Journal of
Sedimentary
Research

Journal of Sedimentary Research, 2011, v. 81, 459–478
Research Article
DOI: 10.2110/jsr.2011.039

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.

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ABSTRACT: **Two distinct and newly recognized, formation-scale stratigraphic units, predominantly red-bed sandstones and shales, are found on the surface and in the shallow subsurface of the central Michigan region. Here, we use core, field, and laboratory observations to document these strata, which we propose as one new formation, the Pewamo Formation. The Pewamo Formation consists of eolian quartz sandstones with red coloration due to iron-oxide diagenesis, and interbedded interdune lacustrine siliciclastic mudstones. We also describe for the first time the Haybridge strata, which contains red sandstones, red and gray shales, and coal, and has plant fossils and paleosol features. Macroscopic plant fossils and palynomorphs suggest a Pennsylvanian age for both units. These newly described continental deposits provide data about past environments, life, and climate for the late Carboniferous of Michigan. In addition, this study is an evaluation of Michigan's controversial "Jurassic red beds" and "Ionia sandstone."**

INTRODUCTION

The Michigan Basin, a major North American intracratonic basin consists mainly of well-described Paleozoic marine sedimentary rocks, some rich in oil and gas. However, there is a large gap in the understanding of the regional geologic history between the early–middle Pennsylvanian Saginaw and Grand River formations and the Pleistocene glacial sediments. The Stratigraphic Lexicon of Michigan (Catacosinos et al. 2001) conveys uncertainty about the geologic record from the Pennsylvanian through the Tertiary.

It has been proposed previously that red beds may be dated to this "missing time" period for the Lower Peninsula of Michigan (Cohee 1965). Anecdotes of central and eastern Michigan surface red beds with plant fossils have circulated for decades. Eastern Michigan once had a thriving coal mining industry (Cohee 1965; Cohee et al. 1950) and coal mine dumps are present locally. Although there have been some mentions of red beds in the shallow subsurface (e.g., Cohee 1965; Kalliokoski and Welch 1977; Shaffer 1968; Shaffer 1969; Westjohn et al. 1994), no comprehensive scientific examination of either the surface or subsurface red rocks has been conducted.

Here, we document two formation-scale stratigraphic units that consist mostly of red beds with minor coal and gray shale. Our core, field, and laboratory studies document the mineralogy, sedimentary textures, sedimentary structures, macrofossils, microfossils, and diagenetic features of these rocks. We use this new data to: (1) describe and propose the Pewamo Formation as a new formation, (2) describe the Haybridge strata as a formation-scale stratigraphic unit, (3) interpret past depositional environments, and (4) evaluate the red-bed controversy for the Michigan Basin.

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BACKGROUND

General Geologic History of the Michigan Basin

The early–middle Paleozoic rocks of the Michigan Basin are relatively well known to many geologists. These are mostly marine sedimentary rocks, many with economic significance for their oil, gas, evaporite, and carbonate resources. The late Paleozoic is less documented in Michigan, but includes early–middle Pennsylvanian Saginaw and Grand River formations (Catacosinos et al. 2001; Dorr and Eschman 1970; Kelly 1930 1931, 1933, 1936; Price and Velbel 2000; Shideler 1969; Velbel et al. 1994; Venable 2006). These formations are exposed at the surface in Grand Ledge, Michigan, and are known from some shallow cores (Price and Velbel 2000; Venable 2006). The gray shale, gray sandstone, and coal of the Saginaw Formation have been interpreted as deposits of marginal marine environments, including deltas and estuaries (Shideler 1969). The age of the Saginaw Formation has been determined to be early Middle Pennsylvanian (Atokan) by conodont identification (Landing and Wardlaw 1981). The overlying Grand River Formation is a cross-bedded, buff-colored sandstone that has been interpreted as a fluvial deposit (Shideler 1969). Other informal sandstone units, the Parma, the Eaton, and the Woodbine, are not adequately described in the literature (Dorr and Eschmann 1970); they are likely members of the Saginaw Formation. Coal beds, typically thin and likely laterally discontinuous, are also associated with some of these Pennsylvanian sandstones, but the studies of these coals has focused on their economic resources and not their stratigraphic positions or associated strata (e.g., Lane 1902, 1908; Cohee et al. 1950; Kalliokoski and Welch 1977). In addition, extensive descriptions of late Paleozoic plant fossils have been made for Michigan, but for rocks that are neither well-constrained stratigraphically nor red (Arnold 1949). Therefore, although the Saginaw and Grand River formations are fairly well known, especially from the outcrops at Grand Ledge, there still are gaps in the knowledge of the late Paleozoic Era.

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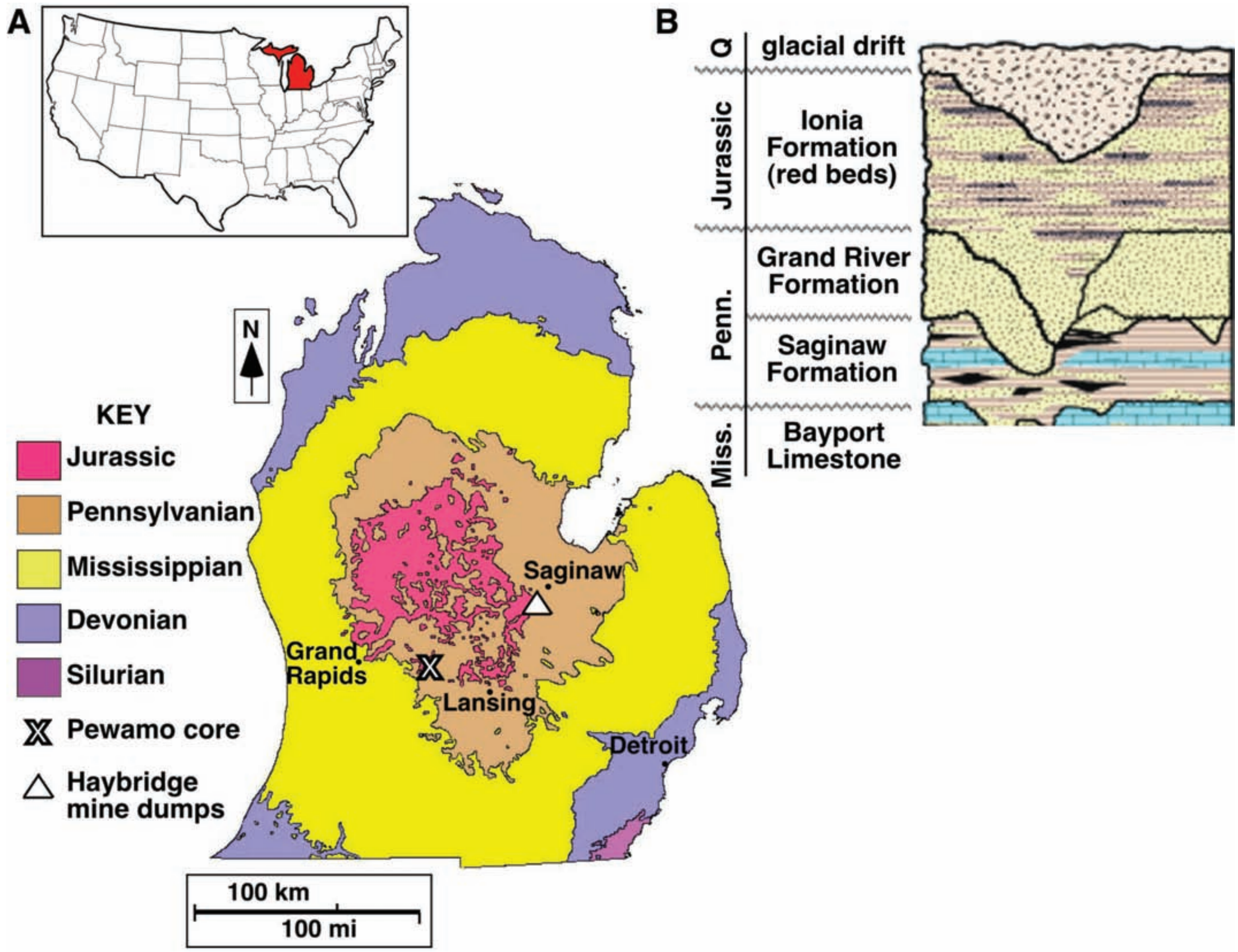

FIG. 1.—Current, but suspect, official descriptions of shallow rocks of the central portion of the Michigan Basin. **A)** Bedrock geologic map of the Lower Peninsula showing strata according to time periods. Note that the Pewamo core location is marked by a white X and the Haybridge mine dumps are designated by a white triangle. Inset map shows Michigan's Upper and Lower Peninsula in red. After Wilson (2006). **B)** Portion of official stratigraphic column for Michigan, showing topmost Mississippian through Quaternary strata. Note that no published sedimentologic or stratigraphic descriptions exist for the "Ionia Formation." After Catacasinos et al. (2001).

The geological history of Michigan between ~ 320 Ma and ~ 1 Ma has been poorly documented, but at least some red beds were deposited sometime during this "missing time." The shallow red beds of the Michigan Basin have remained elusive since the state's first geological surveys. Red siliciclastic rocks have been reported in the forms of red core cuttings from depths down to ~ 150 meters below the surface in the central part of the Lower Peninsula (Cohee 1965). There are also red sandstones used as building stones in ~ 100-year-old structures in this same region (Cross 1998b). In addition, anecdotes of central and eastern Michigan surface red beds, some with plant fossils, have circulated for decades. The sites of these surface red beds coincide with the centers of Michigan's once-thriving coal mines (Cohee 1965; Cohee et al. 1950). Until now, no mineralogic, sedimentologic, or stratigraphic studies have been performed on these rocks.

Most of central Michigan's bedrock is covered with Pleistocene and Holocene sediment. The Pleistocene sediments reach thicknesses of up to ~ 150 meters. Pleistocene gravels, sands, and muds were deposited in glacial and proglacial settings as both till and outwash. Inland from the Great Lakes, some of the glacial sediments have been reworked by winds and rivers. In addition, longshore currents have extensively reworked these sediments, especially along Lake Michigan's eastern shoreline. Some glacial sediments in Michigan contain thin (centimeter-scale) units of dark gray or red, organic-rich mudstones with paleosol features. The Holocene sediment forms a relatively thin veneer (centimeter- to meter-scale) at the surface and is composed of reworked glacial sediments, fluvial sediments, lake sediments, and soils.

"Problematic Jurassic Red Beds"

Cohee (1965) reported red beds in the center of the Lower Peninsula on his bedrock geological map, but he indicated that these red beds were highly speculative and based only on a few core cuttings of various red colors, indeterminate age, and low stratigraphic resolution. However, this uncertain placement of red beds is used for Michigan's official geologic maps (Fig. 1; Wilson 1987, 2006). There have been subsequent reports of red beds in the subsurface (e.g., Kalliokoski and Welch 1977; Shaffer

1969; Westjohn et al. 1994), but no comprehensive scientific examination of either the surface or subsurface red rocks has been conducted until now. Studies of late Paleozoic through Tertiary geology of Michigan are mostly outdated, incomplete, and/or lacking stratigraphic context. For example, Arnold (1949) provided extensive descriptions of late Paleozoic plant fossils in rocks left mostly unidentified in terms of location, stratigraphy, lithology, and/or color (Arnold 1949). The Stratigraphic Lexicon of Michigan (Catacosinos et al. 2001) conveys uncertainty about the geologic record from the Pennsylvanian through the Tertiary.

The Stratigraphic Lexicon of Michigan includes "Jurassic red beds" in its official stratigraphic column for the state. However, the incomplete description of these rocks, the lack of peer-reviewed publication, and the previous use of this name elsewhere in the U.S. led to the "problematic" designator in the Stratigraphic Lexicon of Michigan (Catacosinos et al. 2001). The only detailed study of red beds in Michigan's Lower Peninsula is an unpublished doctoral dissertation (Shaffer 1969) that documented the palynology of some shallow red core cuttings from the red beds mapped by Cohee (1965) from central Michigan. The specific depths of the cuttings are not well documented; typically, 5 to 10 vertical feet of core are represented by a vial containing only ~ 10 to 20 grams of crushed unconsolidated sand and silt. Shaffer processed these crushed red rocks for palynological analyses and reported that the palynomorphs were not abundant, were mostly reworked, and represented Devonian to Jurassic ages. A key, abundant spore identified was of the genus *Classopollis*, which, at the time, was considered to represent only the Jurassic Period (Pocock and Jansonius 1961). Now, four decades later, *Classopollis* has been identified from rocks of a wider age range, Triassic to Paleocene (The Paleobiology Database; http://www.paleodb.org/cgi-bin/bridge.pl). Shaffer cautiously claimed that the red core cuttings were "likely Jurassic," based upon his palynological analysis. Since Shaffer's dissertation, several abstracts have referred to "Jurassic red beds" of the Michigan Basin, yet do not include any sedimentologic descriptions or any new data (Cross 1975, 1986, 1998a, 1998b).

The presence of red sandstone building stones in Ionia, Michigan, led Cross to link them to the red core cuttings studied by Shaffer (1969) and to informally use the name "Ionia sandstone" for the red beds of Michigan (Cross 1998b). No comparison has been formally made of the red sandstones in Ionia buildings with the red core cuttings mapped by Cohee (1965) and studied by Shaffer (1969).

Regardless of the extremely limited knowledge of these red beds of the Michigan Basin, these rocks have been recently used to make detailed interpretations of Jurassic environments. Dickinson et al. (2010a) presented U-Pb analysis of detrital zircons from one building stone of the "Jurassic Ionia sandstone," showing that the youngest zircon ages are Devonian. These detrital zircon data were used to construct a map of rivers for the Jurassic of North America without confirmation that these rocks were either Jurassic or fluvial (Benison and Knapp 2010; Dickinson et al. 2010a, 2010b). Another current study makes interpretations of weathering trends for the Jurassic based upon the interpretation that these rocks are Jurassic (Velbel and Weber 2009). These studies highlight the need for a detailed evaluation of the Michigan red beds.

METHODS

We employed a variety of historical, drilling, field, and laboratory methods to better understand the shallow red sedimentary rocks in central Michigan. Historical methods include the compilation and examination of mine and quarry data from the mid-1800s until the 1950s. We obtained this information by searching the archives of historical libraries, and the state records for mining and drilling permits and leases. We also interviewed local farmers, quarry operators, and historians about the history of coal and red-rock mining, and the presence of any red rocks in central Michigan. Palynologists Aureal Cross and Bernard Shaffer provided some perspectives about their roles in the study and interpretation of the "Jurassic red beds" and "Ionia sandstone." Searches for and cursory examination of red rock core cuttings were also conducted. Some county water well descriptions were obtained to investigate reports of red rocks in the shallow subsurface. Environmental and rock drillers have reported the presence of red core cuttings to us as they have found them over the past several years in central Michigan.

Traditional and nontraditional field methods were used. We searched for outcrops, abandoned quarries, mine dumps, and building stones, following leads gleaned from both our historical research and from local anecdotes. Rocks were photographed and described in the field. Except for in-place building stones, samples were collected and returned to the sedimentology and paleobotany laboratories at Central Michigan University.

Coring was conducted in late July 2008 at the Grand River State Game Area in Ionia County, Michigan between the towns of Ionia and Lyons (latitude 42.98236° N, longitude 84.99596° W). A truck-mounted drill rig performed hollow stem augering and retrieved 2.5 inch diameter (6.3 cm) intact rock core from depths of 10 feet to 92 feet (3 to 28 m) below the surface. Preliminary work done at the coring site included measuring, photographing, and describing the stratigraphic section. We measured the core, using feet instead of meters because the driller's log measured it with the English system, as is still traditional for core measurement by the petroleum industry.

We examined 82 feet (25 m) of core and over 250 hand samples from abandoned quarries and mine dumps. One hundred and forty-six hand samples with macroscopic plant fossils were analyzed in the laboratory. Plant fossils were photographed with low-angle epi-illumination and are housed in the Central Michigan University paleobotanical collection (CMU-PC). Cores were slabbed vertically and re-examined, and the core section was remeasured. Core and surface samples were examined and photographed with naked eye and a low-power Olympus SZX12 binocular microscope (2.5 to 90× magnification). One hundred and thirty-three large-format (2 × 3 inch) thin sections were prepared from core and field samples. Thin sections were examined with a low-power Olympus SZX12 binocular microscope (2.5 to 90 × magnification) and a higher-power Leitz Laborlux petrographic microscope (10 to 480 × magnification) using transmitted plane light, polarized light, reflected light, and combinations of those. We observed and documented mineral composition, sedimentary textures, sedimentary structures, diagenetic features, and fossils in core samples, hand samples, and thin sections.

Mineralogical identifications were done by several means. We used petrographic observations, X-ray diffraction (performed by Attard's Minerals and K/T Geoservices), and reflectance spectroscopy (performed on representative samples at Purdue University).

Palynological preparation was performed at Central Michigan University and Global Geosciences. Analyses of organic materials, including palynomorphs, were conducted at Central Michigan University and Missouri University of Science and Technology.

PEWAMO FORMATION

Results

Basic Core Description.—At the Pewamo 1-08 core drill site 12 kilometers east of Ionia, Michigan (42.98175° N, 84.99513° W), we drilled amid small outcrops and water-filled quarry pits (Figs. 1, 2. Outcrops and quarries described later). Seven feet of Holocene and Pleistocene sand and gravel covered the bedrock at the drill site. Bedrock was encountered at seven feet depth, but the drill crushed the first three feet of bedrock, so no core was retrieved. Red sandstones and less abundant red, gray, and yellow siliciclastic mudstones were recovered from 10 to 86 feet (3 to 26 m)


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depth. Black and gray shales and fine-grained gray sandstones were encountered from 86 to 92 feet (26 to 28 m), the bottom of the hole (Figs. 3, 4, 5). We named the red sandstones and intercalated mudstones between 10 and 86 feet depths the "Pewamo Formation," named after a nearby village with building stones of the same sandstone (Figs. 2, 5). We did not use the names of the closer towns, Ionia and Lyons, because both names are already used for stratigraphic units outside Michigan.

Cross-Bedded Sandstone Lithofacies.—The most common lithofacies in the Pewamo Formation is quartz arenite with cross-bedding (Figs. 4, 5, 6). This sandstone exhibits various shades of orange and red (Figs. 4, 5, 6). Grains are approximately 95% quartz sand grains (Fig. 6). The quartz grains range in size from 0.2 mm to 1.4 mm, although most are between 0.3 and 0.8 mm. The quartz sandstone is well sorted with bimodal grain-size distribution. Grains are subrounded to very well rounded and have moderate to high sphericity. The quartz arenite is moderately friable. Individual quartz grains flaked off the sandstone exhibit pitting and frosting when viewed with a microscope. Rare muscovite mica grains were observed in the sandstone. The mica was not abundant enough to be detected by XRD or reflectance spectroscopy, but it was identified optically. The mica grains are ~ 0.9 to 1.0 mm long, have very low sphericity, and are aligned parallel to cross-bedding. Hematite cement gives the sandstone its colors (Fig. 6).

Cross-bedding is the most common sedimentary structure in this lithofacies. Although cross-bedding type is difficult to identify accurately in cores, it appears to be most commonly high-angle (~ 30°; Figs. 2G, 5A, B, J). The foresets appear planar through much of their length but become tangential at the toes (Fig. 2F, H). There is also some low-angle, planar cross-bedding (Fig. 2D), although this is less common. Cross-bedding is defined by inverse grading and bimodal grain-size distribution, as seen in thin sections (Fig. 6). Some of the cross-bedded sandstone may be characterized as "pinstriped," with ~ 0.5 to 1 mm-thick alternating laminae of coarser grains and finer grains (Fig. 5A). In addition, some cross-bedding is emphasized by a concentration of intergranular pore-filling hematite cement at tops of individual foresets, where sand grains are coarsest. Reactivation surfaces are also noted in this lithofacies (Figs. 2F, 5B).

Rare intervals in the sandstone lithofacies contain carbonized root features. (Figs. 5C, 6F). The root features are characterized by vertically trending carbonized areas in otherwise quartz and hematite sandstone (Fig. 5C). Petrographically, they appear as aligned holes, encircled with carbon (Fig. 6F). We have noted no other biogenic sedimentary structures or fossils in this cross-bedded sandstone lithofacies.

Hematite cement is the main diagenetic feature in this lithofacies and is responsible for color and the various degrees of friability. The hematite cement has variable concentrations (Figs. 5, 6). In some intervals, it is almost absent and the rock is very friable with a porosity of 20 to 30%. In one rare case, the hematite cement has filled almost all intergranular pore space, resulting in a well-cemented sandstone with only ~ 1% porosity. More typically, the cross-bedded sandstone lithofacies contains patchy intergranular hematite cement as very thin grain coatings, as meniscus cements near grain contacts, and as pendant cements that hang down from the undersides of grains (Fig. 6). Other diagenetic features formed by hematite are Leisegang bands and hematite concretions (Fig. 5). In some sandstones, the iron oxide cements overprint the cross-bedding sufficiently to make it difficult to distinguish it (Fig. 5I).

Bleaching features, where iron oxides are lacking, are seen in the Pewamo cross-bedded sandstone. Some of these appear as reduction spots, circular white spots in red or orange sandstone (Fig. 5F). There are also rare white areas with a sharp crosscutting contact with the red rock (Fig. 5H).

Siliciclastic Mudstone Lithofacies.—There are several thin units of siliciclastic mudstones interbedded with the cross-bedded red sandstones in the core. Two distinct mudstones are differentiated by different colors, minerals, and organic content. (Figs. 4, 5D, 7)

One gray siliciclastic mudstone is found in the lower portion of the Pewamo Formation, at 76 feet, 10 inches (23.44 m) to 78 feet depth (23.77 m). It is composed of quartz, muscovite mica, kaolinite, and montmorillonite, with a high content of kerogen and amorphous organic matter. Quartz grains are silt-sized. This rock is thinly bedded and laminated. Thin beds are darker gray, contain more organic matter, and are massive. These thin beds have abundant fine root features. Laminated units are lighter gray, contain less organic matter, and are characterized by thin laminae crosscut by abundant vertical desiccation cracks. Palynological analyses of this rock reveal phytoclasts, abundant kerogen, and three identifiable spores. These spores are *Lycospora pellucida*, *Granulatisporites granularis*, and *Calamospora hartungiana* (Fig. 8; Mohamed Zobaa, personal communication).

Another distinctive siliciclastic mudstone is found from 29 feet, 2 inches (8.89 m) to 29 feet, 8 inches (9.07 m) depth in the core. This mudstone is characterized by pink, yellow-orange, and pale gray thin beds. Each thin bed contains thin laminae. XRD analyses indicates the presence of quartz, hematite, fluorapatite ($Ca_5(PO_4)_3F$), and nontronite ($Na_{0.5}Fe_2(Si,Al)_4O_{10}(OH)_2 \cdot nH_20$, a member of the smectite clay family). Needle-shaped, randomly oriented gypsum crystals were observed petrographically. There are no organic sedimentary structures, but there are abundant vertical desiccation cracks; one thin bed is curled up into mudcracked intraclasts. The pink thin beds contain fine-sand-size, dark red peloids in a matrix of fine-silt-size and clay-size quartz, hematite, fluorapatite, nontronite, and gypsum. Palynological analyses showed that this rock contains abundant phytoclasts and kerogen but no identifiable pollen or spores.

Supplemental Descriptions from Abandoned Quarries, Outcrops, and Building Stones

Abandoned Quarries and Outcrops

We learned that many local people know that the red sandstone building stones were mined somewhere near Ionia, but few actually know the location of these quarry sites. We located the abandoned sandstone quarries in the wooded area administered by the Michigan Department of Natural Resources, south of the Grand River between the towns of Ionia and Lyons, Michigan. This land was originally mined by the Ionia Sandstone Company, owned by John C. Blanchard, in the late 1800s.

Most of the abandoned quarries are filled with water, with less than one meter of rock exposed above water. However, several small open quarry walls up to 2 meters tall were found. In addition, there are small natural outcrops (less than 0.5 meters tall) near the abandoned quarries.

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FIG. 2.—Pewamo Formation in building stones, abandoned quarries, and outcrop. **A)** Blanchard House, built by original quarry owner in 1886, in Ionia, Michigan. **B)** Ionia County Courthouse, Ionia, Michigan, built 1883 to 1886. **C)** Decorative facing stone in Shepherd, Michigan. **D)** Low-angle cross-bedding in building stone, Ionia, Michigan. **E)** Leisegang bands in sandstone from railroad trestle ruins in Lyons, Michigan. **F)** Cross-bedded sandstone with reactivation surface in building stone, Shepherd, Michigan. **G)** Top of abandoned quarry wall, Lyons, Michigan. Note quarry is filled with water. **H)** Outcrops created by quarrying, Lyons, Michigan. Rock face in foreground is 1.5 meters tall. **I)** Small outcrop of cross-bedded sandstone, Lyons, Michigan.

FIG. 3.—Photograph of Pewamo 1-08 core. Note that top of core is at top left, from a depth of 10 feet (3 m) below the surface, and that bottom of core is at lower right, from 92 feet (28 m) depth.

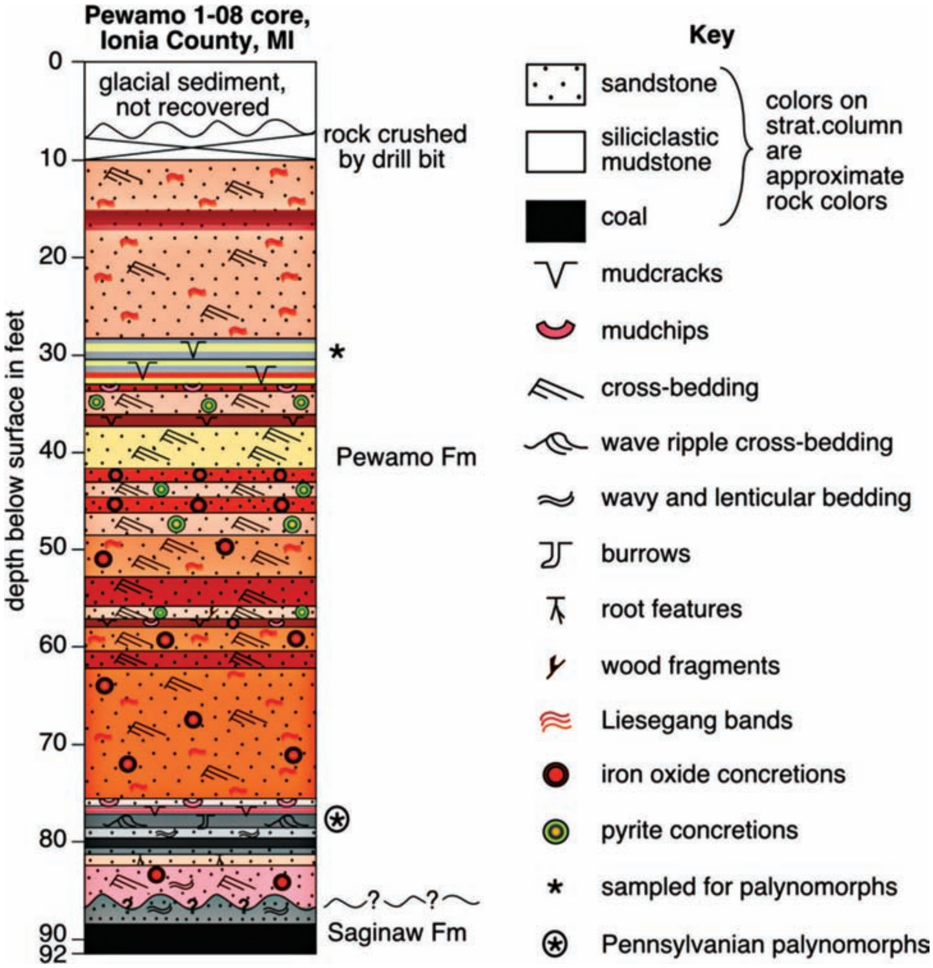


FIG. 4.—Stratigraphic column measured from Pewamo 1-08 core, Ionia County, Michigan.

The sandstones in the quarry walls and outcrops are moss- and lichen-covered, hindering investigations. In the field, medium beds of tabular and wedge, high-angle, tangential cross-bedding and low-angle planar cross-bedding can be distinguished (Fig. 2H, I). Hand samples and thin sections of rocks collected at the abandoned quarries are similar to the sandstone lithofacies in both the core and the building stones.

Building Stones

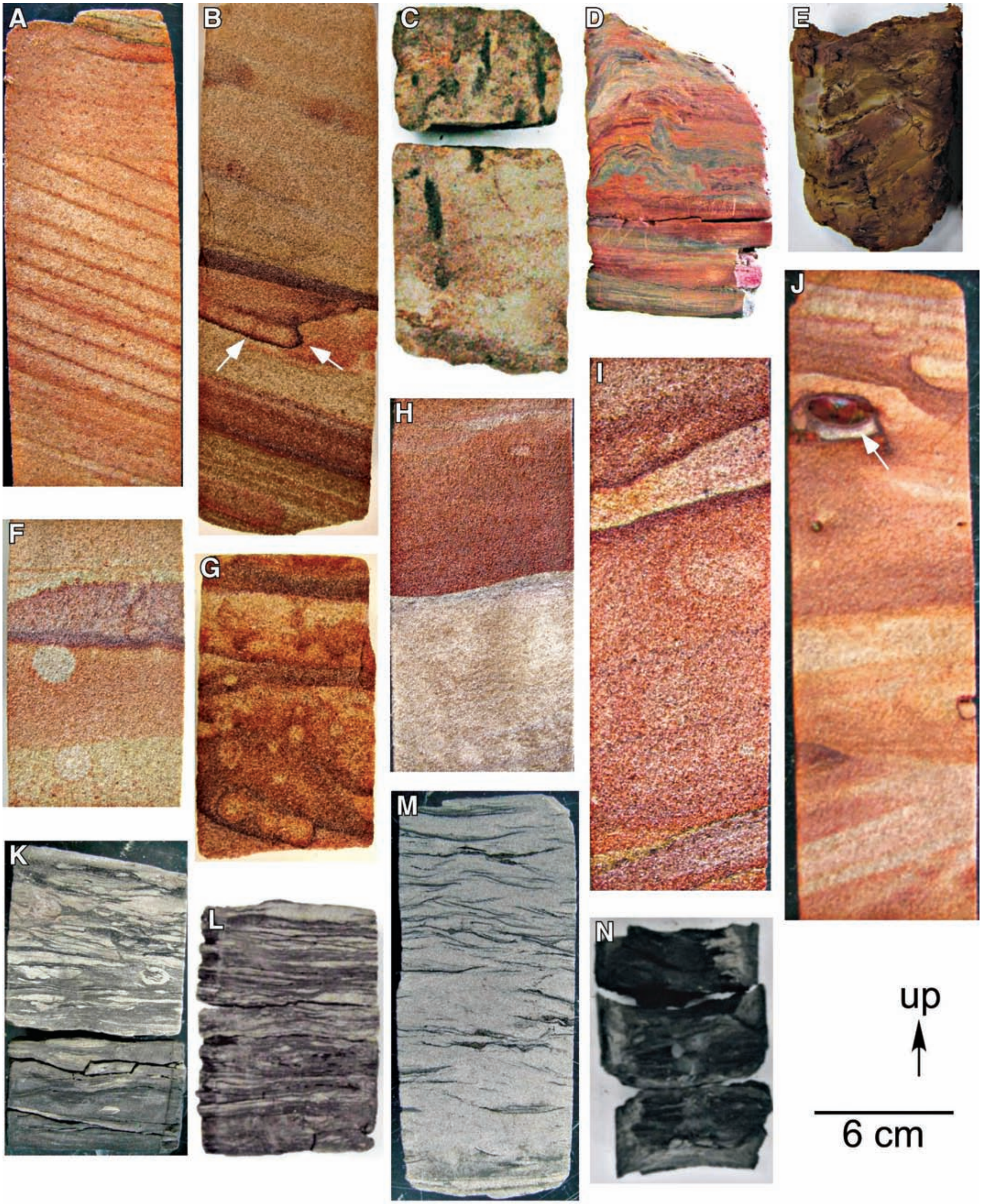
We have found building stones that appear to match the cross-bedded lithofacies of the Pewamo Formation in several cities and towns in the central Michigan region, including Ionia, Lyons, Pewamo, Muir, Plainwell, Lansing, Ludington, Grand Rapids, Owosso, Mt. Pleasant, Clare, Shepherd, and Midland (Fig. 2). The stones were used as primary building stones and as railroad trestles in towns closest to the Ionia County quarries from the late 1800s. They appear to have been used, during the 1950s, strictly as decorative facing stones in buildings at greater distances from the quarries. These dates match the main quarrying in the late 1800s and the renewed but short-lived quarrying in the 1950s. Pewamo Formation building stones seem to have been split along horizontal bedding planes. They form blocky and rectangular building stones that exhibit cross-sectional views perpendicular to bedding. Pewamo Formation building stones are distinctive in the Lower Peninsula of Michigan, where more commonly, other buildings of the same ages are composed of brick, wood, or glacial erratics.

Building stones show the same lithology and sedimentary structures as in the Pewamo 1-08 core, quarry walls, and outcrops, including well-sorted quartz sandstone, bimodal grain size distribution, inverse grading, high-angle cross-bedding, reactivation surfaces, and Leisegang bands (Fig. 2D, E, F).

Interpretations of the Pewamo 1-08 Core and Associated Rocks

Basic Core Interpretation.—We assign the black and gray shales and fine-grained sandstones at depths of 86 feet to the base of the core at 92 feet to the Pennsylvanian Saginaw Formation. These rocks match descriptions made by previous workers from outcrops in Grand Ledge, Michigan, and from cores elsewhere in Central Michigan (Dorr and Eschman 1970; Price and Velbel 2000; Veneable 2006; Venable and Barnes 2006). The Saginaw Formation likely represents deposition in marginal marine environments such as deltas and estuaries (Dorr and Eschman 1970;Venable and Barnes 2006). The sands and gravels above the Pewamo 1-08 core, from the surface down to 7 feet (2.1 m) depth, are likely Pleistocene glacial sediments.

We interpret the core rocks between 7 and 86 feet (2.1 to 26.2 m) depths as the newly defined Pewamo Formation. Although we retrieved no intact core from depths of 7 to 10 feet (2.1 to 3 m) it is likely also Pewamo Formation because the drillers tell us that they encountered bedrock there of the same drilling character as in the underlying Pewamo Formation. Our interpretation of this as a new lithostratigraphic unit is based upon its substantial differences in lithology and composition, color, sedimentary textures, sedimentary structures, fossils, and diagenetic features from the underlying Saginaw Formation and the overlying glacial sediments (Fig. 3, 5).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Assignment of the Pewamo rocks as a formation is supported by the discussion of new formations in the North America Stratigraphic Code (Jordan 2009; North American Commission of Stratigraphic Nomenclature 2005; Owen 2009). The name Pewamo is not currently used in the National Geologic Names Database, maintained by the U.S. Geological Survey (GEOLEX, http://ngmdb.usgs.gov/Geolex/). It is our intent that this paper provides the necessary information, such as geographic location, lithologic description, and historic background to support the naming of this new formation (Owen 2009).

Cross-Bedded Sandstone Lithofacies.—The high-angle cross-bedded sandstone lithofacies contains the distinguishing criteria of eolian dune deposits (i.e., Chan and Archer 2000; Cowan 1993; Hunter 1977; Kocurek 1996; Talbot 1985). The dominant monomineralogic, well-sorted quartz grains are relatively well rounded, have high sphericity, and are pitted and frosted, characteristics of many modern eolian sands. Bimodal grain-size distribution, inverse grading, pinstripe laminae, and high-angle cross-bedding are also criteria that support our eolian dune interpretation. In particular, much of the Pewamo's cross-bedded sandstone lithofacies likely represents grain-flow deposits formed as sand grains avalanched down dune slopes.

The less common low-angle cross-bedded sandstone, seen best in some quarry walls and building stones, is likely the result of deposition as eolian sand sheets. The sedimentary textures and mineralogy are the same as the high-angle cross-bedded sandstone. Only the cross-bedding characteristics differ between these two sandstone types.

Siliciclastic Mudstone Lithofacies.—The siliciclastic mudstones are interpreted as ephemeral interdune lake deposits. The deeper gray mudstone, at 76 feet, 10 inches (23.44 m) to 78 feet (23.77 m) depth, was likely deposited in a shallow freshwater lake, as evidenced by its thin laminations, fine grain size, abundant kerogen, and association with fine root features. Mudcracks suggest episodic desiccation of the lake. The three identified spores from this unit suggest a Pennsylvanian age (Palynodata and White 2008; M. Zobaa, personal communication). *Lycospora pellucida* is known mostly from Pennsylvanian rocks, except for one Cretaceous rock from Montana. *Granulatisporites granularis* and *Calamospora hartungiana* are exclusively found in Pennsylvanian strata. With the exception of the shared occurrence of the spore *Calamospora hartungiana*, the Pewamo mudstones contain a palynological assemblage different from that in the Saginaw Formation (Venkatachala and Salujha 1971).

The pale gray, pink, and orange-yellow mudstone found at 29 feet, 2 inches (8.89 m) to 29 feet, 8 inches (9.07 m) depth in the core is likely another ephemeral interdune lake deposit. However, its unusual mineralogy and less abundant organic matter suggest the possible influence of saline waters. The randomly-oriented gypsum needle crystals indicate displacive mineral growth from a Ca- and SO_4-rich groundwater when the host sediment was still unlithified. The unusual minerals nontronite and fluorapatite have been documented elsewhere in a variety of settings, including hydrothermal springs (not a favored interpretation here) and saline waters such as the Red Sea (Velde 1995). Therefore, we interpret this pale gray, pink, and orange-yellow mudstone as having been deposited in an ephemeral saline lake, suggesting a possible drier climate compared to an earlier wetter climate during the time of deposition of the dark gray mudstone at 76 feet, 10 inches (23.44 m) to 78 feet (23.77 m) depth.

The sedimentary characteristics of the quarry walls, outcrops, building stones, and the Pewamo Formation in the Pewamo 1-08 core are all quite similar. As a group, they are distinctively different than the outcrop and core samples reported from the Saginaw and Grand River formations (Price and Velbel 2000; Shideler 1969). This suggests that the building stones did indeed come from these quarries and outcrops. More importantly, it substantiates that these red sandstones, described here as the Pewamo Formation, are a new, previously undescribed formation that is indeed different than the red core cuttings mapped by Cohee (1965) and examined by Shaffer (1969).

Age and Temporal Trends.—The age of the Pewamo Formation is constrained by its relationship to the underlying Saginaw Formation and the three spore identifications in the Pewamo. Two of the three spore species have been reported only from the Pennsylvanian. The Saginaw Formation is considered Atokan (early Middle Pennsylvanian) in age, based upon conodonts in an intercalated marine limestone (Landing and Wardlaw 1981). Therefore, we conclude that the Pewamo Formation is late Middle–Late Pennsylvanian.

The Pewamo 1-08 core changes in lithology upward, from marginal marine–deltaic gray siliciclastics of the Saginaw Formation to continental red sediments (the Pewamo Formation), suggesting a small marine regression. In addition, although the Pewamo Formation was deposited predominantly by eolian processes, it contains evidence of freshwater interdune lakes near its base and interdune saline lakes and groundwaters stratigraphically higher. There may have been a drying trend in climate during Pewamo time, as suggested by earlier fresh water and later saline water.

HAYBRIDGE STRATA

Results

Basic Field Description.—The east-central region of the Lower Peninsula of Michigan (Allegan, Bay, Midland, Saginaw, and Shiawassee counties) was home to shallow underground coal mining from the 1880s to the 1940s. Since then, most of these mines have been filled with concrete to prevent collapse of the overlying farmland and federal and state conservation land. Piles of mine spoils containing red shale, red sandstone, rare pale gray shale, and coal remain at the surface (Fig. 9). Local farmers pick red shale and sandstone containing macroscopic plant fossils from their crop fields each spring.

A hub of this coal mining from 1860 to 1949 was near St. Charles, Michigan (in Shiawassee County, just southwest of Saginaw; Fig. 1), where the 4.5-foot-thick (1.4 m-thick) main coal seam was at a depth of ~ 70 meters. A historic bridge built originally for carrying wagonloads of hay is situated here on the border between the Shiawassee River State Game Area and the Shiawassee Federal Wildlife Refuge. Because this hay bridge is a local landmark, we have chosen to call the rocks here the "Haybridge strata." The Haybridge strata consists of at least four lithologies: coal, rare gray shale, red shale, and red sandstone (Figs. 9, 10).

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FIG. 5.—Pewamo Formation (A to J) and Saginaw Formation (K to N) unpolished slabs from Pewamo 1-08 core, Ionia County, Michigan. **A)** Pin-stripe cross-bedding in red sandstone. **B)** Reactivation surface (arrows) in cross-bedded red sandstone. **C)** Vertical dark root features in sandstone. **D)** Laminated and mudcracked siliciclastic siltstone. **E)** Laminated gray siliciclastic mudstone. **F)** Red sandstone with various amounts of hematite cement and pale reduction spots. **G)** Red sandstone with reduction spots possibly following burrows. **H)** White reduced sandstone below red sandstone. **I)** Leisegang bands in sandstone. **J)** Leisegang bands and partially plucked hematite concretion (arrow). **K)** Lenticular- and wavy-bedded gray siliciclastic mudstone and fine sandstone with some soft-sediment deformation. **L)** Lenticular-bedded gray siliciclastic mudstone and fine sandstone. **M)** Gray sandstone with flaser bedding. **N)** Coal.

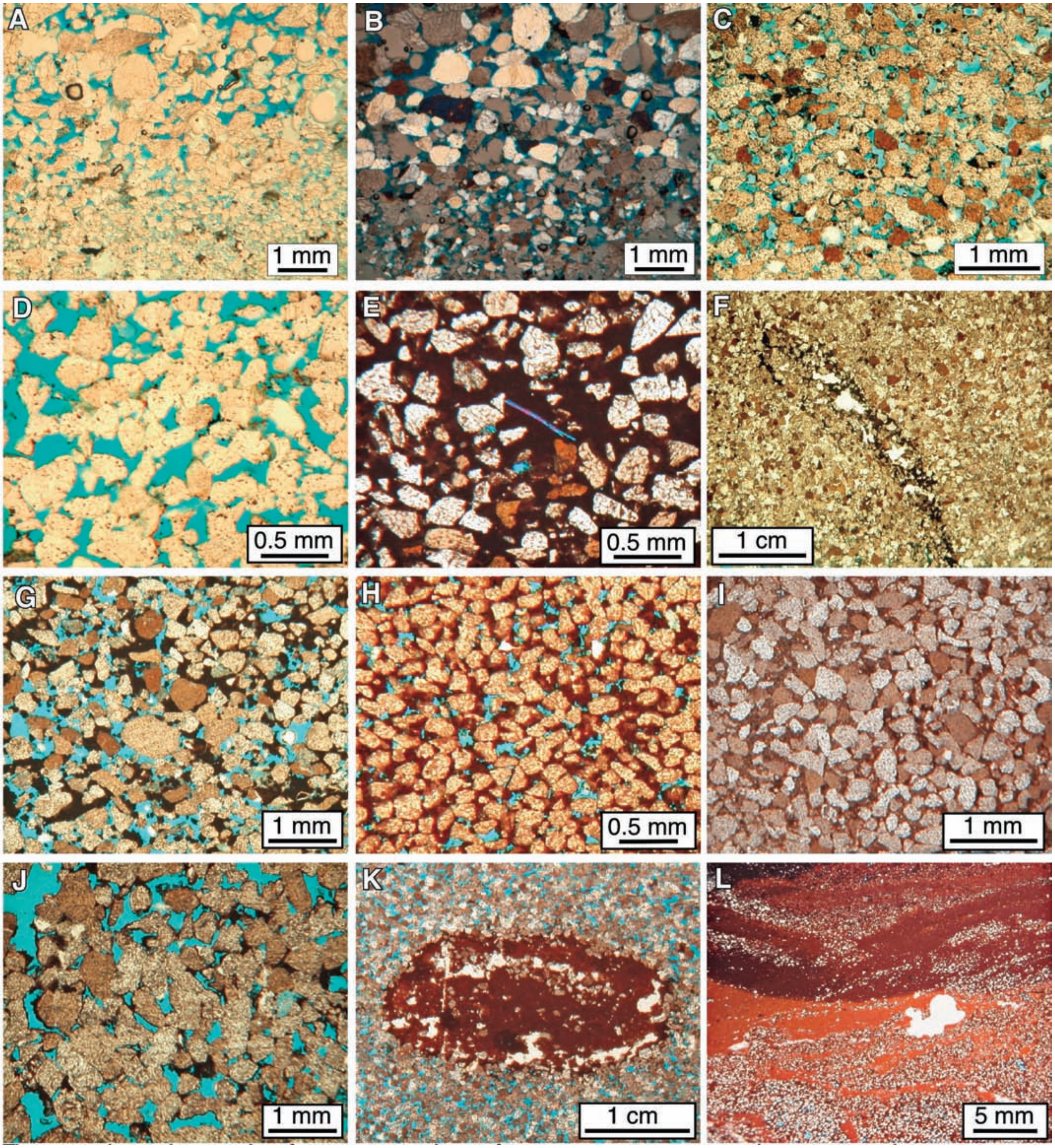


FIG. 6.—Photomicrographs of Pewamo Formation from Pewamo 1-08 core and outcrops, Ionia County, Michigan. **A)** Quartz sandstone with bimodal grain size distribution; 50 feet (15.2 m) depth; plane transmitted light. **B)** Quartz sandstone with bimodal grain size distribution; surface sample; partial polars. **C)** Quartz sandstone with some black organics (upper left); 80 feet, 6 inches (24.5 m) depth; combined partial polars and reflected light. **D)** Quartz sandstone with high porosity and little hematite cement; 38 feet, 6 inches (11.7 m) depth; plane transmitted light. **E)** Quartz sandstone with rare mica grain (blue, center) and abundant intergranular hematite cement; 60 feet, 6 inches (18.4 m) depth; combined partial polars and reflected light. **F)** Root mold lined with black organic matter in quartz sandstone; 80 feet, 10 inches (24.7 m) depth; partial polars. **G)** Quartz sandstone with bimodal grain size distribution and patchy distribution of intergranular hematite cement; 12 feet, 8 inches (3.9 m) depth; combined partial polars and reflected light. **H)** Quartz sandstone with intergranular hematite cement; 60 feet, 7 inches (18.5 m) depth; combined partial polars and reflected light. **I)** Quartz sandstone with almost all pore space filled with intergranular hematite cement; 80 feet (24.4 m) depth; combined partial polars and reflected light. **J)** Meniscus and pendant hematite cement in quartz sandstone 18 feet, 8 inches (5.7 m) depth; combined patia polars and reflected light. **K)** Hematite concretion in quartz sandstone; 57 feet, 6 inch (17.5 m) depth; combined partial polars and reflected light. **L)** Leisegang bands made by varying amounts of hematite cement; white hole in center is suspect root cast; 63 feet (19.2 m) depth; combined plane transmitted and reflected light.

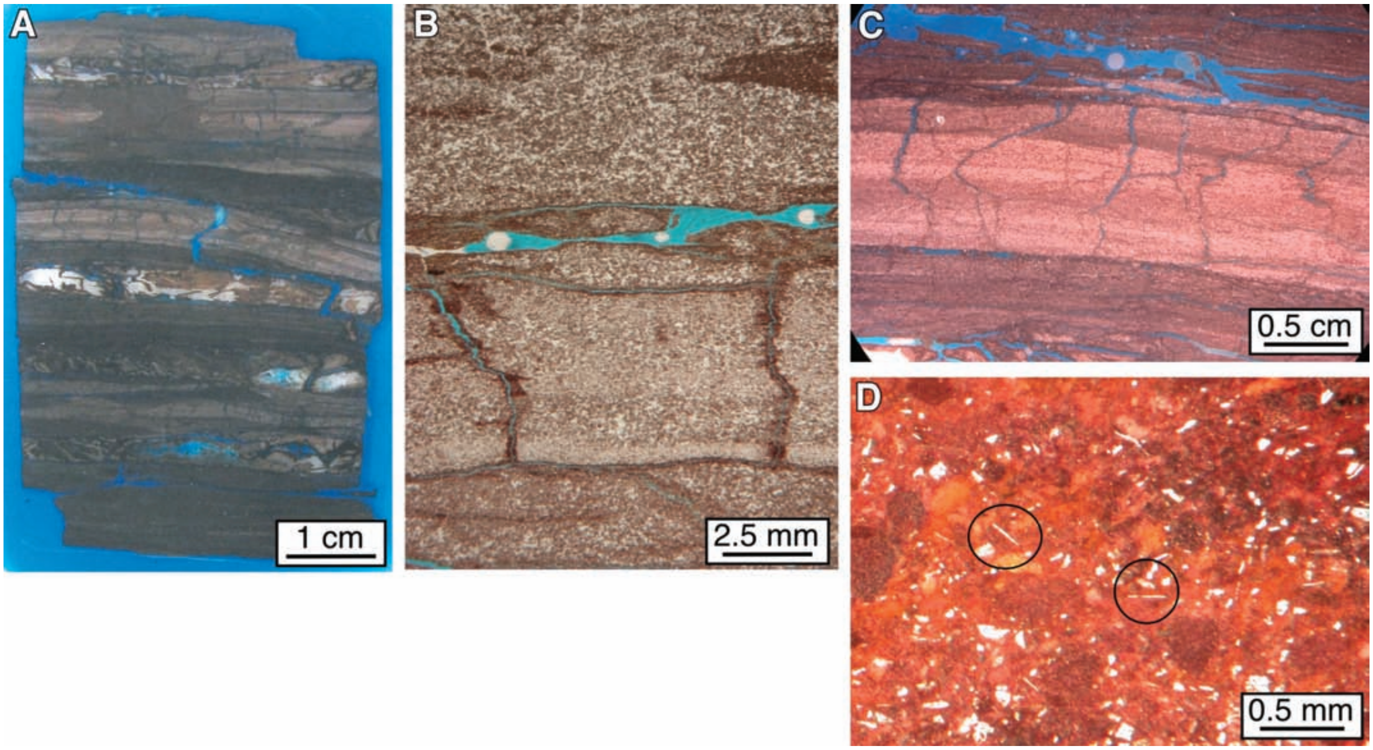


FIG. 7.—Photographs of siliciclastic mudstones in the Pewamo Formation; all oriented up. A to B, gray mudstone. C to D, pink mudstone. **A)** Large-format thin-section view of laminations and mudcracks. Blue is epoxy; white is space where epoxy was plucked during thin-section preparation. **B)** Vertically mudcracked laminae overlain by laminae with abundant root casts. **C)** Mudcracked thin lamina. **D)** Mudstone composed of dark red and orange peloid-like hematite mud clumps and mud, white quartz silt grains, and displacive gypsum needle-shaped crystals (in circles).

Lithofacies Descriptions

Coal Lithofacies.—The coal is a bituminous-grade, sulfur-poor, low-ash, black coal. It is found uncommonly in the mine piles as blocks up the 10 centimeters thick and 24 centimeters long. Palynological analysis yielded abundant amorphous organic matter but no identifiable pollen or spores.

The coal contains a few fragments of plant fossils preserved as compressions. These plant fossils seem to represent the same plant-fossil assemblage that we describe herein from the three other lithofacies of the Haybridge strata. The coal is closely associated with the red sandstone and shale. Both red lithologies contain coal within root features.

Gray Shale Lithofacies.—The gray shale of the Haybridge strata is rare. It is composed of quartz, K-feldspar, illite, muscovite mica, kaolinite, and chlorite. The grains are of clay size and cannot be distinguished by optical microscope petrography. The shale is massive, with some mudcracks. It has only rare plant fossils, mostly preserved as compressions, and some root features. Palynological analyses yielded abundant amorphous organic matter and wood.

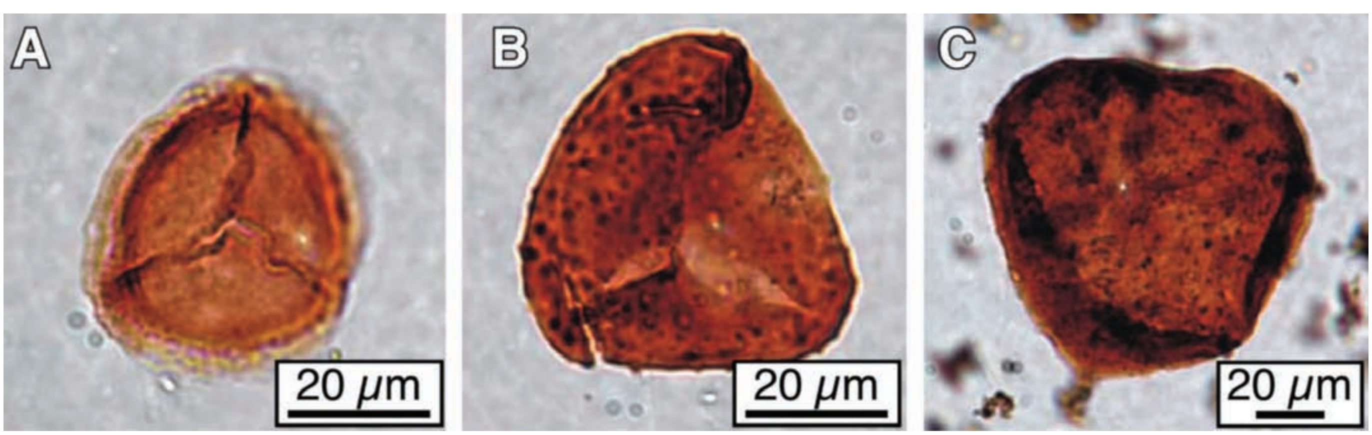


FIG. 8.—Photomicrographs of palynomorphs extracted from gray mudstone of Pewamo Formation, 78 feet (23.8 m) depth, Pewamo 1-08 core. **A)** *Lycospora pellucida*. **B)** *Granulatisporites granularis*. **C)** Suspect *Calamospora hartungiana*. Photomicrographs and identification by Mohamed K. Zobaa.

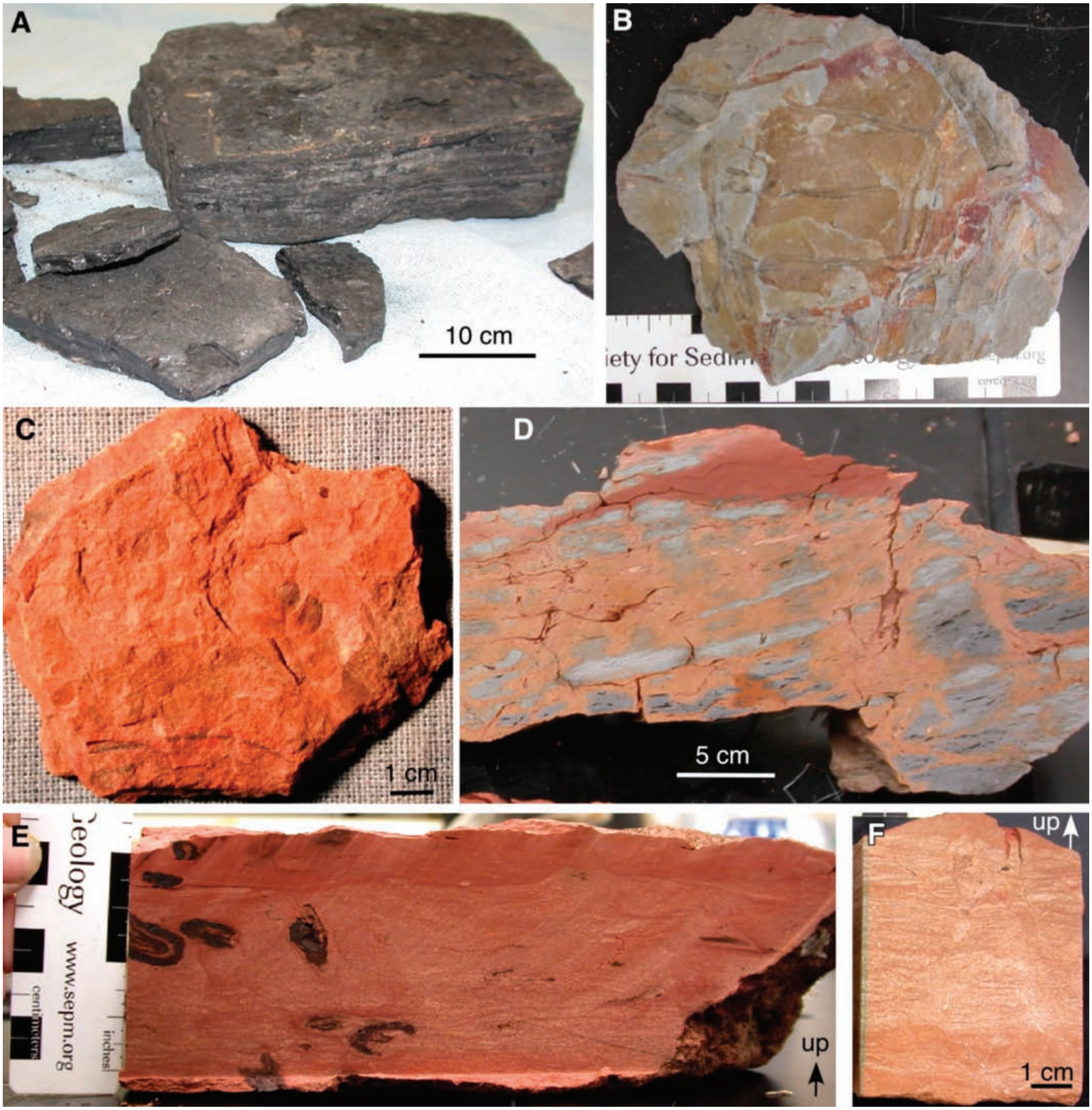


FIG. 9.—Photographs of hand samples representing the lithologies of the Haybridge strata. **A)** Bituminous coal. **B)** Rare gray shale. Bedding-plane view with plant fossil. **C)** Bedding-plane view of fossiliferous red shale. **D)** Cross-sectional view of fine red sandstone with silver-gray mullite patches. **E)** Cross-sectional view of fine red sandstone with wavy laminae, cross-laminae, and rhizoliths. **F)** Cross-sectional view of fine red sandstone with wavy laminae truncated by root features and burrows.

Red Shale Lithofacies.—The red shale is the most abundant lithofacies found in the mine piles and in the farm fields up to several kilometers away from the mile piles. It is fissile and is composed of quartz, muscovite mica, K-feldspar, illite, hematite, and rare calcite. The grains are mostly of silt-size, are moderately sorted, and are moderately to highly spherical but highly angular. Inorganic sedimentary structures include thin and thick laminae, climbing-ripple cross-lamina, vertical, horizontal, crazed plane cracks, circumgranular cracks, and autoclastic breccia (e.g., Freytet 1973; Goldstein 1988), and raindrop impressions. Root molds and burrows are abundant. The red shale contains abundant plant-fossil impressions, some rare carbon plant imprints, some coarse sand- and pebble-size fragments of organic material, and amorphous organic matter.

Red Sandstone Lithofacies.—Red sandstone is abundant in the mine piles and in the farm fields up to several kilometers away from the mile

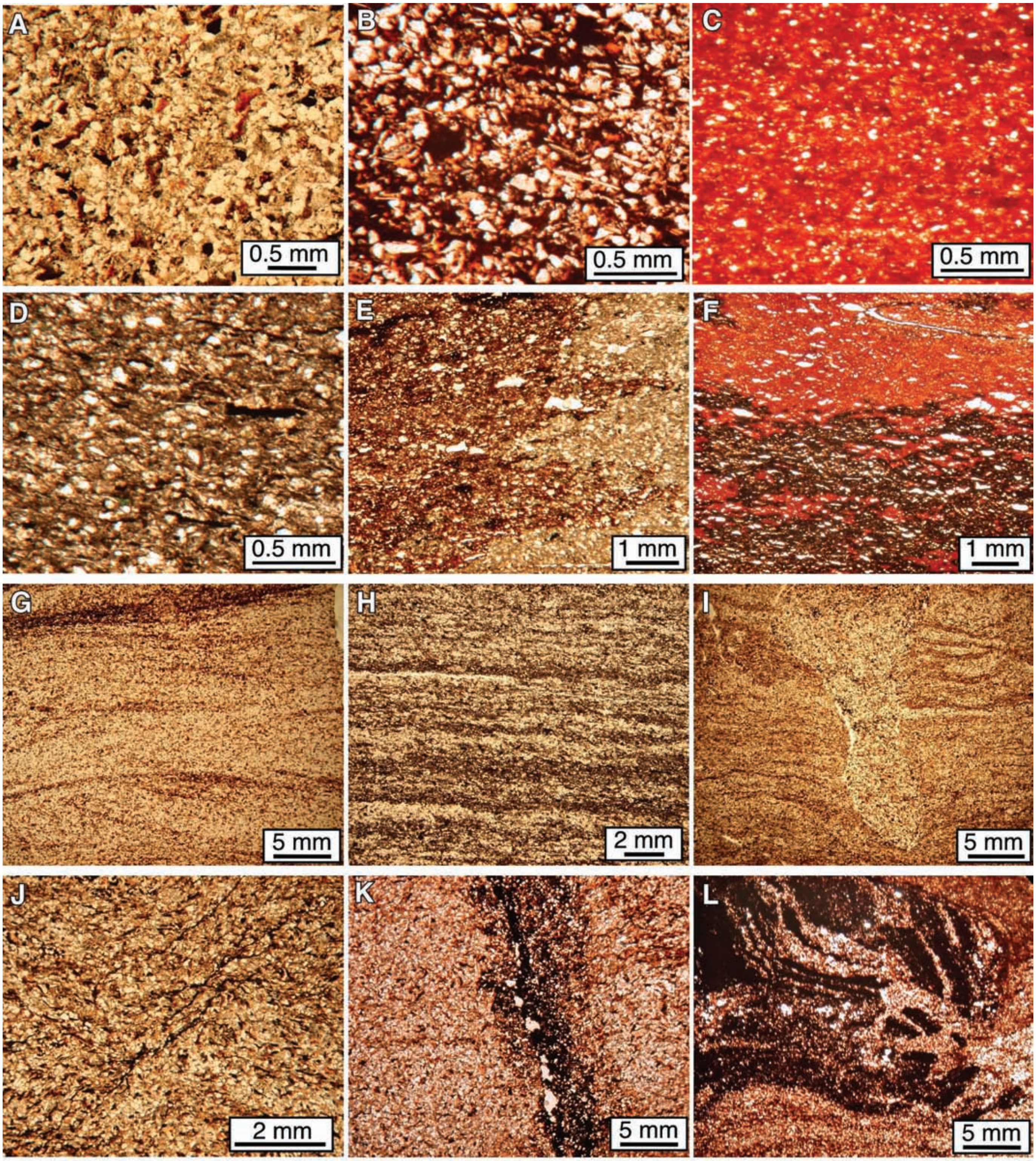
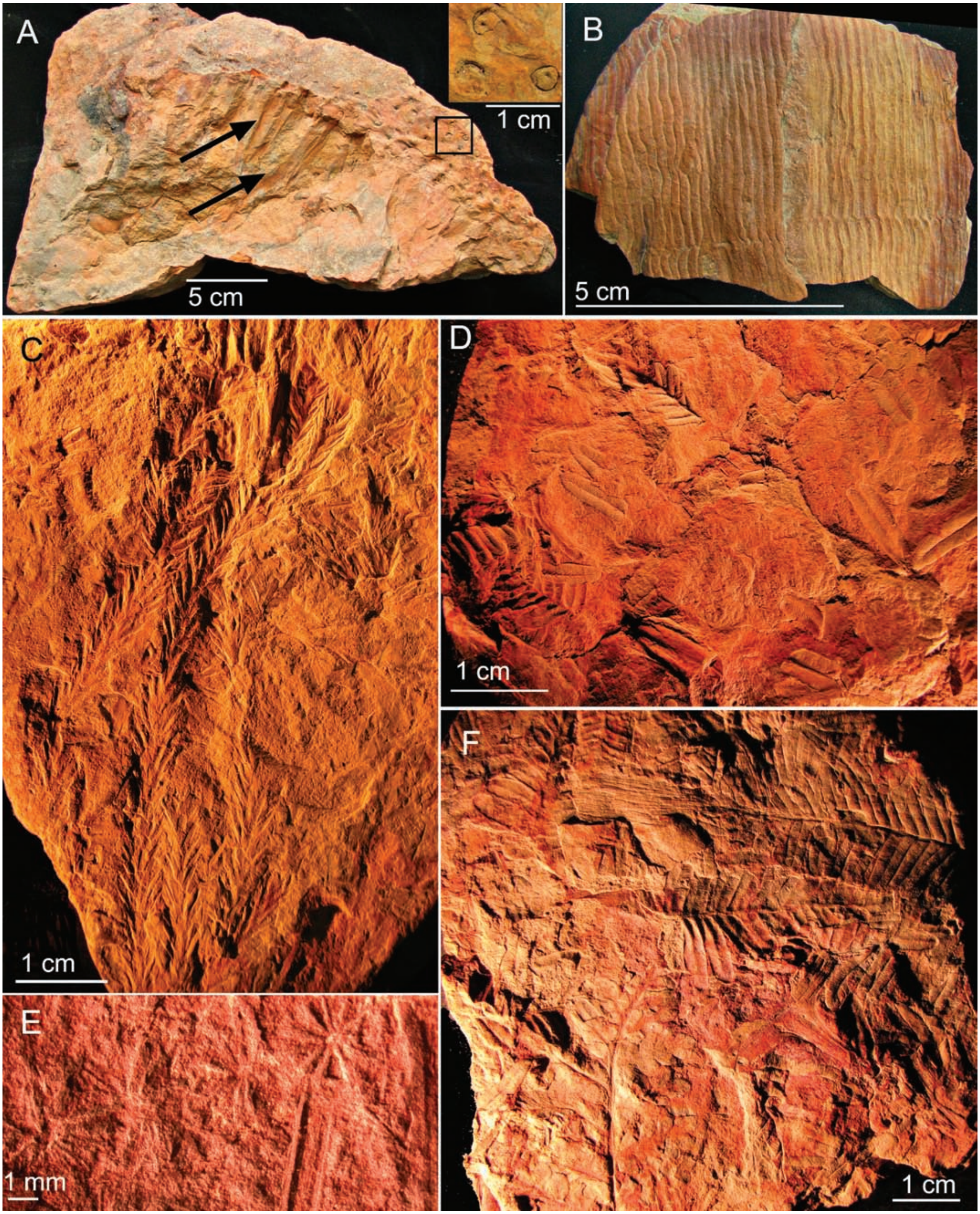


FIG. 10.—Photomicrographs of Haybridge rocks. **A**, **B)** Fine red sandstones. **C)** Red shale. **D)** Rare gray shale. **E)** Fine red sandstone with silver-gray mullite patches (on right). Note that white spots throughout the thin section view are root casts. **F)** Red shale with gray mullite patches (at bottom) and abundant root casts. **G)** Faint cross-lamination in fine red sandstone. **H)** Lamination in gray shale. **I)** Back-filled burrow in laminated fine red sandstone. **J)** Remains of thin, dark root hairs in gray shale. **K)** Root feature in fine red sandstone. **L)** Autoclastic breccia of red shale and red sandstone. All viewed with combined plane transmitted and reflected light.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piles. It is composed of quartz and K-feldspar, and less common muscovite mica grains. Intergranular hematite cement is ubiquitous. The grains are of fine to medium sand size, are moderately well sorted, have low to moderate sphericity, and are subangular to angular. Sedimentary structures include climbing-ripple cross-laminae and wave ripples. Bedding is commonly disrupted by vertical, horizontal, and crazed plane cracks and autoclastic breccia. Cracks are empty or are filled with slightly coarser-grained sand. There are some backfilled, rounded-bottom burrows. Some of the sandstones have preserved plant impressions and root casts of *Stigmaria* (form genus of tree lycopsids, including *Lepidodendron*) that have diameters and lengths up to 6 centimeters and 30 centimeters, respectively. Coal commonly is found in the shape of roots in this red sandstone.

Plant-Fossil Assemblage.—Plant fossils of the Haybridge strata were collected from the mine piles. Most are impressions in the red sandstone and shale, but the same fossil plants are also represented in lesser quantities in the coal and gray shale. Plant fossils occur but are poorly preserved impressions that represent four major plant groups: lycopsids, sphenopsids, seed ferns, and tree ferns. Lycopsid fossils include multiple ($>$ 10) specimens of *Stigmaria* root casts of various sizes, some with attached rootlets (Fig. 11A). Additional specimens contain impressions of detached rootlets. One rock has several lycopsid twigs with attached leaves (Fig. 11C). No lycopsid bark or leaf cushions have been found. The sphenopsids are represented by more than 10 stem impressions of *Calamites* (Fig. 11B) and a single poorly preserved specimen suggestive of a *Sphenophyllum* leaf whorl or *Annularia*, calamitalean foliage (Fig. 11E). In some rocks, numerous impressions of pinnules are preserved with random orientation and overlapping each other, suggesting parautochthonous preservation (Fig. 11D, F). Specimens include single pinnules and sections of intact pinnae (Figs. 12A, B, C, D). Venation is open dichotomous with only once or twice dichotomized lateral veins characteristic of Paleozoic tree ferns and pteridosperms. Positive identification is difficult due to the lack of detail. One specimen resembles the pteridosperm *Sphenopteris* (Fig. 12A). A large number of pinnules resemble *Pecopteris polymorpha*, a marattialean tree fern (Fig. 12B, D). They have a central midrib running the length of a more or less parallel-sided pinnule. Lateral veins branch at a low angle and are once or twice dichotomized. The pinnules are broadly attached (Fig. 12D). Other specimens that resemble *Mariopteris or Pseudomariopteris* have pinnules with decurrent, confluent bases and a midrib that extends to the tip. Lateral veins fork at least once (Fig. 12C). In a third pinnule type (Fig. 12F), the midrib is prominent only through one half of the pinnule, at which point widely spaced laterals fork into fine dichotomizing veins that arch towards the margin. The vein pattern and pinnule shape suggest *Neuropteris*. In addition to pteridosperm pinnules, there were also two specimens of *Aulacotheca*, a medullosean pteridopserm pollen organ (Fig. 12E).

Unusual Mullite Diagenesis.—Some red sandstones and red shales of the Haybridge strata have unusual silvery slag-like patches (Fig. 9D). In some cases, the silver patches clearly take the shape of roots. They give some of the rocks the appearance of a conglomerate, as if silver pebbles are hosted by finer-grained red sediment. However, close examination shows that the silver coloration crosscuts depositional textures in the sandstones and shales (Fig. 10E, F). The silver coloration also crosscuts hematite cements. XRD analysis indicates that the mineral mullite ($Al_6Si_2O_{13}$; also known as porcelanite) is unique to the silver areas of the rocks.

Interpretations of the Haybridge Strata

Haybridge Stratigraphic Resolution.—We found no outcrops of the Haybridge strata. However, we have found red-bed sandstones and shales are closely associated with coals for which depths are known from mining records. Mine dumps composed of all four Haybridge lithologies (coal, gray shale, red shale, and red sandstone) strongly suggest that these four lithologies are stratigraphically related. Coal fragments found within the red sandstone is further evidence of a stratigraphic association between coal and red beds. Local farmers report that they must clear their agricultural fields of plant-fossil-rich red shales and sandstones each spring. This suggests that the Haybridge strata was *in situ* less than $\sim$ 70 m, and in places less than $\sim$ 10 m, below the present surface. However, coal mining may have removed much of the Haybridge in the St. Charles, Michigan, area.

We propose that the Haybridge rocks be grouped as a stratigraphic unit. Although there are four different lithologies, they are related in that: (1) they share the same fossil assemblage; (2) the three siliciclastic rocks have similar mineralogical and sedimentary characteristics; (3) some coal is found within the red sandstones, and vice versa; and (4) they represent laterally adjacent depositional environments. Mine records demonstrate the subsurface depths of these rocks, which are found together at the mine piles. However, because we have no outcrops and have not yet recovered the rocks in place from the subsurface, we cannot formally assign a formation name to them. Future goals for the study of the Haybridge rocks should include a shallow drilling program to attempt to confirm and constrain the *in situ* location of the strata.

Coal Lithofacies.—The black, sulfur-poor, low-ash, bituminous coal of the Haybridge strata may have formed in an inland, continental wetland setting, such as that in a fluvial floodplain setting. Low sulfur content is characteristic of inland coal environments, in contrast to the high sulfur content of marginal marine coals (McCabe and Shanley 1992). The Haybridge coal is different in character from coal of the older Saginaw Formation, which has high sulfur content and is rich in pyrite and iron oxide concretions.

Gray Shale Lithofacies.—The gray shale of the Haybridge strata gives few clues to its depositional environment. The fine grain size but angular grain shape and immature composition suggest that this sediment may not have undergone extensive chemical or physical weathering before being deposited. Transport may have been by streams or by wind. Deposition may have been in a low-energy water body such as an oxbow lake or a flood plain. Mudcracks suggest desiccation, and plant fossils, abundant organic matter, and wood suggest a continental setting.

Red Shale Lithofacies.—The red shale shows evidence of slightly more physical reworking than the rare gray shale. The grains are moderately to highly spherical, yet still are angular and compositionally immature. The thin and thick laminae suggest changes in sedimentation rate. Climbing-ripple cross-laminae suggest waning flow. Vertical, horizontal, crazed plane cracks and autoclastic breccia are evidence of wetting and drying of the sediment. Raindrop imprints, root features, and abundant plant fossils are all indicative of subaerial exposure. We interpret the red shale lithofacies as a floodplain deposit.

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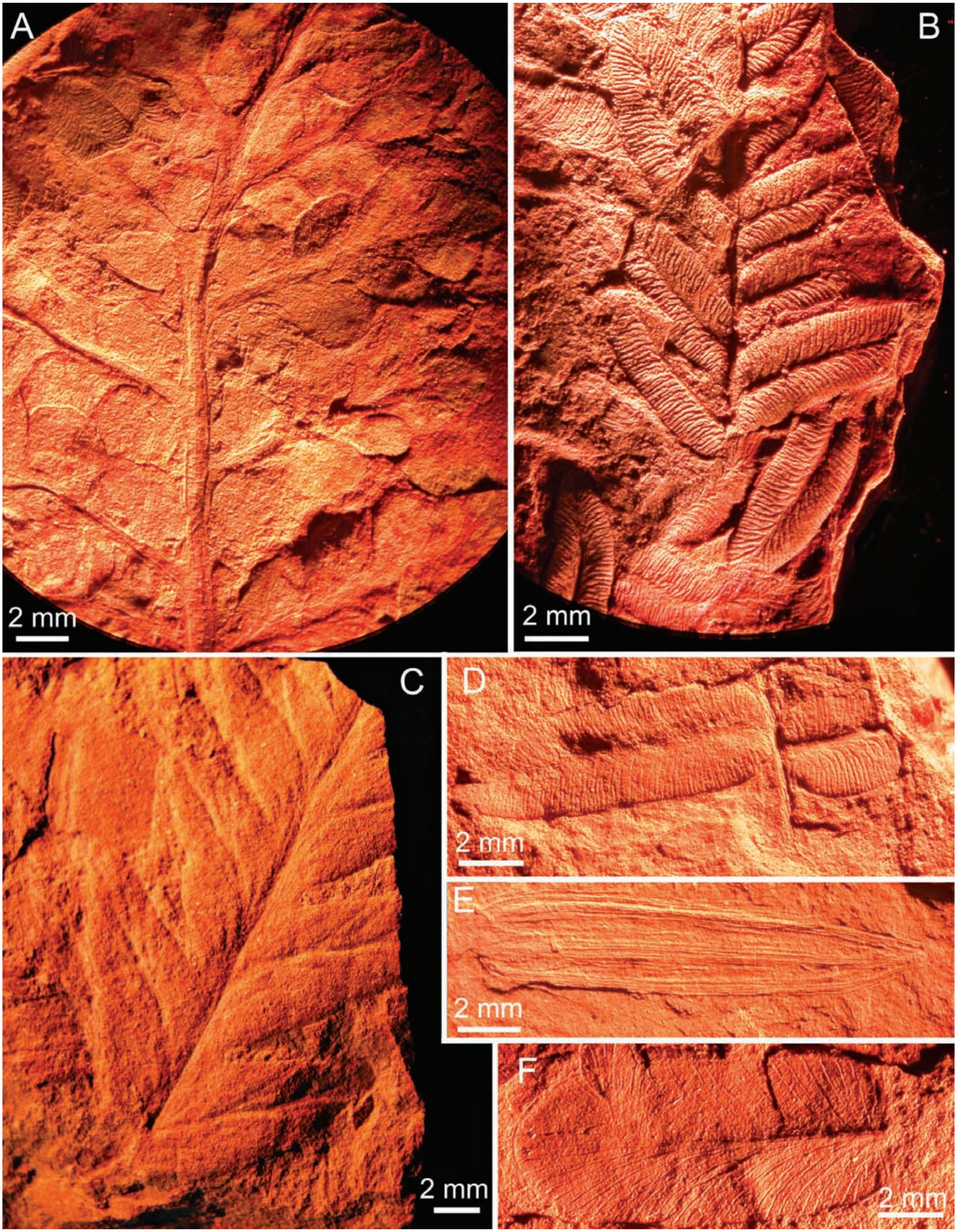
FIG. 11.—Photographs of plant fossils in Haybridge strata rocks. **A)** *Stigmaria* root cast with *in situ* rootlets (arrows) and rootlet scars (inset). CMUPC 1. **B)** *Calamites (possibly C. undulatus)* stem cast with part of two internodes. CMUPC 23. **C)** Branch or twig of lycopsid tree. CMUPC 35. **D)** Fossilized pinnules and pinnae of tree ferns and pteridosperms. CMUPC 145. **E)** Whorled leaves of sphenopsid. CMUPC 122. **F)** Fossilized pinnules and pinnae of tree ferns and pteridosperms. CMUPC 146.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Red Sandstone Lithofacies.—The red sandstone likely was deposited in an environment similar to and adjacent to that of the red shale setting. Current-ripple cross-bedding and climbing-ripple cross-laminae indicate shallow water deposition under a current and a waning current, respectively. Cracks, autoclastic breccia, root features, and plant fossils attest to soil formation after deposition. We interpret that the red sandstones in the Haybridge strata were deposited in channels or ephemeral channels that underwent pedogenesis.

Plant-Fossil Assemblage.—The plant-fossil assemblage indicates a Middle Pennsylvanian age for the Haybridge rocks. The plants are indicative of a flora before the major extinctions at the Middle to Late Pennsylvanian (Desmoinesian to Missourian or Westphalian to Stephanian) boundary because of the presence of arborescent lycopsids (Phillips et al. 1974). The assemblage resembles the Michigan coal-basin assemblage of Arnold (1949), although it is more limited in species diversity and is much less well preserved.

Unusual Mullite Diagenesis.—The unusual silvery slag-like patches composed of the mineral mullite ($Al_6Si_2O_{13}$) in some of the red shales and sandstones suggests thermal alteration. Mullite, nicknamed "porcelanite," forms when clay is fired in a kiln. Kaolinite alters to mullite at temperatures of ~ 1100°C (Martinon-Torres et al. 2006). In nature, mullite is rare, but it may form by coal fires. The crosscutting nature of the mullite in the red sandstones and shales indicates that it is a diagenetic feature. The presence of mullite in some root features suggests that organic matter burned to form the mullite. We interpret the mullite in the Haybridge rocks to be the product of fire. However, it is not known if the fire responsible was an ancient forest fire, a more recent underground coal fire, or a recent surface fire on the mine dumps.

Age and Temporal Trends.—The age of the Haybridge strata can be more narrowly defined than that of the Pewamo Formation. We deduce that the Haybridge strata are younger than the underlying early Middle Pennsylvanian (Atokan) Saginaw Formation (Landing and Wardlaw 1981). The presence of arborescent lycopsids that disappeared at the Desmoinesian to Missourian (Westphalian to Stephanian) boundary suggests the Haybridge strata dates to late Middle Pennsylvanian time.

DISCUSSION

Relationships of the Pewamo Formation and the Haybridge Strata to Each Other and to Other Strata of the Michigan Basin

Both the Pewamo Formation and the Haybridge strata are Pennsylvanian (Fig. 13). Evidence for this age is: (1) identification of two palynomorph species unique only to, and a third found almost exclusively in, Pennsylvanian strata in the Pewamo mudstones; and (2) a Pennsylvanian macrofossil plant assemblage in the four lithologies of the Haybridge strata. Furthermore, both the Pewamo Formation and the Haybridge strata lie above the early Middle Pennsylvanian Saginaw Formation. The Saginaw to Pewamo contact in the new Pewamo 1-08 core shows that the Pewamo Formation was deposited after the Saginaw Formation. Haybridge strata are more difficult to place in stratigraphic position because the only evidence of its *in situ* location is from coal-mine records that place it as deep as ~ 70 m in the vicinity of St. Charles, Michigan. However, several reasons lead us to place the Haybridge strata stratigraphically above the Saginaw Formation: (1) the Saginaw Formation and underlying strata are well known from cores from throughout central Michigan; (2) no red beds have been observed in or below the Saginaw Formation except possibly for the Proterozoic Jacobsville Sandstone, Freda Sandstone, and Copper Harbor Conglomerate, which crop out far to the north along Lake Superior and may be located thousands of meters below the Saginaw Formation in the Lower Peninsula. Instead, Mississippian carbonates are well documented stratigraphically below the Saginaw Formation (Dorr and Eschman 1970). No outcrops of the Saginaw Formation are known in the vicinity of the mine dumps, which contain the Haybridge rocks. The Saginaw Formation has been recorded in cores relatively nearby, at depths below the Haybridge strata coal mines (Venable 2006). We surmise that both the Pewamo Formation and the Haybridge strata are situated stratigraphically above the Saginaw Formation.

We also hypothesize that the Pewamo Formation and Haybridge strata lie above the Grand River Formation, although admittedly we have less evidence for this. The Grand River Formation is known from outcrops in Grand Ledge, Michigan. There, it clearly overlies the Saginaw Formation, forming the locally famous sandstone ledges along the Grand River for which the town is named. But the Grand River Formation was not observed in our Pewamo 1-08 core or in abandoned quarries or associated outcrops in Ionia, also along the Grand River. There are no reports of the Grand River Formation in other parts of central Michigan. Its interpretation as an early Middle Pennsylvanian fluvial deposit projects a ribbon-shaped geometry. This ribbon-shaped fluvial geometry of the deposit, plus subsequent erosion since the Pennsylvanian, explains the highly localized nature of the Grand River Formation. The Pewamo Formation and Haybridge strata may either be slightly younger than or age-equivalent to the Grand River Formation. Another complicating factor in deciphering the stratigraphic relationships among the Grand River and Pewamo formations and the Haybridge strata is that the Grand River Formation is not specifically dated. Regardless, the Pewamo Formation is late Middle to Late Pennsylvanian and the Haybridge strata is late Middle Pennsylvanian in age.

The stratigraphic relationship between the Haybridge strata and the Pewamo Formation is not known. We have observed the Pewamo Formation only in the vicinity of Ionia and Lyons, Michigan, on the southwestern side of the central Michigan area. We have observed the Haybridge strata directly only in the east-central part of the basin. Although both the Pewamo Formation and the Haybridge strata contain fossils that trace deposition to the Pennsylvanian, the wider range interpreted for the Pewamo Formation prevents distinguishing their relative ages.

The lithologic, paleontologic, and sedimentologic characteristics of the Pewamo Formation and Haybridge strata differ enough to consider them separate stratigraphic units. In addition, they are both distinctly different from the underlying Saginaw and the Grand River formations. The depositional settings of the Pewamo Formation and Haybridge strata, eolian desert system and vegetation-rich fluvial floodplain system, respectively, at first seem to contrast enough to suggest deposition at different times. The Pewamo Formation likely formed in a dry climate, while the Haybridge strata likely formed in a humid climate. However, both units may have been deposited during times of monsoonal climate, making it possible to have vegetation-poor dunes, and ephemeral lakes to the west and fluvial floodplains to the east. Although not a monsoonal climate, modern Michigan hosts both vegetation-poor eolian dunes and vegetation-rich fluvial environments within tens to hundreds of kilome-

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FIG. 12.—Photographs of fossil foliage from Haybridge strata. **A)** Higher magnification of *Sphenopteris*-like specimen in Figure 11F. CMUPC 146. **B)** Portion of *Pecopteris polymorpha* pinna. CMUPC 50. **C)** Portion of ?*Mariopteris* pinna. CMUPC 55c. **D)** Portion of *Pecopteris polymorpha* pinna showing attachment of pinnules. CMUPC 50. **E)** *Aulacotheca* pollen organ of medullosean pteridosperm. CMUPC 37. **F)** *Neuropteris* pinnule. CMUPC 31d.

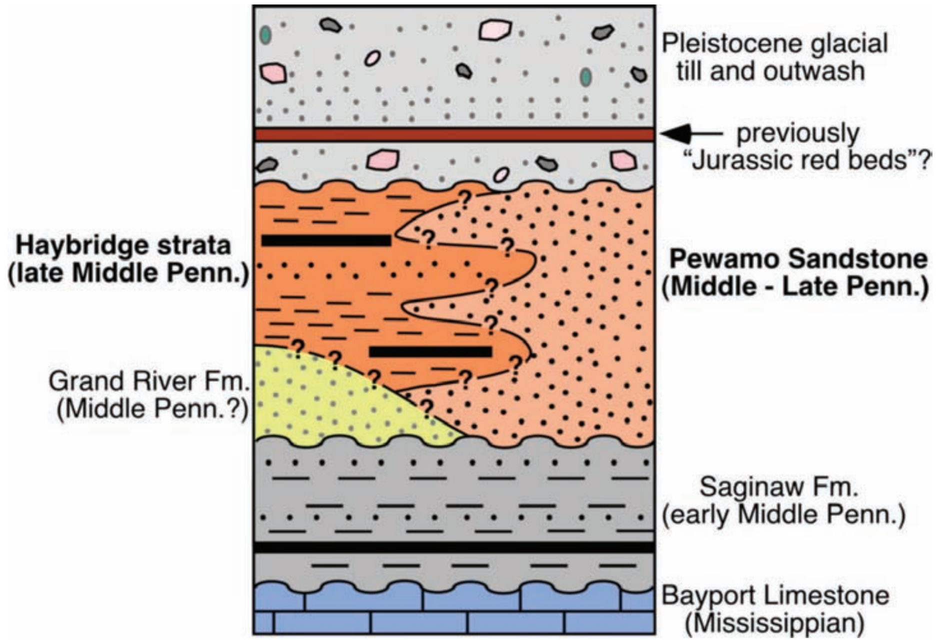

FIG. 13.—Working model for a revised stratigraphic column for the late Paleozoic to Cenozoic stratigraphy of the Michigan Basin. Actual thicknesses are not represented here. Question marks along the contacts amongst the Grand River Formation, the Haybridge strata, and the Pewamo Formation denote speculative stratigraphic relationships. Note the absence of any Jurassic rocks. Reddish-brown beds in the glacial deposits may be the "Jurassic red beds" mapped by Cohee (1965) and studied by Shaffer (1969).

ters from each other. Thus, the Pewamo Formation and Haybridge strata may be age-equivalent.

What about the "Jurassic Red Beds" of Michigan?

An informal stratigraphic unit in Michigan has come to be known as "Jurassic red beds" and "Ionia sandstone," with names used interchangeably even though the former term was originally applied to subsurface, fine-grained red beds and the latter term was used as a name for red sandstone building stones. The stratigraphy and sedimentology of these rocks have never been described in any peer-reviewed publication. We started our study with the assumption that the Pewamo Formation and Haybridge strata rocks were likely Jurassic. We have found no evidence of Jurassic age in these rocks, but instead have documented evidence for Pennsylvanian palynomorphs and macroscopic plant fossils. Detrital zircons from an Ionia building stone date from the Precambrian to the Devonian (Dickinson et al. 2010a), which is not inconsistent with our interpretation of Pennsylvanian deposition of the Pewamo Formation. We also examined old core cuttings of the red beds described by Shaffer (1969), as well as a recent core of red mud from 200 feet (61 m) below St. Louis, Michigan (~ 70 km north of Lansing). We have examined this mud in hand sample and petrographically and find that it does not correspond to either the Pewamo Formation or the Haybridge strata. This mud is unlithified and brown when fresh, but it lithifies and turns reddish-brown overnight due to oxidation. Its color is different from the more orange-red of the Pewamo Formation and Haybridge strata rocks. The mud contains lithic coarse sand grains, some identified as gneiss clasts, in a matrix of brown mud. The mud is massive and contains no sedimentary structures or macroscopic fossils. It is found in the subsurface on top of the bedrock, at the base of the unconsolidated sedimentary column. We have observed similar strata in glacial sediments at sand and gravel quarries throughout the central portion of the Lower Peninsula. We propose that it is likely a Pleistocene glacial deposit. Furthermore, we suspect that this sediment may in fact be the subsurface red beds mapped by Cohee (1965) and analyzed for palynomorphs by Shaffer (1969), the original "Jurassic red beds" of the Michigan Basin.

In summary, we found no evidence of Jurassic rocks, but we documented new red beds of Pennsylvanian age. Many old questions remain about the stratigraphy of the Michigan Basin. And many new questions should be posed, such as: What is the relationship between the Pewamo Formation and the Haybridge strata? What environmental and climate trends can be resolved from the Pewamo and Haybridge rocks? How might this new data for the Pennsylvanian of Michigan contribute to our understanding of global tectonic, environmental, and climate patterns? We recommend a systematic shallow coring program, followed by comprehensive sedimentological, paleontological, and geochronological study of the cores to resolve these questions. Such a study would undoubtedly contribute significant new data about the environments, life, and climate of the northeastern midcontinent.

Implications for Reassessment of Stratigraphic Problems in Michigan and Elsewhere

This study corrects a fundamental flaw in the previous understanding of the paleogeography and stratigraphy of a major intracratonic basin in North America. Previous interpretations of subsurface extent, age, and depositional environment were made from poorly constrained subsurface drill cuttings. At this time, any claim of Jurassic rocks from a fluvial environment (Dickinson et al. 2010a) in the Michigan Basin is highly questionable. Our work justifies the updating of the stratigraphic nomenclature and geologic map of Michigan, as well as North America. Our work also demonstrates a need to identify and reexamine Michigan and North American strata previously described without the benefit of outcrop and core, and to exercise caution and critical evaluation when interpretations of Earth history come from data obtained from drill cuttings.

Implications for Late Paleozoic Paleoenvironments and Paleoclimate

The new recognition of the Pewamo Formation and Haybridge strata adds to the understanding of past environments, life, and climate of the

Pennsylvanian of the Michigan Basin. Younger Pennsylvanian rocks in the Saginaw Formation represent marginal marine environments (Shideler 1969). We now know that diverse continental environments, including dunes, lakes, floodplains, and soils, existed later, showing that a marine regression occurred from the Saginaw to Pewamo–Haybridge time. In addition, there is now evidence to suggest paleoclimatic trends during the Pennsylvanian. These findings are consistent with other studies that have shown the late Paleozoic as a significant time of rapid change in environments, climate, and life (e.g., DiMichele et al. 2009; Montañez et al. 2007; Soreghan and Soreghan 2007; Soreghan et al. 2008a; Tabor and Montañez 2002). It also fits a new interpretation of the late Paleozoic ice age (e.g., Falcon-Lang and DiMichele 2010; Soreghan et al. 2008b; Sweet and Soreghan 2008). Future study of these two newly described formation-scale strata should include comparisons to age-equivalent red beds (e.g., Sweet and Soreghan 2008) and coals (e.g., DiMichele and Phillips 1996). Placing the new Michigan strata in such a context may allow a better understanding of spatial and temporal trends in environments, climates, and life of Pangea. The late Paleozoic, as a time of significant and rapid change, may be somewhat analogous to the modern and, thus, provide an enhanced understanding of the potential for future environmental changes in light of current global warming trends.

Implications for Reassessment of Stratigraphic Problems in Michigan and Elsewhere

This single shallow core (Pewamo 1-08 core) in one of the major intracratonic basins of North America adds the identification and first scientific descriptions of a formation and justifies the updating of the stratigraphic nomenclature of Michigan. A more extensive continental coring program may yield similar results for many other problematic stratigraphic units in other locales around the world. In addition, knowledge of shallow aquifers and seals in intracratonic basins is especially important now and in the near future for informed decisions to be made for CO_2 sequestration (Bachu 2003).

CONCLUSIONS

Two new formation-scale stratigraphic units of the Michigan Basin have been identified and described. The Pewamo Formation formed in a continental setting composed of eolian dunes, sand sheets, and ephemeral interdune lakes during the Middle to Late Pennsylvanian. Haybridge strata were deposited as coals, sands, and muds in a fluvial floodplain system, also during the late Middle Pennsylvanian.

The use of the "Jurassic red beds" in the Stratigraphic Lexicon of North America must be reconsidered. The new sedimentologic, paleontologic, mineralogic, chronologic, and stratigraphic data presented here, in combination with a shallow coring project in central Michigan, may serve as a foundation for future detailed studies of past life, past environments, and climate for the "missing time" of Michigan.

ACKNOWLEDGMENTS

Scott Oliver gave us the rock that led to this study. Lisa Boettcher, Bill Boggess, Brenda Beitler Bowen, Elliot Jagniecki, Mike Jury, Cynthia Knapp, Phil Knapp, and Dan Manke helped with field work. Larry Herron and the drillers of Sterns Drilling Company are thanked. Brenda Beitler Bowen conducted reflectance spectroscopy, and James Talbot of K/T Geoservices and John Attard of Attard's Minerals provided XRD analyses. Reed Wicander and Global Geosciences prepared samples for palynological analyses. Reed Wicander and Mohamed Zobaa made palynomorph interpretations. We thank Aureal Cross, Kathleen Pigg, Bernard Shaffer, Lynn Soreghan, Mike Soreghan, Ralph Taggert, and Tom Taylor for discussions. Editorial handling and reviews by editor Paul McCarthy and associate editor Mike Rygel, reviews by Mitch Blake and Bill DiMichele, and technical editing by John Southard are gratefully acknowledged. Funding includes a Jury Family Foundation award, a CMU Research Excellence Fund award to KCB and JMD, a CMU Summer Scholar's Award to JPK, and a CMU Undergraduate Research grant to JPK.

REFERENCES

Arnold, C.A., 1949, Fossil flora of the Michigan coal basin: Contributions from the Museum of Paleontology, University of Michigan, v. 79, no. 9, p. 131–269.

Bachu, S., 2003, Screening and ranking of sedimentary basins for sequestration of CO_2 in geological media in response to climate change: Environmental Geology, v. 44, p. 277–289.

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, e228 p.

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

Chan, M.A., and Archer, A.W., 2000, Cyclic eolian stratification in the Jurassic Navajo Sandstone, Zion National Park: periodicities and implications for paleoclimate, *in* Sprinkel, D.A., Chidsey, T.C, Jr, and Anderson, P.B., eds., Geology of Utah's Parks and Monuments: Utah Geological Association, Publication 28, p. 1–11.

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

Cohee, G.V., Burns, R.N., Brown, A., Brant, R.A., and Wright, D., 1950. Coal Resources of Michigan: U.S. Geological Survey, Circular 77, 56 p.

Cowan, G., 1993, Identification and significance of aeolian deposits within the dominantly fluvial Sherwood Sandstone Group of the East Irish Sea Basin, U.K., *in* North, C.P., and Prosser, D.J., eds., Characterization of Fluvial and Aeolian Reservoirs: Geological Society of London, Special Publication 73, p. 231–245.

Cross, A.T., 1975, Jurassic plants of the Michigan Basin: American Association of Petroleum Geologists, Annual Meeting, Program with Abstracts, 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: American Association of Petroleum Geologists, Annual Meeting, Program with Abstracts: New York, 5 p.

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

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

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.

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, e229 p.

DiMichele, W.A., and Phillips, T.L., 1996, Climate change, plant extinctions and vegetational recovery during the Middle–Late Pennsylvanian Transition: the case of tropical peat-forming environments in North America, *in* Hart, M.L., ed., Biotic Recovery from Mass Extinctions: Geological Society of London, Special Publication 102, p. 201–221.

DiMichele, W.A., Montañez, I.P., Poulsen, C.J., and Tabor, N.J., 2009, Climate and vegetational regime shifts in the late Paleozoic ice age earth: Geobiology, v. 7, p. 200–226.

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

Falcon-Lang, H.J., and DiMichele, W.A., 2010, What happened to the coal forests during Pennsylvanian glacial phases?: Palaios, v. 25, p. 611–617.

Freytet, P., 1973, Petrography and paleo-environment of continental carbonate deposits with particular reference to the Upper Cretaceous and Lower Eocene of Languedoc (southern France): Sedimentary Geology, v. 10, p. 25–60.

GEOLEX, National Geologic Names Lexicon Database, U.S.G.S.: http://ngmdb.usgs.gov/Geolex/

Goldstein, R.H., 1988, Paleosols of Late Pennsylvanian cyclic strata, New Mexico: Sedimentology, v. 35, p. 777–803.

Hunter, R.E., 1977, Basic types of stratification in small eolian dunes: Sedimentology, v. 24, p. 361–387.

Jordan, R.R., 2009, Layer by layer: an account of the North American Commission on Stratigraphic Nomenclature: Stratigraphy, v. 6, p. 170–182.

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: Journal of Geology, v. 41, p. 77–89.

Kelly, W.A., 1936, The Pennsylvanian system of Michigan: Michigan Geological Survey, Publication 40, v. 34, pt. 2, p. 155–219.

Kocurek, G., 1996, Desert aeolian systems, *in* Reading, H.G., ed., Sedimentary Environments; Processes, Facies and Stratigraphy, Third Edition: Oxford, England, Blackwell Science, p. 125–153.
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, v. VIII, Part II, 74 p.
Lane, A.C., 1908, Annual Report of the State Geologist: Michigan Geological Survey, Annual Report, p. 7–31.
Martinon-Torres, M., Rehreh, T., and Freestone, I.C., 2006, Mullite and the mystery of the Hessian wares: Nature, v. 444, p. 437–438.
McCabe, P.J., and Shanely, K.W., 1992, An organic control on shoreface stacking patterns—bogged down in the mire: Geology, v. 20, p. 741–744.
Michigan Department of Natural Resources homepage: (http://www.michigan.gov/deq/documents/deq-ogs-gimdl-GGBRG.pdf)
Montañez, I.P., Tabor, N.J., Niemeeier, D., Dimichele, W.A., Frank, T.D., Fielding, C.R., Isbell, J.L., Birgenheier, L.P., and Rygel, M.C., 2007, CO_2-forced climate and vegetation instability during late Paleozoic deglaciation: Science, v. 315, p. 87–91.
North American Commission on Stratigraphic Nomenclature (2005), North American Stratigraphic Code: American Association of Petroleum Geologists, Bulletin, v. 89, p. 1547–1591.
Owen, D.E., 2009, How to use stratigraphic nomenclatures in papers, illustrations, and talks: Stratigraphy, v. 6, p. 106–116.
The Paleobiology Database: http://www.paleodb.org/cgi-bin/bridge.pl
Palynodata, Inc. (2008), , and White, J.M., 2008. Palynodata datafile: 2006 version, with Introduction by White, J.M.: Geological Survey of Canada, Open-File 5793, 1 CD-ROM.
Phillips, T.L., Peppers, R.A., Avcin, M.J., and Laughnan, P.F., 1974, Fossil plants and coal: patterns of change in Pennsylvanian coal swamps of the Illinois Basin: Science, v. 184, p. 1367–1369.
Pocock, S.J., and Jansonius, J., 1961, The pollen genus *Classopollis* Pflug 1953: Micropaleontology, v. 7, p. 439–449.
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.
Shaffer, B.L., 1968, Palynology and geology of newly discovered Jurassic sediments in the Michigan Basin (abstract): Geological Society of America, Special Paper 115, p. 376–377.
Shaffer, B.L., 1969. Palynology of Michigan "red beds" [Unpublished Ph.D. dissertation]: Michigan State University: East Lansing, Michigan, 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., Soreghan, M.J., Poulsen, C.J., Young, R.A., Eble, C.F., Sweet, D.E., and Davogustto, O.C., 2008b, Anomalous cold in the Pangaean tropics: Geology, v. 36, p. 659–662.
Soreghan, M.J., and Soreghan, G.S., 2007, Whole-rock geochemistry of upper Paleozoic loessite, western Pangaea: implications for paleo-atmospheric circulation: Earth and Planetary Science Letters, v. 255, p. 117–132.
Soreghan, M.J., Soreghan, G.S., and Hamilton, M.A., 2008a, Glacial–interglacial shifts in atmospheric circulation of western tropical Pangaea: Palaeogeography, Palaeoclimatology, Palaeoecology, p. 260–272.
Sweet, D.E., and Soreghan, G.S., 2008, Polygonal cracking in coarse clastics records cold temperatures in the equatorial Fountain Formation (Pennsylvanian–Permian, Colorado): Palaeogeography, Palaeoclimatology, Palaeoecology, v. 268, p. 193–204.
Tabor, N.J., and Montañez, I.P., 2002, Shifts in late Paleozoic atmospheric circulation over western equatorial Pangaea: insights from pedogenic mineral $\delta^{18}O$ compositions: Geology, v. 30, p. 1127–1130.
Talbot, M.R., 1985, Major bounding surfaces in aeolian sandstones: a climatic model: Sedimentology, v. 32, p. 257–265.
Velbel, M.A., and Weber, J., 2009, Evidence for hundreds of meters of erosion during the early Middle Jurassic of Michigan (abstract): Geological Society of America, North-Central Section, 43rd, Annual Meeting, Abstracts with Programs, v. 41, 28 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.
Velde, B., 1995. Origin and Mineralogy of Clays: Clays and the Environment: Berlin, Springer-Verlag, 334 p.
Venable, N.B., 2006, Sedimentology and stratigraphy of the Pennsylvanian Saginaw Aquifer, central lower Michigan, U.S.A. [unpublished Master's thesis:] 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. (abstract): Geological Society of America, Abstracts with Programs, v. 38, 5 p.
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., Weaver, T.L., and Zacharias, K.F., 1994. Hydrogeology of Pleistocene glacial deposits and Jurassic "red beds" in the central Lower Peninsula of Michigan: U.S. Geological Survey, Water-Resources Investigations, Report 93–4152, 14 p.
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
Wilson, S.E., 2006, Generalized Bedrock Geology in Michigan Map: http://www.michigan.gov/documents/deq/ogs-gimdl-GTLH_geo_307674_7.pdf

Received 13 June 2010; accepted 21 February 2011.