

Unusual Sandstone Cylinders from the Lower Permian Glorieta Sandstone, Northern New Mexico

Spencer G. Lucas¹, William A. DiMichele², and Joseph M. Karnes³

¹ New Mexico Museum of Natural History and Science, 1801 Mountain Road NW, Albuquerque, NM 87104; spencer.lucas@dca.nm.gov

² Department of Paleobiology, Smithsonian Institution National Museum of Natural History, Washington, D.C. 20560; dimichel@si.edu

³ Joseph M. Karnes, P.O. Box 2980, Santa Fe, NM 87504; joseph@sommerkarnes.com

<https://doi.org/10.58799/NMG-v44n3.63>

Abstract

On Glorieta Mesa in San Miguel County, northern New Mexico, the lower Permian Glorieta Sandstone contains numerous sandstone cylinders from two areas and two stratigraphic intervals of interdunal sedimentary deposits in the lower part of the formation. Most of these cylinders are perpendicular to bedding, although some are slightly oblique to the layers of enclosing sediment. They range in diameter from 2.6 to 43 cm and are as much as 58 cm long. Most of the cylinders have smooth exteriors and, in cross section, have a structureless core surrounded by thin, concentric laminae. Some cylinders taper toward one end, which in situ specimens indicate is the lower end, and some are slightly curved. Some have one or more external grooves that demarcate a helical trajectory of flat to very slightly concave, slightly imbricated surfaces around the circumference of the exterior, sometimes with grooves spiraling in opposite directions. The lack of deformation of the sediment in and around the cylinders and the preservation of the external markings on some of the cylinders preclude their identification as inorganic dewatering structures or other forms of water conduits. Nevertheless, the concentric laminae of the cylinders are likely a diagenetic feature. The sandstone cylinders do not resemble any known cylindrical or plug-shaped trace fossils, and the lack of ornamentation (bioglyphs) on the cylinder walls is one of several reasons that preclude their identification as animal burrows. The most likely origin of these cylinders is as the fill of molds left by plant stems that were buried upright. However, the botanical affinity of these molds and casts is uncertain because they do not contain diagnostic features of anatomy or external morphology. By a process of elimination, the Glorieta sandstone cylinders are most likely to have been produced by woody calamitaleans.

Introduction

During part of early Permian time, a vast sand sea (erg) covered much of northern Arizona and northern and central New Mexico. In Arizona, the eolian sedimentary deposits of this erg are preserved as the Coconino Sandstone (e.g., McKee, 1933; Blakey and Knepp, 1989). Across the state line into New Mexico, this lithosome is called the Glorieta Sandstone (e.g., Baars, 1961; Lucas et al., 2013; Mack and Bauer, 2014; Krainer and Lucas, 2015). The Coconino Sandstone in Arizona contains diverse trace fossil assemblages, mostly trails and trackways made by arthropods and tetrapod vertebrates (primarily reptiles; e.g., Gilmore, 1926; Francischini et al., 2020; Marchetti et al., 2021; Miller et al., 2021). However, in New Mexico, no trace fossils have been reported from the Glorieta Sandstone, and the only known Glorieta fossils are (reworked) marine foraminiferans (Krainer et al., 2012).

Here, we document unusual sandstone-cylinder casts and cylindrical molds from the Glorieta Sandstone. We have identified these in the lower part of the Glorieta Sandstone in two areas on Glorieta Mesa in San Miguel County, New Mexico (Fig. 1). We evaluate these cylinders and molds to conclude that they are most likely the sandstone infilling of the axes of plants, rather than inorganically created structures or animal-made trace fossils. They are thus a new, unique fossil assemblage from

the New Mexico Permian. In this paper, NMMNH refers to the New Mexico Museum of Natural History and Science in Albuquerque, New Mexico.

Geological Context

The sandstone cylinders and molds described here were discovered by one of us (JK) on the top of Glorieta Mesa in two areas of mostly forested and soil-covered Glorieta Sandstone. In the first area, on a prong of Glorieta Mesa called Sacatosa Mesa, sandstone cylinders, but no molds, were identified at nine discrete localities, assigned locality numbers 12938 through 12946 by NMMNH (precise locality data are in the NMMNH database and available to qualified researchers; field views in Fig. 2). These localities extend over 3 km on strike in a generally north-south direction. In the Cañon de los Diegos drainage, about 7.25 km to the southwest, a mixture of molds and casts, including vertical profiles of in situ cylinders exposed on outcrop, were observed over a strike distance of approximately 100 m (NMMNH locality 13021; field views in Fig. 3).

In both areas of occurrence, the sandstone cylinders have the same lithologic composition as the enclosing rock, although there may be differences in cementation between the casts and the surrounding sediment. Thus, the casts are composed of sandstone

that is mostly medium grained, subangular quartz that is very pale orange (10 YR 8/2) to grayish orange (10 YR 7/4) and weathers pale yellowish brown (10 YR 6/2) to moderate brown (5 YR 4/4).

To establish the stratigraphic position of the cylinder localities on Sacatosa Mesa, we measured a stratigraphic section along the edge of the mesa near the localities (Fig. 1). This section extends from the basal contact of the Glorieta Sandstone on strata of the Yeso Group upward through the stratigraphic interval that includes the sandstone cylinders. Thus, the cylinders are in strata 29–30 m above the base of the Glorieta Sandstone. In the Cañon de los Diegos drainage, molds and the tops of cylinders are exposed in the floor of the canyon; along its lower walls, cylinders can be seen in situ in cross-sectional view (Figs. 3C and 3D). Here, based on the approximate elevation of the top and the base of the Glorieta Sandstone, the molds and cylinders are about 16 m above the base of the Glorieta. In the area of both cylinder localities, overall Glorieta Sandstone thickness is about 91 m (Read et al., 1944; Foster et al., 1972, fig. 4; Milner, 1978, fig. 6). Thus, we conclude that these two occurrences are not at the same level stratigraphically, and both are in the lower part of the Glorieta Sandstone.

Krainer and Lucas (2015) described the type section of the Glorieta Sandstone, which is about 32 km northwest of the Sacatosa Mesa cylinder localities. The Glorieta Sandstone at its type section is 51 m thick, and consists of dunal and interdunal facies according to Krainer and Lucas (2015). Dunal facies are characterized by large-scale cross-beds, whereas the interdunal facies, which involve some degree of deposition by water, are ripple laminated, horizontal laminated, massive, and/or bioturbated sandstones. We interpret the Glorieta Sandstone strata at Sacatosa Mesa and in the Cañon de los Diegos drainage similarly. Thus, the sandstone cylinders are in interdunal facies at different stratigraphic distances above the base of the Glorieta Sandstone (contact with the underlying Yeso Group). This suggests that other such occurrences may exist within the Glorieta. The current dense vegetation and soil cover and the remoteness of the localities that have been discovered thus far suggest that if there are occurrences at other levels, they more likely will be discovered by chance than by a systematic survey.

Like most eolianites, the Glorieta Sandstone consists of two broad facies: wind-deposited dunal and water-deposited interdunal (e.g., McKee, 1979; Ahlbrandt and Fryberger, 1981; Glennie, 1987). Sandstone beds with large-scale cross-beds are readily identified as dunal deposits. The other strata in our measured stratigraphic section—laminar, ripple laminar, and bioturbated sandstone—are identified by us as interdunal deposits (though note that some ripples in the Glorieta are wind ripples of eolian origin: Mack and Bauer, 2014; Krainer and Lucas, 2015). In the Sacatosa Mesa section, there are two interdunal intervals: (1) units 3–7, the basal approximately 7 m of the Glorieta Sandstone, and, above the succeeding 12 m of dunal sandstone, (2) an 8-m-thick interval of tabular and ripple-laminar sandstone capped by 3 m of bioturbated and laminar sandstone. The top of the Sacatosa Mesa section is another dunal sandstone. The sandstone cylinders described here come from the 3-m-thick interval of laminar and bioturbated sandstone near the top of the section (Fig. 1).

The molds and cylinders in the Cañon de los Diegos drainage occur in a 2-m-thick interval of thin-bedded, tabular sandstone that also is of interdunal origin. In this area, due to topography, it was possible to follow the bedding and determine that the cylinders occurred at multiple levels within the 2-m interval, with their bases at different levels determined from the initiation points of the tapered bases of some specimens (Figs. 3C and 3D).

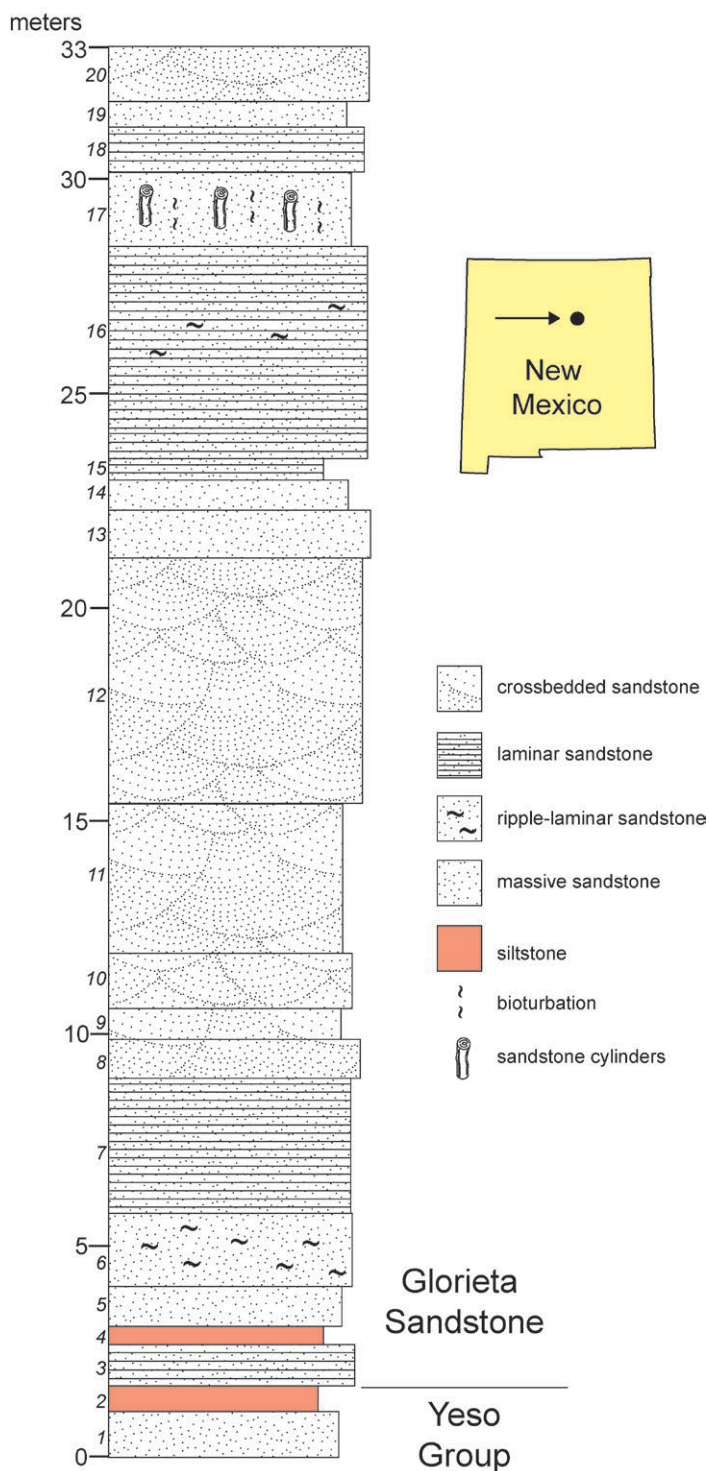
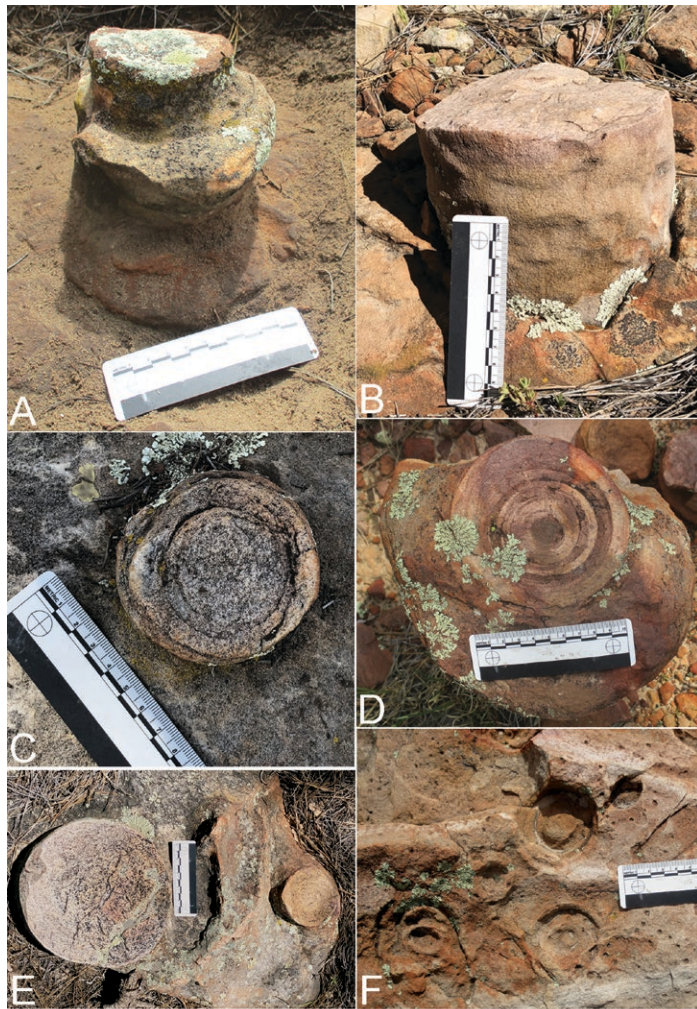


Figure 1. Location map and stratigraphic section of part of the Glorieta Sandstone at the Sacatosa Mesa sandstone cylinder localities.

The Glorieta Sandstone is assigned a late early Permian (late Leonardian, Kungurian) age. Thus, it is bracketed by strata of well-established Leonardian age: the Yeso Group below and the San Andres Formation above (e.g., Lucas et al., 2013, 2022).

Description

We identify three kinds of cylinders from the Glorieta Sandstone: (1) small cylinders with a tapered base, (2) medium-sized cylinders that lack external ornamentation (are smooth externally), and (3) medium and large cylinders with external ornamentation. In Cañon de los Diegos, *in situ* cylinders demonstrate that the smaller ends of the cylinders are the lower ends, and they gradually expand in diameter upward to their top ends, which have a flat to convex terminus (Figs. 3C and 3D). These cylinders are from 27 to 58 cm long, have lower diameters of about 8.9 cm, and widen to upper diameters of about 9.8 cm. Also at Cañon de los Diegos are shallow (4–5 cm deep), subcircular molds where parts of cylinders have eroded away (Fig. 3A).

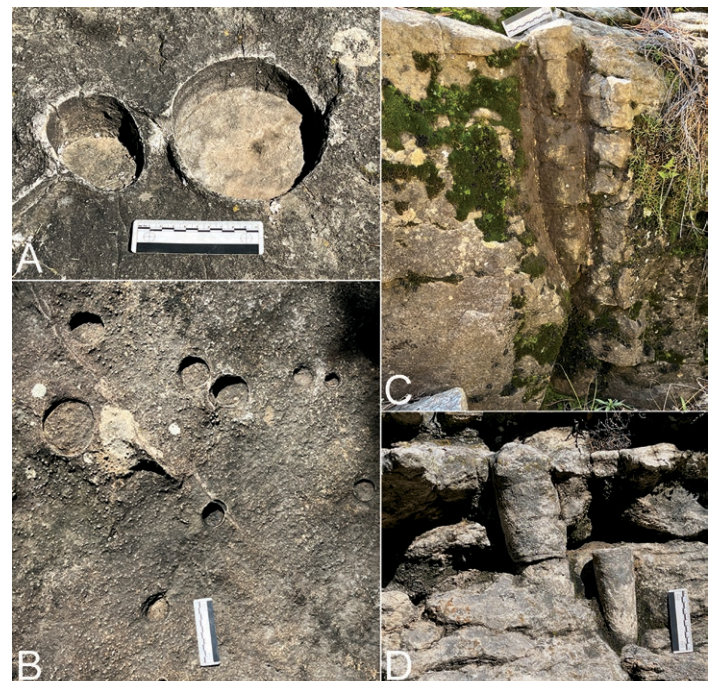


Figures 2A–2F. Outcrop photos of selected sandstone cylinders in the Glorieta Sandstone at Sacatosa Mesa. A and B: Cylinders in situ, perpendicular to bedding. C and D: Cross sections through two upright cylinders show a structureless core surrounded by concentric laminae. E and F: Multiple cylinders in cross section. Note the differential weathering of the fill of the cylinders in F. Scales in cm.

Externally, many of the cylinders have smooth outer walls (Figs. 4 and 5). Several, however, have one or more helical grooves that progress continuously from the bottom to the top of the cylinder, and on one the groove spirals around the outer surface of the cylinder (Figs. 5B and 5C). On different specimens, the grooves run in opposite directions or have different angles of ascent. These grooves do not appear to represent growth features or provide any indication of the attachment points of appendages, as is characteristic of calamitalean stem casts (see DiMichele and Falcon-Lang [2012] and references and illustrations therein). A few specimens have circumferential grooves separated by several centimeters from one another; these grooves are similar to the nodes of calamitaleans, but there are no clear accompanying vertical ribs or indications of the attachment points of appendicular organs. They may be fractures caused by weathering.

Internally, each cylinder has a central core, which ranges in diameter from 3.9 to 4.7 cm. The area between the central core and the outer surface typically consists of a series of concentric arcs that apparently are the result of post-casting mineralization by groundwater, likely penecontemporaneous with the filling of the cylinders (the banding is not found in the sediment surrounding the cylinders); the banding may also be related to the action of microorganisms associated with the decay of original organic matter.

We collected 23 cylinders that are now in the NMMNH collection, and here describe representative specimens. NMMNH P-85041a (Figs. 4A–4C) is a small cylinder piece with a largely smooth exterior and has an oval (not round) cross section. It tapers



Figures 3A–3D. Outcrop photos of selected sandstone cylinders and molds at Cañon de los Diegos. A: Two shallow, weathered molds of parts of cylinders. B: Surface exposing several cylinders, some of which are paired. C and D: Cylinders in situ on outcrop, showing that the narrower ends are the bases. Scales in cm.

from a small end that is 2.6×2.2 cm wide to a large end that is 4.8×3.9 cm wide. It thus has a long, conical shape and is slightly curved along the long axis.

NMMNH P-85048 is a small cylinder (6.1 cm diameter, 16.0 cm long) in a piece of bedrock, oriented perpendicular to the bedding.

NMMNH P-85051 is four pieces of small cylinders (diameters are 5.5–7.0 cm). One of these cylinder pieces has a constricted neck at one end, which, based on the orientation seen in in situ specimens, we interpret to be the basal end.

NMMNH P-85042a (Figs. 5G and 5H) tapers to one end, so that the wider end has a maximum diameter of 7.9 cm and the narrower end has a maximum diameter of 7.0 cm. In cross section, sub-concentric rings of iron mineralization surround a structureless core 4.4 cm in diameter. The external surface of this cylinder has longitudinal striae, although they are not the broad, well-defined ribs of the type found in calamitaleans.

NMMNH P-85043a (Figs. 4F–4H) is a tapered cylinder that in cross section displays sub-concentric rings around a structureless core 4.75 cm in diameter. It has a maximum diameter at the larger end of 8.8 cm and a maximum diameter at the smaller end of 6.9 cm. Two surficial grooves curve around the periphery of the cylinder in oppositely oriented helices.

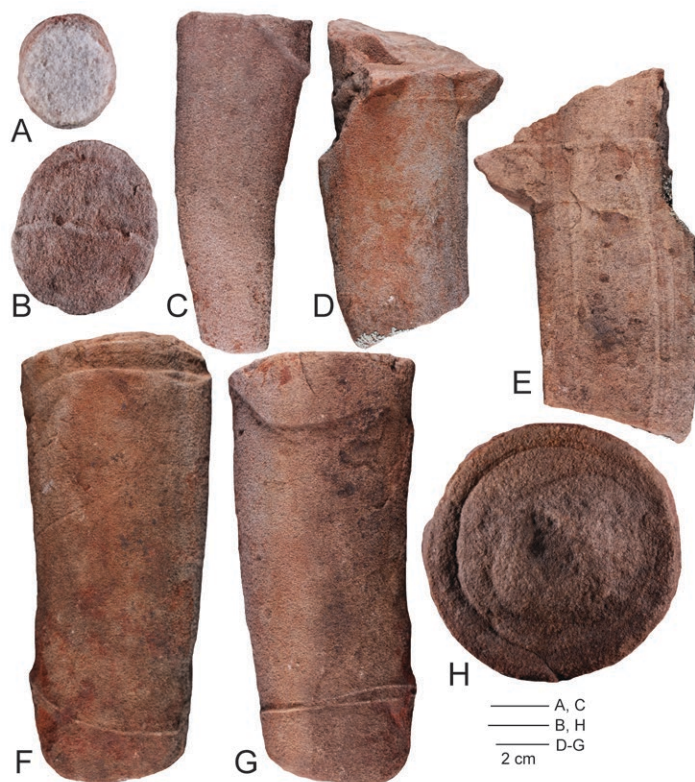
NMMNH P-85043b (Figs. 4D and 4E) is a slightly curved cylinder that exposes a natural longitudinal section showing concentric rings around a structureless core 4.75 cm in diameter. This specimen is 17.0 cm long and has a maximum diameter of 6.7 cm. Near the top (widened end) there is a transverse line on the cylinder's external surface where it flares outward.

NMMNH P-85047 (Fig. 5F) is part of one of the largest cylinders from the Sacatosa Mesa sites. In cross section, it shows sub-concentric rings and a maximum diameter of 29.5 cm.

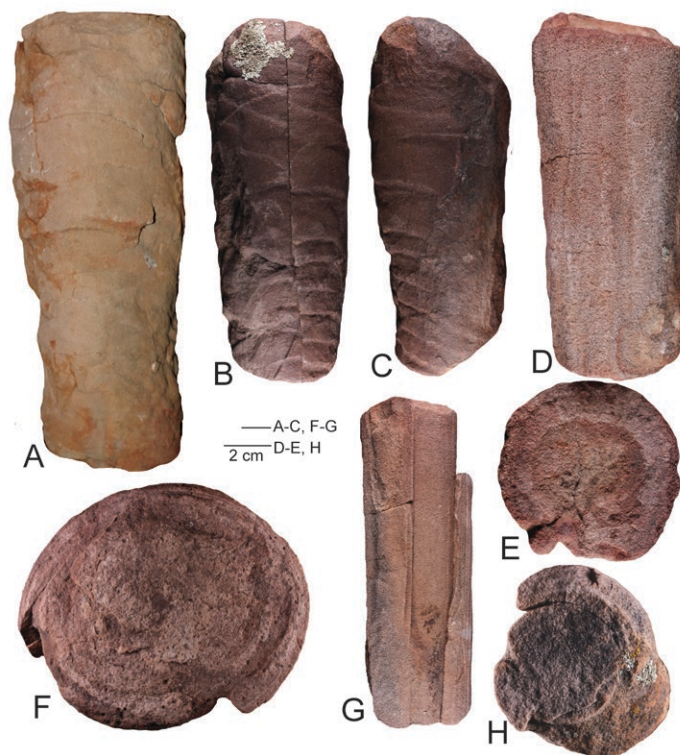
NMMNH P-85050 and 85052 are cylinder cross sections with concentric rings like 85047, but they are smaller (maximum diameter of 85050 = 16.1 cm, of 85052 = 19.0 cm). The central core region of 85050 is 3.9 cm, but 85052 is not well enough preserved to allow a core to be distinguished.

NMMNH P-85049 (Fig. 5A) is a 41-cm-long cylinder that gently tapers from 18.3×16.8 cm to 13.9×11.6 cm. Externally, it has flat layers separated by thin mineralized zones, and the layers are more arc-like than circumferential. Each of these imbricated, cone-shaped layers is 5.5–6.0 cm tall/long. The outer surface of the cylinder is otherwise smooth.

NMMNH P-85044 (Figs. 5B and 5C) best preserves imbricated surfaces and grooves on the external surface of the cylinder. These grooves constitute two or more helices with opposite directions



Figures 4A–4H. Selected sandstone cylinders from the Glorieta Sandstone at Sacatosa Mesa. A–C: NMMNH P-85041a. D and E: NMMNH P-85043b. F–H: NMMNH P-85043a.



Figures 5A–5H. Selected sandstone cylinders from the Glorieta Sandstone at Sacatosa Mesa. A: NMMNH P-85049. B and C: NMMNH P-85044. D and E: NMMNH P-85042b. F: NMMNH P-85047. G and H: NMMNH P-85042a.

of ascent. They appear to conform in an indefinite manner to the sub-concentric layers infilling the internal sandstone mold of the cylinder. This cylinder is 30 cm long and expands from 9.3 cm at the base to 11 cm at its top. There are 10 complete, arc-like imbricated surfaces and one incomplete one (at the narrower end), which decrease in length toward the narrow end (lengths in cm = 5.5, 4.3, 4.0, 3.6, 2.0, 2.2, 2.0, 2.0, 1.6, 0.5+). The boundaries of these surfaces are slightly curved (concave toward the narrower end) and are not continuous around the periphery, being interrupted and slightly offset by a fracture.

NMMNH P-85046 is similar to 85044 but not as well preserved. It has a wider end with diameters of 14.6×14.0 cm and a narrower end with diameters of 11.9×10.7 cm.

We measured the diameters of about 30 cylinders at both the Sacatosa Mesa and Cañon de los Diegos localities (Fig. 6). Both sets of measurements plot as a multimodal distribution skewed to the right, with the long, low, right tail extending toward the end of the distribution made up of the few relatively large-diameter cylinders that were measured. Rinehart et al. (2015, fig. 13A) found a similar distribution of stem diameters in a lower Permian

sample of plant axes, and suggested that the distribution largely reflects taphonomic, geologic, and observational factors. As they noted, such samples should have a larger number of small stems if they reflect an actual biological population.

Discussion

Interpretation of cylinders or cylinder-like structures in sandstone has challenged geologists since the 1800s (e.g., Kavanaugh, 1889; Day, 1928; Hawley and Hart, 1934; Simpson, 1936; Gabelman, 1955; Weiss, 1956; Phoenix, 1958; Allen, 1961; Boyd, 1966; Wnuk and Maberry, 1990; Mossa and Schumacher, 1993; Netoff, 2002; Loope et al., 2011). Three possible origins of such cylinders have been proposed: (1) an inorganic origin, usually as conduits (“pipes”) for dewatering or other transmission of water; (2) burrows made by animals; and (3) casts of plants, most likely of trunks (stems) or pith casts. Here, we evaluate these three possible origins of the Glorieta sandstone cylinders

Inorganic pipes

Buck and Goldring (2003) identified criteria that distinguish inorganic from organic processes that produce conical/cylindrical sedimentary structures. A critical conclusion of their study (and other studies) is that the fluidization of sediment for water transmission creates zones of deformation. Thus, simple water conduits or “water-upwelling pipes” are always associated with some form of soft-sediment deformation, usually concave-up laminae, dish structures, or flare structures (e.g., Massari et al., 2001). No experimental work suggests that a simple cylinder not associated with sediment deformation is the result of transmitting water through sand (e.g., Owen, 1987; Nichols et al., 1994; Frey et al., 2009). Thus, the transmission of water through sand produces collapse structures, U- or V-shaped downwarping of lamination, a zone of deformation that widens upward, a deformation structure that has a flare-shaped outline in cross section, a surface depression, and/or a surrounding zone of soft sediment deformation.

Buck and Goldring (2003, table 3) listed criteria to distinguish collapse structures from locomotion and dwelling structures that are conical to cylindrical in shape. Buck and Goldring (2003, p. 338) concluded that “dewatering pipes are best recognized by a zone of deformed and fluidized sediment at the base.” No such deformation is associated with the Glorieta sandstone cylinders.

Furthermore, the external texture or ornamentation of some of the cylinders, described above (see, for example, Figs. 5B and 5C), are not structures that have ever been associated with dewatering pipes or other inorganic, water-produced features. Those external textures are best understood if the Glorieta sandstone cylinders began as biological structures.

Burrows

The Glorieta sandstone cylinders bear no close resemblance to any of the named ichnogenera of invertebrate burrows that are vertical (perpendicular to bedding) and/or plug shaped (compare

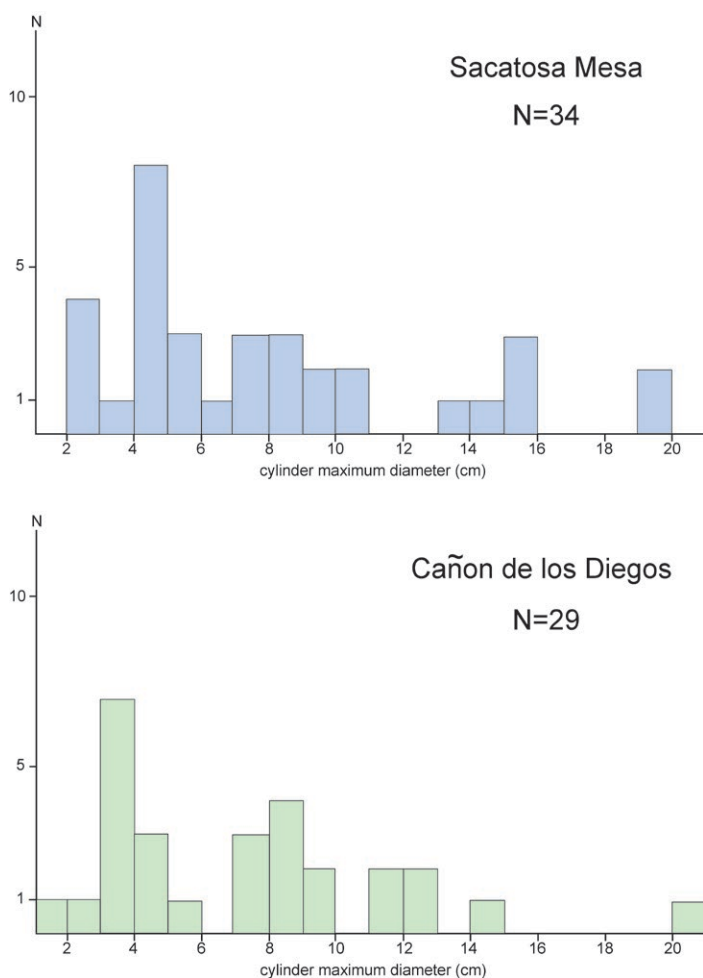


Figure 6. Histograms of cylinder maximum diameters at Sacatosa Mesa and Cañon de los Diegos. Note that at Sacatosa Mesa, the largest cylinder measured has a diameter of 29.5 cm and is off the graph. Also note that at Cañon de los Diegos, the largest cylinder measured has a diameter of 47 cm and is off the graph.

with Pemberton et al., 1988; Buck and Goldring, 2003). Surficial morphologic features (sometimes referred to as bioglyphs) made by burrowers, which characterize most burrows, are lacking on the sandstone cylinders. Some lungfish burrows are vertical cylinders that are superficially similar to the Glorieta sandstone cylinders, but lungfish burrows generally have flask-shaped ends, which are the aestivation chambers, and some cylindrical forms weather to disks (McAllister, 1979; Gobetz et al., 2006).

Concentrically laminated burrows are known and are made either by the burrow producer or by passive filling of burrows with restricted apertures (Goldring, 1996; Buck and Goldring, 2003). However, in the case of vertical shafts, concentric laminae are not easily formed by burrow producers that push sediment aside to form irregular or arcuate laminae and deform the adjacent layers of sediment. Indeed, Buck and Goldring (2003, p. 256) concluded that “actively produced fill is characterized by arcuate and irregular lamination.” No irregular or arcuate laminae or deformation of layers is present in the Glorieta sandstone cylinders, so an animal producer is unlikely. Some producers do make a multilayered burrow wall that can produce regular and even lamination, though nothing as thinly and evenly laminated as is seen in the Glorieta sandstone cylinders. In locomotion structures, according to Buck and Goldring (2003), the laminae in the structures are bent in the direction of locomotion, and in the outer zone of deformation, backfilling produces laminae that are warped opposite to the direction of motion.

Bromley et al. (1975) discussed examples of unusually large tubular burrows in strata of Permian-Pleistocene age, none of which show a close resemblance to the Glorieta sandstone cylinders. Indeed, the Glorieta sandstone cylinders do not resemble known Paleozoic or Mesozoic burrows of comparable size. For example, *Megaplanolites* is 20–30 cm in diameter, bedding plane parallel, and a very long, tubular trace that reaches maximum lengths of 9–10 m (Calvo et al., 1987). *Megapermichnus* is cylindrical and of similar size, horizontal to bedding, and branched (Jenny and Jenny-Dehusses, 1978).

Vertebrate burrows are typically complex structures (Voorhies, 1975; Lucas et al., 2006). Lucas et al. (2006) listed characteristics of vertebrate burrows that are not seen in the Glorieta sandstone cylinders: (1) distinctive architectural morphology (e.g., entrance shaft leading to primary tunnel with secondary or tertiary branches); (2) subcircular or elliptical cross section of constant diameter; (3) burrow fill contrasts with host strata; (4) linings present; (5) distinctive surficial morphology (longitudinal ridges and/or paired grooves interpreted as scratch marks, beak marks, or tooth marks, i.e., bioglyphs); (6) variable branching patterns; (7) multiple terminal chambers, each having multiple entrances; and (8) shallow vertical or low-angled shafts from the ground surface leading to low-angle ramps, helical tunnels, or an underground maze.

Thus, the Glorieta sandstone cylinders do not resemble known burrows. Indeed, they lack the diagnostic features of large invertebrate and vertebrate burrows. So, an origin as animal burrows is unlikely.

Plants

Rygel et al. (2004, p. 531) defined vegetation-induced sedimentary structures (VISS) as “primary structures formed by the interaction of detrital sediments with in situ plants.” However, the Glorieta sandstone cylinders show none of the sedimentary structures detailed by Rygel et al. as characteristic of VISS. In particular, there is no distortion of bedding (scour and fill, upturned beds, etc.) associated with the cylinders, and they penetrate the sandstone they are in without an obvious association of sedimentary structures. This suggests that if there were flow of sand around the cylinders that it was either rotary or multidirectional.

If the cylinders are casts of the bases of stems, formed when their original organic material decomposed, there was no deformation of sediment when the resulting voids were filled. This does not, however, negate the possibility of their origin after the decay of plant remains. Possible variables to consider include the low compaction ratios of coarse-grained sediment and the possibility that decaying organic matter involved the action of microorganisms, the chemical exudates of which may have contributed to the cementation of the sediment immediately surrounding the decaying object. The casts at both Sacatosa Mesa and Cañon de los Diegos indicate differential cementation of the casts and the surrounding sediment. In some instances, the casts protrude from the sediment, whereas in others they have been eroded, leaving only the original molds (Figs. 2 and 3). These patterns suggest that the molds were filled after decay had created the hollow space and that the surrounding host sediment was relatively well compacted and firm at that time.

Another feature of these cylinders worth noting is their frequent pairing, particularly that of a larger-diameter cast with one of smaller diameter (Figs. 2E, 2F, 3A, and 3B). This might be typical of the relationship between a parent axis and a laterally produced branch. Unfortunately, there were only a few exposures of in situ axes in profile view, all in Cañon de los Diegos, where downcutting had in places left steep, straight outcrops bordering the stream (Figs. 3C and 3D). But we encountered no paired axes in that plane of view, which might have revealed a developmental relationship.

Plants also produce roots and subterranean stems of various sizes, and the nature of this kind of preservation also must be considered. As Pfefferkorn and Fuchs (1991, p. 33) noted, root preservation “depends on early diagenetic processes in the sediment or soil.” The Glorieta cylinders provide no evidence of being roots—they are very large, implying large parent plants, yet their close spacing on surface expression does not allow that possibility. They must have been exposed on the surface in order for them to be filled with sand, yet there is no surface expression of stems to which they might have been attached. If, on the other hand, the sandstone cylinders are the casts of plant stems, there is no indication in the sediment below or around them of either horizontal, rhizomatous axes or of roots of any kind; they appear to be free-standing individual objects. Note also that in

those specimens that have tapered bases, there is no indication of soil-like features at the base in which roots might be expected to have been present.

Interpretation

We conclude that plants are the most likely source of the Glorieta sandstone cylinders. Although this interpretation must remain uncertain, the origin of these objects as casts, created by the infilling of molds left by decay of the original organic matter, more fully encompasses the observed phenomena than does an origin from abiotic processes or as the result of biotic disruption of the substrate by burrowing.

There are other examples of such features in which a plant origin was deemed most likely, even if still uncertain. For example, Simpson (1936) described and illustrated sandstone cylinders from the Paleocene of Patagonia, Argentina, that show some resemblance to the Glorieta sandstone cylinders. These are found in mudrock over an area at least 0.8 km long and are 30–60 cm in diameter, 1–3 m tall, perpendicular to bedding, mostly isolated, and circular in cross section; some show horizontal fluting, and they lack root structures and expand toward the base. Simpson offered no definite conclusion as to their origin. He did note a resemblance to “standing trees” but considered that “the evidence is inadequate to advance it as a definite theory” (Simpson, 1936, p. 204). A similar situation involving sediment-filled molds was described by Rinehart et al. (2015) in a 2-m-thick, lower Permian sandstone bed from San Miguel County, northern New Mexico. The exposure in that instance was almost entirely vertical, along an outcrop face, but sample size was larger than in the Glorieta Sandstone exposures. The San Miguel specimens showed clear evidence of lateral branching and size differences between large main axes and smaller-diameter lateral branches. In addition, they were of sufficient number to demonstrate spacing in conformance with self-thinning as is encountered in stands of extant plants.

By a process of elimination, the best conclusion we can provide is that the Glorieta specimens conform most closely to a stand of calamitalean stems, late Paleozoic relatives of modern equisetaleans, known colloquially as “horsetails” or “scouring rushes.” The cylinders do not have the characteristics of arborescent lycopside, which are commonly found as upright, in situ casts in the roof shales of coal beds (e.g., Gastaldo, 1986; DiMichele et al., 1996; Thomas and Seyfullah, 2015), less frequently also including sediment-filled casts of their rooting systems (e.g., Pfefferkorn, 1972; Thomas and Seyfullah, 2015; DiMichele et al., 2022). Lycopside stumps almost universally have flaring, bell-shaped bases and are of quite large size, although it is understood that their large diameters are not due to the addition of woody tissue. As in many seed plants, the developmental dynamics of these plants, especially the way in which they attained large diameters, is not well understood (Boyce and DiMichele, 2016; D’Antonio et al., 2021; DiMichele et al., 2022).

Similarly, the Glorieta sandstone cylinders do not have the characteristic shape that is expected of woody seed plants, such as cordaitaleans or conifers, both of which were extant and common

in moisture-limited ecosystems in the late Paleozoic equatorial regions (Bashforth et al., 2021). Cordaitaleans, and possibly some conifers (dicranophylls), had large-diameter pith regions that were largely hollow and traversed by thin parenchymatous septae (e.g., Falcon-Lang, 2003; Falcon-Lang and Bashforth, 2005; Falcon-Lang et al., 2014); such septae might easily have succumbed to decay, leaving a hollow core region as seen in the Glorieta sandstone casts (e.g., Falcon-Lang et al., 2016). However, these trees also had a lateral meristem, the vascular cambium, that produced wood circumferentially around the stem, beginning very early during growth. As a consequence, they are generally quite broad at the base and taper upward (the Glorieta sandstone cylinders taper downward). A further consideration is that the size range of the Glorieta sandstone casts is relatively narrow (Fig. 6), especially given the area and stratigraphic interval through which the casts have been found, which would not be an expectation of a woodland of coniferophytes (e.g., compare with Falcon-Lang et al., 2016).

Marattialean tree ferns also can be ruled out as a possible plant source. Marattialeans do not have a core region. The stems, although conical and lacking circumferential secondary xylem development, are surrounded by a mantle of adventitious roots, which gave them the typical expanded basal region, even as in situ molds (Falcon-Lang, 2006; Bashforth et al., 2014). In addition, the root mantle gave the trunk exterior a ropy, rough appearance of thick, vertical, often interwoven lines. No such features appear on any of the Glorieta sandstone casts or molds.

Finally, the question of pteridosperms must be addressed. Where known, arborescent pteridosperm stems (excluding consideration of sprawling forms, e.g., Galtier and Béthoux [2002]) may be cylindrical and tapered at the base (consider the examples discussed by Pfefferkorn et al. [1984] and Wnuk and Pfefferkorn [1984]) and within the size range of the cylinders described here. These small trees could be of two forms, either stout cylindrical stems supported by adventitious roots, or thin, flexuous stems, often the taller of the two growth forms, that formed thickets and were mutually self-supporting in addition to having root support. Such growth habits are described from wetland settings, however, which are the environments where pteridosperms are found most commonly. Pteridospermous relatives such as peltasperms (perhaps taeniopterids) or true cycads have been reported from more moisture-stressed habitats as well. However, the pteridosperm reproductive biology also is important to consider here. Most of the better known forms had large seeds, including some of the largest seeds known among late Paleozoic plants (e.g., Sims, 2012), as well as very large pollen grains, likely requiring some sort of insect pollination (Schwendemann et al., 2007). Although this does not rule out pteridosperms as a possible source of these casts, it does make that possibility unlikely. Finally, as far as is known, pteridosperms did not give rise to lateral shoots adventitiously, a possibility indicated by the pairing of large- and small-diameter cylinders found frequently among the in situ specimens observed.

Calamitaleans best fit the morphology of most of the sandstone cylinders described in this report for several reasons. Importantly, where observable, they expand unidirectionally, which in situ

specimens demonstrate to be in the upward direction; this is typical of calamitalean stems (DiMichele and Falcon-Lang, 2012, and illustrations therein). Due to the nature of the exposures, not all of the specimens demonstrate this feature; given their other similarities to those that do taper, we believe the simplest explanation is that those not displaying such a feature also tapered, particularly given that all such specimens are incomplete and show sheared-off bases. Beyond this tapered shape, most of the sandstone cylinders are of relatively small diameter and occur in close proximity to one another, suggesting dense stands, which is typical of calamitaleans (DiMichele et al., 2009; Thomas, 2014; Falcon-Lang, 2015). As demonstrated by DiMichele and Falcon-Lang (2012) and Falcon-Lang (2015), the diameters of upright, in situ calamitalean remains indicate with certainty that they are preserved upright stems; both of these papers also document the occurrence of true “pith casts,” which are much smaller in diameter than the larger circumferences of the stem casts in which they occur, requiring some sort of double filling, as speculated by Taylor et al. (2009). This, too, conforms with the Glorieta sandstone cylinders in which there appears to have been a central core region filled differentially from the surrounding area. Were these woody calamitaleans, this could account for the significant difference between the diameter of the core and the cast as a whole. There is a large form of calamitalean stem, *Calamites gigas*, that is common in Permian-aged strata throughout Eurasia (e.g., Naugolnykh, 2000) and in the United States (Arnold, 1941) and has been postulated, with some interpretive disagreement, to have been tolerant of drought, with a possible cactus-like water-storage stem (Barthel and Rößler, 1996; Naugolnykh, 2005). Based on the analyses of these authors, *C. gigas* stems were large (exceeding 10 cm in diameter in some specimens), woody, and free-standing (that is, not rhizomatous). Naugolnykh (2005), in his detailed morphological and biogeographic study of the species, notes that the basal parts of the trunk were without lateral branches, that the plant commonly occurs in strata interpreted as deposited under seasonally dry conditions, and that specialized, deeply penetrating roots permitted occupancy of this type of habitat.

Nevertheless, there are features of these casts and molds that do not conform with a calamitalean origin. Most importantly is the external morphology, which lacks any indication of the node-internode construction so characteristic and diagnostic of this plant group, among the spectrum of late Paleozoic plants. The stems also lack the vertical ribbing that characterizes calamitaleans, reflective of their internal, primary vasculature and, in some forms, perhaps of the alternation of tracheidal and parenchymatous regions in the wood (directly reflective of the primary vascular organization). In each of these instances, such features might have been obscured by relatively thick wood development, but, nonetheless, they are problematic absences of evidence.

A final possibility, of course, is that some, or even all, of the casts represent some kind of plant that is unknown, even if it may belong to a group that is known, for example, pteridosperms, broadly construed. The inferred habitat of these plants—in wet, interdunal regions within a sand sea—is certainly one unfavorable for the preservation of plant remains (Fig. 7), both

in morphological detail and in general; were preservational conditions even moderate, more plant remains should be known from these environments, when in fact the record is nearly non-existent, at least in the Paleozoic. Consequently, the kinds of plants that might have grown in such habitats would rarely be preserved (or be poorly preserved), and we might expect to know little or nothing of their fine morphological and anatomical details were suspect remains found. However, we must consider this with greater subtlety than would be the case when examining such a pattern in the modern, even post-Early Cretaceous (angiosperm) world. In late Paleozoic context, tropical fossil floras across western and central Pangea are remarkably similar, especially in (micro) habitats with high water tables. During the Late Pennsylvanian and Permian in Euramerica, plants in wetter parts of these landscapes consisted predominantly of marattialean tree ferns, calamitaleans, pteridosperms, and sigillarian lycopsids. This is the case even in the most remote areas, although as indicators of moisture stress increase, the calamitaleans and tree ferns became overwhelmingly the most common elements, with rare lycopsids and variable but generally rare numbers of pteridosperms. Consider, for example, floras from Utah in western Pangea (DiMichele et al., 2014), or various floras from the lower Permian of Texas (e.g., Simon et al., 2018; DiMichele et al., 2018, 2019; Koll and DiMichele, 2021). Or look even farther to the paleowest in New Mexico, where conifers and supaioids dominate the red beds floras, yet a much more diverse flora can be found in gray shales, including “typical” wetland elements (DiMichele et al., 2013). Under conditions of still more extreme moisture stress in these western regions, if present at all, the only typical wetland plants generally are calamitaleans (e.g., DiMichele et al., 2018; Bashforth et al., 2021).

The survival of plants requiring high water tables within otherwise seasonally moisture-limited landscapes also is demonstrated by their occurrences in strata deposited during Pennsylvanian-age interglacials in coal basins from the Midcontinent through the Appalachian Basin. In the Illinois Basin of Indiana, Bashforth et al. (2016) detailed such a flora of Middle Pennsylvanian age, dominated by drought-tolerant xeromorphic taxa but with scattered marattialean tree ferns and calamitaleans. Looy et al. (2014) also documented such patterns using palynology; a Middle Pennsylvanian flora dominated by drought-tolerant cordaitaleans, also containing conifers (Falcon-Lang et al., 2009), is dominated by the spores of arborescent lycopsids, a wetland-dominant group, with smaller amounts of ferns and sphenopsids, signaling that these plants were still present in the seasonally dry landscapes that were predominant between periods of peat/coal formation (Falcon-Lang et al., 2009).

As a consequence of the patterns described above, the interpretation of the Glorieta sandstone cylinders and molds as the remains of calamitaleans seems to be well within possibility even if considerable uncertainty remains (for all or some). That they may represent a particular species from this lineage adapted to a water-stressed setting must be considered. Given the peculiarity of the setting, and the overlapping characteristics of the specimens among those that are complete versus fragmentary, we believe it to be most likely that these specimens, if plants, are representative of a single species.

Conclusions

On Glorieta Mesa in San Miguel County, northern New Mexico, the lower Permian Glorieta Sandstone contains numerous sandstone cylinders from two areas and two stratigraphic intervals of interdunal sediments in the lower part of the formation. The lack of deformation of the sediment in and around the cylinders and the preservation of external markings on some of the cylinders preclude their identification as inorganic dewatering structures or other forms of water conduits. The sandstone cylinders also do not resemble any known cylindrical or plug-shaped trace fossils, and the lack of ornamentation (bioglyphs) on the cylinder walls is one of several reasons that preclude their identification as animal

burrows. The most likely origin of these cylinders is as the fill of molds left by plant stems that were buried upright. However, the botanical affinity of these molds and casts is uncertain because they do not contain diagnostic features of anatomy or external morphology. By a process of elimination, the Glorieta sandstone cylinders are most likely to have been produced by woody calamitaleans. Possible modern analogues can be found in areas bordering oceanic settings where plants, including trees, grow in wet areas behind sand dunes, but can be transgressed by those dunes as the sea level rises or as winds drive the sand landward (Fig. 7).



Figure 7. Dead trees in interdunal deposits of the Namib Desert, Africa. Photograph by Diego Delso, deso.photo, Wikimedia Commons license CC-BY-SA.

Acknowledgments

We thank Paul May and John Rogers for assistance in the field. Comments by Bruce Allen and Arden Bashforth improved the content and clarity of the manuscript.

References

- Ahlbrandt, T.S., and Fryberger, S.G., 1981, Sedimentary features and significance of interdune deposits, *in* Ethridge, F.G., and Flores, R.M., eds., Recent and Ancient Nonmarine Depositional Environments—Models for Exploration: SEPM Society for Sedimentary Geology Special Publication 31, p. 293–314. <https://doi.org/10.2110/pec.81.31.0293>
- Allen, J.R.L., 1961, Sandstone-plugged pipes in the lower Old Red Sandstone of Shropshire, England: *Journal of Sedimentary Petrology*, v. 31, no. 3, p. 325–335. <https://doi.org/10.1306/74D70B6E-2B21-11D7-8648000102C1865D>
- Arnold, C.A., 1941, Some Paleozoic plants from central Colorado and their stratigraphic significance: *Contributions from the Museum of Paleontology, University of Michigan*, v. 6, no. 4, p. 59–70.
- Baars, D.L., 1961, Permian blanket sandstones of Colorado Plateau, *in* Peterson, J.A., and Osmond, J.C., eds., *Geometry of Sandstone Bodies*: Tulsa, American Association of Petroleum Geologists, p. 179–207. <https://doi.org/10.1306/SV22354C11>
- Barthel, M., and Rößler, R., 1996, Paläontologische Fundschichten im Rotliegend von Manebach (Thür. Wald) mit *Calamites gigas* (Sphenophyta): *Veröffentlichungen Naturhistorisches Museum Schleusingen*, v. 11, p. 3–21.
- Bashforth, A.R., Cleal, C.J., Gibling, M.R., Falcon-Lang, H.J., and Miller, R.F., 2014, Paleoecology of Early Pennsylvanian vegetation on a seasonally dry tropical landscape (Tynemouth Creek Formation, New Brunswick, Canada): *Review of Palaeobotany and Palynology*, v. 200, p. 229–263. <https://doi.org/10.1016/j.revpalbo.2013.09.006>
- Bashforth, A.R., DiMichele, W.A., Eble, C.F., and Nelson, W.J., 2016, Dryland vegetation from the Middle Pennsylvanian of Indiana (Illinois Basin)—The dryland biome in glacioeustatic, paleobiogeographic, and paleoecologic context: *Journal of Paleontology*, v. 90, no. 5, p. 785–814. <https://doi.org/10.1017/jpa.2016.25>
- Bashforth, A.R., DiMichele, W.A., Eble, C.F., Falcon-Lang, H.J., Looy, C.V., and Lucas, S.G., 2021, The environmental implications of upper Paleozoic plant-fossil assemblages with mixtures of wetland and drought-tolerant taxa in tropical Pangea: *Geobios*, v. 68, p. 1–45. <https://doi.org/10.1016/j.geobios.2021.04.002>
- Blakey, R.C., and Knepp, R., 1989, Pennsylvanian and Permian geology of Arizona, *in* Jenney, J.P., and Reynolds, S.J., eds., *Geologic Evolution of Arizona*: Arizona Geological Society Digest 17, p. 313–347.
- Boyce, C.K., and DiMichele, W.A., 2016, Arborescent lycopsid productivity and lifespan—Constraining the possibilities: *Review of Palaeobotany and Palynology*, v. 227, p. 97–110. <https://doi.org/10.1016/j.revpalbo.2015.10.007>
- Boyd, D.W., 1966, Lamination deformed by burrowers in Flathead Sandstone (Middle Cambrian) of central Wyoming: *Rocky Mountain Geology*, v. 5, no. 1, p. 45–53.
- Bromley, R.G., Curran, H.A., Frey, R.W., Gutschick, R.C., and Suttner, L.J., 1975, Problems in interpreting unusually large burrows, *in* Frey, R.W., ed., *The Study of Trace Fossils*: Berlin, Springer-Verlag, p. 351–376.
- Buck, S.G., and Goldring, R., 2003, Conical sedimentary structures, trace fossils or not? Observations, experiments, and review: *Journal of Sedimentary Research*, v. 73, no. 3, p. 338–353. <https://doi.org/10.1306/091602730338>
- Calvo, J.M., Gil, E., and Meléndez, G., 1987, *Megaplanolites ibericus* (ichnogen. et ichnosp. nov.), a new trace fossil from the Upper Jurassic (uppermost Oxfordian) of Bueña (Teruel Province, Iberian Chain, Spain): *Palaeogeography, Palaeoclimatology, Palaeoecology*, v. 61, p. 199–204. [https://doi.org/10.1016/0031-0182\(87\)90049-6](https://doi.org/10.1016/0031-0182(87)90049-6)
- D'Antonio, M.P., Boyce, C.K., and Wang, J., 2021, Two new species of *Sigillaria* Brongniart from the Wuda Tuff (Asselian: Inner Mongolia, China) and their implications for lepidodendrid life history reconstruction: *Review of Palaeobotany and Palynology*, v. 294, 104203. <https://doi.org/10.1016/j.revpalbo.2020.104203>
- Day, A.E., 1928, Pipes in the coast sandstone of Syria: *Geological Magazine*, v. 65, p. 412–415.
- DiMichele, W.A., and Falcon-Lang, H.J., 2012, Calamitalean “pith casts” reconsidered: *Review of Palaeobotany and Palynology*, v. 173, p. 1–14. <https://doi.org/10.1016/j.revpalbo.2012.01.011>
- DiMichele, W.A., Eble, C.F., and Chaney, D.S., 1996, A drowned lycopsid forest above the Mahoning coal (Conemaugh Group, Upper Pennsylvanian) in eastern Ohio, USA: *International Journal of Coal Geology*, v. 31, no. 1–4, p. 249–276. [https://doi.org/10.1016/S0166-5162\(96\)00019-5](https://doi.org/10.1016/S0166-5162(96)00019-5)
- DiMichele, W.A., Nelson, W.J., Elrick, S., and Ames, P.R., 2009, Catastrophically buried Middle Pennsylvanian *Sigillaria* and calamitalean sphenopsids from Indiana, USA—What kind of vegetation was this?: *PALAIOS*, v. 24, no. 3, p. 159–166. <https://doi.org/10.2110/palo.2008.p08-051r>

- DiMichele, W.A., Chaney, D.S., Lucas, S.G., Kerp, H., and Voigt, S., 2013, Flora of the Lower Permian Abo Formation redbeds, western equatorial Pangea, New Mexico, *in* Lucas, S.G., Nelson, W.J., DiMichele, W.A., Spielmann, J.A., Krainer, K., Barrick, J.E., Elrick, S., and Voigt, S., eds., *The Carboniferous-Permian Transition in Central New Mexico*: New Mexico Museum of Natural History and Science Bulletin 59, p. 265–287.
- DiMichele, W.A., Cecil, C.B., Chaney, D.S., Elrick, S.D., and Nelson, W.J., 2014, Fossil floras from the Pennsylvanian-Permian Cutler Group of southeastern Utah, *in* MacLean, J.S., Biek, R.F., and Huntoon, J.E., *Geology of Utah's Far South*: Utah Geological Association Publication 43, p. 491–504.
- DiMichele, W.A., Hook, R.W., Kerp, H., Hotton, C.L., Looy, C.V., and Chaney, D.S., 2018, Lower Permian flora of the Sanzenbacher Ranch, Clay County, Texas, *in* Krings, M., Harper, C.J., Cúneo, N.R., and Rothwell, G.W., eds., *Transformative Paleobotany*: Cambridge, MA, Academic Press, p. 95–126. <https://doi.org/10.1016/B978-0-12-813012-4.00006-1>
- DiMichele, W.A., Hotton, C.L., Looy, C.V., and Hook, R.W., 2019, Paleocological and paleoenvironmental interpretation of three successive macrofloras and palynofloras from the Kola Switch locality, lower Permian (Archer City Formation, Bowie Group) of Clay County, Texas, USA: *PalZ*, v. 93, p. 423–451. <https://doi.org/10.1007/s12542-019-00485-8>
- DiMichele, W.A., Bateman, R.M., Rothwell, G.W., Duijnste, I.A., Elrick, S.D., and Looy, C.V., 2022, *Stigmara*—A review of the anatomy, development, and functional morphology of the rootstock of the arboreal lycopods: *International Journal of Plant Sciences*, v. 183, no. 6, p. 493–534. <https://doi.org/10.1086/720641>
- Falcon-Lang, H.J., 2003, Late Carboniferous tropical dryland vegetation in an alluvial-plain setting, Joggins, Nova Scotia, Canada: *PALAIOS*, v. 18, no. 3, p. 197–211. [https://doi.org/10.1669/0883-1351\(2003\)018%3C0197:LCTDVI%3E2.0.CO;2](https://doi.org/10.1669/0883-1351(2003)018%3C0197:LCTDVI%3E2.0.CO;2)
- Falcon-Lang, H.J., 2006, Latest mid-Pennsylvanian tree-fern forests in retrograding coastal plain deposits, Sydney Mines Formation, Nova Scotia, Canada: *Journal of the Geological Society*, v. 163, p. 81–93. <https://doi.org/10.1144/0016-764905-003>
- Falcon-Lang, H.J., 2015, A calamitalean forest preserved in growth position in the Pennsylvanian coal measures of South Wales—Implications for palaeoecology, ontogeny and taphonomy: *Review of Palaeobotany and Palynology*, v. 214, p. 51–67. <https://doi.org/10.1016/j.revpalbo.2014.10.001>
- Falcon-Lang, H.J., and Bashforth, A.R., 2005, Morphology, anatomy, and upland ecology of large cordaitalean trees from the Middle Pennsylvanian of Newfoundland: *Review of Palaeobotany and Palynology*, v. 135, no. 3–4, p. 223–243. <https://doi.org/10.1016/j.revpalbo.2005.04.001>
- Falcon-Lang, H.J., Nelson, W.J., Elrick, S., Looy, C.V., Ames, P.R., and DiMichele, W.A., 2009, Incised channel fills containing conifers indicate that seasonally dry vegetation dominated Pennsylvanian tropical lowlands: *Geology*, v. 37, no. 10, p. 923–926. <https://doi.org/10.1130/G30117A.1>
- Falcon-Lang, H.J., Kurzawe, F., and Lucas, S.G., 2014, Coniferopsid tree trunks preserved in sabkha facies in the Permian (Sakmarian) Community Pit Formation in south-central New Mexico, USA—Systematics and palaeoecology: *Review of Palaeobotany and Palynology*, v. 200, p. 138–160. <https://doi.org/10.1016/j.revpalbo.2013.09.004>
- Falcon-Lang, H.J., Kurzawe, F., and Lucas, S.G., 2016, A Late Pennsylvanian coniferopsid forest in growth position, near Socorro, New Mexico, USA—Tree systematics and palaeoclimatic significance: *Review of Palaeobotany and Palynology*, v. 225, p. 67–83. <https://doi.org/10.1016/j.revpalbo.2015.11.008>
- Foster, R.W., Frentress, R.M., and Riese, W.C., 1972, Subsurface geology of east-central New Mexico: *New Mexico Geological Society Special Publication 4*, 22 p. <https://doi.org/10.56577/SP-4>
- Francischini, H., Lucas, S.G., Voigt, S., Marchetti, L., Santucci, V.L., Knight, C.L., Wood, J.R., Dentzien-Dias, P., and Schultz, C.L., 2020, On the presence of *Ichniotherium* in the Coconino Sandstone (Cisuralian) of the Grand Canyon and remarks on the occupation of deserts by non-amniote tetrapods: *PalZ*, v. 94, p. 207–225. <https://doi.org/10.1007/s12542-019-00450-5>
- Frey, S.E., Gingras, M.K., and Dashtgard, S.E., 2009, Experimental studies of gas-escape and water-escape structures—Mechanisms and morphologies: *Journal of Sedimentary Research*, v. 79, no. 11, p. 808–816. <https://doi.org/10.2110/jsr.2009.087>
- Gabelman, J.W., 1955, Cylindrical structures in Permian(?) siltstone, Eagle County, Colorado: *Journal of Geology*, v. 63, no. 3, p. 214–227.
- Galtier, J., and Béthoux, O., 2002, Morphology and growth habit of *Dicksonites pluckenettii* from the Upper Carboniferous of Graissessac (France): *Geobios*, v. 35, no. 5, p. 525–535. [https://doi.org/10.1016/S0016-6995\(02\)00070-0](https://doi.org/10.1016/S0016-6995(02)00070-0)
- Gastaldo, R.A., 1986, Implications on the paleoecology of autochthonous Carboniferous lycopods in clastic sedimentary environments: *Palaeogeography, Palaeoclimatology, Palaeoecology*, v. 53, no. 2–4, p. 191–212. [https://doi.org/10.1016/0031-0182\(86\)90044-1](https://doi.org/10.1016/0031-0182(86)90044-1)
- Gilmore, C.W., 1926, Fossil footprints from the Grand Canyon: *Smithsonian Miscellaneous Collections*, v. 77, no. 9, p. 1–41.
- Glennie, K.W., 1987, Desert sedimentary environments, past and present—A summary: *Sedimentary Geology*, v. 50, no. 1–3, p. 135–165. [https://doi.org/10.1016/0037-0738\(87\)90031-5](https://doi.org/10.1016/0037-0738(87)90031-5)
- Gobetz, K.E., Lucas, S.G., and Lerner, A.J., 2006, Lungfish burrows of varying morphology from the Upper Triassic Redonda Formation, Chinle Group, eastern New Mexico, *in* Harris, J.D., Lucas, S.G., Spielmann, J.A., Lockley, M.G., Milner, A.R.C., and Kirkland, J.I., eds., *The Triassic-Jurassic Terrestrial Transition*: New Mexico Museum of Natural History and Science Bulletin 37, p. 140–146.
- Goldring, R., 1996, The sedimentological significance of concentrically laminated burrows from Lower Cretaceous Ca-bentonites, Oxfordshire: *Journal of the Geological Society, London*, v. 153, no. 2, p. 255–263. <https://doi.org/10.1144/gsjgs.153.2.0255>

- Hawley, J.E., and Hart, R.C., 1934, Cylindrical structures in sandstones: GSA Bulletin, v. 45, no. 6, p. 1017–1034. <https://doi.org/10.1130/GSAB-45-1017>
- Jenny, J., and Jenny-Dehusses, C., 1978, Sur la présence de *Megapermichnus ichnogen* nov., nouvel ichnogene de taille géante dans le Permien de l'Elbourz (Iran): Eclogae Geologicae Helveticae, v. 71, no. 2, p. 313–319. <https://doi.org/10.5169/seals-164734>
- Kavanaugh, S.J., 1889, On modern concretions from the St. Lawrence, with remarks (by J.W. Dawson) on cylinders found in the Potsdam Sandstone: Canadian Record of Science, v. 3, p. 292–294.
- Koll, R.A., and DiMichele, W.A., 2021, Dominance-diversity architecture of a mixed hygromorphic-to-xeromorphic flora from a botanically rich locality in western equatorial Pangea (lower Permian Emily Irish site, Texas, USA): Palaeogeography, Palaeoclimatology, Palaeoecology, v. 563, 110132. <https://doi.org/10.1016/j.palaeo.2020.110132>
- Krainer, K., and Lucas, S.G., 2015, Type section of the lower Permian Glorieta Sandstone, San Miguel County, New Mexico, in Lindline, J., Petronis, M., and Zebrowski, J., eds., Geology of the Las Vegas Region: New Mexico Geological Society Fall Field Conference Guidebook 66, p. 205–210. <https://doi.org/10.56577/FFC-66.205>
- Krainer, K., Lucas, S.G., and Brose, R.J., 2012, Reference section of the Lower Permian San Andres Formation, Sierra County, New Mexico, in Lucas, S.G., McLemore, V.T., Lueth, V.W., Spielmann, J.A., and Krainer, K., eds., Geology of the Warm Springs Region: New Mexico Geological Society Fall Field Conference Guidebook 63, p. 395–405. <https://doi.org/10.56577/FFC-63.395>
- Loope, D.B., Kettler, R.M., and Weber, K.A., 2011, Morphologic clues to the origins of iron-oxide cemented spheroids, boxworks, and pipelike concretions, Navajo Sandstone of south-central Utah, U.S.A.: Journal of Geology, v. 119, no. 5, p. 505–520. <https://doi.org/10.1086/661110>
- Looy, C.V., Stevenson, R.A., Van Hoof, T.B., and Mander, L., 2014, Evidence for coal forest refugia in the seasonally dry Pennsylvanian tropical lowlands of the Illinois Basin, USA: PeerJ, v. 2, e630. <https://doi.org/10.7717/peerj.630>
- Lucas, S.G., Gobetz, K.E., Odier, G.P., McCormick, T., and Egan, C., 2006, Tetrapod burrows from the Lower Jurassic Navajo Sandstone, southeastern Utah, in Harris, J.D., Lucas, S.G., Spielmann, J.A., Lockley, M.G., Milner, A.R.C., and Kirkland, J.I., eds., The Triassic-Jurassic Terrestrial Transition: New Mexico Museum of Natural History and Science Bulletin 37, p. 147–154.
- Lucas, S.G., Krainer, K., and Brose, R.J., 2013, The Lower Permian Glorieta Sandstone in central New Mexico, in Lucas, S.G., Nelson, W.J., DiMichele, W.A., Spielmann, J.A., Krainer, K., Barrick, J.E., Elrick, S., and Voigt, S., eds., The Carboniferous-Permian Transition in Central New Mexico: New Mexico Museum of Natural History and Science Bulletin 59, p. 201–211.
- Lucas, S.G., Henderson, C., Barrick, J.E., and Krainer, K., 2022, Conodonts and the correlation of the lower Permian Yeso Group, New Mexico, USA: Stratigraphy, v. 19, no. 2, p. 74–94.
- Mack, G.H., and Bauer, E.M., 2014, Depositional environments, sediment dispersal, and provenance of the Early Permian (Leonardian) Glorieta Sandstone, central New Mexico, in Rawling, G., McLemore, V.T., Timmons, S., and Dunbar, N., eds., Geology of the Sacramento Mountains Region: New Mexico Geological Society Fall Field Conference Guidebook 65, p. 261–271. <https://doi.org/10.56577/FFC-65.261>
- Marchetti, L., Francischini, H., Lucas, S.G., Voigt, S., Hunt, A.P., and Santucci, V.L., 2021, Chapter 9—Paleozoic vertebrate ichnology of Grand Canyon National Park, in Santucci, V.L., and Tweet, J.S., eds., Grand Canyon National Park—Centennial Paleontological Resource Inventory: National Park Service Natural Resource Report NPS/GRCA/NRR—2020/2103, p. 333–379.
- Massari, F., Ghibaudo, G., D'Alessandro, A., and Davaud, E., 2001, Water-upwelling pipes and soft-sediment-deformation structures in lower Pleistocene calcarenites (Salento, southern Italy): GSA Bulletin, v. 113, no. 5, p. 545–560. [https://doi.org/10.1130/0016-7606\(2001\)113%3C0545:WUPASS%3E2.0.CO;2](https://doi.org/10.1130/0016-7606(2001)113%3C0545:WUPASS%3E2.0.CO;2)
- McAllister, J.A., 1979, The lungfish *Gnathorhiza* and its burrows from the lower Permian of Kansas [PhD dissertation]: Lawrence, University of Kansas, 160 p.
- McKee, E.D., 1933, The Coconino Sandstone—Its history and origin, in Papers Concerning the Paleontology of California, Arizona, and Idaho: Carnegie Institution of Washington Publication 440, p. 77–115.
- McKee, E.D., 1979, Ancient sandstone considered to be eolian, in McKee, E.D., ed., A Study of Global Sand Seas: U.S. Geological Survey Professional Paper 1052, p. 187–238. <https://doi.org/10.3133/pp1052>
- Miller, A.E., Marchetti, L., Francischini, H., and Lucas, S.G., 2021, Chapter 8—Paleozoic invertebrate ichnology of Grand Canyon National Park, in Santucci, V.L., and Tweet, J.S., eds., Grand Canyon National Park—Centennial Paleontological Resource Inventory: National Park Service Natural Resource Report NPS/GRCA/NRR—2020/2103, p. 277–331.
- Milner, S., 1978, Genesis, provenance, and petrography of the Glorieta Sandstone of eastern New Mexico: New Mexico Bureau of Mines and Mineral Resources Circular 165, 25 p. <https://doi.org/10.58799/C-165>
- Mossa, J., and Schumacher, B.A., 1993, Fossil tree casts in south Louisiana soils: Journal of Sedimentary Petrology, v. 63, no. 4, p. 707–713. <https://doi.org/10.1306/D4267BC2-2B26-11D7-8648000102C1865D>
- Naugolnykh, S.V., 2000, Mixed Permian floras of Eurasia—A new concept with significance for paleophytogeographic reconstructions: Paleontological Journal, 34(SUPP/1), p. S99–S105.
- Naugolnykh, S.V., 2005, Permian *Calamites gigas* Brongniart, 1828—The morphological concept, paleoecology and implications: Paleontological Journal, v. 39, no. 3, p. 321–332.

- Netoff, D., 2002, Seismologically induced fluidization of Jurassic erg sands, south-central Utah: *Sedimentology*, v. 49, no. 1, p. 65–80. <https://doi.org/10.1046/j.1365-3091.2002.00432.x>
- Nichols, R.J., Sparks, R.S.J., and Wilson, C.J.N., 1994, Experimental studies of the fluidization of layered sediment, and the formation of fluid escape structures: *Sedimentology*, v. 41, no. 2, p. 233–253. <https://doi.org/10.1111/j.1365-3091.1994.tb01403.x>
- Owen, G., 1987, Deformation processes in unconsolidated sands, *in* Jones, M.E., and Preston, R.M.F., eds., *Deformation of Sediments and Sedimentary Rocks*: Geological Society London Special Publication 29, p. 11–24. <https://doi.org/10.1144/GSL.SP.1987.029.01.02>
- Pemberton, S.G., Frey, R.W., and Bromley, R.G., 1988, The ichnotaxonomy of *Conostichnus* and other plug-shaped ichnofossils: *Canadian Journal of Earth Sciences*, v. 25, no. 6, p. 866–892. <https://doi.org/10.1139/e88-085>
- Pfefferkorn, H.W., 1972, Distribution of *Stigmaria wedingtonensis* (Lycopsidea) in the Chesterian (Upper Mississippian) of North America: *American Midland Naturalist*, v. 88, no. 1, p. 225–231. <https://doi.org/10.2307/2424500>
- Pfefferkorn, H.W., and Fuchs, K., 1991, A field classification of fossil plant substrate interactions: *Neues Jahrbuch für Geologie und Paläontologie Abhandlungen*, v. 183, p. 17–36.
- Pfefferkorn, H.W., Gillespie, W.H., Resnick, D.A., and Scheihing, M.H., 1984, Reconstruction and architecture of medullosan pteridosperms (Pennsylvanian): *The Mosasaur*, v. 2, p. 1–8.
- Phoenix, D.A., 1958, Sandstone cylinders as possible guides to paleomovement of ground water, *in* Anderson, R.Y., and Harshbarger, J.W., eds., *Black Mesa Basin, Northeastern Arizona*: New Mexico Geological Society Fall Field Conference Guidebook 9, p. 194–198. <https://doi.org/10.56577/FFC-9.194>
- Read, C.B., Wilpolt, R.H., Andrews, D.A., Summerson, C.H., and Wood, G.H., 1944, Geologic map and stratigraphic sections of Permian and Pennsylvanian rocks of parts of San Miguel, Santa Fe, Sandoval, Bernalillo, Tarrant, and Valencia Counties, north-central New Mexico: U.S. Geological Survey Oil and Gas Investigation Preliminary Map 21, scale 1:190,080. <https://doi.org/10.3133/om21>
- Rinehart, L.F., Lucas, S.G., Tanner, L., Nelson, W.J., Elrick, S.D., Chaney, D.S., and DiMichele, W.A., 2015, Plant architecture and spatial structure of an early Permian woodland buried by flood waters, Sangre de Cristo Formation, New Mexico: *Palaeogeography, Palaeoclimatology, Palaeoecology*, v. 424, p. 91–110. <https://doi.org/10.1016/j.palaeo.2015.02.018>
- Rygel, M.C., Gibling, M.R., and Calder, J.H., 2004, Vegetation-induced sedimentary structures from fossil forests in the Pennsylvanian Joggins Formation, Nova Scotia: *Sedimentology*, v. 51, no. 3, p. 531–552. <https://doi.org/10.1111/j.1365-3091.2004.00635.x>
- Schwendemann, A.B., Wang, G., Mertz, M.L., McWilliams, R.T., Thatcher, S.L., and Osborn, J.M., 2007, Aerodynamics of saccate pollen and its implications for wind pollination: *American Journal of Botany*, v. 94, no. 8, p. 1371–1381. <https://doi.org/10.3732/ajb.94.8.1371>
- Simon, S.S., Gibling, M.R., DiMichele, W.A., Chaney, D.S., and Koll, R., 2018, An exhumed fine-grained meandering channel in the lower Permian Clear Fork Formation, north-central Texas—Processes of mud accumulation and the role of vegetation in channel dynamics, *in* Ghinassi, M., Colombero, L., Mountney, N.P., Reesink, A.J.H., and Bateman, M., eds., *Fluvial Meanders and Their Sedimentary Products in the Rock Record*: International Association of Sedimentologists Special Publication 48, p. 149–171. <https://doi.org/10.1002/9781119424437.ch6>
- Simpson, G.G., 1935, Discussion of papers in volumes 45 and 46—Cylindrical structures in sandstones comment: *Bulletin of the Geological Society of America*, v. 41, no. 12, p. 2011–2014. <https://doi.org/10.1130/GSAB-46-2007>
- Sims, H.J., 2012, The evolutionary diversification of seed size—Using the past to understand the present: *Evolution*, v. 66, no. 5, p. 1297–1673. <https://doi.org/10.1111/j.1558-5646.2011.01527.x>
- Taylor, T.N., Taylor, E.L., and Krings, M., 2009, *Palaeobotany—The Biology and Evolution of Fossil Plants*: Cambridge, MA, Academic Press, 1230 p.
- Thomas, B.A., 2014, In situ stems—Preservation states and growth habits of the Pennsylvanian (Carboniferous) calamitaleans based upon new studies of *Calamites* Sternberg, 1820 in the Duckmantian at Brymbo, North Wales, UK: *Palaeontology*, v. 57, no. 1, p. 21–36. <https://doi.org/10.1111/pala.12045>
- Thomas, B.A., and Seyfullah, L.J., 2015, *Stigmaria* Brongniart—A new specimen from Duckmantian (Lower Pennsylvanian) Brymbo (Wrexham, North Wales) together with a review of known casts and how they were preserved: *Geological Magazine*, v. 152, no. 5, p. 858–870. <http://doi.org/10.1017/S0016756815000035>
- Voorhies, M.R., 1975, Vertebrate burrows, *in* Frey, R.W., ed., *The Study of Trace Fossils*: Berlin, Springer-Verlag, p. 325–350.
- Weiss, M.P., 1956, Tubular structures in Fall River (Dakota) Sandstone: *Journal of Geology*, v. 64, no. 5, p. 521–522. <https://doi.org/10.1086/626383>
- Wnuk, C., and Maberry, J.O., 1990, Enigmatic eight-meter trace fossils in the Lower Pennsylvanian Lee Sandstone, central Appalachian Basin, Tennessee: *Journal of Paleontology*, v. 64, no. 3, p. 440–450.
- Wnuk, C., and Pfefferkorn, H.W., 1984, The life habits and paleoecology of Middle Pennsylvanian medullosan pteridosperms based on an in situ assemblage from the Bernice Basin (Sullivan County, Pennsylvania, USA): *Review of Palaeobotany and Palynology*, v. 41, no. 3–4, p. 329–351. [https://doi.org/10.1016/0034-6667\(84\)90053-8](https://doi.org/10.1016/0034-6667(84)90053-8)