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CARBONIFEROUS-PERMIAN TRANSITION IN THE ROBLEDO MOUNTAINS, SOUTHERN NEW MEXICO: AN OVERVIEW

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Abstract—This volume presents eight articles on the Pennsylvanian-Permian geology and paleontology of the Robledo Mountains in Doña Ana County, southern New Mexico. The reported research resulted from a federally-funded study of the trace fossils in and around the Prehistoric Trackways National Monument (PTNM). We divide the overview by the main topics addressed—stratigraphy, sedimentology, paleobotany, micropaleontology, biostratigraphy and ichnology—and draw attention to the most significant research results. These indicate that the identification of glacio-eustatically driven sedimentary cyclicity in the Robledos Lower Permian strata, paralleling that seen in mid-continent and Appalachian basin cyclothems of Pennsylvanian age, is problematic. There may be some kind of allocyclic signature in the Robledo sections, but autocyclic drivers clearly were important forces in the local Early Permian sedimentary history. The red-bed fossil assemblages in the PTNM were early fit into a rather simple model of intertidal flat depositional environments, but studies here indicate much greater depositional complexity, and identify what are likely a mosaic of local paleonenvironments and taphonomic settings in which the trace fossils and red-bed plant assemblages accumulated. The Early Permian geological record indicates episodically increasing seasonality and climatic dryness around the equatorial regions of central and western Pangea, a trend that began in the late Middle Pennsylvanian. During this period of warming, terrestrial floras became increasingly heterogeneous spatially, and the Robledo paleofloras fit that pattern. Precise and extensive age data for the Hueco Group section based on non-fusulinid and fusulinid foraminiferans indicate that the base of the Leonardian (Artinskian) is very close to the base of the Robledo Mountains Formation. This means the upper part of the local Hueco section is Leonardian, not Wolfcampian as long supposed.

INTRODUCTION

The Robledo Mountains are an isolated fault block mountain range northwest of Las Cruces in southern New Mexico. Paleozoic strata are the primary bedrock exposed in the range (Fig. 1). The youngest Paleozoic rocks, Lower Permian strata of the Hueco Group, are as much as 565 m thick and crop out across most of the central and southern parts of the Robledo Mountains (Seager et al., 2008). In 2009, the U. S. Congress created a new national monument in the Robledo Mountains, primarily because of the world-class Early Permian trace-fossil assemblages preserved in the Hueco Group strata exposed in the southern Robledo Mountains (Lucas and Heckert, 1995; Lucas et al., 1998a, 2011; Minter and Braddy, 2009 and references cited therein).

The Prehistoric Trackways National Monument (PTNM) is approximately 2137 hectares (5280 acres) of land administered by the U. S. Bureau of Land Management (Fig. 1). In 2009, a Federally funded study began of the trace fossils in and around the PTNM, undertaken by the New Mexico Museum of Natural History and Science (NMMNHS) to re-evaluate all of the fossil sites and make specific recommendations to manage the paleontological resources. This required new research, and the NMMNHS worked with a team of collaborators in sedimentology, field geology, paleobotany, micropaleontology and ichnology.

This project provided the evaluations and the recommendations asked for by BLM. It also produced a new round of research on the trace fossil assemblages, the associated plant fossils, invertebrate microfossils and the geological context in which these fossils are found. Some of the results of that research are published here. Other aspects of this research have already been published (Lucas et al., 2011, 2013; Voigt et al., 2013a, b; Falcon-Lang et al., 2014) or will appear in print elsewhere.

Here, we present a brief overview of the articles in this volume. We divide the overview by the main topics addressed—stratigraphy, sedimentology, paleobotany, micropaleontology, biostratigraphy and ichnology. We conclude by drawing attention to the most significant research results to emerge from the studies of the PTNM published here.

LITHOSTRATIGRAPHY

Most of the bedrock exposed in the Robledo Mountains is of Early Permian age (Fig. 1), and most of the articles in this volume are about those Lower Permian strata and their fossils. However, Pennsylvanian strata do crop out along the northern and western periphery of the Robledo Mountains (Fig. 1). Kottlowski (1960) first described these strata in some detail, assigning them Atokan (“Derryan”), Desmoinesian, Missourian and Virgilian ages. He also identified a stratigraphic interval just below the Hueco strata as equivalent to the lower Wolfcampian Bursum Formation to the north.

Seager et al. (2008) mapped these chronostratigraphic subdivisions, and Wahlman and King (2002) described some fusulinids from the Bursum-equivalent and lower Hueco strata (Thompson, 1954 had first described fusulinids from the same interval). Lucas et al. (1995, 1998b) created formal lithostratigraphic nomenclature for the Hueco Group strata in the Robledo Mountains (Fig. 2)

In this volume, **Krainer, Lucas, Vachard and Barrick** present a detailed study of the Pennsylvanian-Permian section on the northern end of the Robledo Mountains. This ~ 418 m thick section is carbonate dominated with diverse fusulinid assemblages. **Krainer et al.** assign this section to the Horquilla Formation (lower 300 m) overlain by the Shalem Colony Formation of the Hueco Group (upper 118 m). They divide the Horquilla Formation into five informal members, in ascending order: member A (~ 82 m thick), characterized by cherty limestone; member B (~ 24 m thick), a slope-forming, shale-dominated interval; member C (~ 52 m thick), consisting of alternating beds of limestone and shale; member D (~ 75 m thick), bedded to massive, non-cherty limestone; and member E (~ 62 m thick), composed of bedded limestone with intercalated shale (Fig. 2).

A detailed study of the entire Lower Permian Hueco Group section in the Robledo Mountains is presented by **Lucas, Krainer and Vachard.** They assign the Hueco Group strata to (in ascending order) the Shalem Colony, Community Pit, Robledo Mountains and Apache Dam formations (Fig. 2). The Shalem Colony Formation is about 127-156 m thick and is a relatively thick-bedded and coarse-grained succession of wackestones, grainstones, rudstones and some oolitic limestones intercalated with mostly covered intervals that represent shale and/or nodular limestone. It rests with apparent conformity on the Pennsylvanian-Permian Horquilla Formation. The Community Pit Formation, 93-177 m thick, is mostly a slope-forming interval of shale and siltstone intercalated with relatively thin intervals of limestone, many of which are mudstones and dolomitic mudstones. The formation has a characteristic brownish gray to grayish orange color. The Robledo Mountains Formation is about 90-125 m thick and is mostly drab-colored marine shale and limestone, but is readily identified by its characteristic siliciclastic red beds (mudstone, siltstone and sandstone), which are intercalated with the marine rocks. At least 107 m thick, the Apache Dam Formation is composed mainly of algal limestone and shale/covered intervals.

The general geology of the PTNM is described in this volume by **Lucas, Krainer, Nelson and Elrick.** Most of the bedrock exposed in

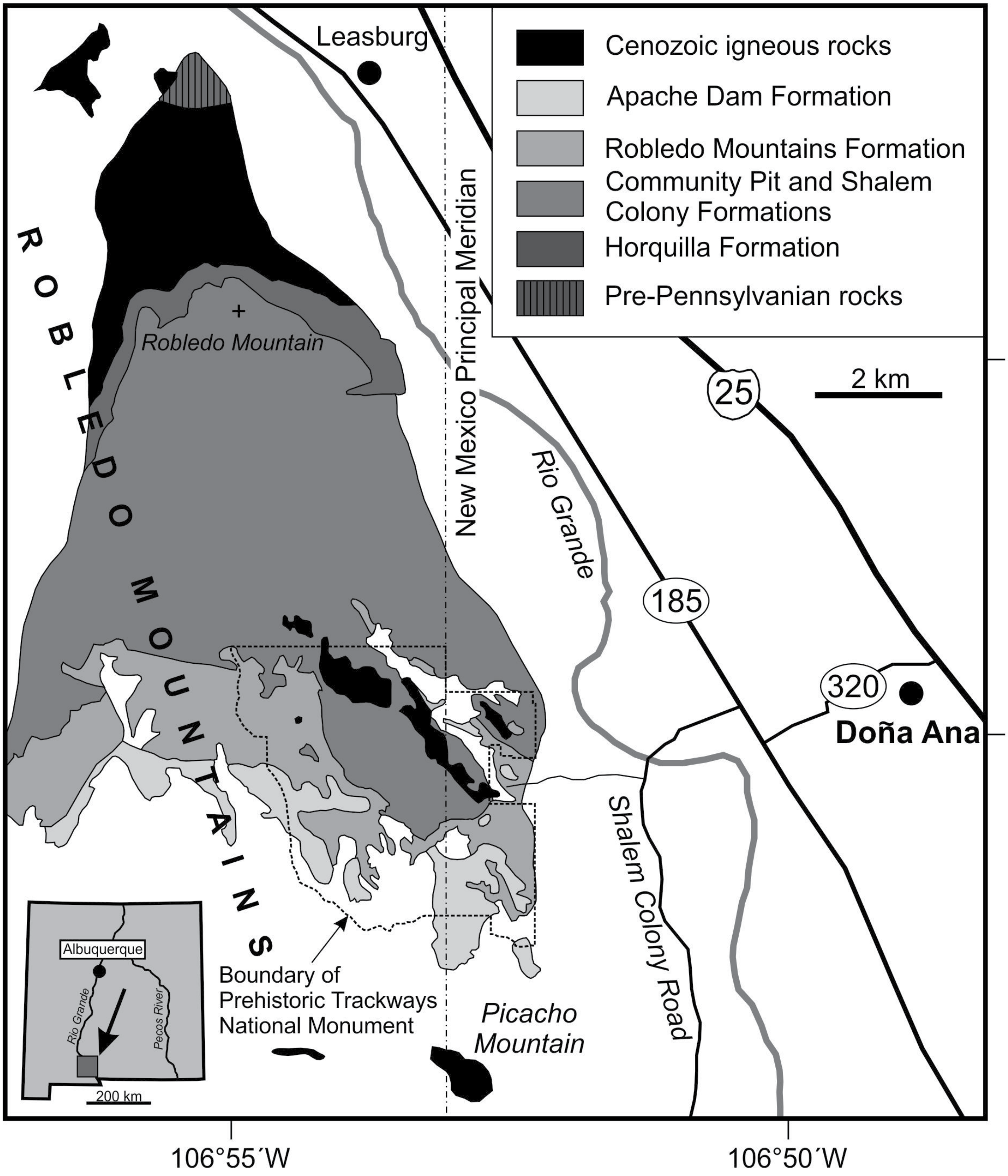

FIGURE 1. Generalized geologic map of the Robledo Mountains in south-central New Mexico (drawn by Karl Krainer). Boundary of Prehistoric Trackways National Monument (PTNM) is shown in the southern part of the range.

group/ frmn.	formation/ member	maximum thickness	principal lithologies
Hueco Group	Apache Dam Formation	107+ m	algal limestone and shale
	Robledo Mountains Formation	90-125 m	grainy limestone, shale and red-bed siliciclastics (sandstone, siltstone, mudstone)
	Community Pit Formation	93-177 m	shale, muddy limestone, dolomitic limestone
	Shalem Colony Formation	127-156 m	thick-bedded, coarse-grained limestone (wackestone, grainstone, etc.)
Horquilla Formation	member E	62 m	bedded limestone with intercalated shale
	member D	75 m	bedded to massive, non-cherty limestone
	member C	52 m	alternating beds of limestone and shale
	member B	24 m	mostly shale
	member A	82 m	cherty limestone

FIGURE 2. Brief summary of Horquilla Formation and Hueco Group stratigraphy in the Robledo Mountains, after **Krainer et al.** and **Lucas et al.**, this volume.

the PTNM can be assigned to the four formations of the Lower Permian Hueco Group. These strata are mainly limestone and mudstone of shallow marine origin, but the Robledo Mountains Formation also includes red-bed siliciclastic coastal plain deposits that yield the trace fossil assemblages that justified creation of the PTNM.

Rocks of Cenozoic age crop out much less extensively in the PTNM than do Hueco Group strata. Cenozoic strata include Eocene fluvial, playa and volcaniclastic deposits of the Laramide orogeny (Love Ranch and Palm Park formations) and Miocene to Pliocene alluvial sediments (Rincon Valley and Camp Rice formations) or igneous rocks (Bell Top Formation, Robledo rhyolite, basalt) associated with late Cenozoic development of the Rio Grande rift. Quaternary rocks are mostly superficial alluvial and terrace deposits. The Rio Grande rifting event, which commenced in the Miocene, determined the current geological structure of the Robledo Mountains and the PTNM. The geological history of the PTNM can thus be divided into two principal phases—Early Permian shoreline and shallow marine environments of the Hueco seaway and late Cenozoic continental rifting and basin-margin sedimentation. The more than 250 million years that divide these two phases left little geological evidence in the PTNM.

SEDIMENTOLOGY

During Pennyslvanian-Permian time, the area of the Robledo Mountains lay along the western edge of the late Paleozoic Orogrande basin (Fig. 3). To the southwest, what has been called the Florida islands or Florida uplift separated the Orogrande basin from the late Paleozoic Pedregosa basin, which covered much of southwestern New Mexico, southeastern Arizona and adjacent portions of the Mexican states of Chihuahua and Sonora. Based on currently posited paleogeography, Pennsylvanian-Permian deposition in the Robledo Mountains area took place on the Robledo shelf, and was part of deposition in the Orogrande basin.

However, as Lucas and Krainer (2011) first pointed out, the Pennsylvanian section at Robledo Mountain differs substantially from the closest Pennsylvanian sections in the Orogrande basin, which are in the Doña Ana Mountains 10 km to the northeast and in the Caballo Mountains-Derry Hills, 40 km to the northwest. Indeed, **Krainer, Lucas, Vachard and Barrick** assign the section at Robledo Mountain to the Horquilla Formation, which is the Pennsylvanian-lowermost Permian lithostratigraphic unit in the Pedregosa basin.

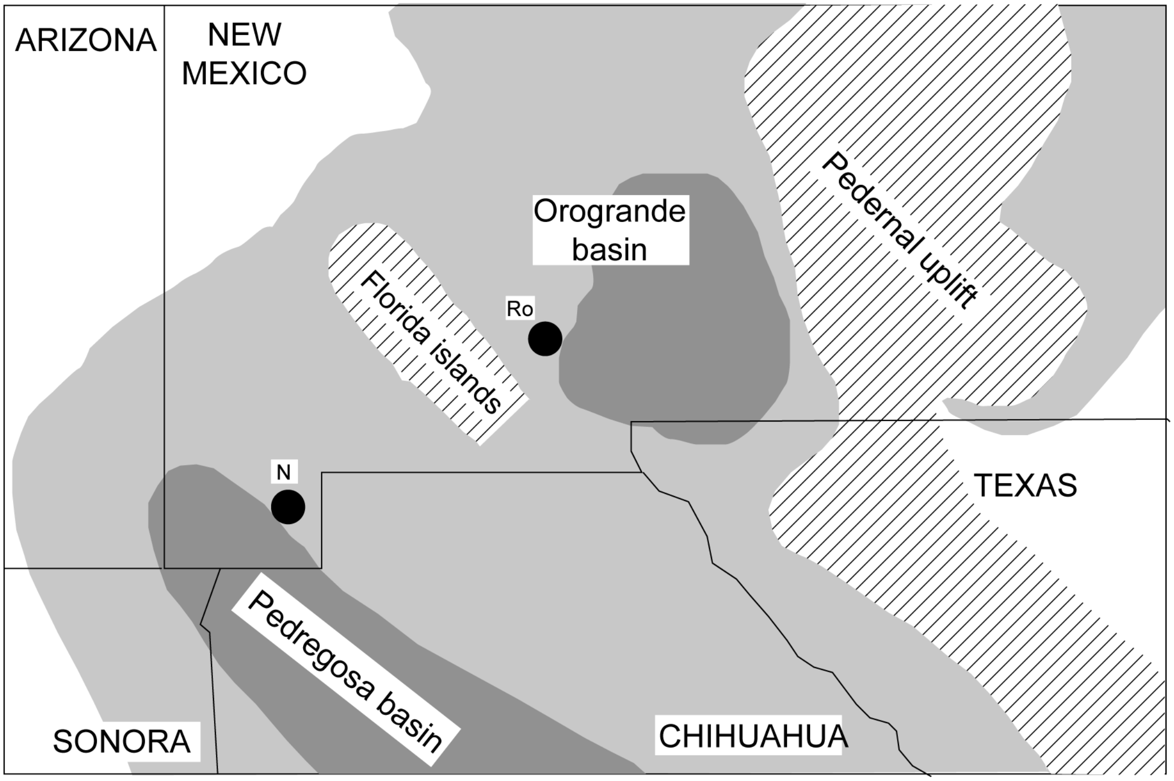

FIGURE 3. Pennsylvanian paleogeography of the divide between the Orogrande and Pedregosa basins during the Pennsylvanian, showing relatively small area of islands and straits dividing the Pedregosa and Orogrande basins, from **Krainer et al.**, this volume. N = Newwell Peak, Big Hatchet Mountains; Ro = Robledo Mountain.

Because of the lithologic similitude of strata to the southwest, **Krainer et al.** argue that the Pennsylvanian strata at Robledo Mountain are more closely related genetically to deposition in the Pedregosa basin than to deposition in the Orogrande basin. Thus, subsidence in the Pedregosa basin and along the Florida shelf (including the Robledo shelf) was relatively even during the Virgilian-Wolfcampian, so that glacio-eustatic cycles are better recorded in these sections than in the more tectonically-influenced sections to the east, within the Orogrande basin. Assignment of most of the Robledo Mountain section to the Horquilla Formation casts doubt on the idea that the Robledo shelf was significantly separated from Horquilla deposition in the Pedregosa basin to the southwest by an intervening Florida uplift (highland). Instead, the original idea of a Florida island, and a strait to the southeast of it, separating the late Paleozoic Orogrande and Pedregosa basins, is more compatible with the stratigraphic and sedimentologic data (Fig. 3).

Based in large part on microfacies and paleontology, **Krainer et al**. interpret the depositional environments of the five informal members of the Horquilla Formation at Robledo Mountain. The microfacies and biota of member A are characteristic of open marine, well-oxygenated and well-circulated conditions with normal marine salinity, deposited below the fair weather wave base in a relatively deep, open marine shelf environment with water depths of at least some tens of meters. These limestones are part of well-developed cycles, and the microfacies and biota indicate a relatively shallow depositional environment. The bulk of member B (shale, wavy and nodular limestone) was deposited in an open marine shelf environment in deeper water and in a more outer shelf position than member A.

Microfacies and biota (particularly algae and fusulinids) indicate that the limestone units of members C, D, and E formed in a shallower depositional environment than the wavy-bedded to nodular limestone units of members A and B. Indistinctly bedded to massive limestone formed in an open, shallow marine, well-oxygenated environment with normal salinity. Water depth did not exceed a few tens of meters. High-energy microfacies (grainstone, packstone, rudstone) and bindstone are also indicative of a shallow marine setting. Thin intercalated conglomerate beds containing marine fossils also point to a high-energy shallow marine environment.

In the Horquilla Formation at Robledo Mountain, the well-developed cyclic pattern with subaerial exposure surfaces on top of many limestone units indicates rapid sea-level fluctuations during deposition of members C, D, and E. Water depth varied between deeper shelf (deposition of offshore mudstone and wavy bedded to nodular limestone) and subaerial exposure, indicating sea-level fluctuations on the order of some tens of meters. Glacio-eustasy seems a likely driver of such cycles.

In their study of the Hueco Group, **Lucas, Krainer and Vachard** analyze microfacies, paleontology and stratigraphic architecture to conclude that: (1) the Shalem Colony Formation accumulated on a platform interior environment of open, normal marine to less common, restricted marine settings; (2) the Community Pit Formation was deposited in shelf settings ranging from shallow, low-energy (rarely high-energy) open marine to restricted marine environments; (3) the Robledo Mountains Formation represents deposition in a restricted to open marine shallow shelf setting where intercalated red beds were deposited on a distal, extensive flood plain (exhibiting crevasse splay deposits, rare channels, and distal sheet flood deposits) during periods of strong siliciclastic influx from uplifts located to the north and northeast; and (4) the Apache Dam Formation was deposited in an open shelf to shelf lagoon environment with normal salinity and open circulation.

The Community Pit and Robledo Mountains formation strata were deposited during a portion of the Early Permian characterized by intense southern hemisphere glaciation (Fielding et al., 2008). However, **Lucas et al.** find the imprint of allocyclicity to be difficult to identify, primarily because of the generally disorganized (chaotic) facies stacking patterns in the Community Pit and Robledo Mountains formations. Instead, the stratigraphic patterns indicate that autocyclic processes strongly influenced deposition. These findings conflict with some earlier interpretations of the stratigraphic framework in the PTNM and surrounding area (Mack, 2007; Mack et al., 2010, 2013).

PALEOBOTANY

Paleobotanical material from the PTNM is known from the Community Pit and Robledo Mountains formations. This consists of numerous fossil logs in shallow marine strata of the Community Pit Formation and one locality where compression foliage of conifers and callipterids is preserved in a small channel-fill deposit (Fig. 4). In the Robledo Mountains Formation, impressions of foliage are present in the siliciclastic red beds. Thus, at least three Lower Permian taphofloras are present.

Among the Early Permian deposits in the PTNM is a localized, limestone-filled paleochannel in the Community Pit Formation discussed in this volume by **DiMichele, Chaney, Falcon-Lang, Kerp, Looy, Lucas, Krainer and Voigt** and by **Falcon-Lang, Kurzawe and Lucas.** The paleochannel, which is ~ 140 m wide and 5-6 m maximum depth, contains a complex fill sequence that yields two distinct fossil plant assemblages (Fig. 4). The base of the channel is a limestone conglomerate that contains permineralized logs and charcoal attributable to indeterminate walchian conifers. The middle channel fill consists of multiple lenses of lime mudstone with a sparse brackish-to-marine water invertebrate fauna and a macroflora consisting largely of an undescribed voltzian conifer, the earliest known occurrence of this plant group, and the callipterid *Lodevia oxydata*, previously known from two areas, one in Central Europe and the other in the Central Appalachian basin. The deposit also contains in situ fossil roots, indicating at least sporadic plant colonization of the micritic muds.

Falcon-Lang et al. describe the stratigraphically lower plant assemblage, which includes large chunks of charcoalified wood, attributed to walchian conifers, associated with a limestone conglomerate in the base of the channel. This charcoalified wood shows dominantly uniseriate, contiguous tracheidal pitting, cupressoid cross-field pits that are solitary or, if paired, show an opposite arrangement, and short uniseriate rays, 1–18 cells high. These anatomical characters match closely the wood of *Macdonaldodendron*, recently described from other sites in PTNM (Falcon-Lang et al., 2014), which is demonstrably a walchian conifer based on aspects of its pith with sclerotic nests, endarch cauline bundles, triangular leaves, and whorled branch pattern. Therefore – while accepting that precise identification of isolated pieces of wood is fraught with difficulties – the overwhelming likelihood is that the charcoalified material from the channel deposit is walchian.

The occurrence of burned fragments of walchian wood in an incised fluvio-estuarine channel suggests that fire-prone walchian trees grew at a time when sea-level was temporarily lowered and the shoreline of the Hueco Seaway had regressed southward. Diverse data indicate that this coastline was subject to strongly seasonal rainfall, but a remarkable feature of the charcoalified woods is that they completely lack growth rings. These facts can be reconciled if the walchian conifers were somehow buffered against seasonal drought. The most likely explanation, consistent with taphonomic considerations, is that they were growing along wet riparian corridors, where elevated water tables provided a reliable year-round water supply. High fuel loads might be expected to have accumulated in these "wet spots" on an otherwise dry landscape, which would have been vulnerable to conflagration in the event of extreme droughts; this fire dynamic may explain the predominant preservation of fossil wood as charcoal.

DiMichele et al. review the stratigraphically higher plant assemblage in the channel fill to note that the voltzian conifer from the channel fill is the earliest member of this evolutionary lineage, extending the known range by approximately 25 million years. Similarly, the geographic range of *Lodevia oxydata* is extended nearly 2500 km, from its previously most westerly known occurrence in West Virginia. Together with the only other report from the Rotliegendes of Poland, this species now has a total known range of approximately 9000 km on today's earth, based on three widely separated and localized occurrences.

Clearly, prior to the latest Permian, when such conifers were abundant, the voltzians were significant tropical landscape elements somewhere, but have been incorporated into the fossil record rarely, so their early history remains largely unknown. For the callipterid, temporal continuity throughout its known range cannot be established, so it cannot be determined if the plant occupied the full range at any given time, or only portions thereof. Nonetheless, the geographic sparseness of its appearances, in light of the high density of plant remains from the sites where it does occur, indicates that its fossil record also is very incomplete.

DiMichele, Lucas, Looy, Chaney and Voigt review the floras of the Robledo Mountains Formation red beds to conclude that they are compositionally similar to those found in the Abo Formation to the north (Hunt, 1983; DiMichele et al., 2007, 2013). These floras are dominated by walchian conifers most similar to the form taxon *Walchia piniformis*. Isolated occurrences of other taxa include the peltasperm *Supaia thinnfeldioides*, the possible peltasperm *Gigantopteridium* sp., the cycadophyte *Taeniopteris* and callipterid peltasperms. The monotony

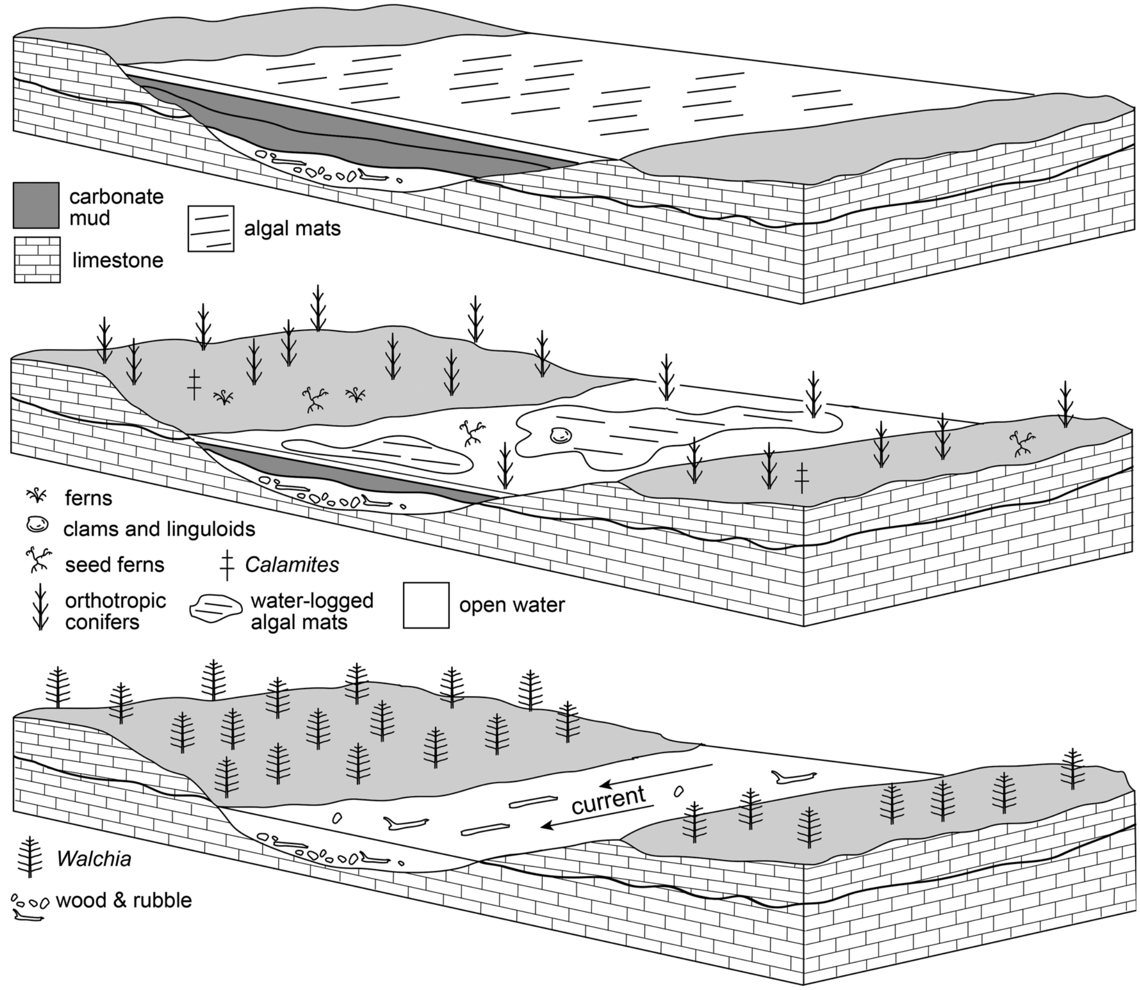

FIGURE 4. Channel-fill progression model of localized deposit in the Community Pit Formation, from **DiMichele et al.** this volume. Bottom— active flow during incision phase and early back filling. Middle— as channel flow volume decreases and carbonate precipitation ensues; surrounding flora changes and plants are incorporated into the micritic muds. Top— evaporitic conditions intensify in final channel fill phases and gypsum is deposited in association with micritic muds. Drawing by Mary Parrish, NMNH.

of these Early Permian red-bed floras over a very large area of New Mexico is noteworthy and perplexing. Notably, other facies from strata within this same time interval, elsewhere in the region, preserve either strikingly different floras or floras of considerably higher diversity. The red-bed floras do not appear to reflect a persistent preservational bias, but suggest that large areas were covered by low diversity forests of conifers. At the outcrops in the Robledo Mountains, the proximity of the red-bed facies to marine conditions bordering the Hueco seaway does not seem to have had any discernible effect on floral composition.

MICROPALEONTOLOGY AND BIOSTRATIGRAPHY

In the Robledo Mountains, marine limestones of the Horquilla Formation and Hueco Group contain diverse assemblages of calcareous microfossils, mostly algae and foraminiferans (including fusulinds). Some of the non-fusulinid foraminiferans and the fusulinids provide the most precise age control of the Pennsylvanian-Permian section in the Robledos. Some conodont biostratigraphy is also available, but it is only based on preliminary sampling (Kozur and LeMone, 1995; Lucas et al., 1995). Ostracods have also been documented in a preliminary way from part of the Robledo Mountains Formation (Kietzke and Lucas, 1995).

Krainer, Lucas, Vachard and Barrick describe microfossils (mostly foraminiferans, including fusulinids, and conodonts) of Morrowan-Wolfcampian age from the section at Robledo Mountain to assign reasonably precise ages, though more data are needed to refine placement of some of the stage boundaries. Thus, the oldest strata of the Horquilla Formation at Robledo Mountain are late Morrowan, and the overlying remainder of member A is of Atokan-Desmoinesian age. Member B is Desmoinesian. The base of the Missourian is not precisely constrained, but conodonts tentatively place the base of the Missourian near the base of member C. The base of the Virgilian is better constrained as high in member C, and the Wolfcampian base is very close to the top of member E, which is just below the base of the Shalem Colony Formation of the Hueco Group. Most of the Shalem Colony Formation section at Robledo Mountain is early Wolfcampian (Newwellian or “Bursumian”), but the uppermost ~50 m of the section are of middle Wolfcampian age.

Lucas, Krainer and Vachard similarly document numerous microfossils from the Hueco Group strata, primarily from in and immediately around the PTNM. They build on work by Vachard et al. (2015) to establish different lineages of foraminiferans, miliolates and nodosariates in the regional Lower Permian, especially the group *Calcivertella*, *Hedraites*, *Hedraites*? and *Pseudovermiporella*, and the group *Nodosinelloides*, *Protonodosaria*, true *Nodosaria*, *Geinitzina*, *Pseudolangella*?, *Rectoglandulina*, and *Pachyphloia*? Thus, a complete Early Permian biozonation by smaller foraminiferans is constructed (Fig. 5).

Lucas et al. thus present new age data, primarily from fusulinids and non-fusulinid foraminiferans, to conclude that the Shalem Colony Formation is early-middle Wolfcampian (Asselian), the Community Pit Formation is middle Wolfcampian-early Leonardian (Asselian-early Artinskian), the Robledo Mountains Formation is early Leonardian (middle-late/latest Artinskian) and the Apache Dam Formation is late Leonardian (latest Artinskian/earliest Kungurian). This indicates

ZONATION	FORMATIONS		Thickness (m)	BIOMARKERS (and representative samples)		REGIONAL STAGES	INTERNATIONAL STAGES
Zone 15		SAN ANDRES FORMATION		*Olgaorlovella davydovi* *Tubiphytes epimonellaeformis* *Geinitzina indepressa*	LEONARDIAN	CATHEDRALIAN	LATE KUNGURIAN
Zone 14				*Hemigordiellina* spp.			MIDDLE KUNGURIAN
Zone 13		GLORIETA SANDSTONE		barren of foraminifers			
Zone 12		YESO GROUP		*Frondicularia* aff. *turae*			EARLY KUNGURIAN
Zone 11				*Ellesmerella rara* *Nestellorella* ? sp.			
Zone 10				*Globivalvulina novamexicana* *Orthovertellopsis protaeformis* *Globomidiella infrapermica*			
Zone 9	HUECO GROUP	Apache Dam Formation					LATE ARTINSKIAN
Zone 8		Robledo Mountains Formation	53	*Pseudoreichelina* sp. *Geinitzina* sp. 2 (?*multicamerata*)		HESSIAN	MIDDLE ARTINSKIAN
Zone 7		Community Pit Formation	10	*Praeneodiscus* sp. *Globivalvulina novamexicana* *Globivalvulina praegraeca* DAB 13 + DAB 14/DAC 1-DAC 5			EARLY ARTINSKIAN
Zone 6			20	*Pseudovermiporella* sp. DAB 10 - DAB 12	WOLFCAMPIAN	LENOXIAN	LATEST SAKMARIAN
Zone 5			50	*Pachyphloia*? sp. *Geinitzina postcarbonica* *Nodosinelloides longissima* DAB 7 - DAB 9			LATE SAKMARIAN
Zone 4			7	*Nodosinelloides pinardae* *Globivalvulina parapiciformis* *Geinitzina postcarbonica* DAA 59 - DAA 69/DAB 2 - DAB 6			EARLY SAKMARIAN
Zone 3			50	*Hedraites* sp. DAA 53 - DAA 58		NEALIAN	LATE ASSELIAN
Zone 2			20	*Geinitzina postcarbonica* *Nodosinelloides netschajewi* DAA 45 - DAA 52			MIDDLE ASSELIAN
Zone 1		Shalem Colony Formation	65	*Leptotriticites* sp. (DAA 43) *Nodosinelloides longissima* *Tubiphytes* sp., *Geinitzina* sp. (DAA 38) *Pseudovidalina* sp., *Pseudoschwagerina* sp. DAA 42	BURSUMIAN		EARLY ASSELIAN - LATEST GZHELIAN

FIGURE 5. Biozonation by foraminiferans and correlation of the Lower Permian strata of the Robledo Mountains, New Mexico, after Lucas et al., this volume.

that the Wolfcampian and Leonardian regional stages/superstages are remarkably complete in New Mexico, where the base of the Wolfcampian is at (or very close to) the base of the Shalem Colony Formation, and the base of the Leonardian is within the Hueco-Abo lithosome.

Note that earlier, Kozur and LeMone (1995) and Lucas et al. (1995) assigned an Artinskian age to the Robledo Mountains Formation based on limited samples of conodonts. Much more conodont sampling and biostratigraphy needs to be undertaken in the Carboniferous-Permian transition section in the Robledo Mountains.

ICHNOLOGY

The trace fossil assemblages from the Robledo Mountains Formation of the Hueco Group are, of course, the basis of the PTNM. Indeed, the PTNM contains one of the most abundant and most extensively discussed assemblages of Paleozoic tetrapod footprints in the world. The red-bed ichnofossil assemblages from the Robledo Mountains Formation (e. g., Minter and Braddy, 2009; Lucas et al., 2011 and references therein) represent an arthropod-dominated invertebrate fauna of terrestrial herbivores and predators such as apterygote insects, myriapods and scorpionids that can be assigned to the *Scoyenia* ichnoguild of the *Scoyenia* ichnofacies. The invertebrate trace fossils are dominated by arthropod trackways, resting traces, jumping traces and grazing traces. Other invertebrate feeding traces, grazing traces, graphoglyptids and helical-shaped burrows are less common. Vertebrate footprints are mostly of small temnospondyls, araeoscelids and pelycosaurs. Tracks of larger amphibians and of primitive amniotes are much less common, and fish swimming traces and tetrapod "swim tracks" are present.

An important issue concerns the amount of tidal influence in the trace-fossil-bearing red beds. The abundance of small amphibian and arthropod traces suggests that the trace fossil assemblages were made in a freshwater setting. However, in apparent contradiction, most sedimentological studies have argued for deposition of the trace-fossil-bearing red beds in the intertidal zone of tidal flats (e.g., Mack and James, 1986; Lucas et al., 1995; Minter and Braddy, 2009). The answer to this lies in Voigt et al. (2013b), who concluded that the red beds of the Robledo Mountains Formation were deposited in the distal parts of an extensive coastal flood plain during alternating dry and wet climatic conditions. Flaser- to wavy-bedded siltstone and fine-grained sandstone represent distal crevasse splay deposits. Most of the trace fossils in the Robledo Mountains Formation occur on mud-draped bedding planes of this lithofacies. The red-bed intervals thus do not show any evidence of marine or tidal influence

An exception to the interpretation of Voigt et al. (2013b) is identified in this volume by **Lerner and Lucas**. They describe a local ichnoassociation of vertebrate and invertebrate ichnotaxa from stratigraphically high in the Robledo Mountains Formation near the eastern border of the PTNM. The vertebrate ichnotaxa of this ichnoassociation include tetrapod "swim tracks" and fish swimming traces. The invertebrate ichnotaxa are dominated by limulid (horseshoe crab) traces, notably the head shield (feeding) trace *Selenichnites*. **Lerner and Lucas** argue that this "*Selenichnites* ichnoassociation" formed subaqueously in two differing nearshore settings: (1) a lower energy setting that contains relatively abundant *Selenichnites;* and (2) a higher energy setting, in which *Selenichnites* is scarce. The higher energy setting includes marine bivalves and possible storm indicators (pot casts), which are not found at the lower energy locality. The ichnogeneric composition and marine-influenced depositional setting of this local *Selenichnites* ichnoassociation distinguish it from those well-known nonmarine Robledo Mountains Formation red bed ichnoassemblages that formed in freshwater settings.

Most prominent among the trace fossils of the Robledo Mountains Formation are those made by vertebrates. In this volume, **Voigt and Lucas** subject more than 700 specimens with tetrapod footprints from the PTNM to an anatomical-feature-based ichnotaxonomic analysis. Based on the results of this study, the tracks belong to eight tetrapod ichnotaxa—*Matthewichnus caudifer*, *Batrachichnus salamandroides*, *Amphisauropus kablikae*, *Dimetropus leisnerianus*, *Notalacerta missouriensis*, *Robledopus macdonaldi*, *Hyloidichnus bifurcatus*, and *Dromopus lacertoides*. These can be referred to lepospondyl, temnospondyl, seymouriamorph, pelycosaurian-grade synapsid, protorothyridid, captorhinid, and araeoscelid trackmakers, respectively. Notable features are the rare occurrence of two more typically Pennsylvanian ichnotaxa (*Matthewichnus*, *Notalacerta*) as well as the only occurrence of the proposed basal non-diapsid eureptilian track *Robledopus*.

About 90% of the material comprises tracks of *Batrachichnus*, *Dimetropus*, and *Dromopus,* suggesting that temnospondyl amphibians, pelycosaurs, and early diapsids represented the most common individuals of the ancient terrestrial tetrapod fauna of the study area. The ichnoassemblage is of typical Early Permian aspect and, in view of the low number and diversity of advanced captorhinomorph footprints, supports assignment to the Artinskian stage.

SIGNIFICANT RESULTS

We can identify four significant results of the research reported here:

1. There is strong evidence for glaciation in the Southern Hemisphere during part of Early Permian time, an interval that is well represented in the PTNM, but the identification of clear cyclicity, paralleling that seen in mid-continent and Appalachian basin cyclothems of Pennsylvanian age, is problematic in the Robledo sections. This does not mean that there are not allocyclic signatures in these rocks. Rather, it indicates how difficult these can be to identify in an area with strong contemporaneous tectonism, complex paleogeography, and a background climate not conducive to the formation and preservation of terrestrial wetland facies, such as coal. Furthermore, this difficulty is not unique to the western regions of Pangea. There have been difficulties identifying clear signatures of glacial-interglacial cycles on 100,000 and 400,000 year time scales throughout the world, though there have been attempts at identification in such areas as carbonate platforms, where one would expect to see incision (see Koch and Frank, 2011). In other cases, however, there is a clear terrestrial vegetational change associated with lithological changes, but seemingly reflecting broad changes in equatorial climate (e.g., Tabor et al., 2013). So, there may be some kind of allocyclic signature in the Robledo sections, but autocyclic drivers clearly were important forces in the local Early Permian sedimentary history.
2. The red-bed fossil assemblages in the PTNM were initially fit into a rather simple model of intertidal flat depositional environments. Studies here indicate much greater depositional complexity, and identify what are likely a mosaic of local paleonenvironments and taphonomic settings in which the trace fossils and red-bed plant assemblages accumulated.
3. The Early Permian was marked by a series of glaciations separated by periods of global warmth. In addition, the geological record indicates episodically increasing seasonality and climatic dryness around the equatorial regions of central and western Pangea, a trend that began in the late Middle Pennsylvanian. During this period of warming, terrestrial floras became increasingly heterogeneous spatially, which might be expected in a world where generally increasing aridity magnifies habitat variability at all scales from the local landscape to broad regions. The Robledo paleofloras fit that pattern.
4. Precise and extensive age data for the Hueco Group section based on non-fusulinid and fusulinid foraminiferans are provided for the first time. These data indicate that the base of the Leonardian (Artinskian) is very close to the base of the Robledo Mountains Formation. This means the upper part of the Hueco section is Leonardian, not Wolfcampian as long supposed.

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