Pennsylvanian-Permian boundary at Carrizo Arroyo, central New Mexico

Lucas, Spencer G., Barrick, James E., Krainer, Karl , Schneider, Jorg W.

2016, pp. 303-311. https://doi.org/10.56577/FFC-67.303

in:

Guidebook 67 - Geology of the Belen Area, Frey, Bonnie A.; Karlstrom, Karl E. ; Lucas, Spencer G.; Williams, Shannon; Zeigler, Kate; McLemore, Virginia; Ulmer-Scholle, Dana S., New Mexico Geological Society 67th Annual Fall Field Conference Guidebook, 512 p. https://doi.org/10.56577/FFC-67

This page is intentionally left blank to maintain order of facing pages.

New Mexico Geological Society Guidebook, 67th Field Conference, Geology of the Belen Area, 2016, p. 303-311.

PENNSYLVANIAN-PERMIAN BOUNDARY AT CARRIZO ARROYO, CENTRAL NEW MEXICO

Spencer G. Lucas[1], James E. Barrick[2], Karl Krainer[3], and Jörg W. Schneider[4,5]

[1]New Mexico Museum of Natural History, 1801 Mountain Road N.W., Albuquerque, NM, 87104; spencer.lucas@state.nm.us;
[2]Department of Geosciences, Texas Tech University, Box 41053, Lubbock, TX, 79409; Jim.Barrick@ttu.edu;
[3]Institute of Geology and Paleontology, University of Innsbruck, Innsbruck, A-6020, Austria; Karl.Krainer@uibk.ac.at;
[4]TU Bergakademie Freiberg, Cottastasse 2, D-09596 Freiberg, Germany;
[5]Kazan Federal University, Kremlyovskaya str. 18, 420008 Kazan, Russia; Joerg.Schneider@geo.tu-freiberg.de

Abstract—At Carrizo Arroyo southwest of Albuquerque, New Mexico, an approximately 105-m-thick section of upper Paleozoic clastic and carbonate rocks yields extensive marine and nonmarine fossil assemblages. Most of the section at Carrizo Arroyo belongs to the Red Tanks Member of the Bursum Formation, ~100-m-thick, mostly variegated shale, mudstone and siltstone of nonmarine origin, intercalated with some beds of limestone and shale of marine origin forming six transgressive depositional sequences. Red Tanks Member fossils include 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 levels 43 m and 68 m above the base of the section are Lagerstätten of plants, insects, crustaceans, eurypterids and other fossils that are unique 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 age. Conodont data 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, and the assemblage is probably equivalent in age to the Midcontinent *Streptognathodus nevaensis* Zone of early to middle Asselian age. A significant amount of latest Pennsylvanian to earliest Permian time apparently is not represented by rock record at the Carrizo Arroyo section, most likely because of a major disconformity at the top of the Atrasado Formation and because of smaller ones at the bases of depositional sequences in the lower part of the Red Tanks Member. The fact that the Bursum Formation section at Carrizo Arroyo has too few cycles to be matched to the succession of Midcontinent cyclothems is prima facie evidence that regional tectonic events of the Ancestral Rocky Mountains exerted a greater control over the creation and preservation of Bursum depositional sequences than did glacio-eustatic events.

INTRODUCTION

Located on the eastern edge of the Colorado Plateau in the Lucero uplift, Carrizo Arroyo is 50 km southwest of Albuquerque (Fig. 1). Here, an approximately 105-m-thick section of upper Paleozoic clastic and carbonate rocks yields extensive fossil assemblages of marine and nonmarine origin (Kues and Kietzke, 1976; Krainer et al., 2001; Lucas and Krainer, 2002; Lucas and Zeigler, 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. Most of the section at Carrizo Arroyo belongs to the Red Tanks Member of the Bursum Formation, a dominantly nonmarine lithofacies that contrasts with the more marine lithofacies that generally characterize the Bursum Formation to the south in New Mexico (Lucas and Krainer, 2003, 2004; Krainer and Lucas, 2004, 2009). At Carrizo Arroyo, the Red Tanks Member is ~100 m thick and is mostly green, gray and red shale, mudstone, and siltstone of nonmarine origin, intercalated with some beds of limestone and shale of marine origin (Fig. 2). Siliciclastic red beds of the 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).

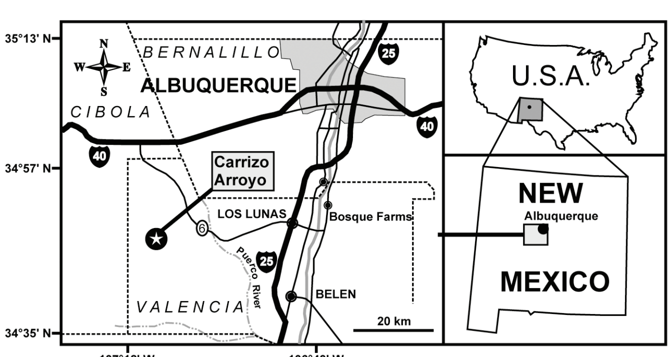

FIGURE 1. Index maps showing location of the Carrizo Arroyo section in central New Mexico

At Carrizo Arroyo, the Red Tanks Member yields fossils from many beds, and at stratigraphic levels 43 m and 68 m above the base of the section are Lagerstätten of plants, insects, crustaceans, eurypterids and other fossils (Fig. 2). Indeed, these Lagerstätten include some of the most important known late Paleozoic arthropod fossil assemblages. Red Tanks Member fossils include palynomorphs (Traverse and Ash, 1999; Utting et al., 2004), charophytes, plant megafossils (Tidwell and Ash, 1980, 2004; Ash and Tidwell, 1982, 1986; Tidwell et al., 1999; DiMichele et al., 2004; Knaus and Lucas, 2004), non-fusulinid

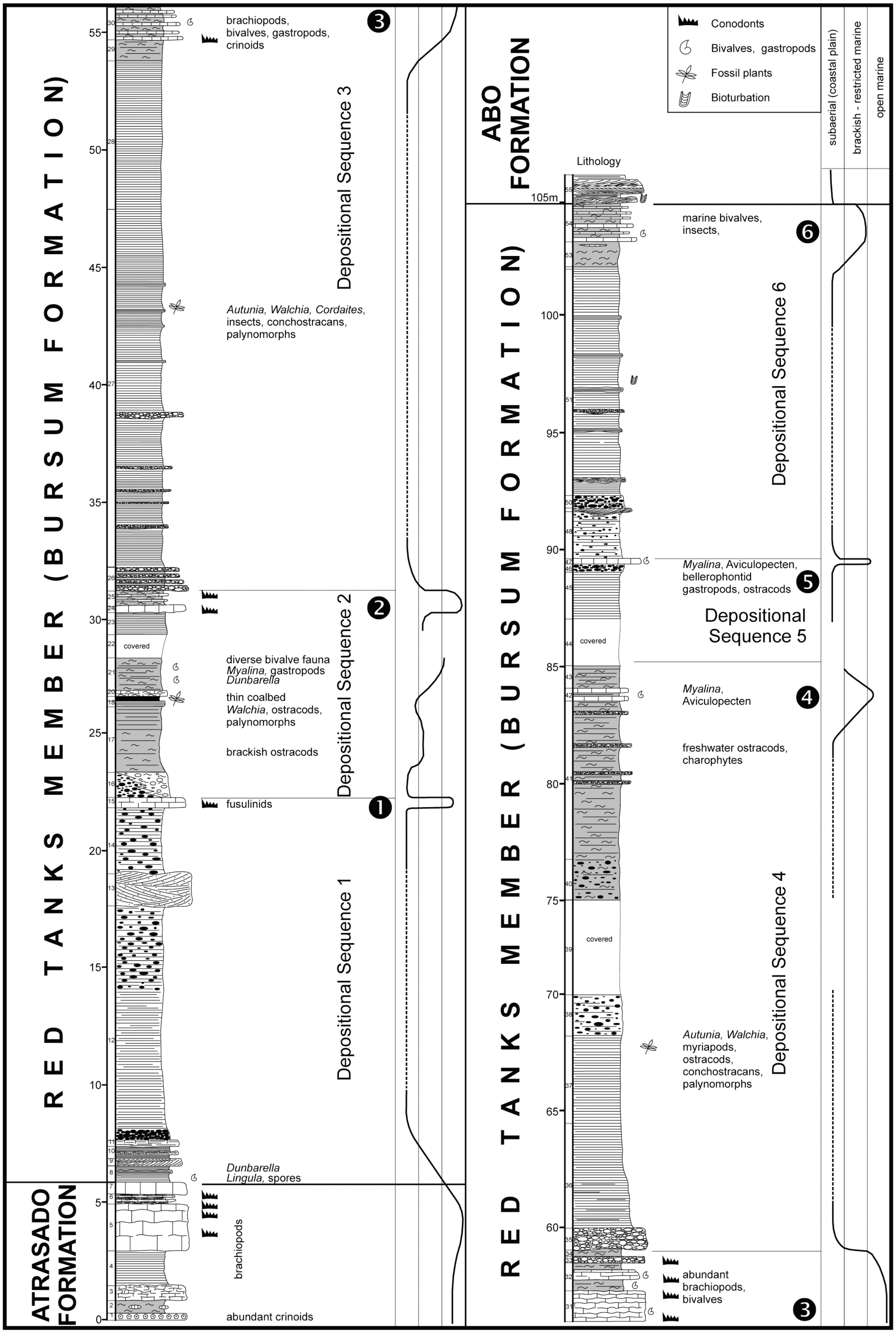

FIGURE 2. Measured stratigraphic section of the Red Tanks Member of the Bursum Formation at Carrizo Arroyo (from Krainer and Lucas, 2004). Conodont symbols indicate beds that yielded conodonts.

foraminifers (Krainer and Lucas, 2004), fusulinids (Wahlman and Kues, 2004), bryozoans, brachiopods, gastropods, bivalves and nautiloids (Kues, 1983, 1984, 2002, 2004), eurypterids (Kues and Kietzke, 1981), ostracods (Kietzke, 1983), syncarid crustaceans (Schram, 1984), conchostracans, insects and some other arthropods (Kukalova-Peck and Peck, 1976; Durden, 1984; Rowland, 1997; Hannibal et al., 2004; Rasnitsyn et al., 2004; Schneider et al., 2004), echinoids, crinoids conodonts (Orchard et al., 2004; Lucas et al., 2013a), fish ichthyoliths (Johnson and Lucas, 2004), and bones of amphibians and reptiles (Cook and Lucas, 1998; Harris and Lucas, 2001, 2003; Harris et al., 2003, 2004).

Despite the fossiliferous nature of the sediments, the precise age of the Red Tanks Member of the Bursum Formation at Carrizo Arroyo and placement of the Pennsylvanian-Permian boundary in the Carrizo Arroyo section were long uncertain. Various workers considered the Red Tanks Member to be entirely Pennsylvanian or entirely Permian, or they placed the Pennsylvanian-Permian boundary at diverse points in the section (Fig. 3).

Given the significance of the nonmarine fossil biota collected at Carrizo Arroyo and its intercalation with marine strata, a precise age of the Carrizo Arroyo section is a major contribution to correlating nonmarine and marine biotic events across the Carboniferous-Permian boundary. Therefore, Lucas et al. (2013a) presented conodont data from the Carrizo Arroyo section that represent the most precise age determinations to the section. Here, we review previously published data relevant to placement of the Pennsylvanian-Permian boundary in the Carrizo Arroyo section and briefly discuss its implications for understanding Bursum Formation deposition. This article is a condensation and update of Lucas et al. (2013a)

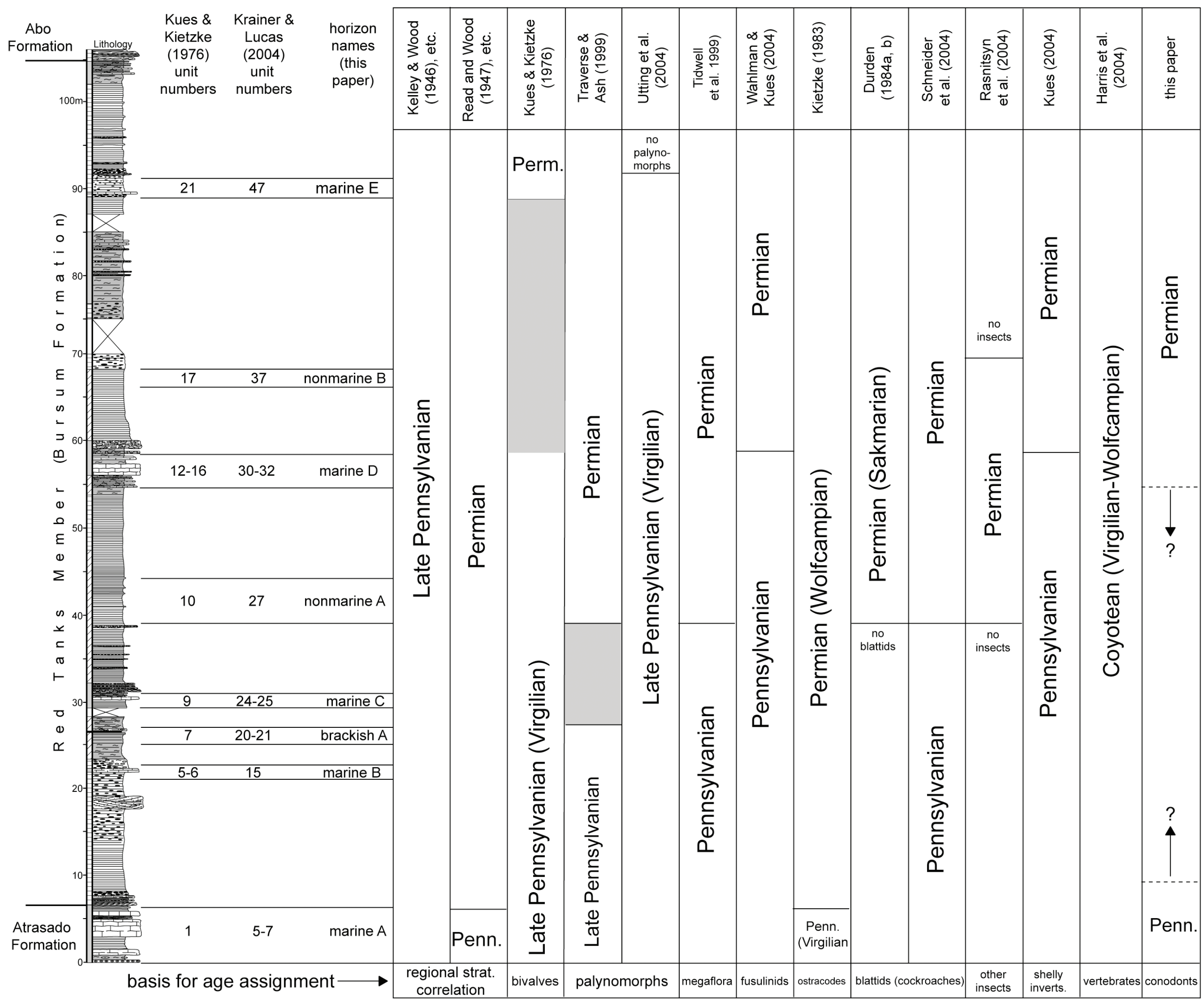

FIGURE 3. Chart showing differing published placements of the Pennsylvanian-Permian boundary at Carrizo Arroyo using different criteria. The lithologic column is a simplification of the column in Figure 2. The two unit-numbering schemes of Kues and Kietzke (1976) and Krainer and Lucas (2004) are correlated, as are the horizon names used in the text. The basis for each age assignment is indicated at the bottom of each column showing placement of the Pennsylvanian-Permian boundary by various workers.

STRATIGRAPHIC CONTEXT

At Carrizo Arroyo, the base of the section (Fig. 2) is relatively thick-bedded, ledge-forming gray limestone (composed mostly of skeletal wackestone and subordinate amounts of crinoidal packstone and skeletal grainstone) and interbedded drab shale of the upper part (Moya Member) of the Atrasado Formation. Most of the section (Fig. 2) can be assigned to the Red Tanks Member of the Bursum Formation; indeed, this outcrop is the type section of the Red Tanks Member (Kelley and Wood, 1946; Lucas and Krainer, 2004). The Red Tanks Member is 98 m thick and is mostly green, gray and red shale, mudstone, and siltstone with minor interbeds of limestone, sandstone and conglomerate.

The stratigraphic architecture of the Red Tanks Member at Carrizo Arroyo has been interpreted to indicate the presence of six depositional sequences (Krainer and Lucas, 2004) (Fig. 2). The base of each sequence is a bed of conglomerate or sandstone sharply incised into underlying mudrock, and each sequence then fines upward into mudrock-dominated floodplain or lacustrine strata. A marine limestone caps each sequence, and these limestone intervals identify six marine flooding events (Fig. 2). The sequences are mostly composed of mudstone/siltstone beds, some of which contain abundant calcrete nodules and other evidence of pedogenesis. A thin cordaitalean-leaf coal bed in the middle of depositional sequence 2 is underlain by fossiliferous siltstone (plants, lingulid brachiopods, "spirorbids" [?microconchids], ostracods and fish remains) and overlain by marly mudstone containing shallow marine molluscs (myalinids), lingulids, cordaitalean leaves up to 40 cm long and other plant debris. Carbonate conglomerate beds at the bases of depositional sequences 3 and 4 probably represent upper shoreface deposits, and, thin layers in depositional sequence 4, small channel fills. Sandstone is present at the base of sequence 1 (shoreface deposits), in the upper part of sequence 1 (fluvial channel fills), and in sequence 6 (thin, fluvial channel-fill deposits).

The tops of each depositional sequence are thin, fossiliferous, gray limestone beds or interbedded gray mudstone and limestone. Limestone beds of the lower three sequences contain abundant marine fossils, such as brachiopods, bryozoans and bivalves, indicating deposition in a shallow, open-marine environment. The dominant microfacies is skeletal wackestone containing fusulinids (sequence 1), foraminiferal wackestones with abundant calcivertellids (sequence 2), and skeletal wackestone (sequence 3) containing abundant fragments of brachiopods, mollusks, small foraminifers, echinoderms, ostracods, bryozoans, rare trilobites, *Tubiphytes*, the problematic alga *Nostocites*, and *Palaeonubecularia* (encrusting bioclasts and forming small oncoids) (Krainer and Lucas, 2004). Limestone beds of sequences 1, 2 and 3 yield conodonts (Orchard et al., 2004; Lucas et al., 2013a). However, the fossils in the limestone beds that cap sequences 4, 5 and 6 indicate a restricted marine environment. Typical microfacies are ostracod wackestones (sequence 5) and skeletal mudstones and wackestones containing gastropods and bivalves, some ostracods, and rare small foraminifers (sequence 6) (Krainer and Lucas, 2004).

Krainer and Lucas (2004) inferred that the Red Tanks Member sequences indicate the coastal plain environment represented by mudstone/siltstone was repeatedly inundated by short-term transgressive events that deposited fossiliferous, shallow-marine limestone during relative highstands of sea level. Although eustatic fluctuations of sea level may be the source of at least some of these transgressive events, the Carrizo Arroyo section was deposited in the ancestral Rocky Mountain orogenic belt, indicating that regional tectonism was also an important force that drove local sedimentation (Krainer and Lucas, 2009). Indeed, the conodont-based age determinations presented by Lucas et al. (2013a) indicate that Red Tanks deposition is not simply a record of eustatic cyclicity driving sedimentation (see below).

At Carrizo Arroyo, nonmarine red beds of the Abo Formation overlie the Red Tanks Member. These strata are regionally assigned a middle Wolfcampian-early Leonardian age, largely because they interfinger with middle Wolfcampian-early Leonardian strata of the marine Hueco Group to the south (e.g., Lucas et al., 2011a, b, 2015a, b). The Abo Formation represents fluvial deposits derived from highlands to the north (Kues and Giles, 2004; Lucas et al., 2012a, b, 2013b). At Carrizo Arroyo the Abo Formation yields fossil plant impressions (mostly the conifer *Walchia* and the peltasperm *Supaia*), invertebrate trace fossils (mostly *Palaeophycus*) and tetrapod footprints (principally *Dromopus* and *Batrachichnus*) (Lucas and Lerner, 2004; Lucas et al., 2004) that are not precise age indicators.

FOSSILIFEROUS HORIZONS

Although the Carrizo Arroyo section yields numerous and diverse fossils from many beds over an approximately 100-m-thick section, there are eight key fossiliferous horizons (thin stratigraphic intervals) relevant to most of the biostratigraphic discussion presented here. Here, we term these horizons marine A, B, C, D, E, brackish A, and nonmarine A and B, based on perceived depositional setting and stratigraphic position (Fig. 3).

Previously, two measured sections at Carrizo Arroyo with different numbering of the lithostratigraphic units were published. Kues and Kietzke (1976) discriminated and numbered 29 units in the Carrizo Arroyo section, whereas Krainer and Lucas (2004) recognized 55 units (Figs. 2-3). Prior to 2004, the articles published on the fossils from Carrizo Arroyo used the numbering system of Kues and Kietzke (1976), whereas beginning in 2004, the scheme of Krainer and Lucas (2004) was referred to. Here, we present and correlate both numbering schemes for easy cross reference so that all previous literature about the biostratigraphy of the Carrizo Arroyo section can be unambiguously understood (Fig. 3).

CARBONIFEROUS-PERMIAN BOUNDARY

To understand the history of age assignments to the Red Tanks Member, we briefly review the placement of the Carboniferous (Pennsylvanian)-Permian boundary (Fig. 4). In 1998, the International Commission on Stratigraphy ratified the definition of the base of the Permian (= base of Asselian Stage) to lie at the level of the first appearance of the conodont species *Streptognathodus isolatus* at Aidaralash Creek in western Kazakhstan (Davydov et al., 1998). Prior to that time, North American workers placed the Permian base at the base of the Wolfcampian Series (or Stage in some usages), basing it on the first appearance of the fusulinid *Schwagerina* (or *Pseudofusulina* in some usages).

This change means that articles about the age of the Red Tanks Member published in the 1990s (even those published in 1999) used this definition of Permian base = base of Wolfcampian. In that usage, the Bursum Formation of central New Mexico, which yields *Schwagerina* and other fusulinids long regarded as of early Wolfcampian age (e.g., Thompson, 1948; Lucas et al., 2000), was considered to be the oldest Permian unit in the region. Thus, from an operational point of view, before 1998 those workers who correlated the Red Tanks Member strata with the Bursum Formation regarded it as of Early Permian age.

However, most workers concluded that the definition of the base of the Permian by the first appearance of the conodont *Streptognathodus isolatus* makes the beginning of the Permian younger than the Wolfcampian base, closer to the base of the middle Wolfcampian (e.g., Baars et al., 1992, 1994; Wahlman, 1998; Sanderson et al., 2001; Wahlman and King, 2002). Thus, rocks of Bursum age ("Bursumian" to some biostratigraphers) have been regarded as latest Pennsylvanian (Fig. 4). Attempts to resolve the mismatch of the bases of the Wolfcampian and Permian have generally redefined the Wolfcampian so that its base is equivalent to the Permian base, and the "early Wolfcampian" of previous usage has either been given a separate stage/substage name (Bursumian of Ross and Ross, 1994; Newwellian of Wilde, 2002, 2006) or simply has been considered the younger portion of a longer Virgilian (e.g., Baars et al., 1994).

Lucas (2013a, b) has recently questioned the use of *Streptognathodus isolatus* to correlate the base of the Permian in Kazakhstan and has advocated returning to the traditional, fusulinid-based correlation of the Permian base, which places the Permian base at the base of the Wolfcampian. In this paper, we do not offer a solution to this chronostratigraphic problem. Instead, our concern is to achieve a clear understanding of differing definitions of the Permian base and to determine which definition of the Wolfcampian was being used by the many workers who published on the age of the Carrizo Arroyo section between 1946 and 2004 (Figs. 3-4).

PREVIOUS CORRELATIONS

When naming the Red Tanks Member, Kelley and Wood (1946) assigned it to the Madera Limestone with a Late Pennsylvanian age (Fig. 3). They based this age assignment on regional stratigraphic correlations that identified the upper part of the Madera Limestone as Late Pennsylvanian, not on any specific analysis of fossils from the Red Tanks Member. Similar considerations led Kottlowski (1960) and Armstrong et al. (1979) to assign the Red Tanks Member a Virgilian age – simply because it was the uppermost part of the Pennsylvanian Madera Limestone, and they considered it to be stratigraphically below the early Wolfcampian Bursum Formation.

However, some other workers noted the similarity in lithology (mixture of marine and nonmarine strata) and stratigraphic position of the Red Tanks Member and the Bursum Formation, and they thus assigned an early Wolfcampian age to the Red Tanks Member (e.g., Bates et al., 1947; Read and Wood, 1947;

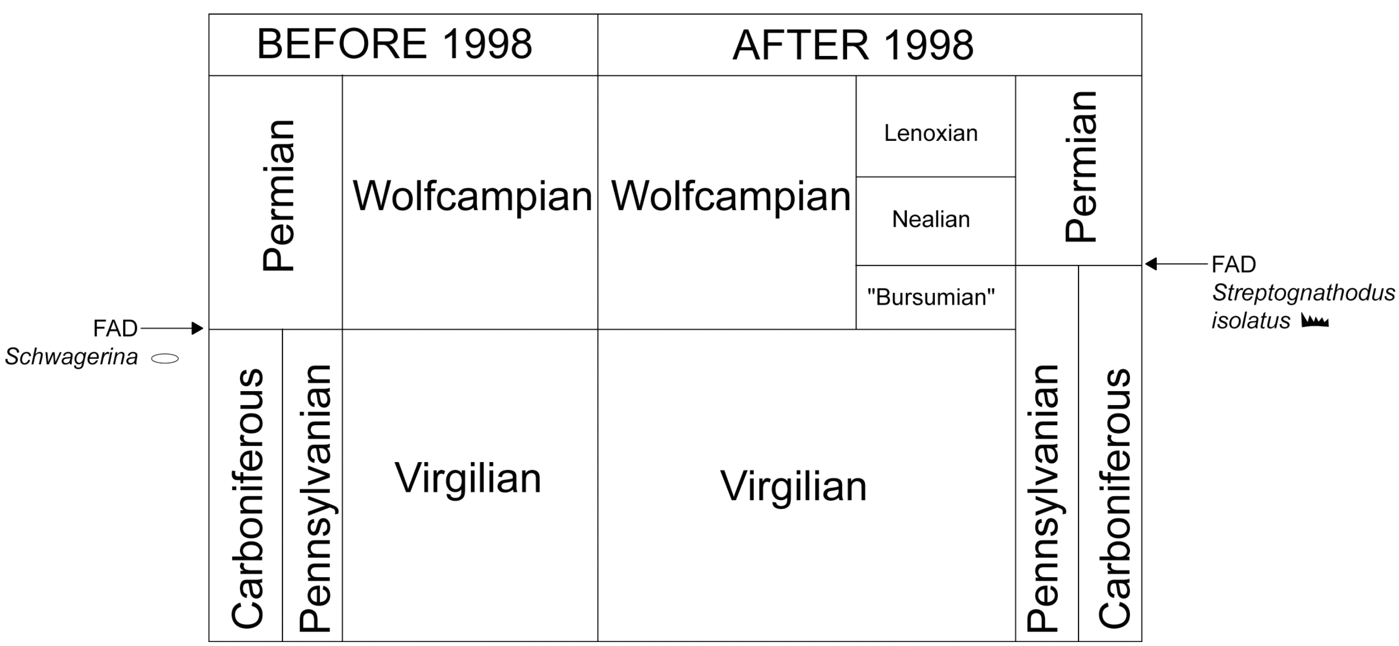

FIGURE 4. The two different definitions of the Carboniferous (Pennsylvanian)-Permian boundary used by various workers at Carrizo Arroyo. The boundary before 1998 was based on the first appearance of the fusulinid *Schwagerina* and corresponded to the base of the regional Wolfcampian "Stage" (or "Series"). The conodont-defined boundary (Davydov et al., 1998) has been correlated with a younger horizon within the Wolfcampian. It is close to or at the boundary between the early and middle Wolfcampian, which is the boundary between the "Bursumian" (= Newwellian) and Nealian fusulinid substages as used by some workers.

Jicha and Lochman-Balk, 1958). This designation meant they considered the Red Tanks Member to be of Early Permian age (Fig. 3).

However, it was not until the work of Kues and Kietzke (1976) that paleontologists actually examined fossils from the Red Tanks Member to determine its age. Kues and Kietzke concluded that fusulinids from the lower part of the Red Tanks Member are Pennsylvanian species of *Triticites* (based on an oral communication from D. Myers, 1975). The brachiopod species *Curvithyris planoconvexa* (Shumard) from horizon marine D in the Carrizo Arroyo section was identified by Kues and Kietzke (1976) as a Pennsylvanian taxon. They further suggested that species of the bivalves *Myalina* and *Aviculopecten* from horizon marine E are Permian species, so they placed the Pennsylvanian-Permian boundary in the Carrizo Arroyo section in the upper part of the Red Tanks Member, between horizons marine D and E (Fig. 3).

Few subsequent workers, however, examined the entire fossil assemblage of the Red Tanks Member to determine its age. Instead, they focused on the age data provided by the specific group of Red Tanks Member fossils being described or discussed (Fig. 3). Lucas et al. (2013a) provided a detailed review of these age assignments by taxonomic group, so they are not reviewed here. They also presented insect- and conodont-based data to correlate the Bursum Formation strata at Carrizo Arroyo (Fig. 3).

CURRENT CORRELATION

The conodont data presented by Lucas et al. (2013a) provide firm biostratigraphic ages for two levels in the Carrizo Arroyo section (Fig. 5). The upper beds of the Atrasado Formation can be assigned to the late Gzhelian *Streptognathodus virgilicus* Zone and horizon marine D at the top of depositional sequence 3 represents the early to middle Asselian *S. nevaensis* Zone of the North American Midcontinent succession. The base of the Permian in this section lies between these two levels, but its exact position cannot be determined at Carrizo Arroyo with current data (Figs. 3-5). A major complication is the presence of multiple disconformities in the section, because some portion of a rock record of the latest Gzhelian and earliest Asselian is likely missing at the base of each depositional sequence.

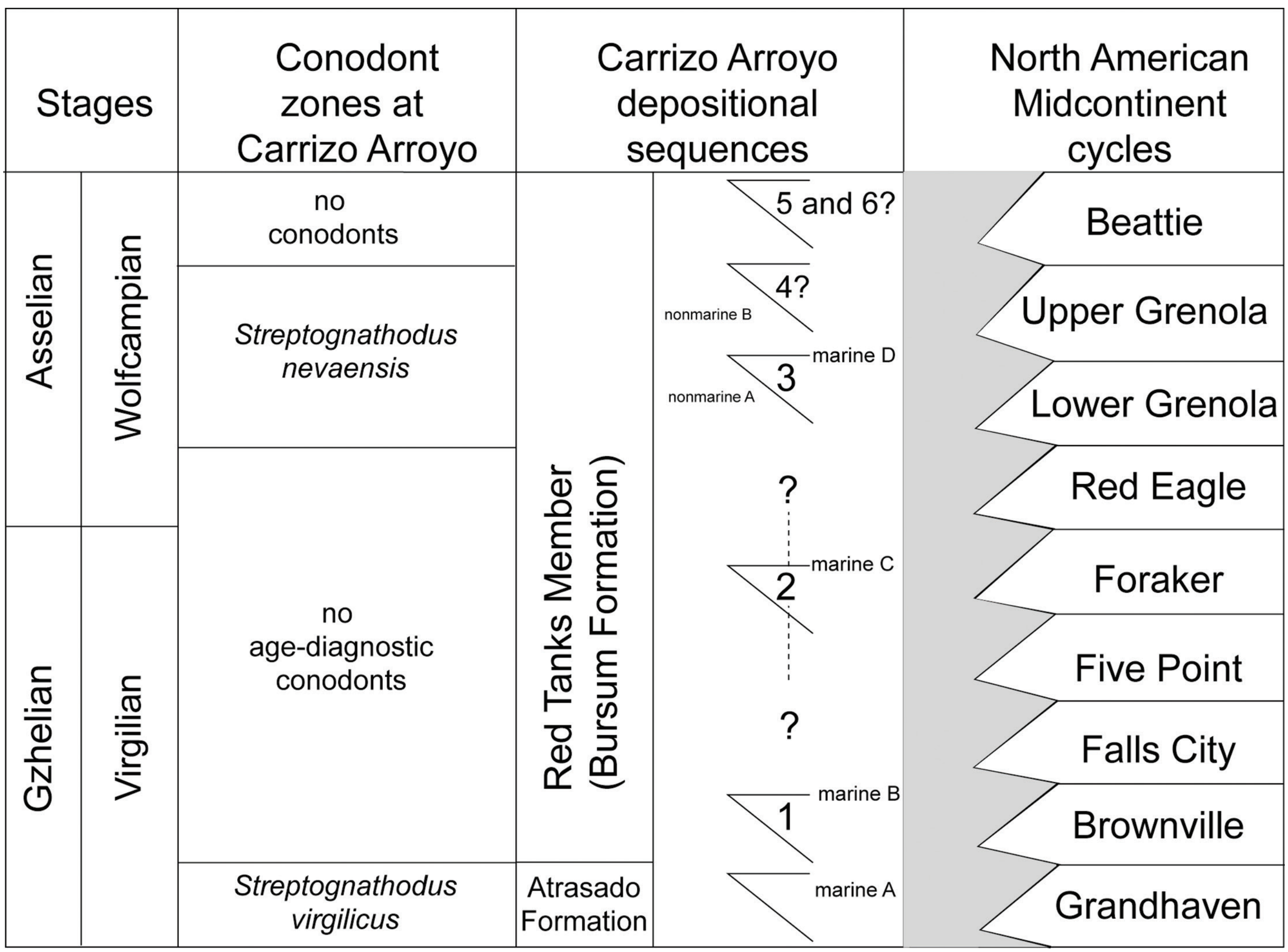

FIGURE 5. Correlation of Midcontinent cyclothems to the Carrizo Arroyo section using conodont biostratigraphy shows that there are too few depositional sequences in the Bursum Formation to correlate with all of the midcontinent cyclothems across the Pennsylvanian-Permian boundary.

In the Midcontinent succession, at least four latest Gzhelian fourth order eustatic sequences (or cyclothems - Brownville, Falls City, Five Point and Foraker) and one basal Asselian sequence (Red Eagle) occur between the *Streptognathodus virgilicus* and *S. nevaensis* zones (Boardman et al., 2009), whereas only two depositional sequences are present that represent this time interval at Carrizo Arroyo (Fig. 5). The fusulinid evidence suggests that the top of depositional sequence 1 may be Gzhelian, and as young as early "Bursumian" (Wahlman and Kues, 2004), but this is not definitive. Other faunal information is inconclusive about the ages of depositional sequences 1 and 2.

The age of the terrestrial fauna and flora of horizon brackish A, which lies within depositional sequence 2, is unknown at this time but should lie near the Pennsylvanian-Permian boundary. The nonmarine Lagerstätte at 43 m (horizon nonmarine A), which lies within depositional sequence 3, is probably early-middle Asselian in age, based on the *Streptognathodus nevaensis* Zone conodont fauna obtained from the top of this sequence. Based on the insect correlation of Lucas et al. (2013a) and the precise isotopic age calibration of the insect zonation of Schneider and Werneburg (2006) in Schneider et al. (2013), the *Sysciophlebia ilfeldensis-Spiloblattina weissigensis*-insect zone straddles the Gzhelian/Asselian boundary. Fragments of both zone species occur in horizon nonmarine A and support the early Asselian age of this level as inferred from conodonts. The non-marine Lagerstätte at 68 m (horizon nonmarine B), which occurs in the overlying depositional sequence 4, is middle Asselian by the correlation of Lucas et al. (2013a) and stratigraphic position.

Most previous workers considered part or all of the Red Tanks Member to be Pennsylvanian (Fig. 3). These age determinations, however, were almost entirely based on groups of nonmarine or marine fossils that are well known to show little or no substantial change across the Pennsylvanian-Permian boundary. Only the fusulinids, which indicate a Virgilian age for strata of the uppermost part of the Atrasado Formation and lowermost part of the Red Tanks Member at Carrizo Arroyo, can be considered to have been reliable age indicators. Nevertheless, the tentative assignment of a Pennsylvanian age to horizon marine D based on fusulinids (Wahlman and Kues, 2004) is contradicted by the conodont data presented here. However, as Wahlman and Kues (2004) indicated, their fusulinid-based age assignment of horizon marine D was not based on strong data.

Particularly significant is that the conodont-determined base of the Permian at Carrizo Arroyo may be between the two nonmarine Lagerstätten in the Red Tanks Member section (Fig. 3). Current understanding of these Lagerstätten is that the plants, insects and other fossils they contain do not differ significantly from each other except in ways that can be currently explained by sampling, intensity of study or minor facies/taphonomic differences.

IMPLICATIONS FOR TECTONICS AND EUSTASY

Krainer and Lucas (2004, 2009) argued that cycles in the Bursum Formation are not strictly glacio-eustatic in origin, indicated largely because of rapid lateral and vertical facies changes from marine to nonmarine (or the reverse). In other words, disorganized facies stacking and a lack of lateral facies continuity argues against simply identifying Bursum Formation cycles as driven by glacio-eustasy. Instead, tectonic movements of the ancestral Rocky Mountain (ARM) orogeny substantially influenced Bursum deposition. The Bursum Formation reflects a series of tectonic pulses that affected large areas of New Mexico during the ARM orogeny. The age data presented by Lucas et al. (2013a) provide the first precise dating of strata within the Bursum lithosome, which allows the correlation of at least one Bursum depositional sequence with Midcontinent fourth-order sequences (cyclothems) by biostratigraphy (Fig. 5). The fact that the Bursum Formation section at Carrizo Arroyo has too few cycles to be matched to the succession of Midcontinent cyclothems is prima facie evidence that regional tectonic events of the ARM orogeny exerted a greater control over the creation and preservation of Bursum depositional sequences than did glacio-eustatic events. It also raises the possibility of local/regional climate cycles, such as cycles of precipitation (see, for example, Cecil et al., 2014), driving some of the cyclic deposition evident in the Bursum Formation, not just glacio-eustasy or tectonics.

CONCLUSIONS

Based on the above, we offer the following conclusions:

1. At Carrizo Arroyo, the approximately 100-m-thick section of the Red Tanks Member of the Bursum Formation yields fossils that include palynomorphs, 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. For the last 30-40 years, 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.

2. At stratigraphic levels 43 m and 68 m above the base of the Carrizo Arroyo section are Lagerstätten of plants, insects, crustaceans, eurypterids and other fossils that form unique, late Paleozoic, lacustrine assemblages. Insect data indicate that the two Lagerstätten in the Red Tanks Member are of early Asselian age.

3. The presence of the conodont *Streptognathodus virgilicus* in the uppermost part of the Atrasado Formation (immediately below the Bursum Formation) 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, and the assemblage is probably equivalent in age to the Midcontinent *Streptognathodus nevaensis* Zone, of early to middle Asselian in age. Therefore, the Pennsylvanian-Permian boundary at Carrizo Arroyo is somewhere between marine horizons A and D, perhaps somewhere near the middle of the interval, because marine horizon A is not the latest Pennsylvanian and marine horizon D is not the earliest Permian.

4. A significant amount of latest Pennsylvanian to earliest Permian time apparently is not represented by rock record at the Carrizo Arroyo section, most likely because of a major disconformity at the top of the Atrasado Formation and because of smaller ones at the bases of depositional sequences in the lower part of the Red Tanks Member. Therefore, conodont biostratigraphy provides compelling evidence that Bursum Formation deposition was not simply driven by glacio-eustatic cyclicity but that local tectonics was a significant driver of deposition.

ACKNOWLEDGMENTS

We are grateful to Larry Rinehart, Sebastian Voigt and Ralf Werneburg for assistance in the field. Bruce Allen, New Mexico Bureau of Geology and Mineral Resources, and Bill DiMichele, National Museum of Natural History, Smithsonian Institution, provided helpful reviews of the manuscript.

REFERENCES

Armstrong, A.K., Kottlowski, F.E., Stewart, W.J., Mamet, S.L., Baltz, E.H., Jr., Siemers, W.T., and Thompson, S., III., 1979, The Mississippian and Pennsylvanian (Carboniferous) systems in the United States—New Mexico: U.S. Geological Survey, Professional Paper 1110-W, p. W1-W27.

Ash, S.A., and Tidwell, W.D., 1982, Notes on the upper Paleozoic plants of central New Mexico: New Mexico Geological Society, Guidebook 33, p. 245-248.

Ash, S.A., and Tidwell, W.D.,1986, *Arnoldia kuesii*, a new juvenile fern-like plant from the Lower Permian of New Mexico: Botanical Gazette, v. 147, p. 236-242.

Baars, D.L., Maples, C.G., Ritter, S.M., and Ross, C.A., 1992, Redefinition of the Pennsylvanian-Permian boundary in Kansas, mid-continent USA: International Geology Review, v. 34, p. 1021-1025.

Baars, D.L., Ross, C.A., Ritter, S.M., and Maples, C.G., 1994, Proposed repositioning of the Pennsylvanian-Permian boundary in Kansas: Kansas Geological Survey, Bulletin 230, p. 5-10.

Bates, R.L., Wilpolt, R.H., Macalpin, A.J., and Vorbes, G., 1947, Geology of the Gran Quivira quadrangle, New Mexico: New Mexico Bureau of Mines and Mineral Resources, Bulletin 26, p. 1-52.

Boardman, D.R., Wardlaw, B.R., and Nestell, M.K., 2009, Stratigraphy and conodont biostratigraphy of the uppermost Carboniferous and Lower Permian from the North American Midcontinent: Kansas Geological Survey, Bulletin 255, p. 1-253.

Cecil, C.B., DiMichele, W.A., and Elrick, S.D., 2014, Middle and Late Pennsylvanian cyclothems, American midcontinent: Ice-age environmental changes and terrestrial biotic dynamics: Comptes Rendus Geoscience, v. 346, p. 159-168.

Cook, C.W., and Lucas, S.G., 1998, Fossil vertebrates from the Lower Permian Red Tanks Member of the Madera Formation, Lucero uplift, New Mexico: Journal of Vertebrate Paleontology, v. 18, p. 35A.

Davydov, V.I., Glenister, B.F., Sinosa, C., Ritter, S.M., Chernykh, V.V., Wardlaw, B.R., and Snyder, W.S., 1998, Proposal of Aidaralash as Global Stratotype Section and Point (GSSP) for base of the Permian System: Episodes, v. 21, p. 11-17.

DiMichele, W.A., Kerp, H., and Chaney, D.S., 2004, Tropical floras of the Late Pennsylvanian-Early Permian transition: Carrizo Arroyo in context: New Mexico Museum of Natural History and Science, Bulletin 25, p. 105-109.

Durden, C.J., 1984, Carboniferous and Permian entomology of western North America: Compte Rendu Neuvième Congrès International de Stratigraphie et de Géologie de Carbonifère, Washington and Champaign-Urbana, 1979, v. 2, p. 81-89.

Hannibal, J.T., Lerner, A.J, Zeigler, K.E., and Lucas, S.G., 2004, A juliform millipede from the Upper Pennsylvanian (Virgilian) Bursum Formation, Carrizo Arroyo, of central New Mexico: New Mexico Museum of Natural History and Science, Bulletin 25, p. 211-213.

Harris, S.K., and Lucas, S.G., 2001, Early Permian vertebrate fossils from the Red Tanks Formation of the Madera Group, Lucero uplift, central New Mexico: New Mexico Geology, v. 23, p. 63.

Harris, S.K., and Lucas, S.G., 2003, Edopoid postcrania from the Red Tanks Member of the Bursum Formation, Lucero uplift, central New Mexico: New Mexico Geology, v. 25, p. 51-52.

Harris, S.K., Lucas, S.G., Berman, D.S., and Henrici, A.C., 2004, Vertebrate fossil assemblage from the Upper Pennsylvanian Red Tanks Member of the Bursum Formation, Lucero uplift, central New Mexico: New Mexico Museum of Natural History and Science, Bulletin 25, p. 267-283.

Harris, S.K., Lucas, S.G., Orchard, M.J., and Krainer, K., 2003, Sphenacodontine pelycosaurs from the Upper Pennsylvanian (Upper Virgilian) Red Tanks Member of the Bursum Formation: New Mexico Geology, v. 25, p. 52.

Jicha, H.L., Jr., and Lochman-Balk, C., 1958, Lexicon of New Mexico geologic names: Precambrian through Paleozoic: New Mexico Bureau of Mines and Mineral Resources, Bulletin 61, p. 1-137.

Johnson, S.C., and Lucas, S.G., 2004, Late Pennsylvanian ichthyoliths from Carrizo Arroyo, central New Mexico: New Mexico Museum of Natural History and Science, Bulletin 25, p. 263-266.

Kelley, V.C., and Wood, G.H., Jr., 1946, Lucero uplift, Valencia, Socorro and Bernalillo Counties, New Mexico: U.S. Geological Survey, Oil and Gas Investigations Preliminary Map 47, scale 1:63,360.

Kietzke, K.K., 1983, Ostracods from the Atrasado and Red Tanks members, Madera Formation (Upper Pennsylvanian-Lower Permian), of central New Mexico: New Mexico Journal of Science, v. 23, p. 17-18.

Knaus, M.J., and Lucas, S.G., 2004, A Permo-Carboniferous tree-like neuropterid from Carrizo Arroyo, central New Mexico: New Mexico Museum of Natural History and Science, Bulletin 25, p. 111–122.

Kottlowski, F.E., 1960, Summary of Pennsylvanian sections in southwestern New Mexico and southeastern Arizona: New Mexico Bureau of Mines and Mineral Resources, Bulletin 66, p. 1-187.

Krainer, K., and Lucas, S.G., 2004, The Upper Pennsylvanian Red Tanks Member of the Bursum Formation at Carrizo Arroyo, central New Mexico: Transition from shallow marine to nonmarine facies: New Mexico Museum of Natural History and Science, Bulletin 25, p. 53-69.

Krainer, K., and Lucas, S.G., 2009, Cyclic sedimentation of the Upper Pennsylvanian (lower Wolfcampian) Bursum Formation, central New Mexico: Tectonics versus glacioeustasy: New Mexico Geological Society, Guidebook 60, p. 167-182.

Krainer, K., Lucas, S.G., and Kues, B.S., 2001, The facies of the nonmarine to shallow marine Red Tanks Formation, Pennsylvanian-Permian, central New Mexico: New Mexico Geology, v. 23, p. 62-63.

Kues, B.S., 1983, Gastropods from the Red Tanks Member, Madera Formation (Upper Pennsylvanian-Lower Permian) of central New Mexico: New Mexico Journal of Science, v. 23, p. 19.

Kues, B.S., 1984, Bivalves from the Red Tanks Member, Madera Formation (Upper Pennsylvanian-Lower Permian), of central New Mexico: New Mexico Geology, v. 6, p. 84.

Kues, B.S., 2002, Brachiopods from the Red Tanks Formation (Madera Group) near the Pennsylvanian-Permian boundary, Lucero uplift, New Mexico: New Mexico Geology, v. 24, p. 61.

Kues, B.S., 2004, Stratigraphy and brachiopod and molluscan paleontology of the Red Tanks Formation (Madera Group) near the Pennsylvanian-Permian boundary, Lucero uplift, west-central New Mexico: New Mexico Museum of Natural History and Science, Bulletin 25, p. 143-209.

Kues, B.S., and Giles, K.A., 2004, The late Paleozoic ancestral Rocky Mountains system in New Mexico, *in* Mack, G.H., and Giles, K.A., eds., The Geology of New Mexico: A Geologic History: New Mexico Geological Society, Special Publication 11, p. 95-136.

Kues, B.S., and Kietzke, K.K., 1976, Paleontology and stratigraphy of the Red Tanks Member, Madera Formation (Pennsylvanian) near Lucero Mesa, New Mexico: New Mexico Geological Society, Special Publication 6, p. 102-108.

Kues, B.S., and Kietzke, K.K., 1981, A large assemblage of a new eurypterid from the Red Tanks Member, Madera Formation (Late Pennsylvanian-Early Permian) of New Mexico: Journal of Paleontology, v. 55, p. 709-729.

Kukalova-Peck, J., and Peck, S.B., 1976, Adult and immature *Calvertellidae* (Insecta: Palaeodictyoptera) from the upper Paleozoic of New Mexico

and Czechoslovakia: Psyche, v. 38, p. 79-93.
Lucas, S.G., 2013a, Reconsideration of the base of the Permian System: New Mexico Museum of Natural History and Science, Bulletin 60, p. 230-232.
Lucas, S.G., 2013b, We need a new GSSP for the base of the Permian: Permophiles, no. 58, p. 8-12.
Lucas, S.G., and Krainer, K., 2002, Carboniferous-Permian transition at Carrizo Arroyo, New Mexico, USA: Newsletter on Carboniferous Stratigraphy, v. 20, p. 40-43.
Lucas, S.G., and Krainer, K., 2003, The Bursum Formation—integrated lithostratigraphy of the Pennsylvanian-Permian transition in New Mexico: New Mexico Geology, v. 25, p. 45.
Lucas, S.G., and Krainer, K., 2004, The Red Tanks Member of the Bursum Formation in the Lucero uplift and regional stratigraphy of the Bursum Formation in New Mexico: New Mexico Museum of Natural History and Science, Bulletin 25, p. 43-52.
Lucas, S.G., and Lerner, A.J., 2004, Extensive ichnofossil assemblage at the base of the Permian Abo Formation, Carrizo Arroyo, New Mexico: New Mexico Museum of Natural History and Science, Bulletin 25, p. 285-289.
Lucas, S.G., and Zeigler, K.E., eds., 2004, Carboniferous-Permian transition at Carrizo Arroyo, central New Mexico: New Mexico Museum of Natural History and Science, Bulletin 25, p. 1-300.
Lucas, S.G., Krainer K., and Vachard, D., 2011a, Stratigraphy, depositional environments, age, and regional tectonic significance of the Powwow Member of the Hueco Canyon Formation, Lower Permian of the Hueco Mountains, West Texas: West Texas Geological Society Bulletin, v. 50(6), p. 20-40.
Lucas, S.G., Krainer, K., and Vachard, D., 2015a, The Lower Permian Hueco Group, Robledo Mountains, New Mexico: New Mexico Museum of Natural History and Science, Bulletin 65, p. 43-96.
Lucas, S.G., Lerner, A.J., and Hunt, A.P., 2004, Permian tetrapod footprints from the Lucero uplift, central New Mexico, and Permian footprint biostratigraphy: New Mexico Museum of Natural History and Science, Bulletin 25: p. 291-300.
Lucas S.G., Barrick, J.E., Krainer, K., and Schneider, J.W, 2013a, The Carboniferous-Permian boundary at Carrizo Arroyo, central New Mexico, USA: Stratigraphy, v. 10, p. 153-170.
Lucas, S.G., Wilde, G.L., Robbins, S., and Estep, J.W., 2000, Lithostratigraphy and fusulinaceans of the type section of the Bursum Formation, Upper Carboniferous of south-central New Mexico: New Mexico Museum of Natural History and Science, Bulletin 16, p. 1-13.
Lucas, S.G., Krainer, K., Corbitt, L., Dibenedetto, J., and Vachard, D., 2011b, The Trans Mountain Road Member, a new stratigraphic unit of the Lower Permian Hueco Group, northern Franklin Mountains, Texas: New Mexico Museum of Natural History and Science, Bulletin 53, p. 93-109.
Lucas, S.G., Krainer, K., Chaney, D.S., Dimichele, W.A., Voigt, S., Berman, D.S., and Henrici, A.C., 2012a, The Lower Permian Abo Formation in the Fra Cristobal and Caballo Mountains, Sierra County, New Mexico: New Mexico Geological Society, Guidebook 63, p. 345-376.
Lucas, S.G., Krainer, K., Chaney, D.S., DiMichele, W.A., Voigt, S., Berman, D.S and Henrici, A.C., 2013b, The Lower Permian Abo Formation in central New Mexico: New Mexico Museum of Natural History and Science, Bulletin 59, p. 161-179.
Lucas, S.G., Krainer, K., Vachard, D., Voigt, S., DiMichele, W.A., Berman, D.S., Henrici, A.C., Schneider, J.W., and Barrick, J.E., 2015b, Progress report on correlation of nonmarine and marine Lower Permian strata, New Mexico, USA: Permophiles, no. 61, p. 10-17.
Lucas, S.G., Harris, S.K., Spielmann, J.A., Berman, D.S, Henrici, A.C., Krainer, K., Rinehart, L.F., DiMichele, W.D., Chaney, D.S., and Kerp, H., 2012b, Lithostratigraphy, paleontology, biostratigraphy, and age of the upper Paleozoic Abo Formation near Jemez Springs, northern New Mexico, USA: Annals of Carnegie Museum, v. 80, p. 323-350.
Orchard, M.J., Lucas, S.G., and Krainer, K., 2004, Conodonts and the age of the Red Tanks Member of the Bursum Formation at Carrizo Arroyo, central New Mexico: New Mexico Museum of Natural History and Science, Bulletin 25, p. 123-126.
Rasnitsyn, A.P., Aristov, D.S., Gorochov, A.Y., Rowland, J.M., and Sinitshenkova, N.D., 2004, Important new insect fossils from Carrizo Arroyo and the Permo-Carboniferous faunal boundary: New Mexico Museum of Natural History and Science, Bulletin 25, p. 215-246.
Read, C.B., and Wood, G.H., 1947, Distribution and correlation of Pennsylvanian rocks in late Paleozoic sedimentary basins of northern New Mexico: Journal of Geology, v. 55, p. 220-236.
Ross, C.A., and Ross, J.P., 1994, The need for a Bursumian Stage, uppermost Carboniferous, North America: Permophiles, no. 24, p. 3-6.
Rowland, J.M., 1997, The late Paleozoic insect assemblage at Carrizo Arroyo, New Mexico: New Mexico Museum of Natural History and Science, Bulletin 11, p. 1-7.
Sanderson, G.A., Verville, G.J., Groves, J.R. and Wahlman, G.P., 2001, Fusulinacean biostratigraphy of the Virgilian Stage (Upper Pennsylvanian) in Kansas: Journal of Paleontology, v. 75, p. 883-887.
Schneider, J.W., and Lucas, S.G., 2013, Sedimentology, taphonomy and origin of Early Permian insect beds at Carrizo Arroyo, New Mexico: New Mexico Museum of Natural History and Science, Bulletin 59, p. 35-37.
Schneider, J.W., and Werneburg, R., 2006, Insect biostratigraphy of the European late Carboniferous and early Permian; *in* Lucas, S.G., Cassinis, G., and Schneider J.W., eds., Non-marine Permian biostratigraphy and biochronology: Geological Society, London, Special Publication 265, p. 325-336.
Schneider, J.W., Lucas, S.G., and Barrick, J.E., 2013, The Early Permian age of the Dunkard Group, Appalachian basin, U.S.A., based on spiloblattinid insect biostratigraphy: International Journal of Coal Geology, v. 119, p. 88–92
Schneider, J.W., Lucas, S.G., and Rowland, J.M., 2004, The Blattida (Insecta) fauna of Carrizo Arroyo, New Mexico - biostratigraphic link between marine and nonmarine Pennsylvanian/Permian boundary profiles: New Mexico Museum of Natural History and Science, Bulletin 25, p. 247-262.
Schram, F.E., 1984, Fossil Syncarida: Transactions of the San Diego Society of Natural History, v. 20, p. 189-246.
Thompson, M.L., 1948, Studies of American fusulinids: University of Kansas Paleontological Contributions, Protozoa, Article 1, 100 p.
Tidwell, W.D., and Ash, S.R., 1980, Preliminary report on a flora in the Red Tanks Member of the Madera Formation, central New Mexico: Geological Society of America, Abstracts with Programs, v. 12, p. 305.
Tidwell, W.D., and Ash, S.R., 2004, Synopsis of the flora in the Red Tanks Formation, Carrizo Arroyo, New Mexico: New Mexico Museum of Natural History and Science, Bulletin 25, p. 97-103.
Tidwell, W.D., Ash, S.R., Kues, B.S., Kietzke, K.K., and Lucas, S.G., 1999, Early Permian plant megafossils from Carrizo Arroyo, central New Mexico: New Mexico Geological Society, Guidebook 50, p. 297-304.
Traverse, A., and Ash, S.R., 1999, Preliminary assessment of the age of the palynoflora of the Red Tanks Member, Madera Formation, Carrizo Arroyo, New Mexico: New Mexico Geological Society, Guidebook 50, p. 293-296.
Utting, J., Früder, C., Lucas, S.G., and Traverse, A., 2004, Palynological investigation of the Upper Pennsylvanian Red Tanks Member, Bursum Formation, Carrizo Arroyo, New Mexico, U.S.A.: New Mexico Museum of Natural History and Science, Bulletin 25, p. 89-96.
Wahlman, G.P., 1998, Fusulinid biostratigraphy of the new Pennsylvanian-Permian boundary in the southwest and midcontinent U.S.A: Geological Society of America, Abstracts with Programs, v. 30(3), p. 34.
Wahlman, G.P., and King, W.E., 2002, Latest Pennsylvanian and earliest Permian fusulinid biostratigraphy, Robledo Mountains and adjacent ranges, south-central New Mexico: New Mexico Bureau of Mines and Mineral Resources, Circular, 208, p. 1-26.
Wahlman, G.P., and Kues, B.S., 2004, Late Pennsylvanian (Virgilian) fusulinaceans from the upper Atrasado and lower Red Tanks formations, Carrizo Arroyo, Sierra Lucero, central New Mexico: New Mexico Museum of Natural History and Science, Bulletin 24, p. 127-136.
Wilde, G.L., 2002, The Newwellian Substage; rejection of the Bursumian Stage: Permophiles, no. 41, p. 53-62.
Wilde, G.L., 2006, Pennsylvanian-Permian fusulinaceans of the Big Hatchet Mountains, New Mexico: New Mexico Museum of Natural History and Science, Bulletin 38, 321 p.

Carrizo Canyon. Photo courtesy of Spencer Lucas.