The Geological Society of America
Special Paper 531

Pennsylvanian Pewamo Formation and Haybridge strata of central Michigan: The youngest rocks of the Michigan Basin?

Kathleen C. Benison*
Department of Geology and Geography, West Virginia University,
98 Beechurst Avenue, Morgantown, West Virginia 26506-6300, USA

ABSTRACT

Pennsylvanian red beds are the youngest known rocks in the Michigan Basin. Two new formation-level units, the Pewamo Formation and the Haybridge strata, have recently been described. The Pewamo Formation, composed of Pennsylvanian red sandstones and minor laminated mudstones, is known from outcrops, abandoned quarries, and one core in Ionia County. The Haybridge unit is located in the shallow subsurface and in coal mine tailing piles in Shiawassee County. It consists of red sandstone, red mudstone, coal, and gray mudstone, all hosting Pennsylvanian macroscopic plant fossils. Neither the Pewamo nor the Haybridge rocks have any demonstrated relationship to red core cuttings reported as Jurassic from the central Lower Peninsula of Michigan. No firm evidence exists for Jurassic, or any other post-Pennsylvanian rocks in the Michigan Basin. The red core cuttings may be glacial sediments with reworked palynomorphs from rocks transported from elsewhere. A shallow coring project, followed by detailed sedimentologic, petrographic, mineralogic, and paleontologic studies, is necessary to: (1) refine the vertical and lateral stratigraphy of the Pennsylvanian rocks in Michigan; (2) solve the "Jurassic red bed problem"; and (3) understand the late Pennsylvanian–Pleistocene history of the Michigan Basin.

INTRODUCTION

The Michigan Basin is rich in geologic resources, including oil, gas, salt, groundwater, and sand and gravel. Michigan even had a small but thriving coal mining industry in the past. Despite subsurface investigations prompted by exploration and extraction for these economic resources, there is still a gap in the knowledge of the middle Pennsylvanian–Pleistocene history of Michigan. This time has been referred to as the "missing interval" for the Lower Peninsula of Michigan.

The purpose of this paper is threefold: (1) to provide an overview of the state of knowledge about the "missing interval"; (2) to pose some possible scenarios that might explain the limited geologic record; and (3) to make a case for future geological investigations, including a shallow subsurface coring program. In particular, we focus on the recently described middle–late Pennsylvanian

*kcbenison@mail.wvu.edu

Benison, K.C., 2017, The Pennsylvanian Pewamo Formation and Haybridge strata of central Michigan: The youngest rocks of the Michigan Basin?, *in* Grammer, G.M., Harrison, W.B., III, and Barnes, D.A., eds., Paleozoic Stratigraphy and Resources of the Michigan Basin: Geological Society of America Special Paper 531, p. 331–339, doi:10.1130/2017.2531(15). © 2017 The Geological Society of America. All rights reserved. For permission to copy, contact editing@geosociety.org.

Pewamo Formation and Haybridge strata, and their stratigraphic relationships to underlying and overlying strata.

BACKGROUND

Shallow Sedimentary Deposits of Mid-Michigan

The great majority of the bedrock of the Lower Peninsula of Michigan is covered by Pleistocene till and outwash glacial sediments, up to ~150 m thick in some parts of central Michigan. Holocene fluvial, lacustrine, and beach sediments, soils, and reworked glacial sediments are thin, localized, and composed of gravels, sands, and/or muds. Outcrops of pre-Pleistocene rocks in the Lower Peninsula are uncommon. In the central Michigan region, above the center of the Michigan Basin, outcrops are rare and are restricted to Pennsylvanian sandstones, shales, and coal.

The early middle Pennsylvanian Saginaw Formation and overlying Grand River Formation are the best studied of the post-Mississippian rocks of the Michigan Basin (i.e., Catacosinos et al., 2001; Dorr and Eschman, 1970; Kelly, 1931, 1933, 1936; Landing and Wardlaw, 1981; Price and Velbel, 2000; Velbel and Brandt, 1989; Venable et al., 2013). Outcrops of the Saginaw and Grand River Formations in Grand Ledge in Eaton County are well known to Michigan's sedimentary geologists. The Saginaw Formation rocks have also been recovered in some shallow cores from Ingham County and Ionia County, just a few miles from the Grand Ledge outcrops (Benison et al., 2011; Price and Velbel, 2000; Venable, 2006; Venable and Barnes, 2006). The Saginaw Formation is composed of gray sandstones, gray shales, and coal, and it has been interpreted as deposits of marginal marine environments, such as deltas and coastal plains (Velbel et al., 1994; Venable et al., 2013). Conodonts in the Saginaw Formation constrain its age to the early middle Pennsylvanian (Atokan; Landing and Wardlaw, 1981). The Grand River Formation, stratigraphically situated above the Saginaw Formation in some outcrops, is a buff, cross-bedded sandstone interpreted as a fluvial deposit (Shideler, 1969; Velbel and Brandt, 1989; Velbel et al., 1994; Venable et al., 2013). The age of the Grand River Formation is not well constrained. Its stratigraphic relationship with the Saginaw Formation indicates that it can be Atokan at the oldest. The only known upper contact for the Grand River Formation is with Pleistocene glacial sediments, making its exact age challenging to interpret. The official *Stratigraphic Lexicon for Michigan* assigned a late Pennsylvanian age to the Grand River Formation (Catacosinos et al., 2001).

Other siliciclastics suspected to be from the Pennsylvanian or Jurassic have been named informally. In general, locations and lithological descriptions for these rocks are limited, and their identification and ages are contested. The Parma sandstone is an informal sandstone unit with rare plant fossils that is considered to be either late Mississippian or early Pennsylvanian (Catacosinos et al., 2001; Westjohn and Weaver, 1998). A small outcrop along U.S. I-94 near Jackson, Michigan, may be the Parma sandstone (Catacosinos et al., 2001). The Eaton and Woodville sandstones are other informal and controversial stratigraphic names for rocks that have not undergone detailed study and may simply be alternate names for parts of the Saginaw and/or Grand River rocks (Catacosinos et al., 2001).

Other rocks of suspect age and location in the central Michigan Basin region include red beds known only from drill cuttings and from building stones (Cross, 1975, 1986, 1998a, 1998b; Shaffer, 1968, 1969). Known as the "Jurassic red beds of Michigan" and the "Ionia formation," respectively, Michigan geologists have used the two names interchangeably and have regarded them as "problematic" for decades (Catacosinos et al., 2001). A palynological study of the red drill cuttings found reworked and poorly preserved pollen of various ages and suggested that the rock was likely Jurassic, based on identification of the genus *Classopollis* (Shaffer, 1968, 1969). However, more recently, a wider geologic time period of Early Triassic–Neogene has been recorded for *Classopollis* (White et al., 2009; The Paleobiology Database: https://paleobiodb.org/#/; accessed on 25 July 2017), calling into question the age of the red drill cuttings (Benison et al., 2011). The red sandstone building stones were assumed to be lithologic- and age-equivalents of the red drill cuttings, despite lack of study of their mineralogy, palynology, or sedimentology (Cross, 1975, 1986, 1998a, 1998b). Regardless of the highly suspect age, lack of any sedimentary description, and no known in situ location for these building stones, one sandstone sample from the Ionia County Courthouse was used for a detrital zircon provenance study. Results were used to make interpretations about flow direction of large rivers through Michigan and across North America during the Jurassic (Dickinson et al., 2010a, 2010b). These interpretations were questioned because only a building stone of unknown depositional location was used, the Jurassic age was debatable, and no sedimentary descriptions had been made to support a fluvial environment of deposition (Benison and Knapp, 2010).

Pewamo Formation and Haybridge Strata: Two Newly Documented Pennsylvanian Units of Michigan

More recently, two other Pennsylvanian formation-scale stratigraphic units from central Michigan were described and named (Benison et al., 2011). The Pewamo Formation is located in outcrops and quarries in the Grand River State Game Area between the towns of Ionia and Lyons in Ionia County (Fig. 1). It was mined for red sandstone building stones in the 1880s and again in the 1950s. In 2008, a core was drilled near these outcrops (Figs. 2 and 3; Benison et al., 2011). The core consisted of Saginaw Formation at the base, unconformably overlain by a 24.1-m-thick (79-ft-thick) section of the Pewamo Formation, and capped by glacial sand and gravel. The Pewamo Formation consists mainly of orange, cross-bedded quartz and hematite sandstone interpreted as eolian deposits. Interbedded with the orange sandstones, there are thin, laminated and mud-cracked, lacustrine siliciclastic mudstones. Palynomorphs extracted from the mudstones, *Calamospora hartungiana*, *Granulatisporites granularis*,

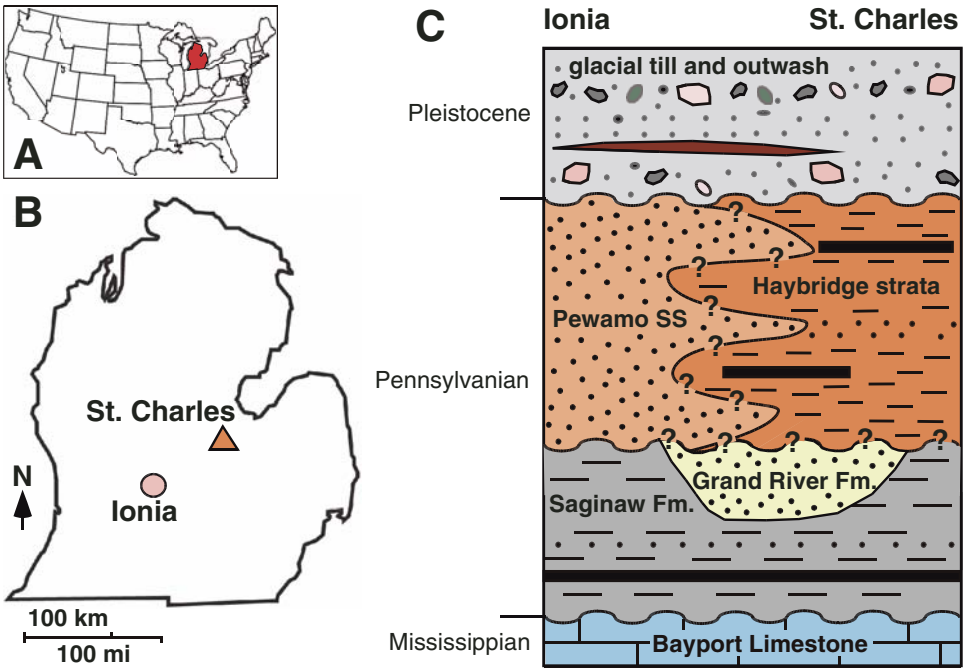

Figure 1. Location and stratigraphic setting of the Pewamo Sandstone and Haybridge strata. (A) Lower Peninsula of Michigan, highlighted in red on map. (B) Approximate location of Pewamo sandstone (SS) near Ionia (pink circle; 42.98175°N, 84.99513°W) and Haybridge strata near St. Charles (orange triangle; 43.3557°N, 84.0726°W). (C) Proposed stratigraphic column for the shallow subsurface of central Michigan.

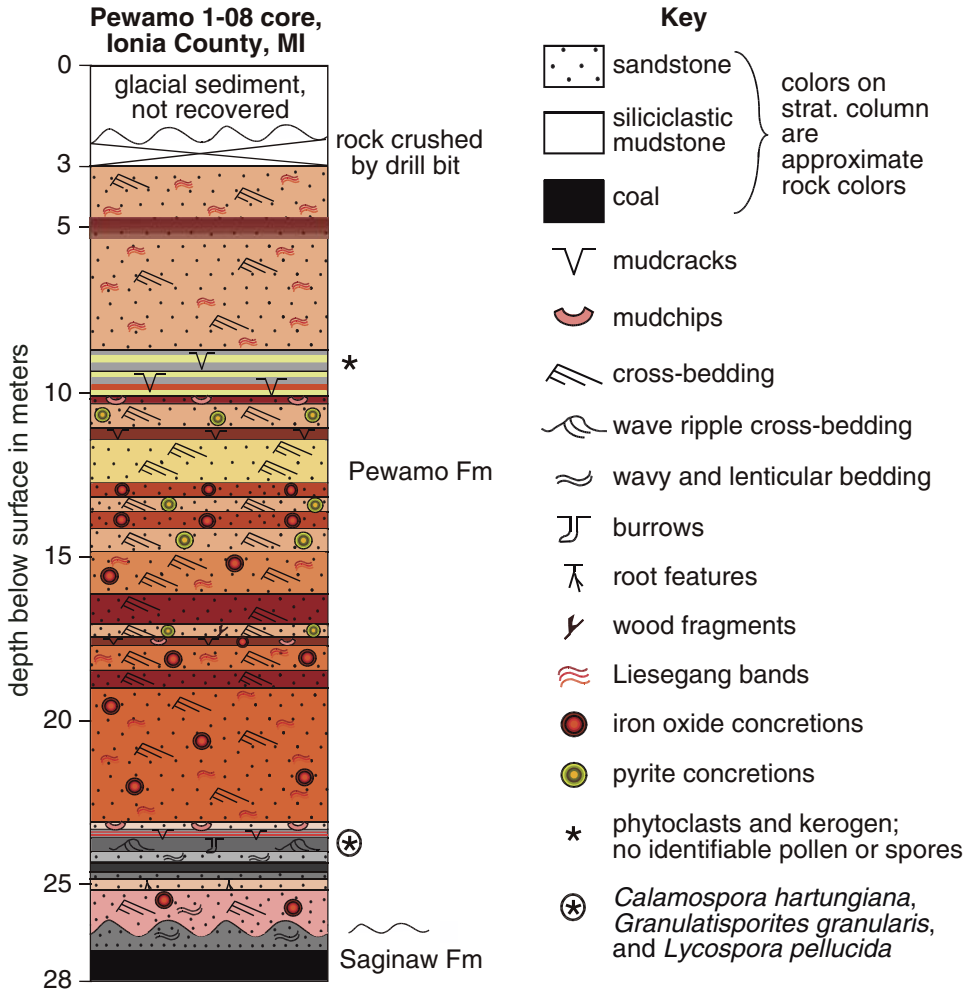

Figure 2. Stratigraphic column measured from Pewamo 1-08 core from Ionia County, Michigan.

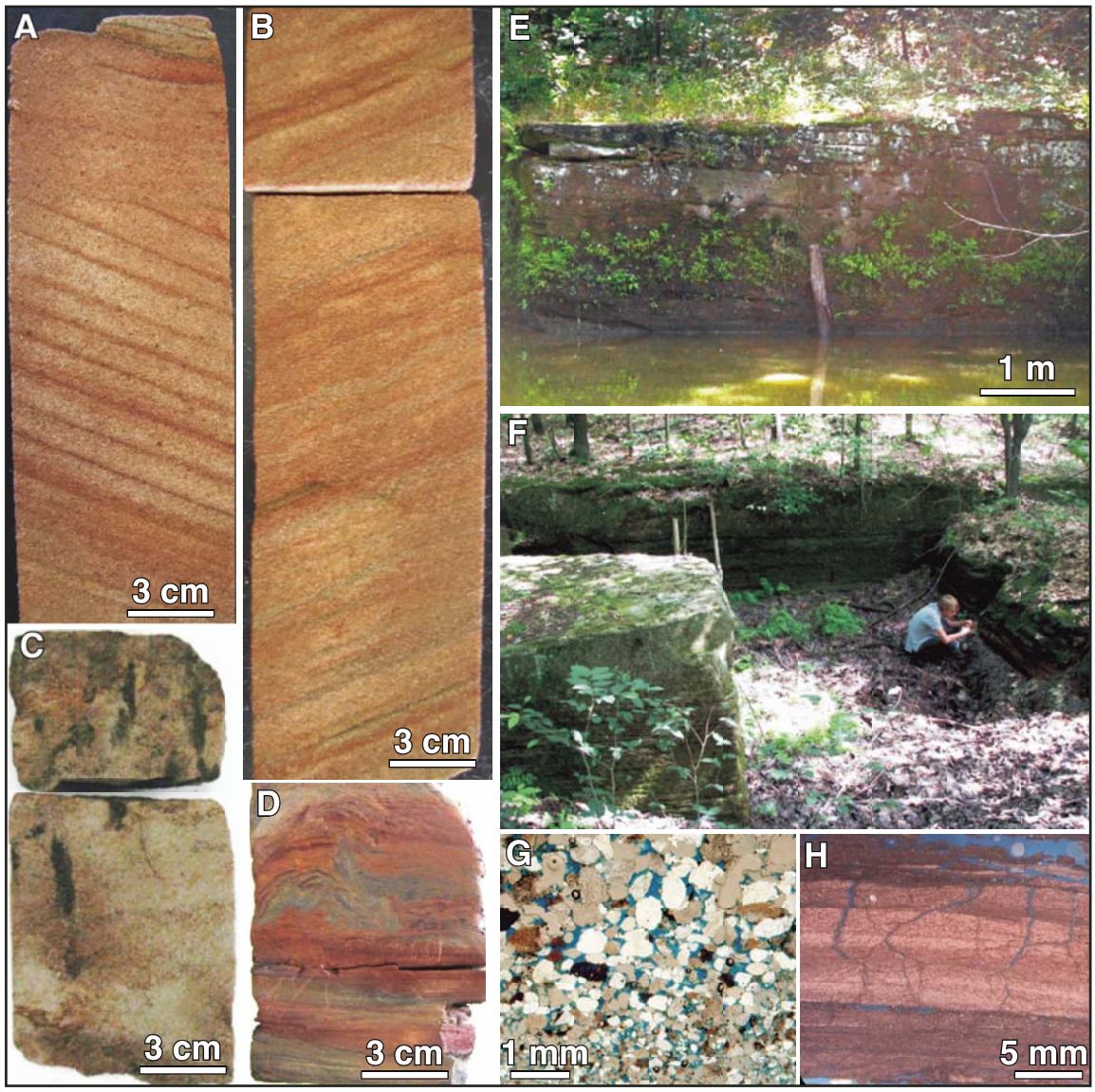

Figure 3. Pewamo Sandstone. (A) Pinstripe cross-bedding in red sandstone, Pewamo 1-08 core. (B) Cross-bedding in red sandstone, Pewamo 1-08 core. (C) Vertical dark root features in sandstone, Pewamo 1-08 core. (D) Laminated and mud-cracked siliciclastic mudstone, Pewamo 1-08 core. (E) Exposure of sandstone in flooded quarry in Grand River State Game Area between Lyons and Ionia, Michigan. (F) Sandstone quarry walls in Grand River State Game Area, ~100 m from Pewamo 1-08 drill site. Wall in foreground is 1.5 m tall. (G) Thin section of sandstone (from quarry wall) with bimodal grain-size distribution; partially polarized light. (H) Mud-cracked, laminated pink mudstone, Pewamo 1-08 core; transmitted light.

and *Lycospora pellucida*, indicate a Pennsylvanian age (Palynodata and White, 2008; M. Zobaa, 2010, personal commun.) and a flora distinct from the Saginaw Formation (Venkatachala and Salujha, 1971). This palynological data, along with the Pewamo's stratigraphic position above the Atokan Saginaw Formation, suggested that the Pewamo is middle–late Pennsylvanian in age. This unit was proposed as a new formation for Michigan because it is lithologically unique in the Michigan Basin, is stratigraphically distinct from the underlying Saginaw Formation and overlying glacial sediments, and is located in situ in outcrops and core (Benison et al., 2011).

The second newly described Pennsylvanian red bed unit in the central Michigan region is the Haybridge strata (Benison et al., 2011). The Haybridge strata are located in situ, but in the shallow subsurface, in and near the Shiawassee River State Game Area and the Shiawassee Federal Wildlife Refuge near the town of St. Charles in Shiawassee County (Fig. 1). There are no true outcrops; the rocks are situated just below the surface,

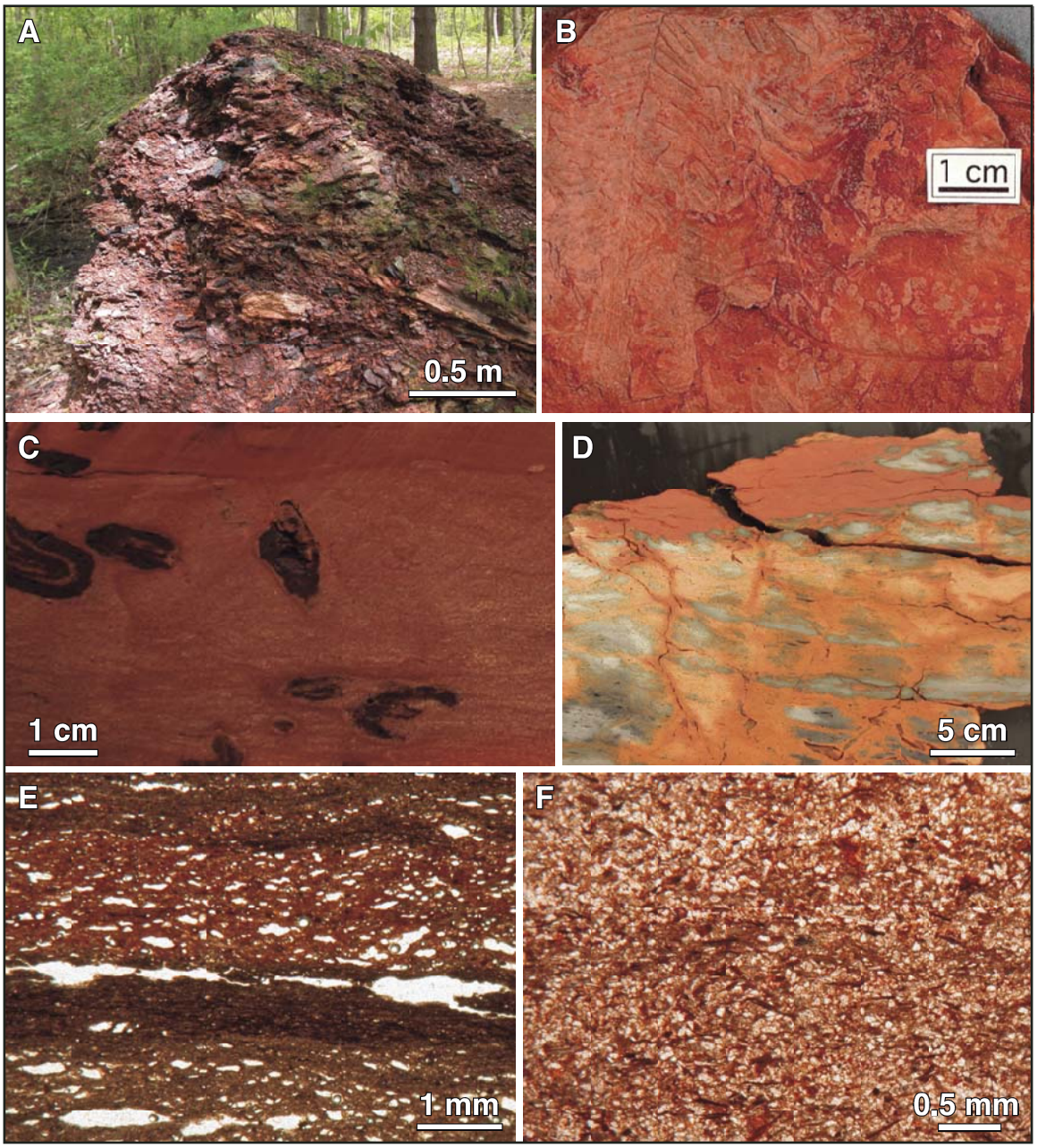

Figure 4. Haybridge strata. (A) Small mine dump near St. Charles, Michigan, containing coal, red sandstone, red mudstone, and rare gray mudstone. (B) Bedding plane of red mudstone with plant fossils. (C) Cross section of red sandstone with charred root remains. (D) Cross-sectional view of fine red sandstone with silver-gray mullite patches. (E) Thin section view of fine red sandstone. Abundant white holes are root molds; transmitted light. (F) Thin section of fine red sandstone with iron-oxide cement and amorphous organic matter; transmitted light.

much of which is covered today by rivers and adjacent wetlands, surrounded by agricultural land composed of thin soils. In the 1880s–1940s, this area contained many working shallow underground coal mines (Lane, 1902, 1908). Historical records indicate that the main coal seam was 1.4 m thick and was ~70 m below the surface (Kalliokoski and Welch, 1977). Some of the coal mines were filled with cement in recent decades to prevent collapse (personal communications with several landowners). These Haybridge rocks are known from old mine waste piles (Fig. 4) and from farmers' fields. Waste mine rocks (mainly the noncoal lithologies) were used to build a small road with a bridge used by local coal miners and later farmers to transport coal and hay by wagons. This was known locally as "the haybridge." Four lithologies have been identified in this region and include:

(1) sulfur-poor bituminous coal with plant fossils; (2) abundant red sandstone composed of quartz, feldspar, and mica grains, hematite cement, climbing ripple cross-lamina, wave ripples, mud cracks, autoclastic breccia, back-filled burrows, root features, and plant fossils; (3) abundant red shale, similar in composition, sedimentary structures, and fossils to the red sandstone, but also containing raindrop impressions; and (4) rare gray shale with abundant mud cracks, some root features, amorphous organic matter, wood, and rare plant fossils (Benison et al., 2011). These lithologies were interpreted as fluvial depositional environments, including channels, ephemeral channels, and floodplains, which underwent pedogenesis (Benison et al., 2011). The same plant fossil assemblage was represented in all four lithologies. Four major plant groups were identified: lycopsids, spenopsids, seed ferns, and tree ferns (for detailed descriptions, photos, and interpretations of plant fossils, see Benison et al., 2011). The plant fossil assemblage defines the age of the Haybridge strata to late middle Pennsylvanian. In addition, some of the red sandstones and red shales contain silvery slag-like patches. These patches are commonly associated with root features, but they are clearly diagenetic because they crosscut sedimentary features. X-ray diffraction showed that the "slag" is mullite ($Al_6Si_2O_{13}$), a mineral nicknamed "porcelainite" because it is formed upon firing of clay in kilns. The Haybridge rocks may have been subjected to wildfires, coal mine fires, or mine pile fires.

THE "MISSING INTERVAL" AND REMAINING QUESTIONS ABOUT POST-PENNSYLVANIAN STRATIGRAPHY OF MICHIGAN

Youngest Known Rocks of Michigan

The Grand River Formation, the Pewamo Formation, and the Haybridge strata are the youngest rocks known in Michigan. No known deposits from the Permian, Mesozoic, or Tertiary exist in Michigan. Pleistocene glacial sediments and Holocene lake, fluvial, beach, and eolian sediments, as well as soils, are known throughout the state. Where the base of these Quaternary sediments has been observed, the underlying rocks are Pennsylvanian or older bedrock. However, the Grand River Formation, Pewamo Formation, and Haybridge strata are found exclusive of one another; that is, these three stratigraphic units have not been documented in the same cores or outcrops. The Grand River and Pewamo have both been found in contact with the Saginaw Formation. The Pewamo and Haybridge have been dated with palynomorphs and macroscopic plant fossils, respectively. No direct dating of the Grand River Formation has been conducted.

Although the Grand River Formation retains a possibility of being post-Pennsylvanian in age, it is most likely Pennsylvanian, and was most likely deposited shortly after the Saginaw Formation. The similarity of the Grand River rocks with the underlying Saginaw rocks has been used as loose evidence that the Grand River is also Pennsylvanian (Westjohn and Weaver, 1998). The nature of the contact between the Saginaw and the Grand River Formations is not clear. Unfortunately, detailed descriptions of plant fossils from rocks in Grand Ledge, where outcrops of both the Saginaw and Grand River Formations exist, do not specify the parent rock (Arnold, 1949; Kelly, 1930). It is unclear whether Pennsylvanian plant fossils have been reported in the Grand River Formation. Regardless, no evidence for a post-Pennsylvanian age has ever been presented for this formation.

What about the "Jurassic Red Beds" of Michigan?

Many geologic maps of Michigan show Jurassic-aged rocks in the center of the Lower Peninsula (Cohee, 1965; Wilson, 1987, 2006). The *Stratigraphic Lexicon of Michigan* includes Jurassic red beds, but it calls them "problematic" (Catacosinos et al., 2001). Cohee (1965) noted red beds from drill holes in the center of the Lower Peninsula of Michigan. However, because his interpretations were based on only a few core cuttings of various red colors, indeterminate ages, and low stratigraphic resolution, Cohee warned that the validity of red beds on his geologic map of the Lower Peninsula of Michigan was speculative. The only detailed study of these red core cuttings was the palynological study conducted by Shaffer (1968, 1969). Shaffer noted reworked pollen and spores of various ages (Devonian–Jurassic), including some from the conifer genus *Classopollis*, which, at the time, was considered to represent only the Jurassic Period. Now, four decades later, *Classopollis* has been identified from rocks of a wider age range, from Triassic to Holocene (White et al., 2009).

These "Jurassic red beds" are known only from core cuttings in the central counties of Michigan (mainly from Clare, Isabella, Mecosta, and Montcalm Counties; Cohee, 1965). Thick glacial deposits in Michigan exist in this area. The locations of these core cuttings are closer to the middle of the basin than the Pennsylvanian Pewamo and Haybridge red bed locations. Neither the Pewamo nor Haybridge strata had a similar paleofloral assemblage to the red bed core cuttings.

Besides Shaffer's (1968, 1969) palynological investigation of the "Jurassic red beds," no geological descriptions have been made from these core cuttings. Their mineralogy, sedimentology, and exact depths are not known. No information is known of their stratigraphic contacts. We do not know if they are indeed rocks or loose sediment.

Orange sandstones used as building stones and called "the Ionia formation" were linked to the red bed core cuttings, presumably due to their color similarities (Cross, 1998b). For many decades, the geologic community did not know from where these sandstones were quarried and only made overly generalized descriptions of them. Finding the quarries and drilling a core led to the first detailed descriptions, and to the realization that the newly described quarries near Lyons and Ionia, Michigan, were the original home of the building stones (Benison et al., 2011). The "Ionia formation" had to be renamed to maintain the rules of the stratigraphic code. Because there are already formations named Ionia and Lyons, this new formation was named after the nearby village of Pewamo. The "Ionia formation" was not the

same at the suspected Jurassic red core cuttings, and the informal Ionia formation name should no longer be used in Michigan.

The limited geological information, combined with the questionable age, about the "Jurassic red beds" of the Michigan Basin leads to a healthy skepticism about any Jurassic deposition there. Multiple scenarios may be possible to explain these core cuttings: (1) They could indeed have been deposited in continental environments during the Jurassic; (2) they could have been deposited in continental environments in the Michigan Basin at any time from the Triassic to Pleistocene; (3) they may have been reworked sediments or sedimentary rock transported and deposited by glaciers during the Pleistocene; or (4) they may have formed as paleosols during interglacial periods in central Michigan. With the little information known about these red bed core cuttings, the scientific community should take care in making any interpretations about Jurassic red beds in the Michigan Basin.

Possible Geologic Scenarios for the Limited Record of the "Missing Interval" of Michigan

To the best of our current knowledge, the post–middle Pennsylvanian geologic record of Michigan consists of unconsolidated siliciclastic sediments. Investigations have focused on studies of Pleistocene glacial landforms, near-surface Pleistocene sediment, and Holocene reworked sediments and their landforms (i.e., Hansen et al., 2009; Howard, 2010; Schaetzl and Weisenborn, 2004). However, much of the Lower Peninsula of Michigan is blanketed with a thick cover of post-Pennsylvanian unconsolidated gravel, sand, and mud; deeper strata from this package have not been studied. What is in the geologic record between the Pennsylvanian Pewamo, Haybridge, and Grand River Formations and the Quaternary sediments near the surface? The best place to look for answers to this question is in the central counties of the Lower Peninsula of Michigan, where the unconsolidated sediments are thickest.

Glacial erosion, reworking, and deposition are the most likely processes that led to the thick unconsolidated sedimentary column above the mid-Pennsylvanian rocks. How many glaciations occurred, and is there evidence of any other geologic events? One likely scenario is that continental environments existed continuously in Michigan from the late Pennsylvanian to today. Sedimentary rocks may remain from past lakes, rivers, and soils, but they have not yet been found. In contrast, such deposits may have been eroded and reworked by the Pleistocene ice sheets. Melting glaciers likely deposited some material original to mid-Michigan to the south. Likewise, some of the material deposited in mid-Michigan was eroded from the north. Some sediments eroded by Pleistocene glaciers in mid-Michigan could have been redeposited locally. We know that ice sheets surged and retreated several times during the Pleistocene. We do not know how much sediment and rock were available to be eroded. If late Pennsylvanian–Pleistocene environments were continental, they may have had close net deposition:erosion ratios, depending upon tectonics and eustasy, sediment supply, surface processes, climate, and timing of cementation (i.e., Benison et al., 2015; Soreghan, 1994). Regardless, it seems feasible that Pleistocene glacial sediments may be the only record left from this missing interval.

There is a possibility that more than one major glaciation acted upon Michigan during the missing interval. If one looks to more regional and global events, glaciation in the late Pennsylvanian must be considered. This major ice age drove ice sheets to low latitudes (i.e., Fielding et al., 2008; Soreghan et al., 2008) and likely would have influenced Michigan. Is there any evidence of late Pennsylvanian glaciation in Michigan? Rhoads et al. (1984) examined well data in Gratiot, Clinton, and Ionia Counties for organic material. They identified organic-rich strata that they interpreted as marking past land surfaces from interglacial times. These wells logs averaged 40 m in depth, so they did not reach bedrock in most wells. Do these organic strata vertically distinguish deposition by different glacial lobes? Are they all Pleistocene glacial events? Could late Paleozoic glacial deposits also be present, or would any late Paleozoic glacial sediment have been reworked by Pleistocene ice sheets? At this time, not enough data exist for detailed interpretations to be made about the geological history of the missing time.

A CASE FOR FUTURE GEOLOGICAL INVESTIGATIONS

The topmost Pennsylvanian rocks and the "missing interval" present unanswered questions about the Michigan Basin. Recent work that located and described the Pewamo Formation and the Haybridge strata (Benison et al., 2011) has added to our knowledge about the Pennsylvanian time in Michigan. This work was made possible by limited shallow coring, extensive field work, and careful historical research of water well, mining, and construction records. This was followed by detailed petrographic, mineralogical, and paleontological studies. However, some of the lateral and vertical stratigraphic relationships, especially amongst the Grand River, Pewamo, and Haybridge formations are unknown (Fig. 1). The thicknesses and lateral extents of these formations are also unknown.

The red core cuttings that launched the "Jurassic red beds" interpretation have remained mysterious for over 50 yr. Their palynological assemblage shows no relationship whatsoever to those of the Pewamo or Haybridge red beds.

The best way to better understand the Pennsylvanian–Holocene history of Michigan is to conduct a shallow drilling program that can retrieve intact cores (i.e., Soreghan et al., 2015). The first goal of this program should be coring the center of the Michigan Basin (in Clare, Isabella, Mecosta, and/or Montcalm Counties) to ~500 m in depth, to aim to retrieve the full package of glacial sediment and the topmost bedrock. This core would greatly help to solve mystery of the "problematic Jurassic red beds" and also allow recognition of the topmost bedrock (likely Pennsylvanian?) of the Michigan Basin. The second objective of a shallow drilling program should focus on drilling one to two shallow (~100 m deep) cores near St. Charles, Michigan,

to investigate the stratigraphic properties of the Haybridge strata and to test its relationship to underlying rocks. Finally, a series of shallow cores (~100 m deep) may target the areas near Grand Ledge and Ionia, Michigan, to gain more subsurface data about the Saginaw, Grand River, and Pewamo Formations and to constrain their stratigraphic relationships.

CONCLUSIONS

The topmost rocks of the Michigan Basin appear to be Pennsylvanian continental sedimentary rocks of the Grand River Formation, Pewamo Formation, and Haybridge strata. No solid evidence for "Jurassic red beds" exists. A shallow coring program is recommended for unraveling the mystery of the "Jurassic red beds" core cuttings, for refining stratigraphic relationships of Pennsylvanian rocks, and for tracing the most recent 300 m.y. of geologic history in the Michigan Basin.

ACKNOWLEDGMENTS

Jonathan Knapp and Joanne Dannenhoffer are gratefully acknowledged for their collaboration in previous studies of the Pewamo Formation and Haybridge strata. James Talbot of K/T Geoservices and John Attard of Attard's Minerals conducted X-ray diffraction analyses for mineral identification. Reed Wicander and Mohamed Zobaa identified the palynomorphs. Sterns Drilling Company is thanked for coring services. Field assistance was provided by Lisa Boetcher, Bill Boggess, Brenda Bowen, Elliot Jagniecki, Mike Jury, Cynthia Knapp, Phil Knapp, and Dan Manke. Mitch Blake, Aureal Cross, Bill DiMichele, Kathleen Pigg, Bernard Shaffer, Lynn Soreghan, Mike Soreghan, Ralph Taggert, and Tom Taylor are thanked for discussions about various aspects of the study. Funding was provided by a Jury Family Foundation award and a Central Michigan University Research Excellence Fund award.

REFERENCES CITED

Arnold, C.A., 1949, Fossil flora of the Michigan coal basin: Contributions from the Museum of Paleontology: University of Michigan, v. 79, p. 131–269.

Benison, K.C., and Knapp, J.P., 2010, Detrital zircons from fluvial Jurassic strata of the Michigan basin: Implications for the transcontinental Jurassic paleoriver hypothesis: Comment: Geology, v. 38, p. e228, doi:10.1130/G31436C.1.

Benison, K.C., Knapp, J.P., and Dannenhoffer, J.M., 2011, The Pennsylvanian Pewamo Formation and associated Haybridge strata: Toward the resolution of the Jurassic Ionia red bed problem in the Michigan Basin, U.S.A.: Journal of Sedimentary Research, v. 81, p. 459–478, doi:10.2110/jsr.2011.039.

Benison, K.C., Zambito, J.J., and Knapp, J.P., 2015, Contrasting siliciclastic-evaporite strata in subsurface and outcrop: An example from the Permian Nippewalla Group of Kansas, U.S.A.: Journal of Sedimentary Research, v. 85, p. 626–645, doi:10.2110/jsr.2015.43.

Catacosinos, P.A., Harrison, W.B., III, Reynolds, R.F., Westjohn, D.B., and Wollensak, M.S., 2001, Stratigraphic Lexicon for Michigan: Lansing, Michigan, Michigan Basin Geological Society, 56 p.

Cohee, G.V., 1965, Geologic history of the Michigan Basin: Washington Academy of Sciences Journal, v. 55, p. 211–223.

Cross, A.T., 1975, Jurassic plants of the Michigan Basin, *in* American Association of Petroleum Geologists Annual Meeting Program with Abstracts: Albuquerque, New Mexico, American Association of Petroleum Geologists, p. 14–15.

Cross, A.T., 1986, Correlation of Jurassic palynofloras of the Michigan Basin with other Mesozoic floras of the eastern mid-continental United States, *in* American Association of Petroleum Geologists Annual Meeting, Program with Abstracts: New York, American Association of Petroleum Geologists, p. 5.

Cross, A.T., 1998a, The Jurassic terrestrial palynoflora of Michigan, *in* American Association of Stratigraphic Palynologists Annual Meeting Program with Abstracts: Ensenada, Baja California, Mexico, American Association of Stratigraphic Palynologists, 251 p.

Cross, A.T., 1998b, The Ionia Formation: New designation for the mid-Jurassic age "red beds" of the Michigan Basin, *in* American Association of Petroleum Geologists, Eastern Section Annual Meeting, Program with Abstracts: Columbus, Ohio, American Association of Petroleum Geologists, p. 1766.

Dickinson, W.R., Gehrels, G.E., and Marzolf, J.E., 2010a, Detrital zircons from fluvial Jurassic strata of the Michigan Basin: Implications for the transcontinental Jurassic paleoriver hypothesis: Geology, v. 38, p. 499–502, doi:10.1130/G30509.1.

Dickinson, W.R., Gehrels, G.E., and Marzolf, J.E., 2010b, Detrital zircons from fluvial Jurassic strata of the Michigan basin: Implications for the transcontinental Jurassic paleoriver hypothesis: Reply: Geology, v. 38, p. e229, doi:10.1130/G31658Y.1.

Dorr, J.A., and Eschman, D.F., 1970, Geology of Michigan: Ann Arbor, Michigan, University of Michigan Press, 476 p., doi:10.3998/mpub.23827.

Fielding, C.R., Frank, T.D., and Isbell, J.L., 2008, The late Paleozoic ice age—A review of current understanding and synthesis of global climate patterns, *in* Fielding, C.R., Frank, T.D., and Isbell, J.L., eds., Resolving the Late Paleozoic Ice Age in Time and Space: Geological Society of America Special Paper 441, p. 343–354, doi:10.1130/2008.2441(24).

Hansen, E., DeVries-Zimmerman, S., van Dijk, D., and Yurk, B., 2009, Patterns of wind flow and eolian deposition on a parabolic dune on the southeastern shore of Lake Michigan: Geomorphology, v. 105, p. 147–157, doi:10.1016/j.geomorph.2007.12.012.

Howard, J.L., 2010, Late Pleistocene glaciolacustrine sedimentation and paleogeography of southeastern Michigan, U.S.A.: Sedimentary Geology, v. 223, p. 126–142, doi:10.1016/j.sedgeo.2009.10.006.

Kalliokoski, J., and Welch, E.J., 1977, Magnitude and Quality of Michigan's Coal Resources: U.S. Bureau of Mines Open-File Report 102-76, 15 p.

Kelly, W.A., 1930, Lower Pennsylvanian faunas from Michigan: Journal of Paleontology, v. 4, p. 129–151.

Kelly, W.A., 1931, A review of the stratigraphy of the Saginaw formation: Michigan Academy of Sciences, Arts, and Letters, Papers, v. 14, p. 453–461.

Kelly, W.A., 1933, Pennsylvanian stratigraphy near Grand Ledge, Michigan: The Journal of Geology, v. 41, p. 77–88, doi:10.1086/624006.

Kelly, W.A., 1936, The Pennsylvanian system of Michigan, *in* Smith, R.A., preparer, Occasional Papers on the Geology of Michigan: Michigan Geological Survey Publication 40, Geological Series 34, Part 2, p. 155–219.

Landing, E.D., and Wardlaw, B.R., 1981, Atokan conodonts from the Pennsylvanian outlier of the Michigan Basin: Journal of Paleontology, v. 55, p. 1251–1269.

Lane, A.C., 1902, Coal of Michigan: Its Mode and Occurrence: Michigan Geological Survey Report VIII, Part II, 74 p.

Lane, A.C., 1908, Annual Report of the State Geologist: Lansing, Michigan, Michigan Geological Survey, Annual Report, p. 7–31.

Palynodata, Inc., and White, J.M., 2008, Palynodata Datafile: 2006 Version, with Introduction by J.M. White: Geological Survey of Canada Open-File 5793, 1 CD-ROM.

Price, J.R., and Velbel, M.A., 2000, Weathering of the Eaton Sandstone (Pennsylvanian), Grand Ledge, Michigan: Geochemical mass-balance and implications for reservoir properties beneath unconformities: Journal of Sedimentary Research, v. 70, p. 1118–1128, doi:10.1306/102199701118.

Rhoads, B.L., Rieck, R.L., and Winters, H.A., 1984, Trend surface analysis of glacially buried Pleistocene organic deposits in central Michigan: The Professional Geographer, v. 36, p. 64–73, doi:10.1111/j.0033-0124.1984.00064.x.

Schaetzl, R.J., and Weisenborn, B.N., 2004, The Grayling Fingers region of Michigan: Soils, sedimentology, stratigraphy, and geomorphic development: Geomorphology, v. 61, p. 251–274, doi:10.1016/j.geomorph.2004.01.002.

Shaffer, B.L., 1968, Palynology and geology of newly discovered Jurassic sediments in the Michigan Basin [abs.]: Geological Society of America Special Paper 115, p. 376–377.

Shaffer, B.L., 1969, Palynology of Michigan "Red Beds" [Ph.D. diss.]: East Lansing, Michigan, Michigan State University, 261 p.

Shideler, G.L., 1969, Dispersal patterns of Pennsylvanian sandstones in the Michigan Basin: Journal of Sedimentary Petrology, v. 39, p. 1229–1237.

Soreghan, G.S., 1994, Stratigraphic responses to geologic processes: Late Pennsylvanian eustasy and tectonics in the Pedregosa and Orogrande basins, Ancestral Rocky Mountains: Geological Society of America Bulletin, v. 106, p. 1195–1211, doi:10.1130/0016-7606(1994)106<1195:SRTGPL>2.3.CO;2.

Soreghan, G.S., Soreghan, M.J., Poulsen, C.J., Young, R.A., Eble, C.F., Sweet, D.E., and Davogustto, O.C., 2008, Anomalous cold in the Pangaean tropics: Geology, v. 36, p. 659–662, doi:10.1130/G24822A.1.

Soreghan, G.S., Benison, K.C., Foster, T.M., Zambito, J.J., and Soreghan, M.J., 2015, The paleoclimatic and geochronologic utility of coring red beds and evaporites: A case study from the RKB core (Permian, Kansas, USA): International Journal of Earth Sciences, v. 104, p. 1589–1603, doi:10.1007/s00531-014-1070-1.

Velbel, M.A., and Brandt, D.S., 1989, Field Guide to the Sedimentology and Paleogeography of the Pennsylvanian Strata of Grand Ledge, Michigan: Lansing, Michigan, Michigan Basin Geological Society, Field Trip Guidebook, 33 p.

Velbel, M.A., Price, J.R., and Brandt, D.S., 1994, Sedimentology, Paleogeography, and Geochemical Weathering of the Pennsylvanian Strata of Grand Ledge, Michigan: Michigan Basin Geological Society, Guidebook, 58 p.

Venable, N.B., 2006, Sedimentology and Stratigraphy of the Pennsylvanian Saginaw Aquifer, Central Lower Michigan, U.S.A. [Master's thesis]: Kalamazoo, Michigan, Western Michigan University 163 p.

Venable, N.B., and Barnes, D.A., 2006, Sedimentology and stratigraphy of the Pennsylvanian Saginaw Aquifer, central lower Michigan, U.S.A. [abs.]: Geological Society of America Abstracts with Programs, v. 38, no. 4, p. 5.

Venable, N.B., Barnes, D.A., Westjohn, D.B., and Voice, P.J., 2013, Pennsylvanian fluvial-deltaic depositional systems in central lower Michigan: Sedimentology, stratigraphy, and hydrogeology of the Saginaw Aquifer, *in* Gillespie, R., ed., Insights into the Michigan Basin: Salt Deposits, Impact Structure, Youngest Basin Bedrock, Glacial Geomorphology, Dune Complexes, and Coastal Bluff Stability: Geological Society of America Field Guide 31, p. 37–56, doi:10.1130/2013.0031(04).

Venkatachala, B.S., and Salujha, S.K., 1971, Pollen and spores from the pre-Verne cyclical formation of the Saginaw Group, Grand Ledge, Michigan, U.S.A.: Contributions from the Museum of Paleontology: University of Michigan, v. 23, p. 263–281.

Westjohn, D.B., and Weaver, T.L., 1998, Hydrogeologic Framework of the Michigan Basin Regional Aquifer System: U.S. Geological Survey Professional Paper 1418, 55 p.

White, J.M., Jessop, C.M., Scotese, C.R., Lai, G., and daRosa, R.J., 2009, Depicting biostratigraphical data from palynodata: Experiments and questions in data presentation and manipulation: Palynology, v. 33, p. 157–174, doi:10.2113/gspalynol.33.2.157.

Wilson, S.E., 1987, Bedrock Geology of Michigan: Michigan Geological Survey, Michigan Department of Natural Resources, http://www.michigan.gov/documents/Bedrock_Geology_Map_19607_7.pdf (accessed 25 July 2017).

Wilson, S.E., 2006, Generalized Bedrock Geology in Michigan Map: http://www.michigan.gov/documents/deq/ogs-gimdl-GTLH_geo_307674_7.pdf (accessed 25 July 2017).

Manuscript Accepted by the Society 9 June 2017
Manuscript Published Online 9 November 2017

Printed in the USA