Unusual Sandstone Cylinders from the Lower Permian Glorieta Sandstone, Northern New Mexico
Spencer G. Lucas, William A. DiMichele, and Joseph M. Karnes

The early Permian Glorieta Sandstone is exposed across much of central and northern New Mexico and is part of the same lithosome termed Coconino Sandstone in northern Arizona. Glorieta and Coconino strata are primarily of eolian origin. In New Mexico, the only Glorieta Sandstone fossils that have been reported are reworked marine foraminiferans, but in Arizona, the Coconino Sandstone contains many vertebrate footprints and other trace fossils. On Sacatosa Mesa near Las Vegas in San Miguel County, New Mexico, the Glorieta Sandstone contains numerous upright sandstone cylinders in interdunal sedimentary deposits in the lower part of the formation. Most of these cylinders are perpendicular to bedding, have smooth exteriors, and, in cross section, have a structureless core surrounded by thin, concentric laminae. 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. The lack of deformation of the sediment in and around the cylinders and the external markings on some of the cylinders preclude their identification as inorganic dewatering structures or other forms of water conduits. The sandstone cylinders do not resemble any known cylindrical or plug-shaped trace fossils, and the lack of ornamentation (bioglyphs) on the cylinder walls precludes 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.

Photos of selected sandstone cylinders in the Glorieta Sandstone on Sacatosa Mesa in San Miguel County, New Mexico. In-place cylinders are seen in lateral/oblique views (top row) as well as cross-sectional views. The cross sections reveal the concentric rings present in some of the cylinders and also show the close spacing of some cylinders. Lack of sediment deformation structures and other features excludes dewatering pipes or burrows as the origin of the cylinders, which instead are most likely stem casts of Permian plants. Scales are in mm and cm.
Unusual Sandstone Cylinders from the Lower Permian Glorieta Sandstone, Northern New Mexico

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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 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).

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 calamitelean 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 calamiteleans, 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...
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-85042b (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.
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, 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
deforation 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 calamitaean stems, late Paleozoic relatives of modern equisetaleans, known colloquially as “horsetails” or “scouring rushes.” The cylinders do not have the characteristics of arborescent lycopsids, 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). Lycopsid 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 peltspermas (perhaps taeniopetrids) 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.

Calamitaean 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.
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Few places in the U.S. boast as rich a diversity of landscapes and public lands as northern New Mexico. With almost 300 full-color geologic maps, graphics, and photographs, this celebrated guide provides a detailed overview of the geology of the region’s parks, monuments, and public lands.