



Megaflora and palynoflora associated with a late Pennsylvanian coal bed (Bursum Formation, Carrizo Arroyo, New Mexico, U.S.A.) and paleoenvironmental significance

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MEGAFLORA AND PALYNOFLORA ASSOCIATED WITH A LATE PENNSYLVANIAN COAL BED (BURSUM FORMATION, CARRIZO ARROYO, NEW MEXICO, U.S.A.) AND PALEOENVIRONMENTAL SIGNIFICANCE

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ABSTRACT—The only known coal bed in the Late Pennsylvanian Bursum Formation crops out in Carrizo Arroyo, Valencia County, New Mexico. Biozonation using fossils of conodonts, insects and plants suggests a latest Pennsylvanian age. The coal was first reported by Darton in 1928, and palynofloras have been previously obtained from strata below and above it. Associated megaflora was noted but not illustrated. Here, we re-describe the coal-bearing interval in detail, describe and illustrate a palynoflora from the coal and some elements of the megaflora from above and below it. The peat body from which the coal is derived appears to have formed in an abandoned channel, possibly an oxbow lake or estuary. It is high in mineral matter and inertinite macerals. It may have formed during a widespread episode of Late Pennsylvanian tropical humid equability. This humid episode was relatively less intense in western Pangea than in central Pangea, where it led to thicker and more widespread peat formation. Long-term preservation of the peat body was likely facilitated by regional syndepositional tectonism.

INTRODUCTION

Coal beds are one of the iconic lithologies of Pennsylvanian and early Permian strata in paleotropical Euramerica and Cathaysia, but Paleozoic coal is rare in the regions that once constituted western equatorial Pangea (i.e., southwestern and western U.S.A.). The near lack of such beds in this region through most of the Pennsylvanian, and virtual absence in the Permian, and their relative thinness and high ash content where they are known, render such coals non-economic, at least for commercial mining. The only significant Paleozoic coal in New Mexico is in the Sandia Formation (Morrowan and Atokan; Early and Middle Pennsylvanian), mainly in San Miguel County, in the northern part of the state. Mined on a small scale for local use during the early 20th century, Sandia Formation coal beds are no more than one meter thick and generally are high in mineral matter content (Gardner, 1910; Read et al., 1950; Baltz and Myers, 1999). As in the rest of the Rocky Mountain region, major coal deposits of New Mexico lie in rocks of Cretaceous and Paleocene age. The absence of high-quality coal beds in New Mexico Pennsylvanian strata (Read et al., 1950) reflects primarily the rarity of climatic conditions necessary

for both the formation of the parent peat bodies and their short-term preservation, where and if they did form.

Western equatorial Pangea, like most of the Euramerican paleotropical belt, underwent a general intensification of climatic seasonality beginning in the Middle Pennsylvanian and continuing into the Permian (Cecil, 1990; Tabor and Poulsen, 2008; Tabor et al., 2008; van Hoof et al., 2013). The effects of aridification were manifested earlier in the western regions of the developing supercontinent than in the more central (Western Interior through the Variscan regions of present day North America and Europe) and eastern (present day China) areas (Roscher and Schneider, 2006; DiMichele et al., 2011). However, floras dominated by coniferopsid vegetation characteristic of seasonally dry conditions began appearing in coal basins across the Euramerican equatorial latitudes of Central Pangea by the latest Viséan–Bashkirian (e.g., van Hoof et al., 2013; Bashforth et al., 2014; Falcon-Lang et al., 2016) and appear to have been dominant during some phases of glacial-interglacial cycles by the Middle Pennsylvanian (e.g., Falcon-Lang and Bashforth, 2005; Falcon-Lang et al., 2009). They alternated spatially with widespread wetlands as climate changed in synchrony with eustatic sea-level fluctuations (Falcon-Lang, 2004; Falcon-Lang

and DiMichele, 2010; Cecil et al., 2014; DiMichele, 2014).

The general state of the climate in the western region of Pangea throughout most of the Pennsylvanian inhibited peat formation for two reasons. Seemingly most obvious might be the “wrong” climate – not wet enough. However, there is ample evidence of plants in western Pangea identical to those that thrived in peat-rich wetlands of the central Pangean equatorial region, strongly suggesting that swampy areas were common enough in the west, perhaps as riparian wetlands, to support populations of these plants at many times during the Pennsylvanian (consider floras mentioned by Pfefferkorn, 1979, documented by Ash and Tidwell, 1982; Mamay and Mapes, 1992; Tidwell et al., 1992, 1999; Lucas et al., 2009). Perhaps equally important, peat formation may have been inhibited by abundant siliciclastic sediment in the streams and rivers of the region, delivered to the swamps where wetland plants thrived, thus diluting out organic accumulations with silt and clay. As discussed by Cecil and Dulong (2003) and Cecil et al. (2003), the degree of rainfall seasonality in modern tropical settings places strong controls on sediment volume in stream drainages; in what might appear counter-intuitive, rainfall at the “ever-wet” end of the warm climate spectrum (humid to perhumid climates in the terminology of Cecil, 2003) encourages lush plant growth, accompanied by intensive rooting of soils and the development of surficial root mats, which strongly bind soils and greatly reduce sediment runoff to streams. Many streams and rivers under perhumid climates are “black water,” carrying minimal amounts of dissolved sediments and humic acids, even if surrounded by relatively high topographic relief (see Cecil et al., 2003 for examples). It is under seasonal rainfall regimes (sub-humid to semi-arid climates) that rooting diminishes, and the largest volumes of sediment are eroded by flowing water. In addition to this climatic scenario, New Mexico during the Pennsylvanian was subject to extensive tectonism that created uplifts of various elevations and spatial extent (see Kues, 2004 for a map illustrating these areas). Consequently, under semi-arid to sub-humid climate regimes, there were numerous ready and nearby sources of sediment to be transported into basinal wetland settings. As a result, even if tectonics created catchments where water ponded and swamps developed, the abundance of sediment flowing into these areas under subhumid-to-semiarid climates would have been anathema to peat formation.

Climate also plays a role in peat preservation, in the short term. Conditions must be wet enough, nearly continuously so, for organic matter to accumulate and be preserved in the short-term time frames of hundreds to thousands of years, the time frames of peat accumulation. If organic matter is not rapidly confined below the vadose zone of surface soils, it will be subject to effectively instantaneous destruction, on the time scales of geology, by aerobic micro- and macro-organisms (Gastaldo and Demko, 2011). The combination of the tectonic regime in New Mexico during the Pennsylvanian, and glacio-eustatic sea-level fluctuations (Theiling et al., 2012), ensured that both intermediate and longer-term preservation of peat would have been possible, were there any peat to preserve. In fact, the active tectonism of Pennsylvanian times would have made the New Mexico region as good or better a place to drown swamps

and bury peat, and subject it to the forces that create coal, than in most of the basins in central Pangea. Although the nature of the structural framework was different, the tectonically active Variscan and Appalachian regions are, by comparison with New Mexico, rich in latest Mississippian and Pennsylvanian coal deposits (Roscher and Schneider, 2006; Opluštil and Cleal, 2007; Greb et al., 2008; Gastaldo et al., 2009; Schneider and Romer, 2010).

In this report we examine a thin, locally developed coal bed that occurs near the base of the Bursum Formation in Carrizo Arroyo, central New Mexico, U.S.A. (Fig. 1). The Bursum Formation, based on many lines of biostratigraphic evidence, encompasses the Pennsylvanian–Permian boundary, whichever definition of that boundary one may choose (Kues, 2001, 2004; Lucas and Krainer, 2002; Lucas et al., 2013a). This is, to our knowledge, the youngest Paleozoic coal bed in the state. It was first reported by Darton (1928) and has been mentioned in a number of publications. The stratigraphic position and depositional setting of this coal has been discussed in detail by Kues (2004), who also made mention of, but did not illustrate, the fossil flora known in association with it. Two additional studies have analyzed the palynomorphs from strata below and above the coal bed (Traverse and Ash, 1999; Utting et al., 2004), focusing mainly on the age of the deposit.

Since the time these studies were published, an organic-rich, coaly deposit has been identified in the Bursum Formation, in Laborcita Canyon, southern New Mexico. An organic-rich coaly bed also has been identified and studied in central Arizona, from approximately the same time interval (Kremp, 1975). Although neither of these latter beds can be positively correlated with the Carrizo Arroyo coal bed, their presence in the same stratigraphic interval does suggest that, at times (or perhaps at a single time) during the Pennsylvanian-Permian transition, climatic conditions were suitable for peat formation. And, where the tectonic setting allowed, these peats were preserved as thin coals.

CARRIZO ARROYO STRATIGRAPHY AND AGE

Carrizo Arroyo is a canyon located about 50 km southwest of Albuquerque and 30 km west of Los Lunas in Valencia County (Fig. 1). The site is on the eastern escarpment of the Lucero uplift, which marks the boundary between the Colorado

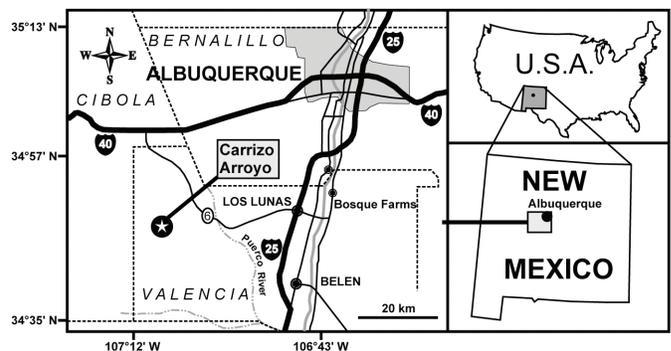


FIGURE 1. Location of Carrizo Arroyo in central New Mexico.

Plateau on the west and the Rio Grande rift (Basin and Range province) on the east at this latitude (Kelley and Wood, 1946). During the Virgilian, the site of Carrizo Arroyo lay along the western margin of the Orogrande basin, a narrow seaway that extended south-southeast from the shrinking Paradox basin toward the western tip of Texas (Nelson and Lucas, 2011).

At Carrizo Arroyo, an approximately 105-m-thick section of Upper Paleozoic siliciclastic and carbonate rocks yields extensive fossil assemblages of marine and nonmarine origin, including two Lagerstätten that have been thoroughly investigated (e.g., Kues and Kietzke, 1976; Krainer et al., 2001; Lucas and Krainer, 2002; Lucas and Zeigler, 2004; Kues, 2004; Lucas et al., 2013a; Schneider and Lucas, 2013). The base of the section (Fig. 2) is relatively thick-bedded, ledge-forming gray limestone and interbedded drab shale of the upper part of the Atrasado Formation (Moya Member). These strata are of marine origin and of unquestioned Late Pennsylvanian (Virgilian) age (Wahlman and Kues, 2004).

Most of the section at Carrizo Arroyo belongs to the Red Tanks Member of the Bursum Formation, a dominantly nonmarine unit that contrasts with the more widespread Bruton Member that generally characterizes the Bursum Formation to the south in New Mexico (Lucas and Krainer, 2003, 2004; Krainer and Lucas, 2004, 2009). The Bruton Member is relatively thin (less than 10 to about 30 m) and comprises alternating beds of nodular and bedded, fossiliferous marine limestone and variegated, non-fissile mudstone, the latter representing paleosols. Coarse, arkosic sandstone and conglomerate are lesser constituents. Exemplified at Carrizo Arroyo, the Red Tanks Member is thicker (30 to 100 m) and contains thick intervals of laminated greenish and olive-gray shale and siltstone, punctuated by thin layers of marine limestone, sandstone, and conglomerate. Fauna of the fine-grained Red Tanks clastics indicate fluctuating salinity, from fresh through brackish to near-normal marine salinity.

At Carrizo Arroyo, the Red Tanks Member is ~100 m thick and is mostly green, gray and minor red shale, mudstone and siltstone of nonmarine to brackish and marine origin, intercalated with some beds of limestone and shale of marine origin (Fig. 2). Siliciclastic red beds of the early Permian Abo Formation overlie the strata of the Red Tanks Member. The Abo Formation records wholly nonmarine deposition by river channels and on floodplains (Lucas et al., 2013b).

Lucas and Krainer (2002) subdivided the Red Tanks Member at Carrizo Arroyo into six depositional sequences. The coal bed discussed here is in the middle of Depositional Sequence 2 and occurs 26.5 m above the base of the Bursum Formation (Fig. 2), which begins just above the marine limestone mentioned above. Sequence 2 includes the coal bed and siliciclastic units below and above it, and, in particular, the plant fossils from these units.

At Carrizo Arroyo, fossils from the Red Tanks Member are palynomorphs, calcareous algae, charophytes, plant megafossils, non-fusulinid foraminifers, fusulinids, bryozoans, brachiopods, gastropods, bivalves, nautiloids, eurypterids, ostracods, syncarid crustaceans, conchostracans, insects and some other arthropods, echinoids, crinoids, conodonts, fish ichthyoliths and bones of amphibians and reptiles. At stratigraphic

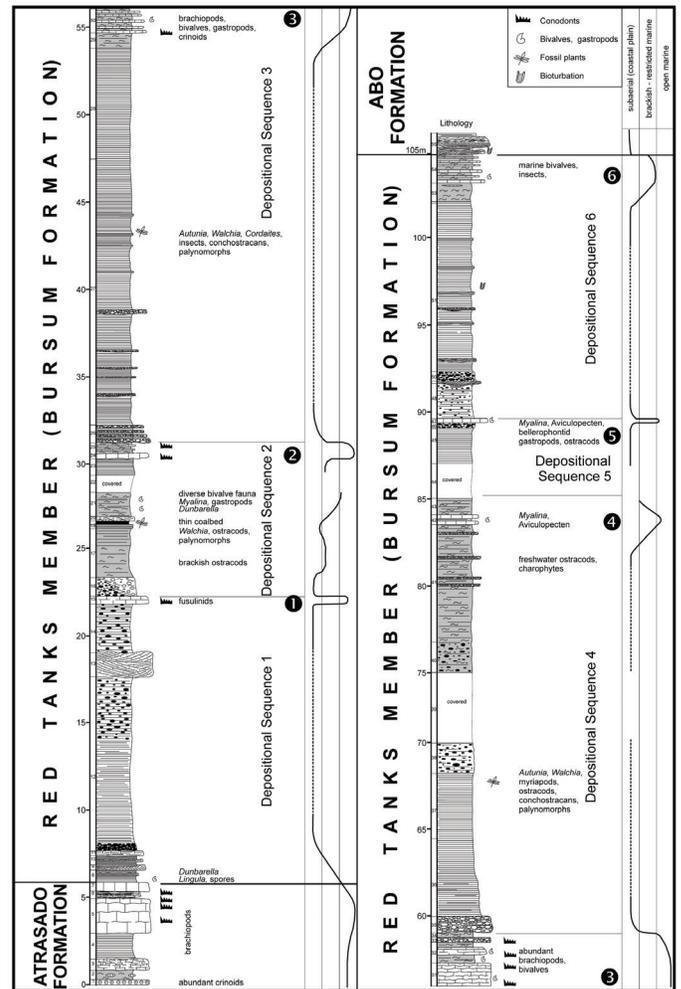


FIGURE 2. Stratigraphy of Red Tanks Member, Bursum Formation in Carrizo Arroyo. Coal bed is located in the middle of Depositional Sequence 2. See Lucas et al. (2016, this volume) for details of geology. From Lucas and Krainer (2002) and Krainer and Lucas (2004).

levels 43 m and 68 m above the base of the section are Lagerstätten of plants, insects, crustaceans, eurypterids (Hannibal et al., 2005) and other fossils that are unique to late Paleozoic lacustrine assemblages.

Most of the fossil groups from the Red Tanks Member have been used to support diverse placements of the Pennsylvanian–Permian boundary at Carrizo Arroyo. The insects indicate that the two Lagerstätten in the Red Tanks Member are of early Asselian (Wolfcampian) age. Conodont data (Lucas et al., 2013a) include the presence of *Streptognathodus virgilicus* in the uppermost part of the underlying Atrasado Formation, which constrains its age to the middle to upper part of the Virgilian. The only biostratigraphically-significant conodont assemblage in the Red Tanks Member comes from a marine horizon near the middle of the member, at the top of Depositional Sequence 3, and the assemblage is probably equivalent in age to the Mid-continent *Streptognathodus nevaensis* Zone, of early to middle Asselian age (Lucas et al., 2013a). The insect data thus are supported by the conodont data to indicate that the two Lagerstätten in the Red Tanks Member are of early Asselian age. In the

Bursum Formation section at Carrizo Arroyo, the coal bed is stratigraphically well below the lowest indicators of a Permian age, so a latest Pennsylvanian (late Virgilian) age seems very likely (Lucas et al., 2013a).

COAL BED CONTEXT

As the only known coal in the Bursum Formation, the Carrizo Arroyo coal bed, because of its peculiarity, has been noted, studied, and described previously. Our observations of the geological interval that includes the coal are broadly similar to those of Kues (2004). Table 1 presents a detailed description of the upper beds of Depositional Sequence 1 and the lower

two-thirds of Depositional Sequence 2, which includes the coal bed. Figure 3 is a graphical representation of these strata. The beds in Table 1 and Figure 3 are numbered to conform to those of the description in Krainer and Lucas (2004). Note, these bed numbers differ from those used by Kues (2004) who was following the bed number sequence of Lucas and Krainer (2002); since its publication, the bed numbers of Krainer and Lucas (2004) have been used widely and now constitute, by practice, the accepted scheme to facilitate communication among studies (Lucas et al., 2013a).

The basal unit of Depositional Sequence 2 is interpreted as a paleosol with a maximum thickness of 120 cm (Table 1, Bed 16a). Thickness varies because the top of the bed is erosively

TABLE 1. Descriptive log of upper portion of Depositional Sequence 1 (Beds 14 and 15) and lower through middle portion of Depositional Sequence 2 (Beds 16-21). Bed numbers from Krainer and Lucas (2004). See also Figure 3.

K&L (2004) Bed Number	Thickness (m)	Lithologic description	Fossils & comments
21	>150 cm (covered by Cenozoic debris)	siltstone shale - limy - olive grey - laminated to fine bedded	- marine pelecypods - lingulids and rhynchonelliform brachiopods - marine gastropods - nautiloids - isolated fish remains - plant remains
20b	30 cm	siltstone - dark grey - laminated	- plant remains - microconchids - marine pelecypods - lingulids
20a	25 cm	limestone - muddy, - grey-black to dark yellowish brown (weathered) - clayish-silty, laminated,	- well preserved plants - charcoal - marine pelecypods - lingulids - brackish ostracods
19	11 cm	coal bed - black, yellowish weathered (?pyrite), in cm-scale beds - coal in sharp contact with black claystone, top of bed 18	- plant remains
18	30 cm	marlstone - silty and gray in lower part, changing to dark gray and black and clayish in upper 1.5 cm - finely bedded to laminated (mm-scale, upper 8 cm in mm- and sub-mm-scale)	- ostracods (smooth shelled) - <i>Lingula</i> (up to 1 cm) - microconchids - last 1 cm with masses of ostracods & lingulids - Conifers (common), cordaitaleans (rare), calamitaleans (rare), in silty layers
17	170 cm	mudstone - light olive gray; clayish, primary horizontal bedding - strong pedogenic overprint - calcareous nodules (1-3 mm in average diameter, max. 5 cm)	- upper 25 cm with plant detritus and walchian fragments
16b	180 – 0 cm	sandstone?? - pebbly silt, calcitic cemented, greenish-gray - single channels up to 20 cm thick and 2 m wide, with clast-supported marine limestone pebbles, 1-2 cm in average diameter, max. 3.5 cm	- rare plant fragments - much corroded marine fossil debris (echinoderms, bryozoans) - channel fill (cut into 16a)
16a	120 – 0 cm	mudstone - pale red purple - violet to light red strong color mottling, - very fine yellowish veined - calcareous nodules (mm to 10 cm in diameter)	- no fossils - paleosol
15	40 – 50 cm	limestone - fusulinids, - greenish grey	- fusulinids - echinoderms - bryozoans
14	380 cm	mudstone - light olive gray with pale reddish brown - strong yellowish-white color mottling around 2-10 cm sized yellowish-brownish calcitic-dolomitic nodules - slickensides & strong pedogenic overprint	- no fossils - paleosol

scoured by a fluvial channel and filled by pebbly to conglomeratic sediments (Table 1, Bed 16b). Above the channel is a 170 cm thick mudstone that appears to be pedogenically overprinted and with calcareous nodules; some plant detritus and walchian fragments have been found only in the upper 25 cm (Table 1, Bed 17; see Fig. 3). The mudstone of Bed 17 is overlain

by 30 cm of finely bedded to laminated sediments, increasingly dark in color and with an increasing clay fraction, the upper portion of which becomes an ostracod marlstone with lingulids and microconchids as well as plant remains (Table 1, Bed 18; see Fig. 3). Xenacanth teeth also occur in this unit. The dominant plants in the upper part of Bed 18 are primarily walchian conifers with a foliated shoot morphology similar to *Culmitzschia speciosa*; cordaitalean leaves have been observed rarely.

The coal bed (Bed Number 19) is as much as 11 cm in thickness. On outcrop, it is dirty and dull, but shows clear banding and brittle fracture (Table 1, Bed 19; see Fig. 3). Based on the yellowish weathering features, the fresh, unweathered coal likely has high pyrite content. Contact with underlying Bed 18 is gradational, within which are indeterminable plant axes. The top of the coal bed also transitions to an organic shale that contains striate axes or cordaitalean leaves (see comment below). The absence of a rooted horizon below the coal suggests that in its initial phases, the organic matter may have accumulated by allochthonous processes; such transitional contacts between coal beds and the underlying siliclastic sediments are common. This disposition suggests that the coal bed filled a channel scour, such as an abandoned oxbow, or coastal pond. Parautochthonous accumulation of the plant matter cannot be ruled out. The full areal extent of the coal bed cannot be determined due to cover. However, from the absence of additional outcrops of the coal bed 1-2 km to the south, where the entire Bursum Formation is exposed, we presume the extent of the deposit was quite limited.

Above the shaly top of the coal deposit, and in sharp contact with it, is a muddy limestone to calcareous siltstone that contains the pectinid *Dunbarella*, brackish ostracods, lingulids and microconchids (Table 1, Beds 20a and b; see Fig. 3). These fossils indicate brackish water. Plant fossils also are part of this assemblage, some of which are large and well preserved. These include calamitalean stems, pteridosperm stems and cordaitalean foliage, as well as fragmentary remains. This unit grades upward into a limey siltstone that becomes finer grained upward. The brackish water fauna near the base (myalinids, lingulids, *Dunbarella*, ostracods) gives way to a fauna that becomes progressively more marine in composition upward, with rhynchonelliform brachiopods and nautiloids (Bed Number 21) (full description in Kues, 2004). These beds indicate the drowning of the peat swamp and cover of the area by some depth of brackish to nearshore, shallow marine waters of normal salinity.

COAL BED ANALYSES

A single sample of the coal bed was subject to proximate and palynological analyses. The sample was highly weathered, although some pieces retained their original clete structure. The degree of weathering may have affected the geochemical and petrographic analyses, and perhaps the palynological content of the coal. Sample preparation followed procedures outlined by ASTM International test method D-2013 (ASTM International, 2013a). Approximately 250g of sample were split off, using a riffler, and reduced to -60 mesh for geochemical and palynological analyses. Another split of the same amount was reduced to -20 mesh size for the construction of petrographic pellets.

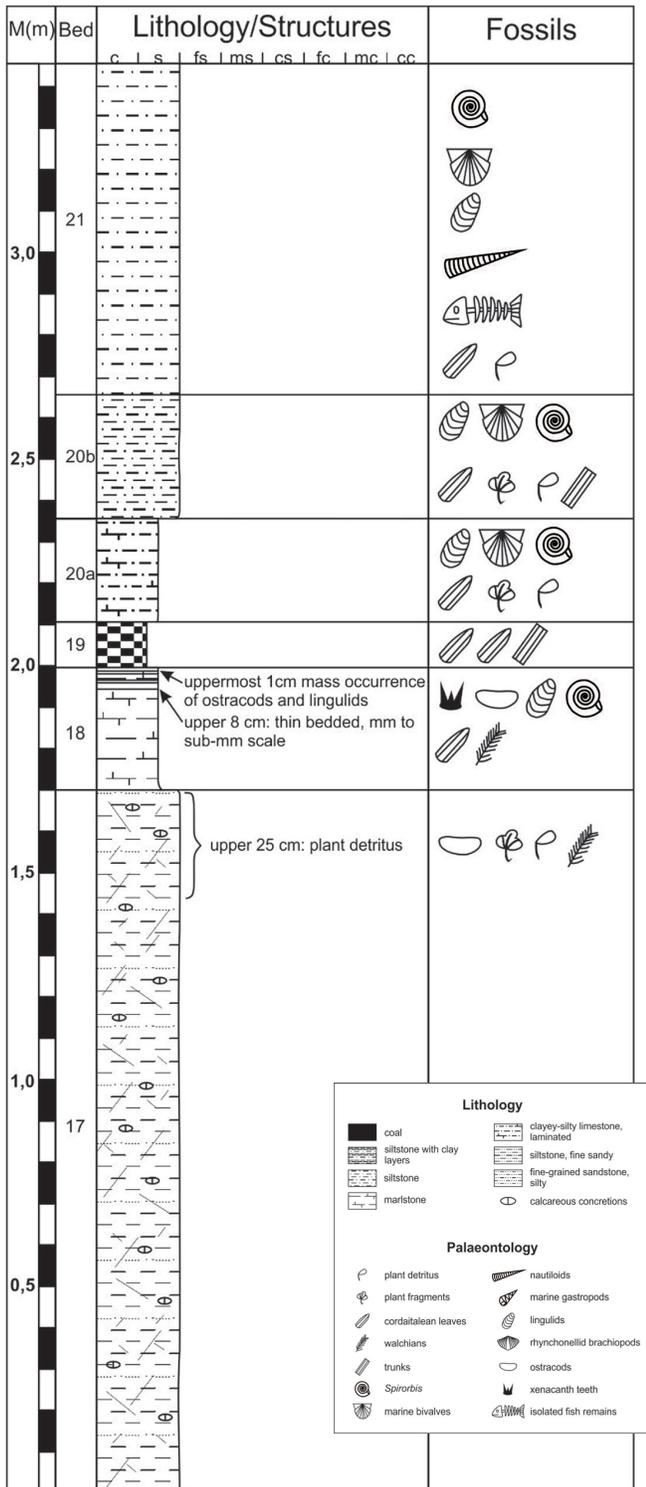


FIGURE 3. Graphic log of the lower and middle portion of Depositional Sequence 2 of Lucas and Krainer (2002), showing the coal bed and enclosing strata.

Geochemical Analysis Methods

Proximate analyses (moisture, volatile matter, fixed carbon contents, and ash yield) were performed according to ASTM International test method D7582–12, using a Leco 701 thermogravimetric analyzer (ASTM International, 2013b). Total carbon and sulfur analyses were performed according to ASTM International test method D4239–12, using a Leco SC-432 carbon/sulfur analyzer (ASTM International, 2013c). Mineral matter (MM) was calculated using the Parr Formula (Parr, 1928), where:

$$\% \text{ MM} = (\% \text{ ash yield} * 1.08) + (\% \text{ total sulfur content} * 0.55).$$

Petrographic Analysis Methods

Coal petrographic pellets were constructed by mixing 2 to 3 g of -20 mesh coal with epoxy resin in 3.2 cm diameter phenolic ring form molds, and allowing them to cure. Once cured, the molds were ground using 400 and 600 grit papers and polished using 1.0, 0.3, and 0.05 micron alumina slurries. Final polishes were obtained using 0.02 micron colloidal silica.

Reflected light analyses were performed on a Zeiss Universal microscope, using a Zeiss epi 40X oil immersion objective coupled with a 1.6X magnification changer (final magnification 640X). Zeiss Immersol oil was used ($n_c = 1.518$, $v_c = 42$). Maceral analysis involved the use of both white and fluorescent light, the latter for positive identification of liptinite macerals. White light was supplied by an Osram Xenophot HLX 12V, 100W bulb. Fluorescent light was provided by a Lumen Dynamics 120 watt, high-pressure metal halide arc lamp, used in conjunction with a Zeiss 09 filter set (450-490 nm excitation, 510 nm beam splitter, and 515 nm emission filters). Vitrinite and inertinite maceral identification follows recommendations outlined by the International Commission for Coal Petrography (ICCP) for vitrinite (ICCP, 1998) and inertinite (ICCP, 2001) macerals. Liptinite maceral identification follows that of Stach et al. (1982). Maceral percentages are presented on a mineral matter free basis.

Vitrinite reflectance analyses were performed by first calibrating a Hamamatsu 928A photomultiplier with a glass standard of known reflectance. Following this, 50 random reflectance measurements were collected for each sample. Reported results include the average, maximum, and minimum Ro random, standard deviation, and calculated Ro maximum. Ro maximum values were calculated from the average Ro random values using the formula:

$$\text{Calculated Ro maximum} = \text{Ro random} * 1.066 \text{ (Ting, 1978)}.$$

Palynological Analysis Methods

Initially, 2 to 3 g of -60 mesh coal (particle size ≤ 250 microns) were immersed in 5% potassium hydroxide to digest the coal, which was already highly oxidized when received. After repeated washing with distilled water, the remaining organic material was concentrated with zinc chloride (specific gravity 1.9). Amorphous organic matter (AOM) was removed from the

residues using ethylene glycol monoethyl ether (2-ethoxyethanol), ultrasonic vibration, and short centrifugation. Samples were strewn-mounted onto 25 mm square cover glasses with polyvinyl alcohol, and fixed to 75 X 25 mm microscope slides with a synthetic, acrylic resin. Unfortunately, this technique failed to yield any identifiable spores and pollen.

Upon discovering that the sample had an ash yield of 38.8%, another 3 to 4 g of coal were immersed in a mixture of concentrated hydrofluoric, hydrochloric, and nitric acids to remove silicate, carbonate, and sulfide minerals, respectively. Following this demineralization step, the coal was treated as outlined above. This extra demineralization step produced fairly abundant, and moderately well preserved palynomorphs.

Palynomorph data are listed according to natural affinity for the following plant groups: lycopsid trees, small lycopsids, tree ferns, seed ferns, small ferns, calamitaleans, cordaitaleans, and conifers. Parent plant affinities of dispersed Carboniferous miospore taxa were determined based on extensive summaries provided by Ravn (1986), Traverse (1988), and Balme (1995).

Results of Geochemical and Petrographic Analyses

Geochemical analyses of the Carrizo Arroyo coal sample (Table 2, Figs. 4-5) indicate that, though high in ash yield (38.8%, dry basis), it still qualifies as coal because it contains more than 50 % organic matter by weight (Schopf, 1956). It would be classified as impure coal, according to ASTM International terminology (ASTM International, 2013d). The moderate sulfur content (2.5%) may reflect the oxidation and removal of some of the sulfur during weathering of the coal, given field observations of yellowish surface staining on outcrop.

Petrographically (Table 3, Fig. 5), the coal contains abundant inertinite (46.0%, mineral matter free basis), mainly in the form of fusinite and inertodetrinite (Fig. 6). Although inertinite macerals can form through the combustion of plant materials, or through intense biodegradation, the origin of fusinite is primarily attributed to the effects of wildfire (Stach et al., 1982; Teichmüller, 1989). Vitrinite macerals (48.0%, mmf) occur

TABLE 2. Carrizo Arroyo coal bed geochemical analysis results (daf = dry, ash free basis).

% Moisture	11.33
% Ash Yield, dry	38.80
% Volatile Matter, dry	30.71
% Volatile Matter, daf	50.18
% Fixed Carbon, dry	30.49
% Fixed Carbon, daf	49.82
% Total Sulfur, dry	2.52
% Total Carbon, dry	43.37
% Total Carbon, daf	70.87
% Mineral Matter, dry	43.29

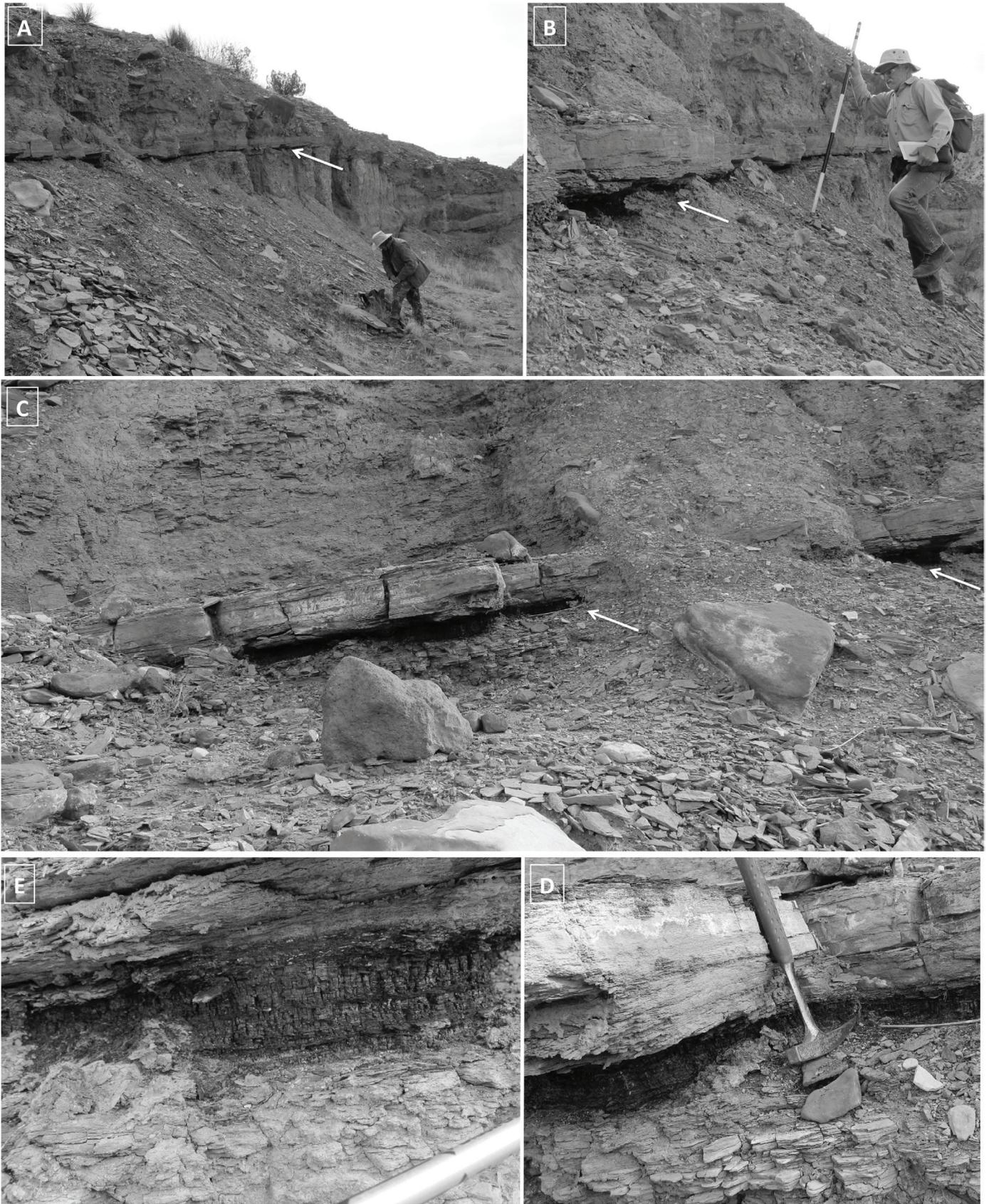


FIGURE 4. Field photographs of Bursum Formation coal bed, series of increasingly proximate images. **A)** General aspects of outcrop. Coal bed marked by white arrow. **B)** Location of excavation to extract plant and animal fossils, to left of white arrow, which marks position of coal bed. **C)** Coal bed (white arrows), underlain by gray shale with brackish water fauna, overlain by calcareous siltstone, plant fossils at the base. **D)** Closer view of coal bed and strata above and below. **E)** Closeup view of coal bed showing gradational upper and lower contacts, banding and dull luster. Photographs by S.D. Elrick.

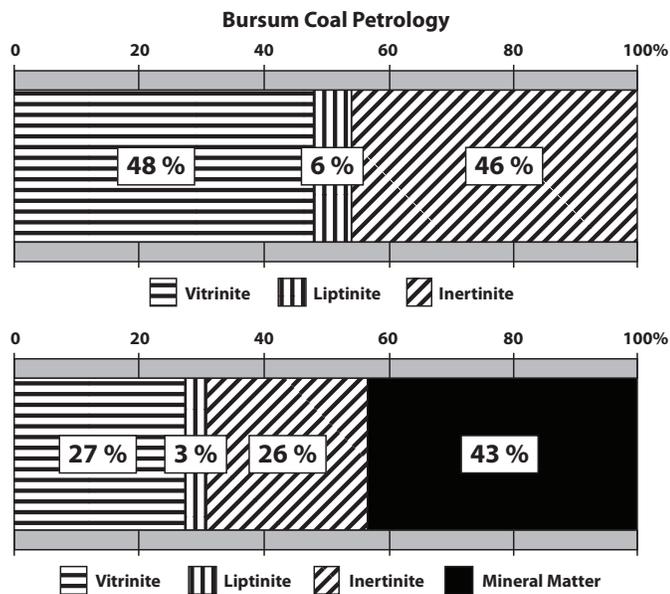


FIGURE 5. Petrographic profiles of the Carrizo Arroyo coal sample. The top diagram shows maceral group distribution on a mineral matter free (mmf) basis. The bottom diagram shows the same distribution on a whole coal basis, with the inclusion of mineral matter.

mainly in the form of telovitrinite (TV, 35.6 %, mmf), with devitrinite (DV) and gelovitrinite (GV) occurring less frequently (DV + GV = 12.4%). Liptinite macerals were rare in the coal sample (6.0%, mmf), and occurred mainly as liptodetrinite.

The sample had an average R_o random of 0.59%, and a calculated R_o maximum of 0.63% ($n=50$), indicating a high volatile bituminous B rank assignment. It should be noted, however, that weathering can, and often does, affect vitrinite reflectance negatively. Therefore, the reflectance value of the weathered sample may be (probably is) less than the coal would have been in an unweathered condition.

MEGAFLORA ABOVE AND BELOW THE COAL BED

Megafloral assemblages have been recovered and identified from beds above and below the coal. We recovered only walchian conifers immediately below the coal bed from Bed 18 (Table 1, Fig. 3). The walchian remains are concentrated in the ostracod-rich, organic shales immediately below the coal. The morphology of the ultimate shoots of these conifers is comparable to that of *Culmitzschia speciosa* (Clement-Westertof, 1984; Visscher et al., 1986) (Fig. 7A-B). Calamitalean remains, also, have been reported in earlier studies, including *Annularia*-type foliage, in the same ostracod-rich beds as the walchian conifer remains (Kues, 2004). Cordaitalean foliage also has been observed in field examination of the exposures.

As part of the walchian conifer assemblage recovered from Bed 18, we found a small branch axis, up to 5 mm diameter, that is peculiarly preserved, apparently showing details of the pith and primary vasculature, as a result of differential compaction of these plant tissues (Fig. 7C). The pith, 2.8 mm diameter, contains plate-like raised features, 0.7-1.2 mm wide and 0.3 mm high, interpreted as sclerotic nests, composed of compac-

TABLE 3. Carrizo Arroyo coal bed petrographic analysis results.

A. Petrography (mineral matter free basis)	
Telinite	0.0
Collotelinite	35.6
Collodetrinite	2.0
Vitrodetrinite	10.4
Corpogelinite	0.0
Gelinite	0.0
Total Vitrinite (mmf)	48.0
Telovitrinite	35.6
Devitrinite + Gelovitrinite	12.4
TV/DV + GV	2.9
Sporinite	0.8
Cutinite	0.0
Resinite	0.0
Alginite	0.0
Exsudatinitite	0.0
Liptodetrinite	5.2
Total Liptinite (mmf)	6.0
Fusinite	17.0
Semifusinite	1.6
Macrinite	0.0
Micrinite	0.0
Secretinite	0.8
Funginite	0.0
Inertodetrinite	26.6
Total Inertinite (mmf)	46.0
B. Vitrinite Reflectance	
Average R_o random	0.59
Maximum R_o random	0.68
Minimum R_o random	0.54
Standard Deviation	0.04
Calculated R_o maximum	0.63
C. Petrography (whole coal basis)	
Vitrinite (whole coal)	27.2
Liptinite (whole coal)	3.4
Inertinite (whole coal)	26.2
Mineral Matter (dry basis)	43.3

tion-resistant sclerenchyma, separated by low-lying areas, presumed to represent parenchyma. Overprinted on this pith structure is a pattern of longitudinal striations, spaced 0.2 mm apart, and interpreted as marking the position of compaction-resistant cauline bundles. The spacing of these features suggests the axis had about 20 bundles arranged around the end of the pith, although this is a rough estimate only. A coaly layer surrounding the pith, up to 1.5 mm wide, is interpreted as a slender cylinder

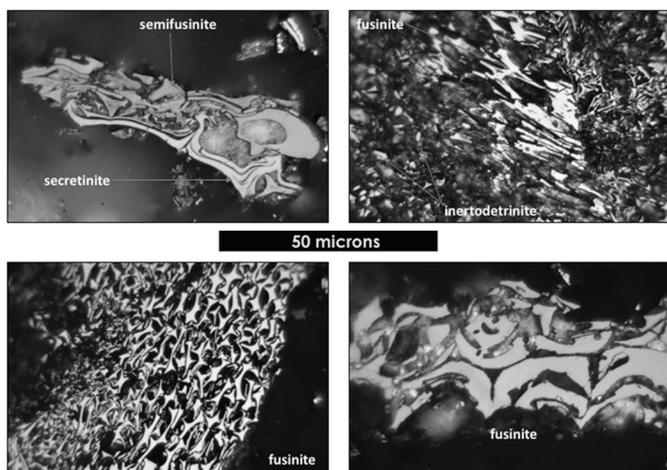


FIGURE 6. Inertinite macerals in the Carrizo Arroyo coal sample.

of secondary xylem. The poorly preserved exterior of the axis appears to have some attached narrow, triangular leaves that may, possibly, show terminal bifurcation. Bifurcation is a common character for penultimate leaves in walchian conifers. A pith structure with sclerotic nests of the size, shape, and distribution seen in this specimen is especially characteristic of the lebachoid walchian clade that includes *Barthelia*, *Hanskerpia*, *Emporia*, *Otovicia* and *Utrechtia* (Rothwell and Mapes, 2001; Rothwell et al., 2005; Hernandez-Castillo et al., 2009a, b, c). Like the material described here, these taxa are known from relatively small axes; however, a similar pith structure has, also, been documented from tree trunks, termed *Macdonalodendron*, in rock straddling the Pennsylvanian–Permian boundary, elsewhere in New Mexico (Falcon-Lang et al., 2014, 2016). These trunks show attached leaves (Falcon-Lang et al., 2014), are locally found in association with foliated branches with a morphology similar to *Walchia piniformis*, and have other features consistent with a walchian conifer affinity, including the preservation of plagiotropic branches borne in whorls (Falcon-Lang et al., 2014, 2016).

From the limestone-siltstone roof of the coal bed (Beds 20 and 21, Fig. 7D), well preserved remains of calamitalean stems and probable pteridosperm stems (Fig. 8A) were recovered in recent excavations. However, no foliage of either of these groups was found. The calamitalean stems are easily recognizable by strong, longitudinally oriented ribs and transverse nodes, through which the ribs alternate (Fig. 8B, C). The stem in Figure 8A identified as a pteridosperm contains a single divergent appendage (at arrow) into which some vertical striations of the stem can be seen to diverge, a pattern typical of medullosan pteridosperm stem remains; the lateral appendage is likely the base of a leaf. Cordaitalean leaves also have been reported. However, medullosan stem and rachial remains are frequently misidentified as cordaitalean leaves (and vice versa) because they can be of about equal widths and both are striated longitudinally. In medullosans, the longitudinal striations are mainly sclerenchyma bundles that anastomose or have foreshortened paths, whereas the striations of cordaitalean leaves are highly ordered vascular bundles. Higher in the section above the coal bed (Bed 20b), the plant

remains are closely intermixed with the remains of invertebrates (Figs. 7E, 8C) and fragmentary plant debris is common. This is not a rich flora, and the absence of conifers is conspicuous, suggesting an environmental change associated with the flooding and burial of the channel-bound coal bed.

PALYNOFLORA

Shales Above and Below the Coal

The palynoflora of the beds immediately below and above the Carrizo Arroyo coal bed has been described in two previous publications and will be summarized here briefly. Traverse and Ash (1999) analyzed only the bed immediately beneath the coal (Bed 18). The beds Utting et al. (2004) analyzed are keyed to the Krainer and Lucas (2004) bed-numbering scheme. They are identified as beds number 17 and 20 and thus come from the second bed beneath and the bed immediately above the coal. Aspects of the empirical findings of these two studies are similar. In combination, therefore, these two studies encompass two different beds beneath the coal and one immediately above it, but not the coal itself.

Traverse and Ash (1999) found the palynoflora immediately beneath the coal to be poorly preserved due to overgrowths of pyrite crystals on the palynomorphs; they attributed this to deposition of the palynomorphs in anoxic, possibly marine or brackish water. A total of only seven genera were identified (plus three categories of indeterminable morphotypes). The microflora is dominated by monosaccate pollen, particularly *Potonieisporites*, but also includes common *Florinites*, pollen types produced by walchian conifers and cordaitaleans, respectively (for botanical affinities of palynomorphs see Looy and Hotton, 2014). Two of the identifications of minor taxa were challenged by Utting et al. (2004), which does not significantly change the overall findings of a very low diversity flora dominated by coniferopsids.

Utting et al. (2004) identified six genera from the bed immediately beneath that analyzed by Traverse and Ash (1999), and differing significantly in composition from it. The pollen *Potonieisporites* and the monolete spore *Laevigatosporites* are the only taxa in common. Conifer pollen, *Potonieisporites*, dominates the Bed 17 assemblage, with subdominant *Alisporites*, bisaccate pollen known in situ from the pollen organs of peltasperms and conifers. The second sample analyzed by Utting et al. (2004), from Bed 20, immediately above the coal bed, contains only four taxa, and only one of those, *Potonieisporites*, is represented by more than a single palynomorph. Another conifer, *Alisporites*, and the spore taxa *Laevigatosporites* and *Punctatisporites*, of possible sphenopsid and/or tree fern affinity, make up the rest of the assemblage.

Coal Palynology

The results of the palynological analysis are presented in Table 4 and Figure 9. The coal palynoflora (Fig. 10) is dominated by the tree fern spore taxa *Laevigatosporites minimus*, *Punctatisporites minutus*, and to a lesser extent *Punctatospo-*

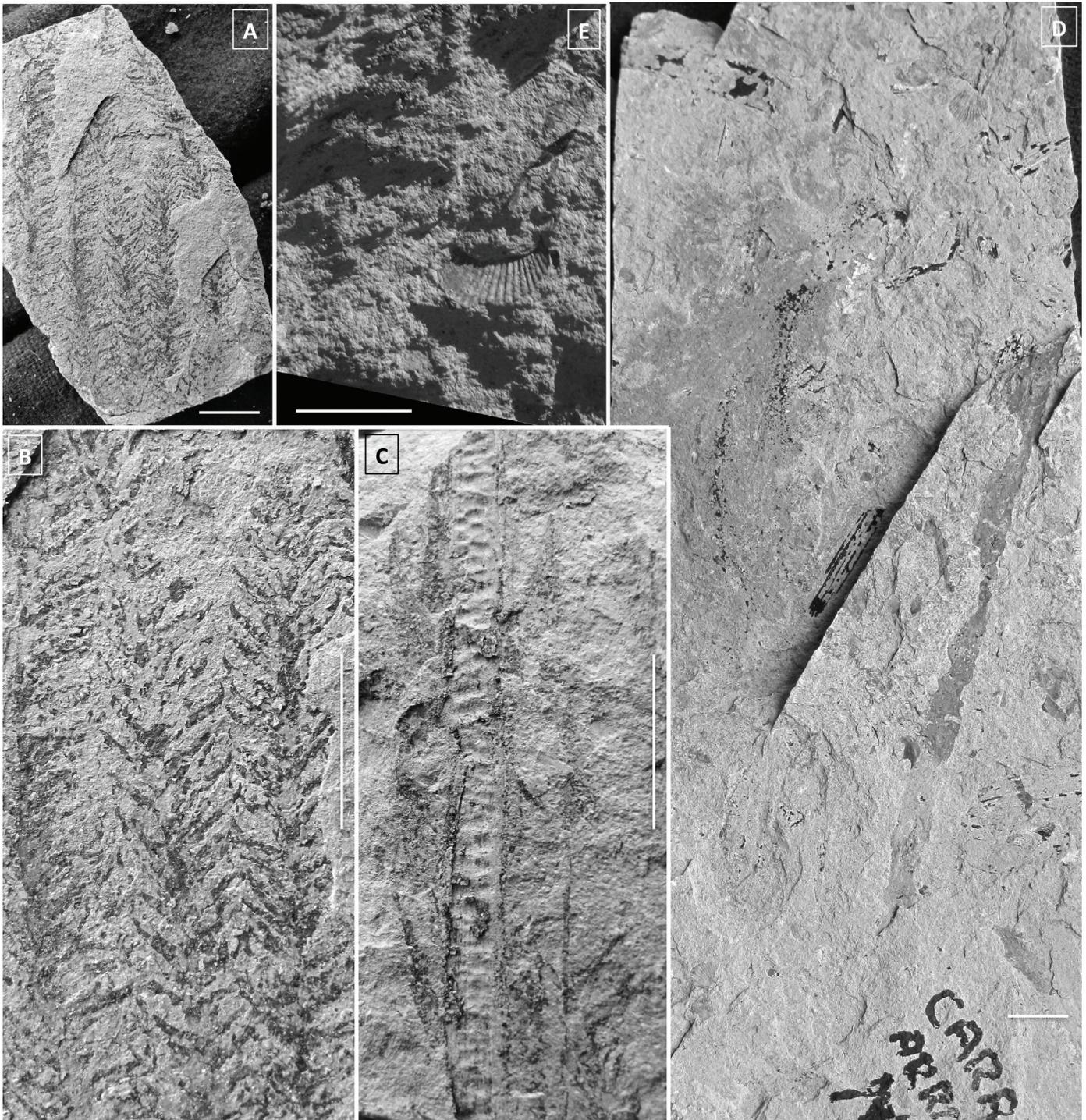


FIGURE 7. Selected fossils from Depositional Sequence 2. **A)** Walchian conifer branch fragment with a morphology similar to *Culmitzschia speciosa*. Top of Bed 18. USNM Specimen 619206, USNM Locality 43592. **B)** Magnification of a portion of specimen in (A), showing detail of foliage. **C)** Walchian conifer stem with transversely disposed nests of sclerotic cells; leaves attached along the sides. Top of Bed 18. USNM Specimen 619207, USNM Locality 43592. **D)** Plant debris intermixed with invertebrate fossils (upper right) from Bed 20, the immediate roof of the coal bed. USNM Specimen 619208, USNM Locality 43592. **E)** Invertebrate remains from Bed 20. Field photograph, S.D. Elrick. Scale bars = 1 cm.

rites minutus (collectively, 78.0%). Small fern taxa (e.g., *Granulatisporites* and *Deltoidospora*) were observed, but did not occur in statistical abundance. Pteridosperm pollen, *Vesicaspora wilsonii*, was next most abundant behind tree fern spores (16.0%). Cordaitalean pollen, *Florinites* spp., and spores of calamitaleans, represented by species of *Calamospora*, and larg-

er forms of *Laevigatosporites*, also were present, but in low amounts (3.2 and 2.0%, respectively). Single occurrences of *Endosporites globiformis*, which was produced by the small lycopsid *Polysporia* (aka *Chaloneria*), and *Pityosporites westphalensis*, which is attributed to conifers, also were recorded in the palynomorph count.

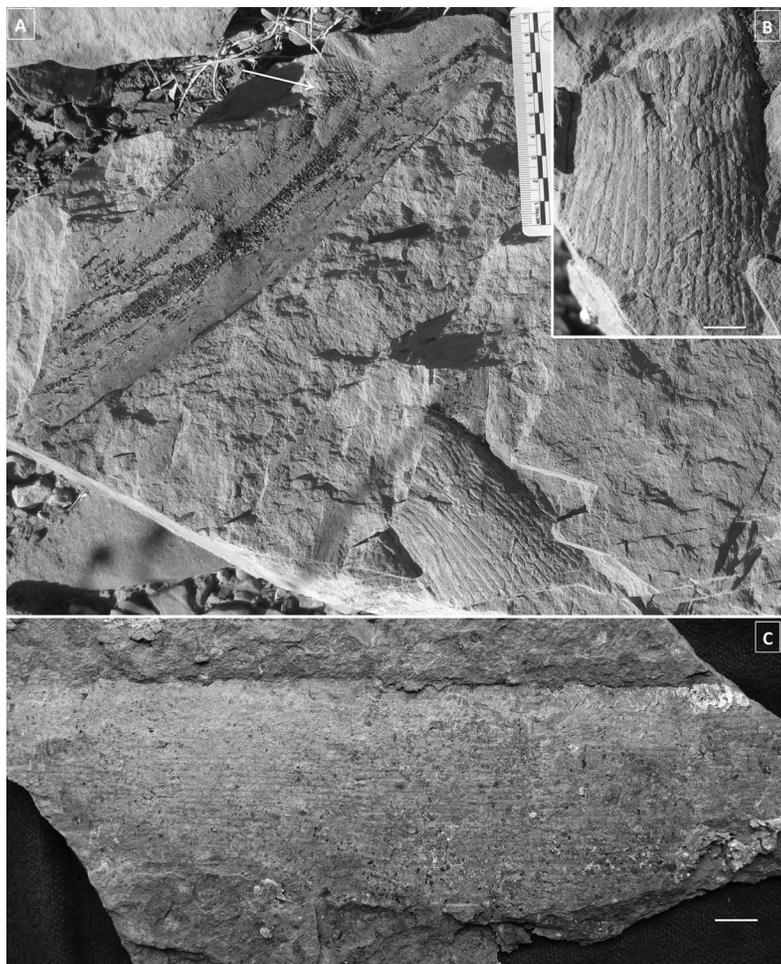


FIGURE 8. Selected fossil plants from Depositional Sequence 2, Bed 20, immediately above the coal bed. **A**) Pteridosperm stem (upper left) and calamitalean stem (lower right). Note longitudinal striations on the pteridosperm and the diverging leaf base (at arrow). Field photograph, S.D. Elrick. Scale = 10 cm. **B**) Calamitalean stem from image (A) enlarged. Scale bar = 1 cm. **C**) Calamitalean stem in silty carbonate matrix in association with invertebrate remains. USNM Specimen 619209, USNM Locality 42338. Scale bar = 1 cm.

DISCUSSION

The Carrizo Arroyo coal bed is of interest because of its uniqueness both at the time, the Pennsylvanian-Permian transition, and in light of the regional landscape, which appears to have been an oscillating terrestrial coastal plain to nearshore marine depositional setting under a seasonally dry climate most of the time. Coal is a rare lithology in western equatorial Pangea, particularly in post-Atokan (mid-Moscovian) time. The presence of coal indicates a shift to a climate sufficiently wet to permit organic matter to accumulate more rapidly than it was destroyed by oxidation and the action of organisms, and to accumulate to some thickness, in the short term. The Carrizo Arroyo coal bed likely accumulated in a shallow body of standing water somewhat isolated from siliciclastic input, probably reflective of a period of greater climatic humidity. It also indicates conditions suitable to preserve the organic accumulation in the longer term. With accelerating rise in relative sea level, limestone and siliciclastic sediments then buried and preserved the small peat body.

In this context, the peat body was primarily an autocyclic deposit, in the terms of Beerbower (1969; see also Cecil, 2013), controlled mainly by conditions created by local environmental dynamics. In this instance, the site where peat ultimately accumulated began as a small, shallow, coastal-floodplain lake or perhaps an estuary, given faunal evidence (lingulids) for brackish coastal water above and below the coal. Xenacanthid sharks, recorded from directly beneath the coal, have been inferred to be either freshwater or euryhaline fishes (Fischer et al., 2013; Carpenter et al., 2015). However, for peat to accumulate to reach sufficient thickness and be of sufficient organic content to make a coal bed, rather than an organic shale, the site of peat formation would have to have been isolated from high siliciclastic input, and have remained sufficiently wet to preclude oxidation or biotic destruction of the deposit. This was most likely caused by a period of elevated rainfall, an allocyclic process driven by changes in regional to global tropical atmospheric circulation. This proposed combination of autocyclic and allocyclic drivers will be discussed below.

Peat Formation

Peat is a highly compactible substance, with estimates of the compaction ratio varying from 3:1 to over 20:1 for Pennsylvanian peats (e.g., Winston, 1986; Nadon, 1998). Thus, 0.11 m thickness of high-ash coal might translate into a parent peat bed of between 0.33 m to over 1 m thick. This thickness of peat would not be expected to form in less than 100–200 years and perhaps as long as 1500 years, based on accretion rates of modern, tropical woody peats at up to 2 mm/year (Page et al., 2004), although these are rates for domed peats, which the Carrizo Arroyo deposit almost certainly was not. Planar peats, such as those in the Florida Everglades, which are neither tropical nor composed primarily of woody material, can accumulate at rates of 4 mm/year in areas of nutrient enrichment and long hydroperiod, but at half or less of that rate if the peat is periodically exposed for longer intervals (e.g., Craft and Richardson, 1993). If the Carrizo Arroyo peat were planar, it may be comparable to some Pennsylvanian planar peats from the U.S., Europe and China, which contain coal balls. A study of the taphonomy of Pennsylvanian coal-ball peats from central Pangean coals (Phillips, Elrick and DiMichele, in preparation) has found very high decay rates of aerial litter and points to strongly oscillatory episodes of peat aggradation, punctuated by intense decay, rooting and thickness deflation. Furthermore, roots were a major biomass component of these planar Pennsylvanian peats (Raymond, 1988; Covington and Raymond, 1989; Phillips and DiMichele, 1990), as they are of many modern peats, again indicating high rates of aerial litter decay. With these observations in mind, the Carrizo Arroyo peat is expect-

TABLE 4. Carrizo Arroyo coal bed palynological analysis results.

Taxon	%
<i>Punctatisporites minutus</i>	31.2
<i>Punctatosporites minutus</i>	1.2
<i>Laevigatosporites minimus</i>	45.6
Total Tree Ferns	78.0
<i>Granulatisporites parvus</i>	X
<i>G. piroformis</i>	X
<i>Deltoidospora levis</i>	X
Total Small Ferns	0.0
<i>Vesicaspora wilsonii</i>	16.0
<i>Schopfipollenites ellipsoides</i>	X
Total Seed Ferns	16.0
<i>Laevigatosporites minor</i>	1.6
<i>Calamospora breviradiata</i>	0.4
<i>C. straminea</i>	X
Total Calamites	2.0
<i>Florinites florini</i>	2.8
<i>F. mediapudens</i>	X
<i>F. milotti</i>	0.4
<i>F. similis</i>	X
Total Cordaites	3.2
<i>Endosporites globiformis</i>	0.4
Total Small Lycopods	0.4
<i>Pityosporites westphalensis</i>	0.4
Total Conifers	0.4

ed to have been a highly dynamic deposit and to have formed on a landscape of sufficient stability to preclude disturbance of conditions favorable for peat accumulation and in a location isolated from excessive siliciclastic dilution.

These environmental conditions notwithstanding, the coal bed appears to have occupied an abandoned fluvial channel or coastal estuary during its final phases of filling. The 0.3 m thick Bed 18, which is rich in aerial remains of conifers, may have been an open water environment of fresh to brackish salinity, surrounded by coniferous vegetation. Beneath it, Bed 17b appears to have been pedogenically altered, suggesting plant growth either in the channel during an earlier swamp phase, or during actual subaerial exposure of the deposit at some point prior to re-flooding. In its initial phases, then, the organic matter that comprised the peat was likely drawn from the riparian vegetation surrounding the site.

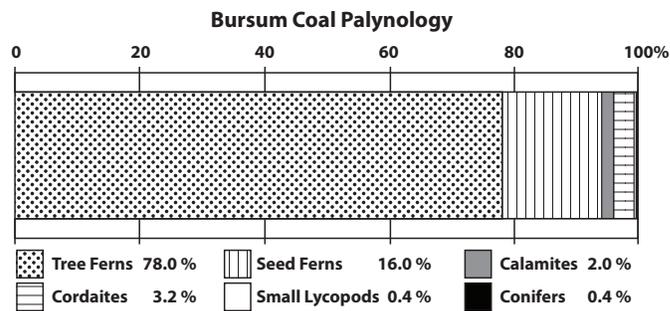


FIGURE 9. Major plant-group palynological profile of the Carrizo Arroyo coal sample. Bar width approximate (see Table 4 for details).

The high ash yield of the coal would indicate that swampy conditions in which the peat formed were subject to frequent, but low volume, clastic influx. Wildfire in, or near, the swamp resulted in high concentrations of fusinite and inertodetrinite. Due to its decay resistance and high transport capacity, fusinite may, however, also have been concentrated by peat decay. The palynoflora is tree-fern dominated with subdominant seed ferns, although it is unknown if all, or most, of the palynomorphs are autochthonous. Given the high ash yield of the coal, and the fact that dispersed palynomorphs act as ideal sedimentary particles (very small, and highly resistant), the possibility that some portion of the palynoflora is allochthonous must be considered. Recent alteration of the original palynoflora also must be considered, in light of the highly weathered nature of the sample.

Peat Preservation

As an organic-rich deposit, peat is subject to rapid destruction by abiotic (e.g., fire) and biotic factors (as a carbon source for fungi and bacteria, in particular) if subaerially exposed for even short periods of time. As discussed by Gastaldo and Demko (2011), there are three, successive steps needed for the preservation of terrestrial organic matter: short-term preservation, on the scale of 10s to 100s of years, intermediate term preservation, on the scale of 100s to 1000s of years, and long-term preservation, on the scale of thousands to 10s of thousands of years. In the case of the Carrizo Arroyo coal bed, the first of these steps, short-term preservation, was made possible by the creation of a low area on the landscape, under a sufficiently humid climate to allow for standing water most of the time, and shallow enough for plants to grow on the site. Intermediate-term preservation was effected by drowning of the swamp by the influx of marine waters, represented by both limestone and mudstone. It is the matter of long-term preservation, however, that may be unique to the Carrizo Arroyo area, possibly reflecting the actions of syndepositional tectonism.

Strong evidence is at hand that contemporaneous tectonic activity created the accommodation space, a shallow enclosed depression, in which the Red Tanks Member, with its many unusual fossil assemblages, was deposited in Carrizo Arroyo. The site lies immediately west of the Comanche fault zone, the structure that bounds the eastern margin of the Lucero uplift. The Comanche zone underwent eastward-verging compress-

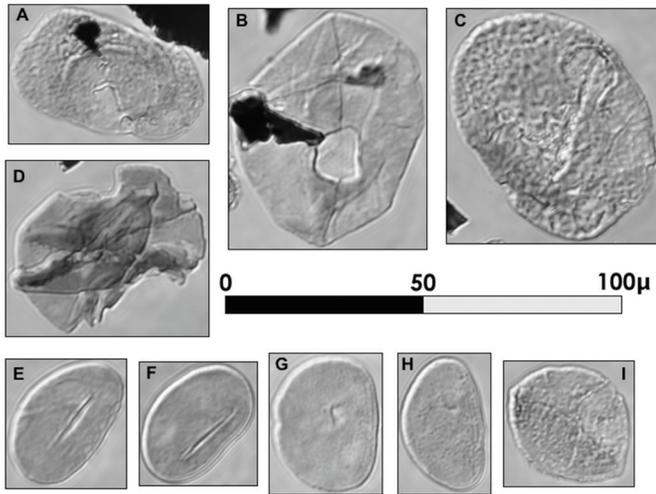


FIGURE 10. Palynomorphs in the Carrizo Arroyo coal sample. A) *Vesicaspora wilsonii*, B) *Calamospora straminea*, C) *Florinites florini*, D) *Calamospora breviradiata*, E and F) *Laevigatosporites minimus*, G and H) *Punctatosporites minutus*, and I) *Punctatisporites minutus*.

sive folding and thrust faulting during the Laramide orogeny, followed by down-to-the-east normal faulting during development of the Rio Grande rift (Kelley and Wood, 1946; Callender and Zilinski, 1976). Although Ancestral Rocky Mountains (ARM) activity along the Comanche fault zone has not been documented, the zone is parallel and in line with the prevalent north-south trend of ARM faults in this area of New Mexico (Woodward et al., 1999; see also Plate T, page 146, in Pazzaglia et al., 1999). A large sandstone dike in the Bursum Formation, just west of the coal outcrop and in close stratigraphic proximity, is possibly a seismic sand blow that formed in response to late Paleozoic earth movements along the Comanche fault zone (Nelson et al., 2013).

The unusually thick laminated clastics of the Red Tanks facies at Carrizo Arroyo point to strong tectonic subsidence compared with the more widespread Bruton facies of the Bursum. In the Bruton facies, subsidence was slow and steady, so subaerial exposure and soil formation prevailed, along with small fluvial channels that left coarse arkose and conglomerate. During major eustatic transgressions, the sea briefly overtopped the landscape, forming limestone layers. Opportunities to preserve plants fossils and peat did not exist. The thick Red Tanks facies at Carrizo Arroyo reflects repeated episodes of tectonic subsidence along the western margins of the Orogrande seaway. These episodes allowed thicker deposits of fine clastics to accumulate in standing bodies of water that varied from fresh to near-normal marine salinity.

Flora of the Coal and Associated Strata

The flora associated with this localized, wet habitat appears to have had a complex ecological history. The flora below the coal, which contributed the initial organic matter in the mineral-to-peat swamp transition, is not a typical Pennsylvanian-swamp flora as is known from the coal measures of the Midwestern and eastern United States, the Canadian Mari-

times, or across Great Britain and mainland Europe, characterized in hundreds of published works. Rather, it appears to have been drawn from the immediately surrounding species pool, one rich in plants that could tolerate moderate to significant seasonal drought. In this instance, those plants appear to have been mostly conifers and perhaps cordaitaleans. There also is evidence of calamitaleans, reported from macrofossil remains, and ambiguous evidence of marattialean tree ferns from palynological data (*Punctatisporites*, a form of spore with taxonomically broad affinities, beyond marattialean ferns). Marattialeans and calamitaleans were the most important wetland plant groups throughout western Pangea during the later Pennsylvanian and well into the early Permian, reflecting their tolerance of soil moisture fluctuation and also their dispersal capacities, along riparian corridors and via wind dispersal of spores. Spores attributed to lycopsids, among the most important plants in coal-swamp wetlands, were reported by Traverse and Ash (1999) from bed 18, immediately beneath the coal; however, this identification was challenged by Utting et al. (2004), making it unlikely that this group was represented in the early phases of swamp development.

The flora of the coal bed is much like those from Late Pennsylvanian and early Permian coals in the northern Appalachian Basin (Eble et al., 2013) and Illinois Basin (Peppers, 1985, 1996), which are commonly dominated by tree fern spores. The flora lacks a significant lycopsid component, the only element being the small lycopsid *Polysporia*, represented by the spore *Endosporites*. No tree lycopsid spores were identified. The presence of cordaitalean pollen (3.2%), and of a single grain of conifer pollen, indicate that plants more tolerant of seasonal drought remained present in the regional landscape. An early Permian coal from the Kerr Basin in west-central Texas (Barker et al., 2003) also was found to be dominated by tree-fern spore taxa. And, Late Pennsylvanian coaly shales from north-central Texas have been shown by macrofossil analysis to be dominated by medullosan pteridosperms, marattialean ferns and calamitaleans (Tabor et al., 2013a; Looy and Hotton, 2014). Thus, the core coal swamp flora is much like wetland floras across the Euramerican tropics. The north-central Texas examples, however, have similarities to that reported here in the pattern of macrofloral and palynofloral succession. In coals or coaly shales from different stratigraphic horizons, a dryland vegetation was documented in the mudstones beneath the coaly beds. Palynology indicated that pollen typical of this dryland flora persisted into the lower coaly beds, suggesting a gradual environmental transition. And, although considerably thicker than the coal reported from Carrizo Arroyo, the Texas coals or organic shales may have been confined to abandoned channels or thicker channel-form areas, where peat accumulation and aggradation may have been initiated.

The flora of the shaly limestone roof of the coal contains the fossil remains of pteridosperms and calamitaleans, and rare wetland palynomorphs. The palynoflora from this bed, reported by Utting et al. (2004) is dominated by coniferous pollen, although there were no conifers found in the limestone.

It is noteworthy that the palynological record and macrofossil record are in general accord for the beds beneath the coal,

at least at the level of the dominant plant groups. However, in the bed overlying the coal, these records deviate; palynology continues to indicate dominance by conifers, whereas the macrofossil record suggests sphenopsids, pteridosperms and, perhaps, cordaitaleans, none of which are prominently represented in the palynoflora from that bed. Perhaps the broader landscape was dominated by conifers, while, at the same time, plants typical of wet soils fringed the depositional site as brackish waters invaded. There are several recent examples of comparative studies that have found considerable (and troubling) discord between the palynoflora and macrofossil records from the same deposit, suggesting significant taphonomic preservational biases under certain conditions. In particular, these studies have found an extreme under-representation of palynomorphs from dryland taxa in sediments where the megafloora is dominated by such plants (Mander et al., 2010; Looy and Hotton, 2014; Looy et al., 2014; Slater and Wellman, 2015). The palynoflora-megafloora discord in the Carrizo Arroyo bed above the coal is opposite to that found in these other studies in the under-representation of wetland plants in comparison to their presence in the megafloora.

The closest western coal analog to be analyzed in a manner similar to the Carrizo Arroyo Bursum Formation coal bed is from the Kerr Basin in west-central Texas. That coal is 2+ meters in thickness, and high in both ash yield (>30 % ash) and sulfur content (>3%). Although early Permian in age, based on fusulinid data from an overlying limestone, the coal contained a palynomorph assemblage dominated by tree fern and calamite spore taxa with minor small fern (e.g., *Granulatisporites*), pteridosperm (*Vesicaspora*), and cordaitalean (*Florinites*) taxa. No bisaccate-saccate pollen was seen. Overall, the coal palynoflora resembles Late Pennsylvanian (Monongahela Group) and early Permian (Dunkard Group) coals from the northern Appalachian Basin (Eble et al., 2013). Petrographically, the Carrizo Arroyo Bursum coal contains much more inertinite than the coal from the Kerr Basin, and the Monongahela/Dunkard coals. The Kerr Basin and Monongahela/Dunkard coals are mainly dominated by vitrinite macerals (>75 to 80%, mmf).

Global Context

A final note should be made of the stratigraphic position of this coal bed, near the transition from the Pennsylvanian to the Permian. Studies of invertebrate fossils from the Carrizo Arroyo stratigraphic section indicate close proximity to the boundary (e.g., Kues, 2004; Lucas and Krainer, 2004; Lucas et al., 2013a). The coal bed falls between invertebrate-determined stratal ages of late Virgilian (late Gzhelian) and Wolfcampian (Asselian). Accordingly, the palynological studies, referenced above, also place the boundary near the Pennsylvanian-Permian transition, but put the sequence of beds in the Late Pennsylvanian. Eastern coal basins in the U.S., particularly the Appalachian Basin, record a transition from strong seasonal dryness in the earlier, Missourian (Kasimovian) part of the Late Pennsylvanian to a period of increased wetness in the latter part of the Pennsylvanian (Virgilian, Gzhelian) (Cecil, 1990). A similar pattern is seen in European basins (Roscher

and Schneider, 2006). This time of renewed wetness saw the formation of the Pittsburgh coal bed, one of the thickest and most areally widespread coals in the world, together with several other thick, economic coals (Eble et al., 2006), a pattern that continued into the latest Pennsylvanian and possibly into the Permian (Eble et al., 2013). The Late Pennsylvanian also was a time of step-wise increases in sea level (Rygel et al., 2008; Eros et al., 2012), suggesting ice melting in the Southern Hemisphere, prior to major ice expansion in the latest Pennsylvanian and/or earliest Permian (Koch and Frank, 2011; Montañez and Poulsen, 2013), which may have had a major effect on global sea level and climate, seemingly a shift to increasing tropical aridity (Tabor et al., 2013b; Davydov, 2014). The occurrence of a thin, coaly horizon, at approximately the same temporal interval in southern New Mexico, in Laborcita Canyon, near Alamogordo (Fig. 11), and of a thin coal bed in Arizona (Kremp, 1975), also mapped at approximately the same stratigraphic position (Weir and Beard, 1994), might indicate a period of environmental humidification reaching well into western Pangea, conditions that in the eastern coal basins may have contributed to much thicker coal deposits (Gzhelian-Asselian wet phase C of Roscher and Schneider, 2006).

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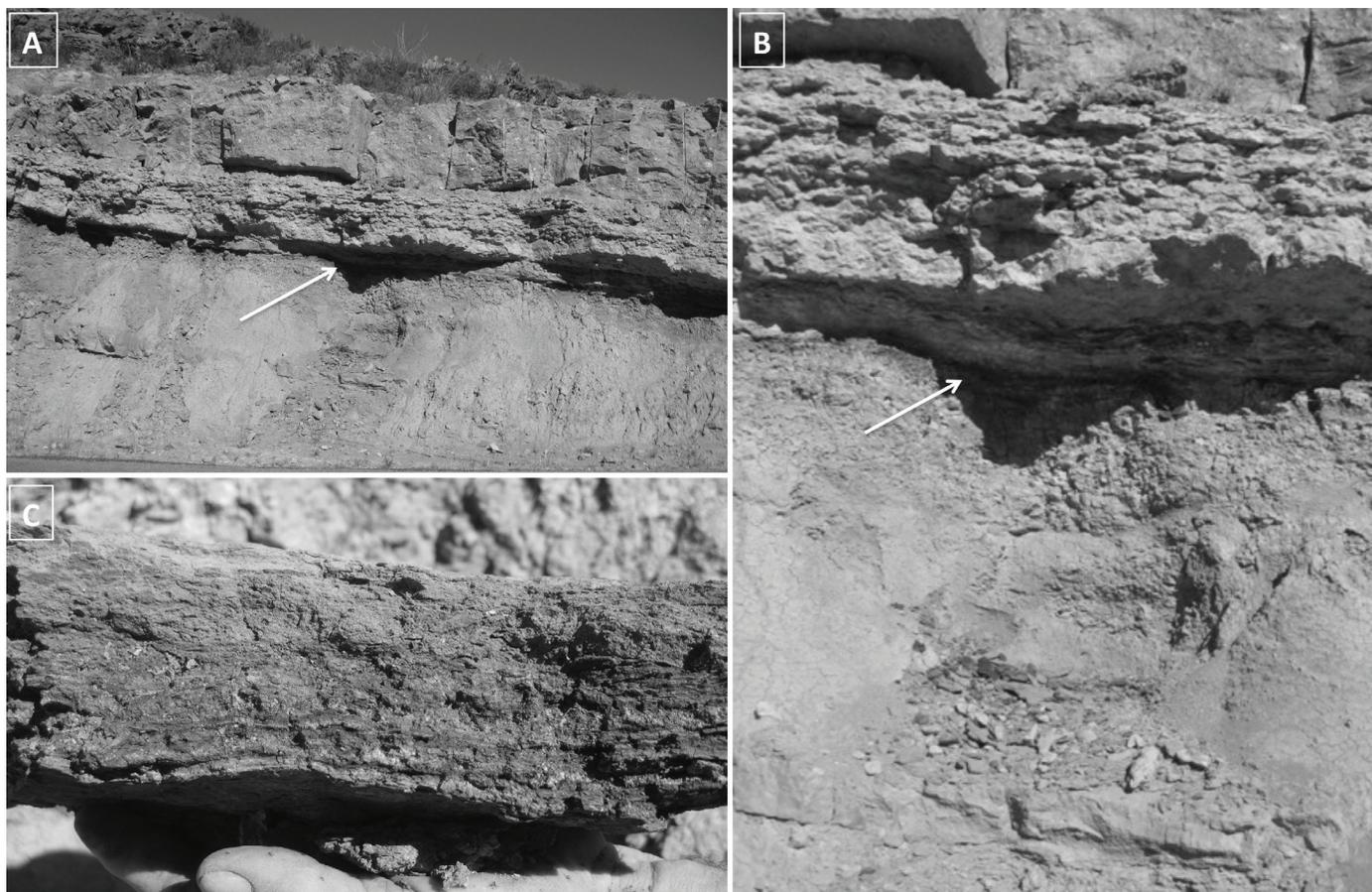


FIGURE 11. Organic horizon in Bursum Formation strata exposed in Laborcita Canyon, northeast of Alamogordo, New Mexico. Series of increasingly proximate images. **A**) Roadcut. Organic horizon is a dark streak (white arrow) above a paleosol below, siltstone immediately above, overlain by a marine limestone. **B**) Closeup of carbonate-rich paleosol, organic layer (white arrow), siltstone and marine limestone. **C**) Hand-sample of organic layer and siltstone immediately above. Photographs by authors.

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