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Supplemental report on the geologic map of the Dells of the Wisconsin River State Natural Area

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Overview

The geologic map of the Dells of the Wisconsin River State Natural Area is the first in a series of planned maps of state parks and natural areas. This report supplements the map plate by including expanded unit descriptions and a more thorough discussion of depositional environments.

Description of map units and facies

Quaternary

Modern lake sediment

Well sorted fine- to medium-grained sand deposited along the margins of the Wisconsin River north of Kilbourn Dam, located in the town of Wisconsin Dells.

Alluvium

Sandy and silty deposits along streambeds in gorges between outcrops. Deposits are sourced from local bedrock.

Loess

Many of the flat benches around the Wisconsin Dells are covered by loess (fine sand and silt). Loess was observed on a ridge near Witches Gulch (43.674°N, 89.795°W), whereas most of the rest of the loess in the area is inferred from the presence of loose, sandy soils.

Cambrian

Tunnel City Group

One outcrop of the Tunnel City Group is observed in the map area. The hill near the Chapel Gorge Trail (43.644°N, 89.781°W) is capped by the Tunnel City Group. The outcrop consists of commonly pale-orange or yellow, uncommonly pink, fine-grained, well sorted vuggy, carbonate-cemented sandstone. Trace fossils, especially *Skolithos*, are a distinctive marker of this group. Exposures are likely part of the Mazomanie Formation of the Tunnel City Group, which is found proximal to the Wisconsin Arch (Ostrom, 1966). The Tunnel City Group overlies the Wonewoc Formation.

Upper sandstone (Wonewoc Formation)

The upper sandstone is interpreted to be the Wonewoc Formation. It is pale-tan to white, and composed of moderately well cemented rounded, fine- to medium-grained quartz arenite. Bedding is of centimeter-scale thickness and contains occasional crossbeds. The upper portion of the Wonewoc Formation contains some vuggy sandstones, as well as shaley layers and layers with iron cement. This upper portion is likely the Ironton Member of the Wonewoc

Formation (distinguishable from the pure sandstone of the lower Galesville Member). The Wonewoc Formation overlies the delineating layer.

Delineating layer (previously interpreted as Eau Claire Formation)

The delineating layer lies above the Mt. Simon Formation and has been previously interpreted as the Eau Claire Formation (Clayton, 1987). It is divided into three facies: a silty facies, an iron facies, and a sandstone facies. This layer is commonly observed just below topographic benches and displays resistance to erosion, especially in the iron facies. It is commonly only a meter or two thick, and less commonly several meters thick, although its thickness is difficult to define due to the gradational contact with the underlying Mt. Simon Formation. Beds of the three different individual facies are commonly only a few centimeters thick. These repeat across the delineating layer interval, forming stacked tabular beds within the layer. The silty facies is the only facies that is discontinuous.

The silty facies is red, dark-red, reddish-brown, or maroon. Grain size ranges from clay to coarse sand. Some beds are reddish, fine-grained, poorly sorted sand to silt, while others are massive siltstone or shale. Alternating laminae of fine and coarse sand occur, but grading is not observed. Beds are commonly a few millimeters thick, and less commonly 2 centimeters thick. Silty beds are commonly interbedded with centimeter-scale beds of fine sand and uncommonly interbedded with thicker (up to 5 centimeters) beds of the sandstone facies. Beds are flat-lying and serve as effective parting surfaces in samples and cores. Silty beds of this facies are associated with thin white clasts of kaolinite (fig. 1A). The clasts are commonly 1 millimeter thick and 0.5–2 centimeters across. They are smooth, massive, irregularly shaped, slightly curved, and tend to lie flat within the silty laminae. Thickness of this facies is difficult to define; it is similar to the iron facies, although it can extend up to a meter or so.

The iron facies contains black, dark brown, dark red, or dark purple bands woven into the sandstone facies of the delineating layer. Bands contain sand grains that commonly are more angular and darker in color than those in the sandstone facies. Grains are commonly fine to coarse and poorly sorted. Relative quantities of cement and sand grains within the bands vary from sandstone with iron staining to pieces of hematite with embedded sand grains. Most bands fall between these end members. Bands are wavy and jagged, akin to Liesegang banding (fig. 1B). Iron bands are generally either around 1 centimeter thick or around 1 millimeter thick. The millimeter-thick layers are commonly observed in repeating and vertically stacked groups, while the centimeter-thick layers are commonly isolated. Iron staining commonly extends into the sandstone facies, but otherwise the line between the two facies is sharp. Silty flakes and rip-up clasts as well as kaolinite clasts are uncommonly observed. This facies' thickness is difficult to define; the overall zone in which iron banding occurs is a few tens of centimeters thick.

The sandstone facies is pale, predominantly white, and uncommonly pink, reddish, yellow, beige, or orange. Iron staining is likely responsible for much of the coloration. Grains are poorly sorted and fine- to coarse-grained. Liesegang banding commonly gives a folded or hummocky appearance. Beds are commonly 0.5 to 5 centimeters with cross-beds that dip 5 degrees or less.

Thin, flaggy bedding and subtle crossbedding are common. Flaggy bedding contains irregular contacts, with iron-bands commonly tracing out possible scours. Silty flakes and rip-up clasts are uncommonly observed (fig. 1C). This facies is a meter to a few meters thick and forms a gradational contact with the Mt. Simon formation over one or two meters.

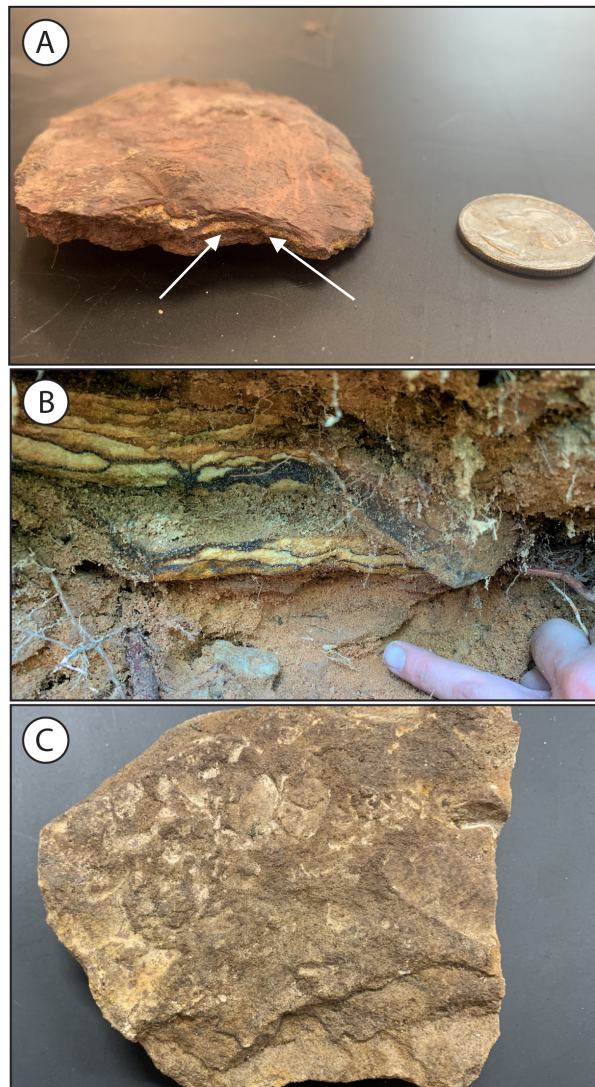


Figure 1. Representative samples of the distinct facies of the delineating layer. Panel A, silty facies with white kaolinite clasts between the laminae (arrows pointing to clasts). Quarter for scale. Panel B, iron banding in the iron facies. Panel C, sandstone facies with white kaolinite clasts on the surface. Length of rock approximately 15 centimeters.

Lower sandstone (Mt. Simon Formation)

The lowest sandstone formation is believed to be the Mt. Simon Formation. It is generally pale in color and can be white, beige, yellow, orange, and pink. It consists of fine- to medium-grained, well sorted, moderately well cemented sandstone. Grains are very round and almost entirely quartz; the endmember/archetype looks like granulated sugar with spherical grains. Bedding thickness ranges from around 0.5–15 centimeters. Crossbedding is common, with bed sets varying widely in dip (0 to 15 degrees) and thickness (10 to 100 centimeters). The upper 25 meters of the formation is exposed in the map area.

Interpretation of map units and facies

Quaternary

Modern lake sediment

Well sorted sand along the banks of the Wisconsin River north of the town of Wisconsin Dells is interpreted to have been deposited from the damming of the Wisconsin River. The completion of the Kilbourn dam in 1909 led to a rise in base level north of the dam, causing alluvial sediments transported from tributary streams to be deposited in a near shore lake setting.

Alluvium

Alluvium washed into the area from various streams and from the Wisconsin River. Presumably alluvium accumulated during Holocene floods as it contains compositionally similar sand and silt to the bedrock and sediment around it. The Wisconsin River could easily transport other sediments from further north, so the exact sources of alluvium are uncertain. Rivers likely washed away or buried older lake or tundra sediments in the area.

Loess

Loess is presumed to have blown into the area following the retreat of the Green Bay Lobe and the draining of Glacial Lake Wisconsin. The lake and glaciers would have covered the rocks and prevented deposition of loess on the bedrock. The lake drained in a catastrophic flood that scoured the bedrock and carved the Dells (Clayton and Attig, 1990), and would have eroded any unconsolidated sediments. Following the retreat of the glaciers and drainage of the lake, there would have been a “tundra interval” before forests reached far enough north to cover the area. During this interval, winds likely transported fine sediment into the area and deposited it on the bedrock.

Cambrian

Tunnel City Group

The Tunnel City Group is interpreted as a quiet-water marine deposit, possibly below storm wave base. Sediment output would have been low enough to allow significant deposition of

carbonate cement, and calm conditions would have deposited fine sand and preserved burrows.

Wonewoc and Mt. Simon Formations

The Wonewoc and Mt. Simon Formations have historically been interpreted as shoreface, intertidal, and aeolian dunes, braided streams, and sheet sands on the high elevation end of a gentle slope (less than one percent grade) that descended into a tropical sea (Driese and others, 1981; Dott and others, 1986; Runkel and others, 1998).

Delineating layer

This delineating layer is an important marker horizon in the map area because it provides a clear boundary between the otherwise-indistinguishable sandstones of the underlying Mount Simon and overlying Wonewoc Formations. The delineating layer defined in this work is coincident, in topographic and stratigraphic location, and partially coincident in character, to the Eau Claire Formation described in northeastern Sauk County and Juneau County (Clayton, 1989; Clayton and Attig, 1990). However, work done for this project provides evidence that the delineating layer is not a facies of the marine-deposited Eau Claire Formation, and instead represents a subaerial depositional environment.

The Eau Claire Formation is described at several outcrops west and northwest of the study area including its type-section near the city of Eau Claire, WI (e.g. Aswasereelert and others, 2008; Driese and others, 1981; Clayton, 1989; Clayton and Attig, 1990; Walcott, 1914). It has also been described in core and other subsurface datasets south and southeast of the study area in Dane County; although it is noted as absent in northeastern Dane County (Clayton and Attig, 1990; Aswasereelert and others, 2008; Parsen and others, 2016). Based on lithology, sedimentary structures, and fossils, the Eau Claire Formation is interpreted as a marine deposit (e.g. Driese and others, 1981; Clayton, 1989; Aswasereelert and others, 2008). Several facies representing deposition at varying water depths have been documented. Walcott (1914) and Aswasereelert and others (2008) describe the deeper water facies in Eau Claire and Chippewa Counties. Aswasereelert and others (2008) document the shallower facies in southeastern Dane County. Evidence for the more distal depositional environment comes from shale beds interspersed with sandstone, glauconite and dolomite, and bioturbation and fossils. Aswasereelert and others (2008) describe the following lithologic changes as deposition shallows from below storm-wave base through fair-weather wave base, at which point the Eau Claire Formation grades into the Wonewoc Formation: increased sand and decreased shale, with shale stringers coarsening upward into fine sandstone; increased bed thickness; crossbeds growing in size and then thickening into massive beds; and bioturbation and fossils throughout.

The Eau Claire Formation thins up-gradient, or is absent, approaching the ancient topographic highs of the Wisconsin Dome and Arch (e.g. Parsen and others, 2016). Identification of the formation has remained difficult in south-central Wisconsin, including near the study area, as many of the defining features of the Eau Claire Formation are not present (Clayton and Attig, 1990; Clayton, 1989 ; Parson and others, 2016). In northeastern Dane County, the Eau Claire

Formation is noted as absent (Parsen and others, 2016). In southern Sauk County, Clayton and Attig (1990) describe the Eau Claire as up to 20 meters of dolomitic sandstone with silt, shale, glauconite, and fossil fragments. Clayton and Attig (1990) also define an iron-rich, silty, moderately to poorly sorted and bioturbated interval with some rip-up clasts as the Eau Claire Formation in northeastern Sauk County. In southern Juneau County, Clayton (1989) interpreted the presence of a 1- to 3-meter-thick shaley interval, coincident in topographic and stratigraphic location with the delineating layer of this study, as the Eau Claire Formation. However, this work suggests this shaley interval of Clayton (1989) may correlate to the delineating layer in the Dells area, and the delineating layer is not the Eau Claire Formation, nor does it represent marine deposition.

Outcrops and core samples of the delineating layer in the Dells area from this work include poorly sorted sand, kaolinite, thin, discontinuous, and iron-rich silty layers, iron banding, no dolomite, glauconite, bioturbation, or fossils. These observations, combined with the geographic position high on the Wisconsin Arch, are lines of evidence that support the hypothesis that the delineating layer was deposited in a nonmarine, subaerial environment characterized by quiet ephemeral pools where clayey and silty layers were deposited. We interpret the iron bands as a secondary characteristic based on the rarity of primary iron deposition in the early Paleozoic. Yet, the concentration of diagenetic or reprecipitated iron in the delineating layer silts and sands in the Dells area is broadly uncommon in the Elk Mound Group. This feature may be related to some characteristic, such as grain size, of the delineating layer.

If the delineating layer was equivalent to the Eau Claire Formation, then the sea level transgression that deposited the Eau Claire Formation must have extended up the arch far enough to submerge the aeolian dunes and braided rivers of the Mount Simon Formation in the Wisconsin Dells (Dott and others, 1986). In this scenario, the delineating layer could have been deposited around storm wave base, where the thin silty layers were deposited on calm days, and storms subsequently buried them in poorly sorted sand. Kaolinite clasts could have washed out in these storms and settled amidst the sands and silts. Following a regression, a basin-ward shift in facies resulted in nonmarine dune and river deposits during deposition of the lower Wonewoc Formation. However, the above scenario is not supported by the data gathered in this study for many reasons.

First, if a sea level transgression was extensive enough to submerge what is now the Dells, a facies gradient should be observed in this region (Aswasereelert and others, 2008), with the more distal facies transitioning into more proximal facies toward the Wisconsin Arch. The fact that we cannot trace these facies in their progression between central and western Wisconsin makes it unlikely that the delineating layer represents a facies of the Eau Claire Formation.

Second, it is challenging to reconcile the various grain sizes present in the delineating layer around the Wisconsin Dells. The silty laminae are thin enough to have been disturbed by powerful storms, but the coarser sand grains could not have been transported to the same distal environment as the silty layers by calmer waters. The kaolinite clasts present a similar

difficulty; they either flocculated *in situ*, meaning clay particles were able to settle in extremely calm waters, or they washed out as rip-up clasts in violent waves. The sand itself is unsorted, except for uncommon alternating laminae of fine and coarse sand. Importantly, it lacks graded bedding, which one would expect of storm-transported sediments. The most likely marine depositional environment for the delineating layer lies between fair weather wave base and storm wave base. This depth is described as a facies of the Eau Claire Formation in western Wisconsin by Aswasereelert and others (2008). However, this facies is marked by hummocky and swaley crossbeds and common fossils and bioturbation, which is not found around the Wisconsin Dells. It is thus incredibly difficult to imagine a marine depositional environment that would have allowed for the deposition of the delineating layer.

Finally, the presence of kaolinite in this layer all but rules out the possibility of marine deposition. Kaolinite, an aluminosilicate, converts to illite and smectite in the presence of potassium, and potassium was a common ion in seawater in the Paleozoic (e.g. Kovalevich and others, 1998). As a result, it is very unlikely for kaolinite to deposit in marine environments and survive chemically. X-ray diffraction analysis of the clasts and silt show kaolinite as the primary clay constituent and present no evidence of illite or smectite (Bojdak-Yates, 2022), which provides very strong evidence that the silty laminae were not deposited in seawater at all.

The implausibility of the idea that the delineating layer formed in a marine environment, and the substantial differences in physical and chemical characteristics between the layer in the Dells and the type section of the Eau Claire Formation suggests that this layer does not represent the Eau Claire Formation and necessitates an alternate interpretation.

Based on the surrounding sandstone and the presence of kaolinite in the silty facies, it seems likely that the delineating layer formed on land, likely in a dune and braided river-dominated environment, possibly near a beach, with ephemeral ponds and lakes. Rivers may also have been ephemeral. The flaggy bedding of the sand contains irregular contacts, and iron bands often trace out possible scours, which supports the idea of a braided river system. However, a river would have been too energetic to deposit the silty laminae. The laminae can be explained by ephemeral ponds and lakes or very calm, slow-moving ephemeral streams. These ponds and lakes could have formed in quieter pockets amidst the migrating dunes and rivers and been fed by rivers or groundwater. Kaolinite clasts, transported from ponds and lakes by streams, could have been deposited in thin layers before the sands shifted again and buried the silt; then the sand was reworked by rivers. In some places, the ponds might have lasted long enough to deposit a centimeter or more of silt, but in many places they disappeared after leaving no more than 1-2 millimeters. The fine laminae of the silty facies is similar to lacustrine sediments, and it is reasonable to assume that some lakes would have formed in the humid, tropical environment of Wisconsin during the late Cambrian.

There are still difficulties with the nonmarine hypothesis. First, it implies the presence of larger lakes or delta structures in the Elk Mound Group, which this study did not find. Second, the iron bands represent secondary deposition in this interpretation, likely due to groundwater flow. Groundwater moving through the sandstone could have dissolved iron that was present in the

silt. This iron was then redeposited along coarser-grained scour surfaces, along which the groundwater flowed more readily. Alternatively, the iron could have been sourced from outside the delineating layer. However, with either interpretation, the high concentration of iron in this layer relative to the rest of the Elk Mound Group is not well understood. Third, the source of the kaolinite clasts is not well explained. Finally, it is unclear why no similar deposits are found at other elevations in the Wisconsin Dells area. Lakes and ponds presumably could have formed throughout the late Cambrian, but there is no evidence of them outside of this thin interval at this locality. (This difficulty exists for any terrestrial interpretation of this layer.)

Alternate hypotheses present their own difficulties. The layer could represent an oxisol, given that it contains high iron and aluminum concentrations and formed in a humid, tropical environment. However, it would represent an incredibly thin oxisol, and it shows none of the chemical horizons or gradients one would expect from a paleosol. It could also represent a floodplain deposit; perhaps occasional floods drowned the sheets of sand and deposited silt. This hypothesis is less plausible because a flood would leave graded bedding, which we do not find in this layer. Finally, a third explanation could be a lagoon or other quiet coastal environment. The presence of kaolinite precludes this hypothesis because kaolinite would have converted to illite or smectite in potassium-rich seawater, and a marine lagoon would have contained potassium-rich seawater. Therefore, despite its difficulties, the most likely depositional setting of the delineating layer in the Wisconsin Dells area is a series of ponds or lakes in a braided river and interdune environment. Streams and rivers may have been ephemeral.

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