

A COAL-MEASURE FOREST NEAR SOCORRO, NEW MEXICO

SPENCER G. LUCAS¹, WILLIAM A. DIMICHELE², KARL KRAINER³,
DAN S. CHANEY² AND JUSTIN A. SPIELMANN¹

¹New Mexico Museum of Natural History and Science, 1801 Mountain Road NW, Albuquerque, NM 87104

²Department of Paleobiology, NMNH Smithsonian Institution, Washington, D. C. 20560

³Institute of Geology and Paleontology, University of Innsbruck, Innsbruck A-6020, AUSTRIA

ABSTRACT—In 1904, Clarence Luther Herrick described a lycopsid flora (including three new species of *Lepidodendron*) from “fire clay” of Pennsylvanian age being mined for brick manufacturing east of Socorro. Herrick’s description of the locality was vague, and it has not been revisited in nearly a century. In 2002 we relocated Herrick’s locality. The “fire clay” is a refractory gray to black shale in the lower part of the Middle Pennsylvanian (Atokan) Sandia Formation that can be followed on strike through a series of fault blocks for more than 2 km. The Sandia Formation at the lycopsid locality contains basal trough-crossbedded quartzose sandstone and quartzite-pebble conglomerate about 4 m thick, filling channels scoured into Proterozoic granite. These coarse clastics are sharply overlain by ~2.5 m of gray and yellow, fine-grained, massive to thinly laminated sandstone, which has lycopsid bark concentrated near the top. This in turn is overlain by the “fire clay” interval, ~4 m of gray and black shale, siltstone, and fine sandstone, which in the lower part contains lenses of coal, a few *Lingula*, and a flora. We suggest this succession represents fluvial deposits directly overlain by an estuarine deposit (lycopsid beds and “fire clay”). Our collections of fossil plants from the lycopsid bed include *Lepidodendron aculeatum*, *Lepidostrobus*, possibly *Synchysidendron*, stigmarian roots and strap-like leaves of the lepidodendrids, *Sphenophyllum*, and neuropterid foliage. Because the type specimens of the species of *Lepidodendron* Herrick named were destroyed in a fire in 1910, we collected new specimens to serve as “topotypes” of the species. However, most of Herrick’s species appear to be within the range of variability known from the single species *Lepidodendron aculeatum*. This lycopsid locality in the Sandia Formation is significant because it indicates that a typical wetland swamp flora existed in New Mexico during early tectonism of the Ancestral Rocky Mountain orogeny.

INTRODUCTION

In 1904, Clarence Luther Herrick (1858-1904), one of the pioneer geologists of the New Mexico Territory, reported on what he termed a “coal-measure forest” near Socorro. This “forest” was an unusual Pennsylvanian fossil plant locality exclusively yielding remains of the lycopsid *Lepidodendron*. Although Herrick (1904) gave precise data on the geologic setting of the fossil site, he offered very vague information about its geographic location. Indeed, this fossil locality remained unknown (or overlooked) for almost a century, until we relocated it in 2002 (Lucas et al., 2003). Here, we provide thorough documentation of Herrick’s site and discuss the paleoecology of the paleoflora he reported.

HERRICK’S DOCUMENTATION

Although Herrick (1904) provided an extensive discussion of the *Lepidodendron* locality near Socorro, he knew of the site before 1900, because Herrick and Johnson (1900, pl. 7) first illustrated plant fossils from the locality. As Herrick (1904, p. 237) put it, “such an area [with a “coal flora”] became known to the

writer a number of years ago, but it long proved impossible to study the locality in person.” The plant fossils came from a bed of “fire clay” being mined east of Socorro, for brick manufacturing. The fossil plants apparently were first brought to Herrick’s attention by George Thwaites, whom Herrick honored by naming a new species, *Lepidodendron thwaitesi*.

A key element of Herrick’s description of the *Lepidodendron* locality is his geological cross section (Fig. 1), which shows two “granite ribs” where the “Sandia formation of the Coal Measures is exposed in basin-like relation upon the granite...” across two faults (Herrick, 1904, p. 239). He further noted (p. 240) that “it is in the V formed by these two faults that the best example occurs of the “fire clay” beds with the enclosed plant remains.” Herrick (1904, p. 241) stated that “the fire clay, with its attendant shales, reposes directly upon the granite, or with a thin layer of quartzite in between” and that “in the clay and especially in the shales overlying are the remains of lepidodendrids and other coal plants referred to.” Herrick (1904) described the stratigraphic section at the *Lepidodendron* locality in some detail, referring to the “fire clay” beds as the “Incarnacion” fire clay, and assigning it and adjacent strata to the Sandia Formation.

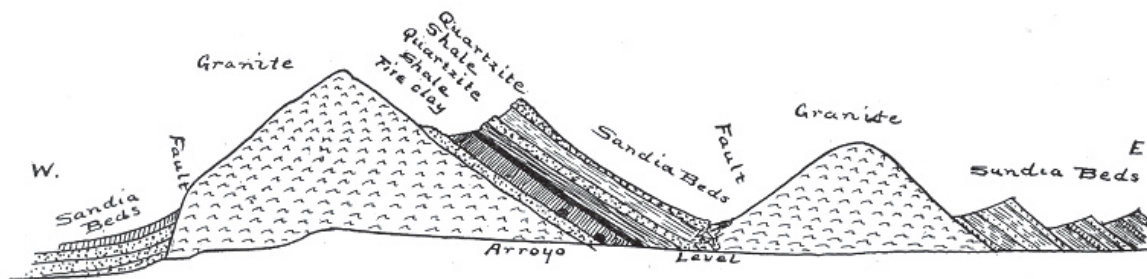


FIGURE 1. Herrick’s (1904, fig. 1) geological cross section at the *Lepidodendron* locality. The plant-bearing bed is just below the “fire clay” above the Precambrian granite in the middle of the cross section. Compare to Figure 3A.

Herrick (1904, figs. 3-10) also illustrated specimens of *Lepidodendron* (Fig. 2) to which he assigned three new species names (*L. thwaitesi*, *L. socorroense* and *L. keyesi*) and one new variety name (*L. thwaitesi* var. *striolatum*). His text (Herrick, 1904, p. 250-251) described characteristics of these new taxa and thus

provided what can be construed as diagnoses – so the taxonomic names Herrick (1904) introduced are available. However, in 1910 the type specimens of the *Lepidodendron* species and variety he named were destroyed in a fire at Denison University in Ohio (Herrick, 1955). Herrick's (1904, p. 248) summary comment

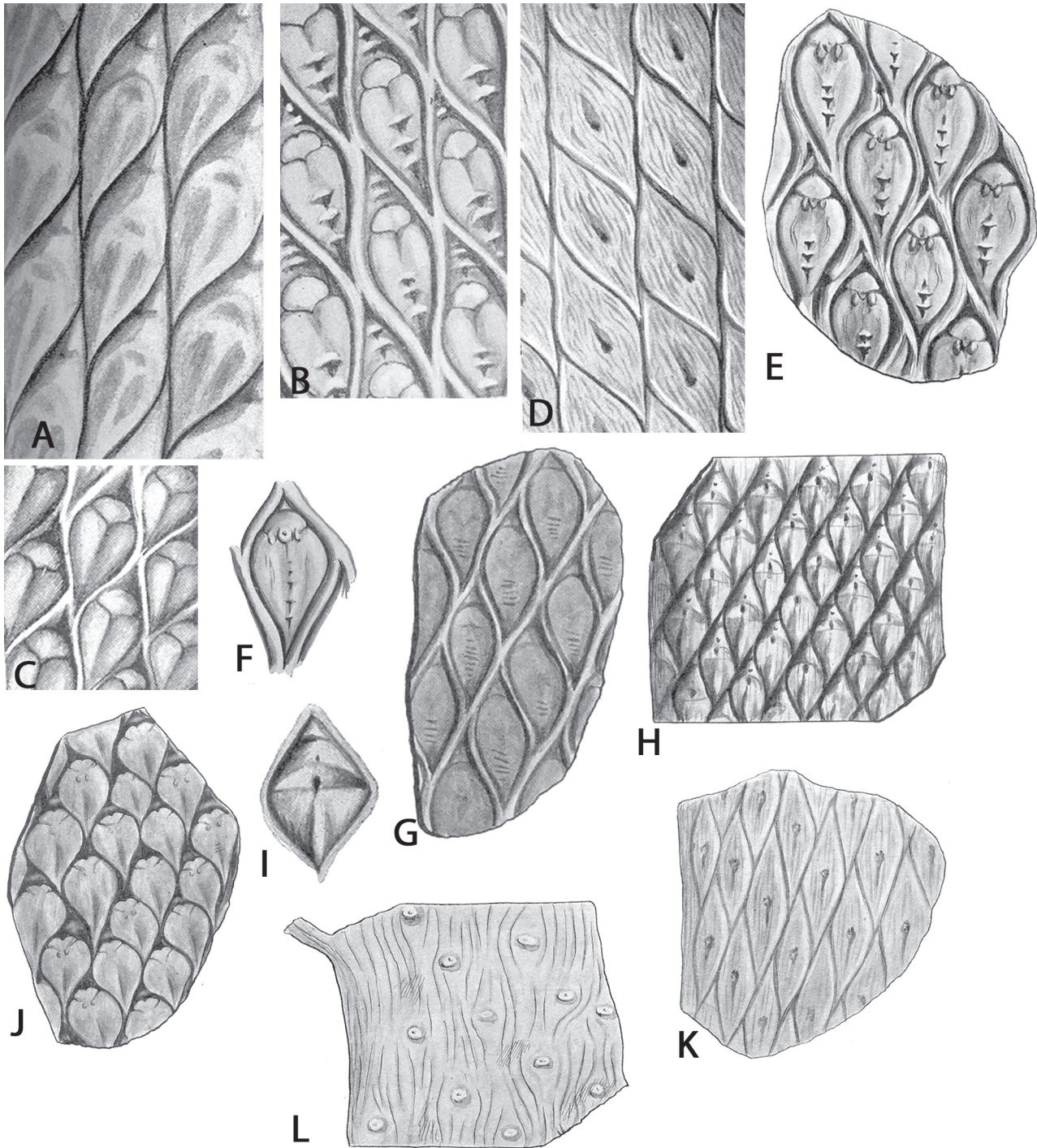


FIGURE 2. Fossil plants from Herrick's "coal-measure forest" illustrated by Herrick and Johnson (1900) and Herrick (1904). **A-D**, *Lepidodendron* sp., from Herrick and Johnson (1900, pl. 7). **E**, *L. thwaitesi* (from Herrick, 1904, fig. 3). **F**, *L. thwaitesi* (from Herrick, 1904, fig. 4). **G**, *L. thwaitesi* var. *striolatum* (from Herrick, 1904, fig. 5). **H**, *L. socorroense* (from Herrick, 1904, fig. 6). **I**, *L. socorroense* (from Herrick, 1904, fig. 7). **J**, *L. keyesi* (from Herrick, 1904, fig. 8). **K**, *L. sp.* (from Herrick, 1904, fig. 9). **L**, "*Stigmaria*" (from Herrick, 1910, fig. 10). No scale indicated by Herrick and Johnson (1900) for **A-D**, but all figures are close to natural size.

about these fossil plants was that “the forms seem to be new, and may serve to assist in calling attention to similar occurrences in the Southwest.”

REDESCRIPTION OF HERRICK'S LOCALITY

Subsequent to Herrick (1904), we are unaware of any specific mention of or analysis of his *Lepidodendron* locality until we rediscovered it in 2002 (Lucas et al., 2003). It is particularly interesting that Darton (1928, p. 68) described a measured section at Herrick's site, noting that “impressions of the bark of a large plant, *Lepidodendron obovatum* (Sternburg), accompany the fire clay. This species identified by David White, indicates a Pottsville (basal Pennsylvanian) age for the lowest Pennsylvanian in this region.” Darton (1928, pl. 19C) also published a photograph of the outcrops at Herrick's (1904) locality, but makes no reference to Herrick, so Darton apparently did not realize that he had rediscovered Herrick's locality. The subsequent paleobotanical literature on late Paleozoic floras in New Mexico (e.g., Read and Mamay, 1964) makes no mention of Herrick's site.

By our determination, the original Herrick/Darton locality is east of Socorro near Arroyo de la Presilla in sec. 11, T03S, R01E (NMMNH [New Mexico Museum of Natural History and Science] locality 5312 and USNM [National Museum of Natural History, Smithsonian Institution] locality 41896). Here, we document its geological context (Figs. 3-4) and the associated flora (Fig. 5), and briefly discuss their paleoecological significance.

STRATIGRAPHY

At Arroyo de la Presilla, the Atokan Sandia Formation is 162 m thick, rests on granitic Precambrian basement and consists of a cyclic succession of siliciclastics and carbonate, nonmarine and marine strata forming well developed transgressive cycles. The *Lepidodendron* locality is only a few meters above the base of the Sandia Formation, so we confine our discussion to the lower 40 m of the Sandia Formation (Figs. 4-5). This part of the section is almost entirely composed of siliciclastic sediments.

At the base of the section (Fig. 4, units 1-2) is a 2-m-thick conglomerate that grades upward to pebbly sandstone and sandstone. The conglomerate consists mostly of subrounded grains being more angular to subangular near the base with a maximum size of about 3 cm. At the base a thin lag of sandstone cobbles up to 20 cm in diameter is developed (Fig. 4, unit 1). The conglomerate is quartz-rich and poorly to moderately sorted. It has an erosive base and is indistinctly to distinctly trough cross-bedded.

This basal conglomerate is overlain by a 1.9-m-thick interval of poorly laminated to massive gray siltstone to fine-grained sandstone containing plant material and roots (Fig. 4, unit 3). The overlying gray siltstone is 1.7 m thick and contains abundant *Lepidodendron* (Fig. 4, unit 4). Above follows gray laminated siltstone (2.1 m), dark gray laminated silty shale containing *Lingula*, and finally the plant-bearing “fire clay,” which is actually a shale (Fig. 4, units 5-7).

There is a discontinuity at the top of the shale overlain by a 7 m thick succession (Fig. 4, units 8-11) composed of alternating, laminated and ripple-laminated siltstone and fine-grained sandstone with a thin channel-fill sandstone at the base. This sandstone has an erosive base and lenses out laterally. In the lower part laminated silty shale is intercalated (Fig. 4, unit 9).

Above a mostly covered slope (light gray silty shale: unit 12), a poorly laminated red and gray sandstone with a thin, basal, poorly sorted, coarse pebbly sandstone at the base is exposed (Fig. 4, unit 13), followed by greenish-brownish silty shale (Fig. 4, unit 14) and a red micaceous sandy siltstone (Fig. 4, unit 15).

The sandy siltstone bed is overlain by 3.6 m of poorly exposed greenish-brownish shale with a thin limestone interbed. (Fig. 4, unit 16). These rocks contain marine fossils, including brachiopods, bryozoans, crinoids and rare rugose corals. Most of these fossils occur in shale above the limestone bed. The microfacies of this limestone is coarse-grained, poorly sorted bioclastic wackestone to packstone containing a few bioclasts > 1 cm. The most abundant fossils in the limestone are bryozoans and crinoids; subordinate are brachiopod shell fragments and spines, echinoderm spines, gastropods and trilobite fragments, rare ostracods and smaller foraminifers (*Endothyra*). Many skeletons are encrusted by cyanobacteria, *Calcivertella* and *Asphaltina*. The rock contains some micritic matrix; in densely packed parts calcite cement is present.

The uppermost 14 m of the measured section comprises reddish, sandy conglomerate, coarse- to fine-grained sandstone and a covered interval probably representing shale (Fig. 4, units 17-25). The sandy conglomerate and sandstone display trough cross-bedding, and a fine-grained sandstone interval is strongly bioturbated (Fig. 4, unit 19). Plant fragments are present in the lower part (Fig. 4, units 17, 18). These strata comprise four fining-upward cycles, each starting with sandy conglomerate or pebbly sandstone, grading into coarse and finally into fine-grained sandstone.

PALEOBOTANY

The paleoflora from the Sandia Formation was examined and collections were made from two sites: (1) the original Herrick locality in Arroyo de la Presilla (USNM 41896) and (2) another nearby site in Arroyo de Tinajas (USNM 41897). The geological sections at the two sites are essentially identical.

At both sites the flora is dominated by arborescent lycopsids, apparently a single species attributable to *Lepidodendron aculeatum* Sternberg (Figs. 3C, 5A-F). Rare elements include lycopsid cones (Fig. 5G-H), indeterminate pteridosperm foliage of neuropterid aspect, *Sphenophyllum* sp., and stems of calamiteans (Fig. 5I). It is also possible that the lycopsid *Synchysidendron* is present in low abundances. Preservation of the material occurs as both impressions and compressions, and the plants appear to have been subject to local transport, though of limited extent, leading to poor preservation of the more delicate elements (the non-lycopsids).

The paleoflora occurs in several different beds in the two exposures, in two different lithofacies. Abundant impressions of

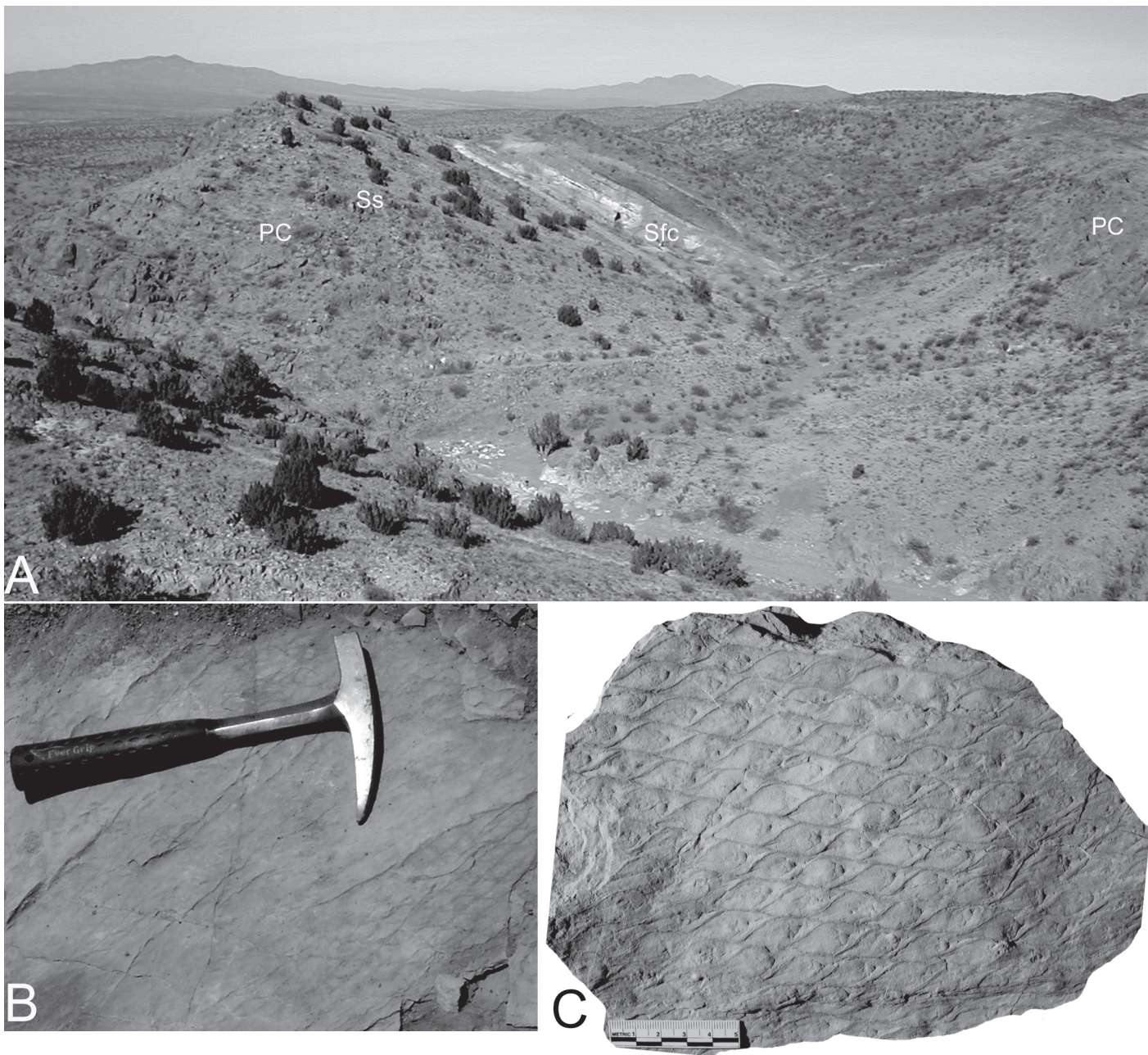


FIGURE 3. **A**, Photograph looking north of Herricks' *Lepidodendron* locality (compare to Herrick's, 1900, fig. 1, cross section reproduced here as Figure 1). **PC** = Proterozoic granite; **Sfc** = "fire clay" in lower Sandia Formation (note old mine adit; the *Lepidodendron* locality is at the base of the fire clay); and **Ss** = sandstone/conglomerates at base of Sandia Formation. Note two ridges of granite (across fault) as shown in Herrick's cross section. **B**, Close-up of *Lepidodendron* bed in situ. **C**, Example of a *Lepidodendron* bark impression, NMMNH P-58001.

various-sized fragments of lycopsid stem (Fig. 3B-C), sometimes with organic matter still adherent, occur in medium to coarse siltstone to fine sandstone with a clay fraction, often finely laminated (?tidal origin). Better preserved material was collected from a single bed, a coarsening upward, medium gray clayey siltstone, with sandy laminae in its upper portion; this was the target of the clay mining operation in Herrick's day. The plant fossils in this siltier lithofacies appear to have been little transported, based on lack of preferential orientation, the wide mixture of sizes and shapes, and the inclusion of many different organs (leaves, stems,

leaf-bases, reproductive organs). It is within this lithofacies that calamites and pteridosperm foliage were identified. The siltstone may have accumulated under brackish water conditions, given the presence of linguloid inarticulate brachiopods (Fig. 5J).

The lycopsid remains from Arroyo de la Presilla were originally described and illustrated by Herrick (1904) as three new species and a new variety: *Lepidodendron thwaitesi*, *Lepidodendron thwaitesi* var. *striolatum*, *Lepidodendron socorroense*, and *Lepidodendron keyesi*. All three of these species names are likely synonyms of older names. Based on the original descriptions and

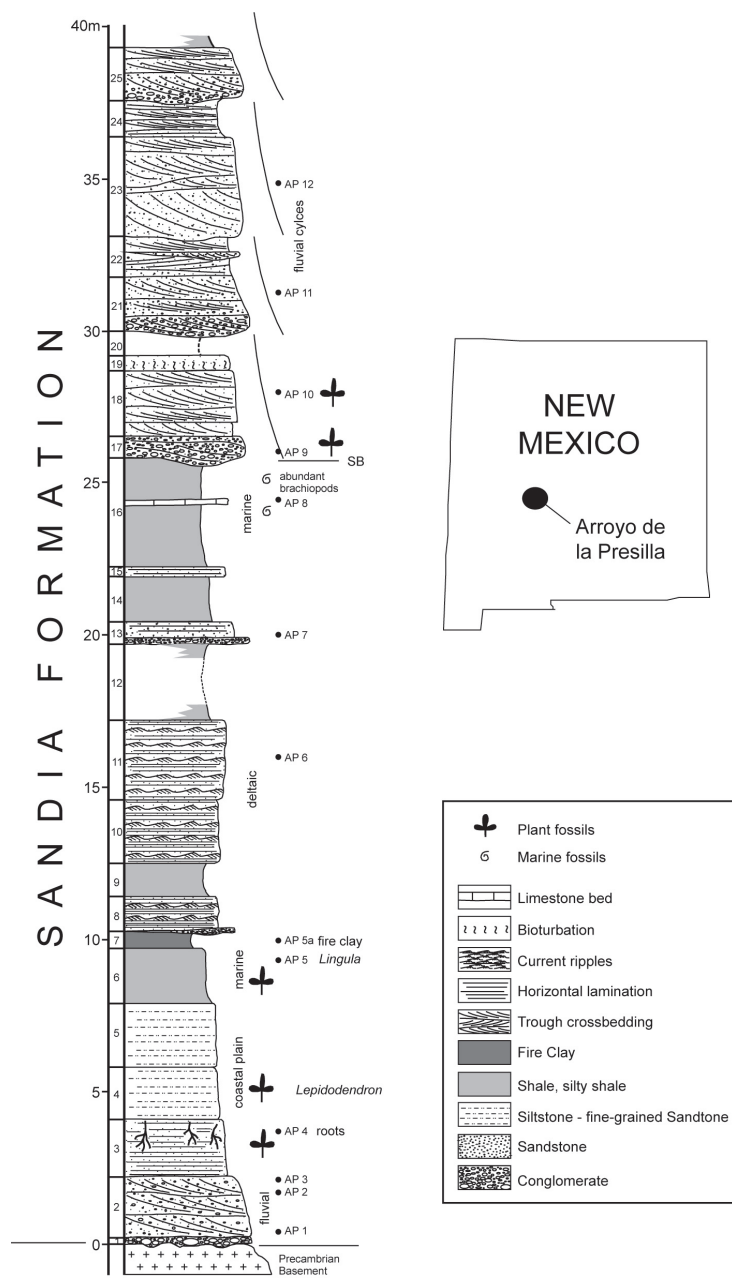


FIGURE 4. Measured stratigraphic section of lower part of Sandia Formation at Herrick's *Lepidodendron* locality. See text for description of units.

illustrations, *L. thwaitesi* and *L. keyesi* appear to represent different parts of the stem of *Lepidodendron aculeatum* Sternberg (see Thomas, 1970 and DiMichele, 1983, for interpretations of this species in compression and petrification, respectively), which changed in certain stereotypical ways during growth (a description of such patterns is provided by Leary and Thomas, 1989).

In order to appreciate why such variation in gross form and, to some degree, shape, might all fall within the circumscription of a single species, it is necessary to consider briefly the growth form of some of these giant lycopsid trees. All of the large lepidodendrid trees appear to have been determinate in their growth.

Lepidodendron species grew for most of their lives as unbranched poles, reaching heights of more than 30 m in some instances (e.g., Thomas and Watson, 1976), prior to the onset of branching. With each branching, the size of the stem decreased until growth ceased. Reproductive organs were borne only in these determinate crowns, meaning that reproduction was confined to a short interval at the end of the life of any individual tree. Leaf cushion shape changed in different ways in different species as axis diameter began to diminish. In *Lepidodendron aculeatum*, the larger leaf cushions are from larger diameter stems, and characteristically have a distinctly elongated diamond shape. Sometimes these cushions have tails that distinctly curve in opposite directions, whereas in other instances the tails are straight. Leaf cushion shape becomes more rhomboidal on progressively smaller diameter axes from more apical areas of the crown.

Lepidodendron aculeatum also has a pair of distinctive infrafoliar parichnos prints present beneath the leaf scar, a feature of the several genera that comprise the Lepidodendrales (Thomas, 1978; Leary and Thomas, 1989; Bateman et al., 1992; DiMichele and Bateman, 1996). This feature is crucial to be able to separate this genus from others that have vertically elongate leaf cushions, not all of which belong in the genus *Lepidodendron*, despite the colloquial use of the name in such a fashion (see DiMichele, 1983). In fact, there are several kinds of arborescent lycopsids with higher-than-wide leaf cushions that otherwise have distinctive anatomical features, different reproductive organs, and subtle leaf-cushion differences. The leaf-cushion features, when linked to anatomy, permit the different genera to be identified by leaf-cushion morphology alone.

Nearly all the lepidodendrid specimens examined on site or collected from the two fossiliferous sites are typical of *Lepidodendron aculeatum*. The cushions are generally higher than wide. They have a distinct leaf scar located in the upper half of the leaf cushion in the larger, more elongate forms (Fig. 5A-D), or near the very top of the cushion, in the smaller, more rhomboidal forms (Fig. 5E-F). Each leaf scar contains, in the middle to lower third, a distinct leaf trace flanked by two small aerating "parichnos" strands (Fig. 5B-C). Beneath the leaf scar is an elongate ridge or "keel". This keel may have folds, also called "bars" or "plications" (Fig. 5A, C), or it may be unornamented (Fig. 5B, E-F). In the larger cushions, there also is a keel that runs from the top of the scar to the apex of the cushion that also may have small folds (Fig. 5A-D). The ends of the keels may be straight (Fig. 5A, C, E) or curved, and if curved, in opposite directions (Fig. 5 B, D, F). Prominently developed in some of the larger cushions is a hood above the leaf scar, with lateral lines that run down below the scar to the edge of the leaf cushion (Fig. 5B, C). At the apex of the leaf scar a small depression or notch often can be observed (Fig. 5B), the location of a pit in which a small secretory structure, the ligule, was located in life; the function of the ligule is uncertain but it is characteristic of two of the major groups of lycopsids, the isoetoids (to which the lepidodendrids belong) and the selaginelloids. Also present flanking the lower keel, immediately below the leaf scar, are infrafoliar parichnos aerating strands (note especially Fig. 5A, C-D). This pair of prints, visible often with the naked eye, or with a handlens, is a feature that puts these fossils

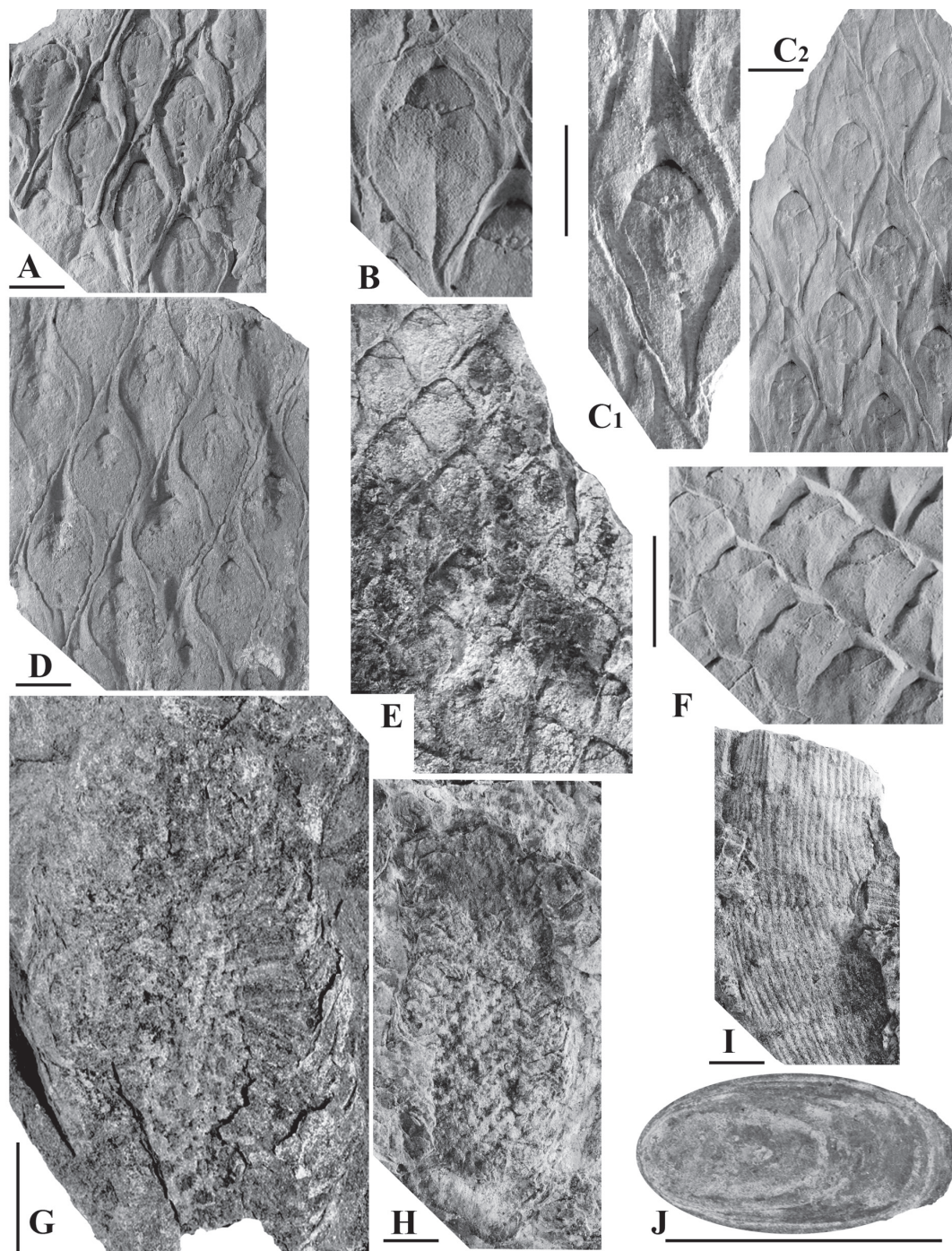


FIGURE 5. Selected fossil plants and brachiopod from the Sandia Formation at Herrick's locality. A, *Lepidodendron aculeatum* USNM 536619 leaf cushions, showing barred keels. Note parichnos strands both within leaf scars and below the scar flanking the keels. Scale bar = 1 cm. B, *Lepidodendron aculeatum* USNM 536611 leaf cushion. Note lack of folds on keel, ligule pit immediately above leaf scar, and leaf trace flanked by parichnos strands at the base of the leaf scar. Faint infrafoliar parichnos are present below the leaf scar. Scale bar = 1 cm. C, *Lepidodendron aculeatum*. USNM 536614 C1: Cushion closeup. C2: Multiple cushions in helical phyllotaxy. Scale bars = 1 cm. D, *Lepidodendron aculeatum* USNM 536618 leaf cushions, showing curved keel tails. Scale bar = 1 cm. E, *Lepidodendron aculeatum* USNM 536616 leaf cushions. Cushions are from smaller diameter axes and are, themselves of small size. Note that proportions have changed to more equidimensional and leaf scar is much closer to the top of the leaf cushion. Scale bar = 1 cm. F, *Lepidodendron aculeatum* USNM 536615 leaf cushions, showing smaller cushions associated with smaller diameter stems. As in (E), cushions are more equidimensional and the leaf scar is closer to the apex of the leaf cushion. Keels are clearly marked. Scale bar = 1 cm. G, *Lepidostrobus* sp., USNM 536621 presumed cone of *Lepidodendron aculeatum*. Note central axis surrounded by sporophylls. Scale bar = 1 cm. H, *Lepidostrobus* sp., USNM 536622 presumed cone of *Lepidodendron aculeatum*. Note central axis surrounded by sporophylls. Scale bar = 1 cm. I, *Calamites* sp. USNM 536624 Stem of arborescent sphenopsid, or 'horsetail'. Note characteristic vertical ribs and nodes. Scale bar = 1 cm. J, Linguloid inarticulate brachiopod. USNM 536625 Scale bar = 1 cm.

securely in the *Lepidodendrales*, and not in one of the other lineages of giant lycopsids with higher-than-wide leaf cushions.

Leaves and cones of these lycopsid trees also were found in association with the stem remains, mainly in the finer siltstones. The leaves are typical of giant lycopsids in their narrow, grass-like gross morphology, with a single central vein. The cones show both the central axis and the surrounding sporangia, including some coalified remains (Fig. 5G-H). Dr. Debra Willard of the U.S. Geological Survey kindly prepared some of the organic material to see if spores could be extracted, which would have improved our diagnosis of the stem material (Willard, 1989). Unfortunately, the specimens proved barren.

A few lepidodendrid specimens had leaf cushions that were vertically elongate and relatively wide, lacked infrafoliar parichnos, and appeared to be thick during life. These are potentially assignable to the genus *Synchysidendron* (DiMichele and Bateman, 1992). However, this also could be a preservational happenstance, given the coarseness of the preserving matrix and the decay state of the some of the specimens. Herrick's *Lepidodendron socorroense* is potentially assignable to this genus, allowing for the same caveats regarding preservation mentioned above. This species is represented in Herrick's original paper by two figures (herein, Fig. 2H-I; Herrick, 1904, figs.6-7), neither of which show enough leaf cushion details for a confident identification or for comparison of this species with other described species of arborescent lycopsid. Herrick himself noted (page 250) that "the specimens leave much to be desired in detailed structure of the leaf scars." As illustrated, the leaf cushions show no evidence of infrafoliar parichnos, which is a diagnostic feature of true *Lepidodendron*. On that basis, it could be speculated that *L. socorroense* is actually a member of a genus such as *Synchysidendron* or *Diaphorodendron* (DiMichele and Bateman, 1992), which have higher-than-wide leaf cushions but lack infrafoliar parichnos. Based on the size of the cushions and their apparent thickness, they are more likely to be *Synchysidendron*. Without more specimens it is not possible to evaluate leaf-cushion shape changes, which differ in these genera from those seen in *Lepidodendron*.

The flora also contains other elements, all rare. The most prominent of these are stems of calamitaleans, the giant horsetails (Fig. 5I). The illustrated specimen clearly shows the characteristic ribbing and several nodes – the point at which leaves and, if present, lateral branches would have been attached. Fragmentary remains of *Sphenophyllum* were identified in the field. Small bits of pinnules similar in form to those of neuropterid pteridosperms (seed ferns) were also found, but all are fragmentary.

DEPOSITIONAL ENVIRONMENT

In the lower part of the Sandia Formation at Arroyo de la Presilla, we identify a succession of depositional cycles: cycle 1 – units 1-7, cycle 2 – units 8-12, cycle 3 – units 13-16, etc (Fig. 4). Textural and structural properties of the sandstones and conglomerates at the bases of these cycles include basal erosional scour, trough cross-bedding, poor sorting and rounding, and fossil plants indicative of a fluvial origin (multistoried channel

fills). The siliciclastic material was derived mostly from granitic and subordinately from metamorphic source rocks. Poor sorting and rounding of the larger clasts indicate short transport distances. The small amount of detrital feldspars, which are mostly diagenetically altered to clay minerals, indicates that most of the feldspars and other unstable grains underwent intense chemical weathering.

The basal 26 m of the Sandia Formation section at the Arroyo de la Presilla (Fig. 4, units 1-16) reflect a transgressive sequence, starting with cross-bedded fluvial conglomerate with a coarse lag deposit at the base. The overlying siltstone and silty shale are interpreted as deposits of a coastal plain with some ponds (swamp) in which plants accumulated, with the first marine influence indicated by the occurrence of *Lingula* below the fire clay. The horizontally and ripple-laminated succession above the fire clay is assumed to represent a deltaic facies that grades upward into a shallow marine facies indicated by fossiliferous shale and an intercalated thin fossiliferous limestone bed containing a diverse fossil assemblage (Fig. 4, unit 16).

PALEOECOLOGY

The *Lepidodendron* locality is in the stratigraphically lowest cycle in the Sandia Formation (Fig. 4). Above the basal fluvial deposits of the cycle, the beds fine upward to what we interpret as estuarine black shales with fossil plants and the brachiopod *Lingula*, an indicator of brackish water. The most fossil-rich bed at the *Lepidodendron* locality is an organic rich bed full of bark and root impressions (Fig. 4, unit 4) that may represent the plants that grew locally after the flooding of the fluvial channel complex, creating a swampy environment perhaps only slightly above sea level that was subsequently flooded by an estuary. Fossils also occur at other places in the succession, especially at the base of sandstones.

At both the Arroyo de la Presilla and Arroyo de Tinajas sites, the fossiliferous beds lie above an organic shale layer, 10-15 cm thick. At the Arroyo de la Presilla site, the plant-rich clay-rich siltstone is separated from the organic zone by as much as 2 m of sandstone. At Arroyo de Tinajas, the plant-rich siltstone is separated from the organic bed by as little as 3 cm of sandstone. In either instance, this documents that the flora of the organic siltstone grew in wetlands likely distinct from that in which the organic mudstone accumulated.

The organic beds are clastic rich, so much so that they cannot be categorized as "coals," but rather should be designated organic shales. They are rich in the remains of stigmarian axes and rootlets, the rooting systems of giant lycopsid trees. They probably originated as organic mucks formed in swampy lowlands under seasonal, but permanently humid conditions. Note that peat formation requires 10 or months a year during which rainfall exceeds evapotranspiration (Cecil, 1990). The presence of abundant remains of *Lepidodendron* in these deposits does indicate, however, the presence of large stands of giant lycopsids. As far as is understood, these trees were obligate swamp dwellers. Their root systems were not capable of penetrating hard substrates and penetrated those substrates only to very shallow depths (Phil-

lips and DiMichele, 1992). In addition, their reproductive organs consisted of small microspores and large, seed-like megaspores that likely were water dispersed and probably aquatic fertilized, a form of reproductive organ Phillips (1979) labeled an aquacarp.

The presence in New Mexico during the Atokan of small swamp deposits, limited organic accumulation, but clearly indicative of wet climates, is of considerable significance, given the paleogeographic location at the equator and on the edge of the accreting Pangaeon supercontinent. In eastern North America, at this same time, massive peat accumulations were commonplace during the wetter parts of glacial-interglacial cycles that dominated the tropical region. Those coal beds appear to have formed under perhumid conditions, that is; rainfall exceeded evapotranspiration at all times during the year, resulting in ombrotropic geomorphology, indicated by patterns of petrographic and palynological composition (Greb et al., 2002). In contrast, moving to the west, similar aged coals in the Illinois Basin were much less abundant and, although possibly ombrotrophic, were thinner and more discontinuous (Mastalerz et al., 2003), implying that wetter intervals may have been less common or less persistent than in the Appalachians. This trend to westward, drier conditions during the wettest parts of glacially driven climate-sea-level cycles is strongly manifested in the limited nature of the wetland deposits in the New Mexico Pennsylvanian succession.

On the other hand, the presence of mineral substrate swamp deposits of a kind that are essentially the same as classic “roof-shale” floras associated with coal-beds of equivalent age in the eastern United States and Europe (Gastaldo et al., 1995), is significant as a paleoclimatic indicator. It demonstrates that the areal extent of non-peat forming wetlands was both greater than and inclusive of the conditions suitable for peat formation and preservation. Here, in central New Mexico, on the western edge of the Pennsylvanian tropical belt, were wetlands but no peat-forming habitats of any significance. This lends strong support to assertions, such as that of Cecil (1990), that the climates under which peat formed were subtly different from those under which mineral substrate swamps and other non-peat-forming wet landscapes of the Pennsylvanian formed (though note, also, that the hydraulic regime and amount of clastic material being delivered into the area would also affect the presence/absence of peat-forming habitats). As this pattern is manifested regionally in space, it is probable that within the coal basins, similar subtle changes in climate through time accompanied the change from peat formation (coal) to the deposition of terrestrial and marine roof shales.

ACKNOWLEDGMENTS

Jess Hunley and John Nelson assisted in the field. Bob Eveleth provided information that helped us relocate Herrick’s locality. Chris Cleal, Jason Hilton and John Nelson provided helpful reviews of the manuscript.

REFERENCES

- Bateman, R.B., DiMichele, W.A. and Willard, D.A., 1992, Experimental cladistic analysis of anatomically-preserved arborescent lycopsids from the Carboniferous of Euramerica: an essay on paleobotanical phylogenetics: *Annals of the Missouri Botanical Garden*, v. 79, p. 500-559.
- Cecil, C.B., 1990, Paleoclimate controls on stratigraphic repetition of chemical and siliciclastic rocks: *Geology*, v. 18, p. 533-536.
- DiMichele, W.A., 1983, *Lepidodendron hickii* and generic delimitation in Carboniferous lepidodendrid lycopsids: *Systematic Botany*, v. 8, p. 317-333.
- DiMichele, W.A. and Bateman, R.M., 1992, Diaphorodendraceae, fam. nov. (Lycopsida: Carboniferous): systematics and evolutionary relationships of *Diaphorodendron* and *Synchysidendron*, gen. nov.: *American Journal of Botany*, v. 79, p. 605-617.
- DiMichele, W.A. and Bateman, R.M., 1996, The rhizomorphic lycopsids: a case study in paleobotanical classification: *Systematic Botany*, v. 21, p. 535-552.
- Gastaldo, R.A., Pfefferkorn, H.W. and DiMichele, W.A., 1995, Characteristics and classification of Carboniferous roof shale floras; in Lyons, P.C., Morey, E.D. and Wagner, R.H., eds., *Historical perspectives of early Twentieth Century Carboniferous paleobotany in North America*: Geological Society of America, *Memoir* 185, p. 341-352.
- Greb, S.F., Eble, C.F., Hower, J.C. and Andrews, W.M., 2002, Multiple-bench architecture and interpretations of original mire phases – Examples from the Middle Pennsylvanian of the Central Appalachian Basin, USA: *International Journal of Coal Geology*, v. 49, p. 147-175.
- Herrick, C.J., 1955, Clarence Luther Herrick: pioneer naturalist, teacher, and psychobiologist: *Transactions of the American Philosophical Society*, new series, v. 45, p. 1-85.
- Herrick, C.L., 1904, A coal-measure forest near Socorro, New Mexico: *Journal of Geology*, v. 12, p. 237-251.
- Herrick, C.L. and Johnson, D.W., 1900, The geology of the Albuquerque sheet: Denison University Scientific Laboratory, *Bulletin* 11, p. 175-239 [also published in 1900 as *New Mexico University, Bulletin* 2, 67 p.].
- Leary, R.L. and Thomas, B.A., 1989, *Lepidodendron aculeatum* with attached foliage – Evidence of stem morphology and fossilization processes: *American Journal of Botany*, v. 76, p. 283-288.
- Lucas, S.G., DiMichele, W.A., Chaney, D.S. and Nelson, J., 2003, Rediscovery of Herrick’s “coal-measure forest” in the Pennsylvanian Sandia Formation, Socorro County, New Mexico: *New Mexico Geology*, v. 25, p. 43.
- Mastalerz, M., Ames, P.R. and Padgett, P.L., 2003, Coals of the Brazil Formation (Pennsylvanian) in Indiana: observations of correlation inconsistencies and their implications: *International Journal of Coal Geology*, v. 54, p. 209-222.
- Phillips, T.L., 1979, Reproduction of heterosporous arborescent lycopsids in the Mississippian-Pennsylvanian of Euramerica: *Review of Palaeobotany and Palynology*, v. 27, p. 239-289.
- Phillips, T.L. and DiMichele, W.A., 1992, Comparative ecology and life-history biology of arborescent lycopsids in Late Carboniferous swamps of Euramerica: *Annals of the Missouri Botanical Garden*, v. 79, p. 560-588.
- Read, C.B. and Mamay, S.H., 1964, Upper Paleozoic floral zones and floral provinces of the United States: U.S. Geological Survey, *Professional Paper* 454-K, 35 p.
- Thomas, B.A., 1970, Epidermal studies in the interpretation of *Lepidodendron* species: *Palaeontology*, v.13, p. 145-173.
- Thomas, B.A., 1978, Carboniferous Lepidodendraceae and Lepidocarpaceae: *Botanical Review*, v. 44, p. 321-364.
- Thomas, B.A. and Watson, J., 1976, A rediscovered 114-foot *Lepidodendron* from Bolton, Lancashire: *Geological Journal*, v. 11, p. 15-20.
- Willard, D.A., 1989, *Lycospora* from Carboniferous *Lepidostrobus* compressions: *American Journal of Botany*, v. 76, p. 1429-1440.