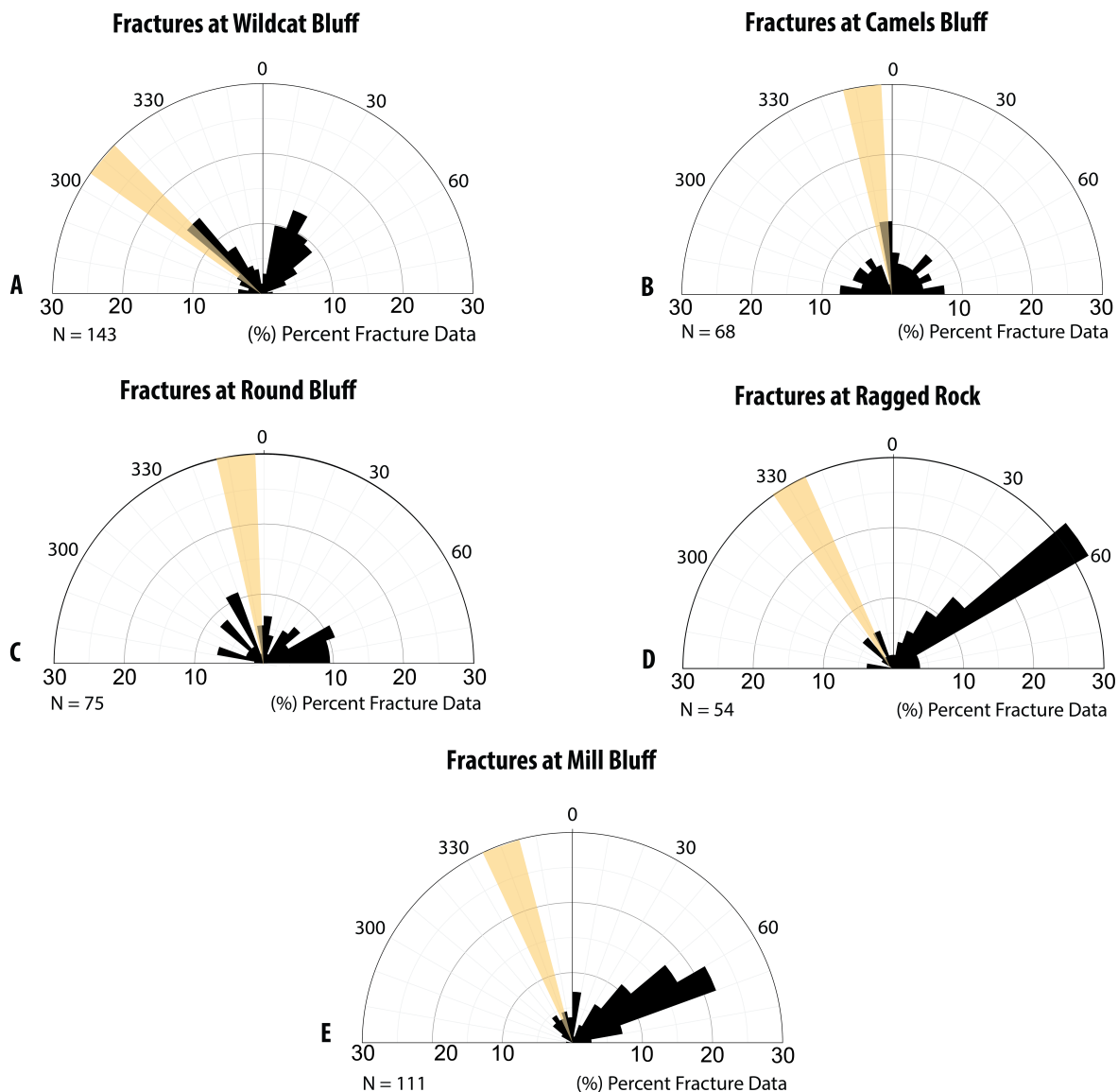


Figure 1. Half-circle rose diagrams representing strikes of fractures (black) measured at multiple bluffs within the park. Yellow shaded regions represent bluff orientations with a 5° error. Panel A, fractures at Wildcat Bluff, bluff orientation is $310 \pm 5^\circ$ NW. Panel B, fractures at Ragged Rock, bluff orientation is $330 \pm 5^\circ$ NW. Panel C, fractures at Round Bluff, bluff orientation is $350 \pm 5^\circ$ NNW. Panel D, fractures at Camels Bluff, bluff orientation is $352 \pm 5^\circ$ NNW. Panel E, fractures at Mill Bluff, bluff orientation is $340 \pm 5^\circ$ NNW.

All bluffs have a distributed range of fracture-strike orientations and all but Camels Bluff and Round Bluff have at least one dominant fracture set (fig. 1). At all bluffs, there is a set of fractures that strike parallel to the bluff elongation direction; however, only at Wildcat Bluff, does the dominant fracture set parallel the bluff elongation (fig. 1A). Additionally, Wildcat Bluff is the only bluff that exhibits two dominant fracture sets, one striking NNE-SSW and one striking NW-SE (bluff elongation direction). The largest percentage of fractures (approximately 10% of those measured) at Camels Bluff strike parallel to bluff elongation (roughly N-S), but the fracture orientations at the bluff are very widely distributed (fig. 1B). The difference between the N-S set and other fractures is only a few percent, making it difficult to state that Camels Bluff has a dominant fracture set. Round Bluff also shows a very wide range of fracture orientations without a dominant fracture set (fig. 1C). The bluff itself is elongate in the N-S direction. Ragged Rock and Mill Bluff are both elongated in the NW-SE direction and both show one dominant fracture orientation striking NE-SW (fig. 1D and 1E).

Fracture characteristics within the park are variable. A cement-fill is recognized within fractures at Wildcat Bluff (19% of all fractures), Round Bluff (3% of all fractures), and Mill Bluff (23% of all fractures). This cement is primarily an iron oxide cement, however, silica cement is commonly present instead, as noted previously by Black (1974). The iron oxide and silica cements commonly coat grains within the fracture planes but do not form veins. Fractures with a cement-fill present positive relief to the host rock, signifying a resistance to the erosion affecting the host rock. Cement-filled fractures are observed to be absent from other areas of the park, including Ragged Rock, Camels Bluff, and Long Bluff.

Limited observations of shear displacement are recognized within Mill Bluff State Park. Shear offset is recognized on a scale of less than an inch (mm to cm-scale) on several of these conjugate shear fractures. With limited evidence of shear displacement and the high-angle dip of the majority of fractures, fractures within the park are assumed to largely be opening-mode extension fractures. An opening-mode mechanism which “pulls apart” the fractures would also explain the void space seen in many fractures documented within the park (Waldron and Snyder, 2020).

Deformation structures

Common within the EMG sandstones are structures referred to as deformation bands. In this study, deformation bands located within the park were cataloged similarly to fractures. Orientation data were recorded using strike and dip measurements.

Deformation bands deviate from fractures in terms of their structural character. While different types of deformation bands may vary, typical characteristics that are associated with these features are increased cohesion and decreased porosity and permeability (Fossen and Bale, 2007; Fossen and others, 2007). Each of these properties can affect the movement and flow of fluid within the EMG sandstones. In addition, the orientations of these bands could provide context to former stress orientations that acted on the Paleozoic strata within the park to form these structures.

Two types of deformation bands were observed and identified within the park using descriptions from previous work on deformation bands: pure compaction bands and shear-enhanced compaction bands (Mollema and Antonellini, 1996; Eichhubl and others, 2010; Fossen and others, 2011).

Pure compaction (phyllosilicate) bands

Deformation bands oriented parallel to bedding within the park are recognized to be pure compaction bands (fig. 2). These pure compaction bands are characterized by bands composed of very fine-grained silicate materials, while the surrounding host rock typically is composed of medium-grained rock. Typical to previous work on compaction bands (Fossen and others, 2007), these features exhibit positive relief from the host rock.



Figure 2. Deformation bands showing positive relief on outcrop surface at Camels Bluff in Mill Bluff State Park. The bands are interpreted to result from pure compaction.

The contrast in grain size within the band and surrounding host rock indicates compaction. There is no evidence in the observed compaction bands of any shear component; however, it is possible that there is micro-scale shearing impacting these structures. Further analysis with microscopes and sampling would be necessary to determine the presence and impact of shear. Assuming that shear is micro-scale, or non-existent, these bands further fit the classification of pure compaction bands within the EMG.

The orientation of compaction bands can be used to infer maximum stress orientation during formation. The bands are parallel to the orientation of bedding, which is shallowly dipping and essentially negligible over the park's scale, indicating a vertical compressive force. This vertical force likely comes from the weight of overlying rock that may have eroded away since the formation of this structure.

The significance of these compaction bands in the EMG is their influence on fluid flow within the rock, as compaction bands have reduced porosity relative to the surrounding rock (Fossen and others 2007). The implications of changes in porosity are recognized by unique patterns of iron oxides distributed throughout the EMG sandstones where localized changes in grain-size and porosity are observed.

In addition, the positive relief of the band demonstrates a greater resistance to erosive forces than the host rock. This could prove to be an additional variable to the overall structure and reinforcement of bluff structures seen within the park.

Shear-enhanced compaction bands

Subparallel cross-cutting structures with positive relief were observed in three locations within Mill Bluff State Park (fig. 3). These features are characterized by two fine-grained bands which crosscut one another at an acute angle of $30\pm3^\circ$. Based on prior descriptions in the Aztec (Eichhubl and others, 2010) and Navajo sandstones (Fossen and others, 2011), these features are recognized to be cross-cutting shear-enhanced compaction bands (SECBs). In previous work on SECBs, these features have also been referred to as thick compaction bands (Mollema and Antonellini, 1996) but are representative of the same deformation features.

The fine-grained composition of the band relative to the surrounding rock are indicative of the compaction mechanism acting to form these structures. In field observation, no evidence of shear offset is recognized. However, a study of SECBs by Fossen and others (2011) suggests that small-scale shear occurs on a mm-scale to form these features, and can be hard to identify in field observations. This interpretation of shear effect follows observations made in previous work which similarly note a probable shear effect (Mollema and Antonellini, 1996; Eichhubl and others, 2010; Fossen and others, 2011).



Figure 3. Positive relief cross-cutting shear-enhanced compaction bands (SECBs) in the undifferentiated Elk Mound Group at Wildcat Bluff in Mill Bluff State Park.

The maximum stress orientation bisects the acute angle of the SECBs (Fossen and others, 2011). At Mill Bluff State Park, this would indicate a maximum horizontal stress orientation in the SSE and NNW directions. This maximum horizontal stress orientation aligns with the stress orientation forming the opening-mode subvertical fractures recognized at Wildcat Bluff, and to a lesser extent elsewhere.

Varying from prior observations of SECBs, the dihedral acute angle of the Mill Bluff State Park SECBs does not follow the typical angle of 75° (Eichhubl and others, 2010; Fossen and others, 2011). Considering that both features observed within the park have the same cross-cutting

angle, it is likely that a more recent vertical compressive force caused the angle to decrease. This force could align to the vertical compressive force which could have formed the pure compaction bands. However, further work regarding the interaction between the SECBs and pure compaction bands would be necessary to confirm this hypothesis.

Bluff formation

Outliers, similar to the sandstone bluffs within Mill Bluff State Park, are common throughout the glacial Lake Wisconsin basin. Outliers are seen in the Rocky Arbor State Park area on the margin of Juneau, Adams, Sauk, and Columbia counties of Wisconsin. Rattlesnake Mound, Roche a Cri, and Friendship Mound, all located within Adams County are similar outliers elongate in the north-south direction. In addition to geomorphic resemblance to the bluffs at Mill Bluff State Park, these outliers also contain EMG sandstones.

In the case of Rocky Arbor State Park, Clayton and Attig (1989) attribute the formation of the outliers to water eroding soft sandstones during the rapid draining of glacial Lake Wisconsin. It is possible that the bluffs within Mill Bluff State Park were created by a similar rapid erosional event; however, the timing and location of this downcutting and the existence of glaciation within the park are unclear and undocumented. It seems more likely that streams, existing prior to glacial Lake Wisconsin—or possibly prior to the Wisconsin Glaciation—and heavily influenced by already-existing fractures, eroded the soft sandstones of the EMG within the park that over time resulted in the elongation orientation seen today.

Spoolman (2018) and signage at Roche-A-Cri State Park discuss and recognize the importance of a lithologic “hard sandstone cap” on the formation of the glacial Lake Wisconsin basin outliers. The cap rock reinforces the lower more friable and less consolidated sandstones from erosion. The Ironton Member forms this hard cap on some bluffs at Mill Bluff State Park. However, a hard sandstone cap is not present at all bluffs within the park and is interpreted as lacking from the Roche a Cri outlier, which is observed to be eroding more quickly than the bluffs at Mill Bluff State Park (Spoolman, 2018).

Based on work completed within Mill Bluff State Park and previous work on outliers within the glacial Lake Wisconsin basin, bluff formation is interpreted to result from multiple factors, including, but not limited to, lithology, fracture type and abundance, and presence of deformation bands.

Fractures and cementation history may help explain bluff morphology in cases with no Ironton cap at Mill Bluff State Park. The propagation of fractures at Mill Bluff State Park is theorized to be a combination of opening-mode and shear kinematics. In settings where an opening-mode mechanism drives fracturing, bimodal fracturing (such as that seen at Wildcat Bluff) would indicate two major stress orientations forming the fractures. These major stress orientations would align with the dominant strike directions at Wildcat Bluff, Ragged Rock, and Mill Bluff, which are generally NW-SE and NE-SW. This, coincidentally, aligns with the maximum stress orientations necessary to form the shear-enhanced compaction bands. However, as previously stated, the presence of shear-enhanced compaction bands within Mill Bluff State Park suggests

the influence of shear and challenges a solely opening-mode fracture mechanism. A further understanding of the extent of these mechanisms in fracture propagation at Mill Bluff State Park would require sampling and microscope analysis to determine the extent, if any, of the sense of shear and offset.

Fracture character (e.g., cement content) is not recognized to affect the elongation direction of the bluffs; however, cement content of fractures provides an overall resistance to erosion. Analysis of cement-filled fractures shows no preference in orientation, instead following the general NE-SW, ESE-WNW, NW-SE, and SSW-NNE directions. The positive relief observed in cement-filled fractures acts to reinforce the weak EMG host rock of these features in a similar manner to the hard sandstone cap idea. Previous work by Black (1974) explains the influence of these iron cement fractures as reinforcement by case-hardening the rock, making it more resistant to normal weathering and erosion.

Conclusions and future work

Mill Bluff State Park stands as a landmark of unique Cambrian sandstone bluffs amid the flat-lying Driftless and Central Sands regions of Wisconsin. Their modern existence—more than 500 million years post-deposition—cannot be attributed to a sole factor, but rather a collection of variables that play different roles in resisting erosion mechanisms. This work targeted the influence of geography, lithology, and fracture patterns on the sandstone bluffs of the park. Collectively, these variables contributed to forming the primary features of Mill Bluff State Park.

Our work finds that fractures likely play a role in the formation of the bluffs by localizing both planes of weakness and creating a case-hardening effect, depending on the type and abundance of cementation. Lithology also plays a role in bluff formation by influencing fluid flow and erosional susceptibility. Further, a mode of reinforcement is introduced through the existence of the Ironston Member capping some of the bluffs in the park. Finally, possible geographic influences from stream flow in this region of Wisconsin are recognized.

This work would be complemented by quantification of the influence of individual variables, presented here, on bluff geomorphology. Future work should characterize and distinguish the formations of the lower undifferentiated EMG to better understand the geologic setting and stress history of these rocks. Other variables acting to resist erosion could also be investigated, such as weathering patterns and biological variability throughout the park. Further, analysis of the shear mechanisms within the park could provide detail to the extent of shear or opening-mode fracturing. This approach could be applied to outliers across the glacial Lake Wisconsin basin.

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