

The Carboniferous-Permian boundary at Carrizo Arroyo, Central New Mexico, USA

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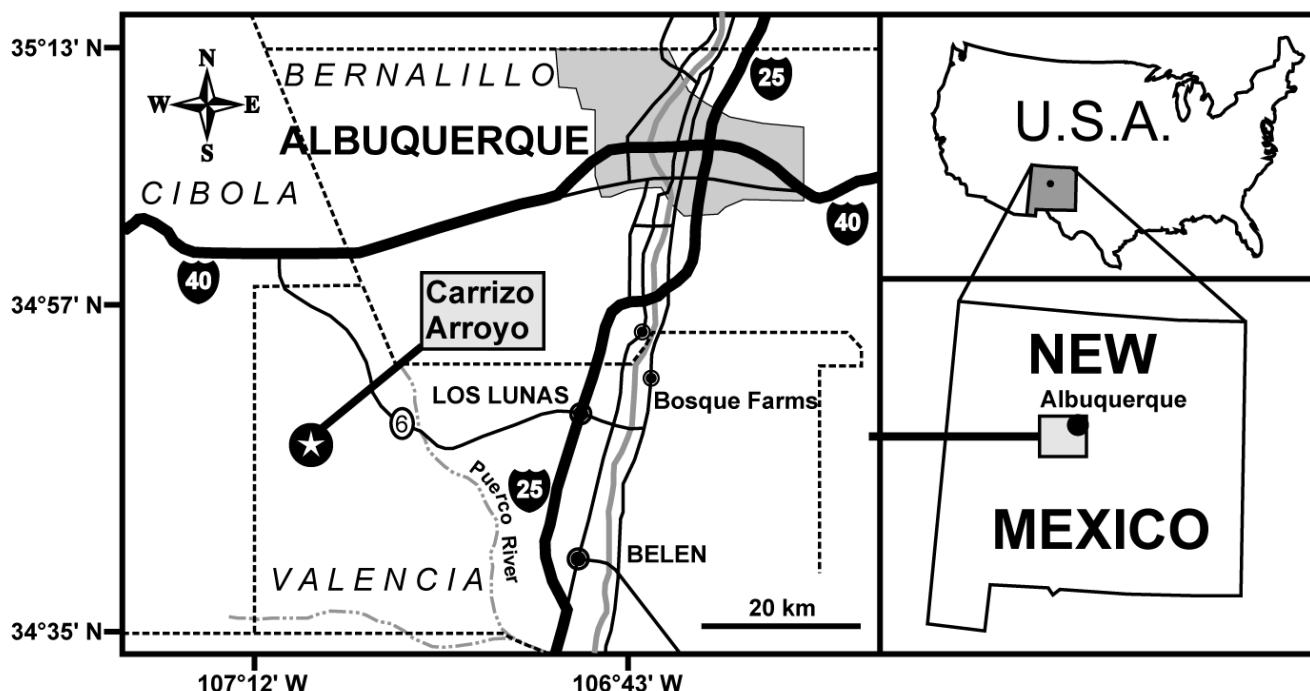
ABSTRACT: At Carrizo Arroyo southwest of Albuquerque, New Mexico, USA, an approximately 105-m-thick section of upper Paleozoic clastic and carbonate rocks yields extensive fossil assemblages of marine and nonmarine origin. Most of the section at Carrizo Arroyo belongs to the Red Tanks Member of the Bursum Formation, ~ 100m thick and mostly variegated shale, mudstone and siltstone of nonmarine origin, intercalated with some beds of limestone and shale of marine origin. Red Tanks Member fossils 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. At stratigraphic levels 43m and 68m above the base of the section are Lagerstätten of plants, insects, crustaceans, eurypterids and other fossils that form unique Late Paleozoic nearshore arthropod 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. We review previous placement of the Pennsylvanian-Permian boundary in the Carrizo Arroyo section and present newly collected insect and conodont data. The insects indicate that the two Lagerstätten in the Red Tanks Member are of early Asselian age. The new conodont data include the presence of *Streptognathodus virgilicus* in the uppermost part of the Atrasado Formation, which constrains its age to the middle to upper part of the Virgilian and to a comparable position in the Gzhelian. 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. A significant amount of latest Pennsylvanian to earliest Permian time apparently is not represented by rock record at the Carrizo Arroyo section, most likely at a major disconformity at the top of the Atrasado Formation and smaller ones at the bases of depositional sequences in the lower part of the Red Tanks Member. Conodont biostratigraphy provides compelling evidence that Bursum Formation deposition was not simply driven by glacio-eustatic cyclicity, but in this area it was partly overprinted by local tectonics..

INTRODUCTION

Located on the eastern edge of the Colorado Plateau, Carrizo Arroyo (text-fig. 1) is 50km southwest of Albuquerque, New Mexico, USA (~ 34°45'N, 107°07'30"W). 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). The base of the section (text-fig. 2) is relatively thick-bedded, ledge-forming gray limestone and interbedded drab shale of the upper part of the Atrasado Formation. These strata are of marine origin 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 ~ 100m 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 (text-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.

At Carrizo Arroyo, the Red Tanks Member yields fossils from many beds, and at stratigraphic levels 43m and 68m above the base of the section are Lagerstätten of plants, insects, crustaceans, eurypterids and other fossils (text-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 foraminifers (Krainer and Lucas 2004), fusulinids (Wahlman and Kues, 2004), bryozoans, brachiopods, gastropods, bivalves and nautiloids (Kues 1983, 1984, 2004), eurypterids (Kues and Kietzke 1981), ostracods (Kietzke 1983), syncarid crustaceans (Schram 1984), conchostracans, insects and some other arthro-



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

pod (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), 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 Carboniferous (Pennsylvanian)-Permian boundary in the Carrizo Arroyo section, have long been uncertain. Various workers have considered the Red Tanks Member to be entirely Carboniferous, entirely Permian or have placed the Carboniferous-Permian boundary at diverse points in the section (text-fig. 3).

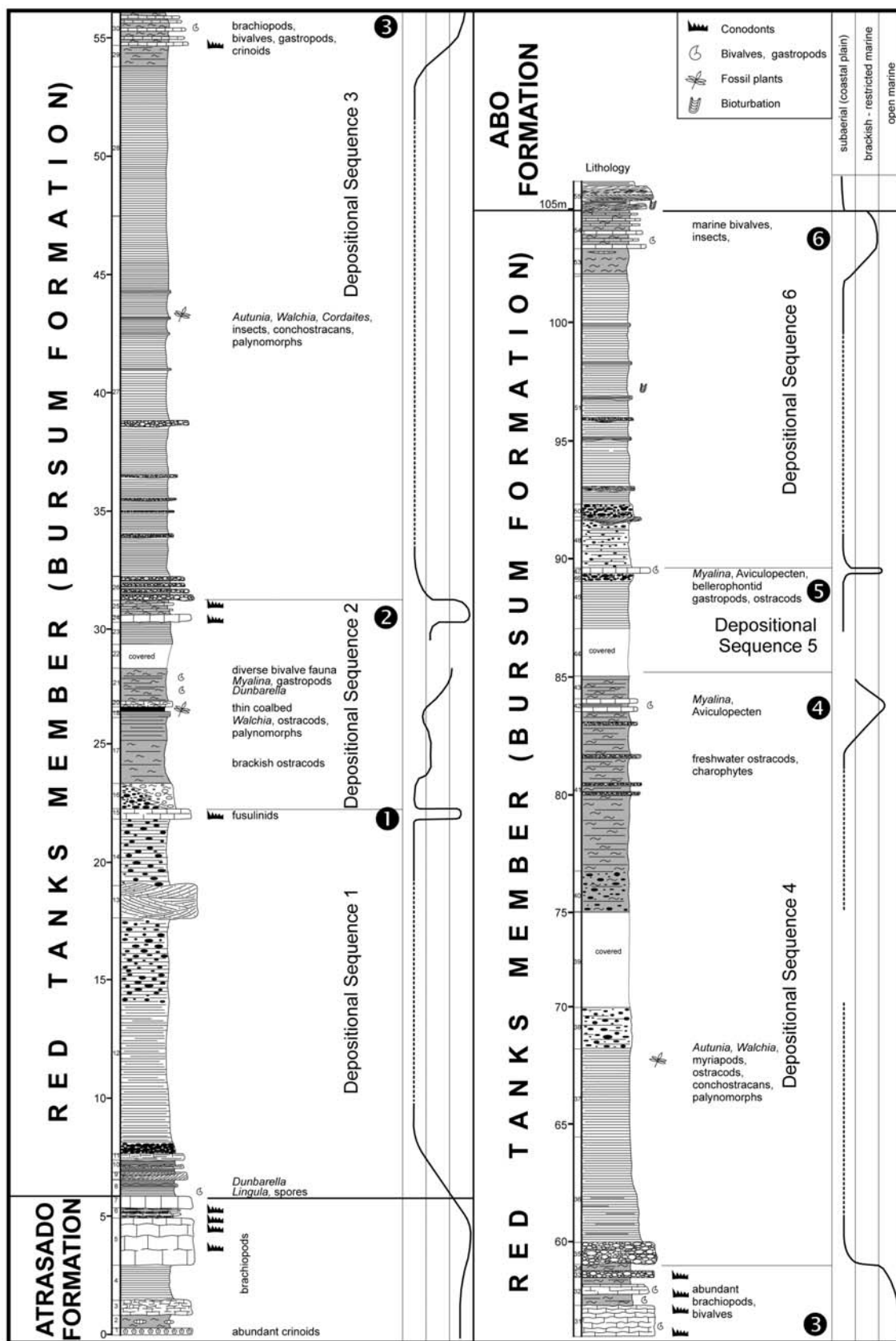
Given the significance of the nonmarine fossil biota collected at Carrizo Arroyo, and its intercalation with marine strata, a precise age of the Carrizo Arroyo section will be a major contribution to correlating nonmarine and marine biotic events across the Carboniferous-Permian boundary. Here, our goals are two-fold: (1) to review previously published data relevant to placement of the Pennsylvanian-Permian boundary in the Carrizo Arroyo section; and (2) to present new insect and conodont data that more precisely place the base of the Permian in the Carrizo Arroyo section.

STRATIGRAPHIC CONTEXT

At Carrizo Arroyo, the base of the studied section (text-fig. 2) is relatively thick-bedded, ledge-forming gray limestone (composed mostly of skeletal wackestone, and subordinate crinoidal packstone and skeletal grainstone) and interbedded drab shale

of the upper part of the Atrasado Formation. Most of the studied section (text-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). The Red Tanks Member is 98m 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) (text-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 (text-fig. 2). The sequences are mostly composed of mudstone/siltstone beds, some of which contain abundant calcrite 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, “sprirorbis” [microconchids], ostracods, fish remains) and overlain by marly mudstone containing shallow marine molluscs (myalinids), lingulids, cordaitalean leaves up to 40cm long and plant debris. Carbonate conglomerate at the bases of depositional sequences 3 and 4 probably represents 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).



TEXT-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.

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 wackestones 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; and see below). 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 that 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, so regional tectonism was also an important force that drove local sedimentation (Krainer and Lucas 2009). Indeed, the conodont-based age determinations presented here 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-late Wolfcampian age, largely because they interfinger with middle-late Wolfcampian strata of the marine Hueco Group to the south (e.g., Lucas et al. 2011a, b). The Abo Formation represents fluvial deposits derived from highlands to the north (Kues and Giles 2004; Lucas et al. 2012a, b). At Carrizo Arroyo it 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).

STRATIGRAPHIC UNITS AND FOSSILIFEROUS HORIZONS

Although the Carrizo Arroyo section yields numerous and diverse fossils from many beds over an approximately 100m 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 and E, brackish A and nonmarine A and B, based on perceived depositional setting and stratigraphic position (text-fig. 3).

Previously, two measured sections at Carrizo Arroyo with different numbering of the lithostratigraphic units have been published. Kues and Kietzke (1976) discriminated and numbered 29 units in the Carrizo Arroyo section, whereas Krainer and

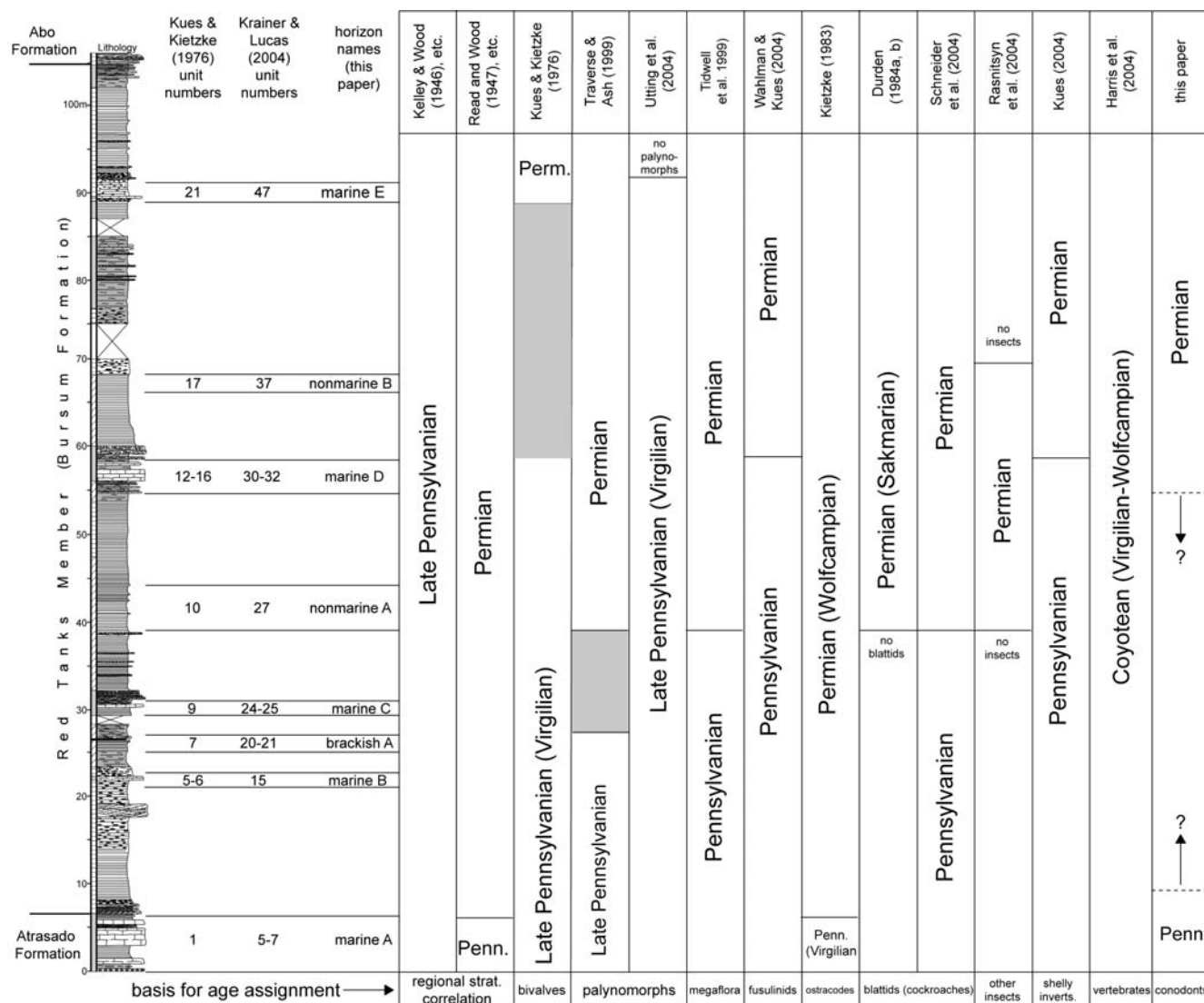
Lucas (2004) recognized 55 units (text-figs. 2-3). Prior to 2004, the articles published on the fossils from Carrizo Arroyo used the numbering system of Kues and Kietzke (1976), whereas beginning in 2004 the scheme of Krainer and Lucas (2004) was referred to. Here, we present and correlate both numbering schemes for easy cross reference so that all previous literature about the biostratigraphy of the Carrizo Arroyo section can be unambiguously understood (text-fig. 3).

CARBONIFEROUS-PERMIAN BOUNDARY

To understand the following review of the history of age assignments to the Red Tanks Member, we briefly review the placement of the Carboniferous-Permian boundary (text-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 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* is 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) are now regarded as latest Pennsylvanian (text-fig. 4). Attempts to resolve the current 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) or simply has been considered the younger portion of a longer Virgilian (e.g., Baars et al. 1994).

The limited information on the conodont distribution from the type Wolfcampian does not help resolve the uncertainty. Wardlaw and Davydov (2000) originally reported that the Asselian conodont *Streptognathodus nevaensis* had been recovered from the top bed of the Gray Limestone Member of the Gaptank Formation, just below the base of the Neal Ranch Formation, and the base of the Wolfcampian. Ross and Ross (2012) mentioned this conodont occurrence in their review of the sequence stratigraphy and fusulinid biostratigraphy of the Lower Permian in the Glass Mountains, but indicated instead that the Gray Limestone Member, which possesses a complex local stratigraphy, was largely Bursumian in age based on fusulinids (Ross and Ross 2012, fig. 2). Recently, Henderson et al. (2012, p. 668) stated that conodonts from the top bed of the Gray Limestone Member "contains *Streptognathodus isolatus* Zone cono-



TEXT-FIGURE 3

Chart showing differing published placements of the Carboniferous-Permian boundary at Carrizo Arroyo using different criteria. The lithologic column is a simplification of the column in text-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 the age assignment is indicated at the bottoms of the columns showing placement of the Carboniferous-Permian boundary by various workers.

donts.” The basis for this statement has been clarified in an unpublished summary provided by B. Wardlaw (pers. Comm., 2013), in which *S. fuchengensis* and *S. invaginatus* are reported from the top bed of the Gray Limestone Member. Because both of these species appear with *S. isolatus* in the Bennett Shale in Kansas (Boardman et al. 2009), an *S. isolatus* Zone assignment was inferred. This would place the base of the Permian, therefore, below the base of the Neal Ranch, and below the base of the type Wolfcampian (Henderson et al. 2013). The first occurrence of *S. isolatus* is reported from the first limestone bed in the Neal Ranch Formation above the Gray Limestone Member. (Wardlaw, pers. comm. 2013).

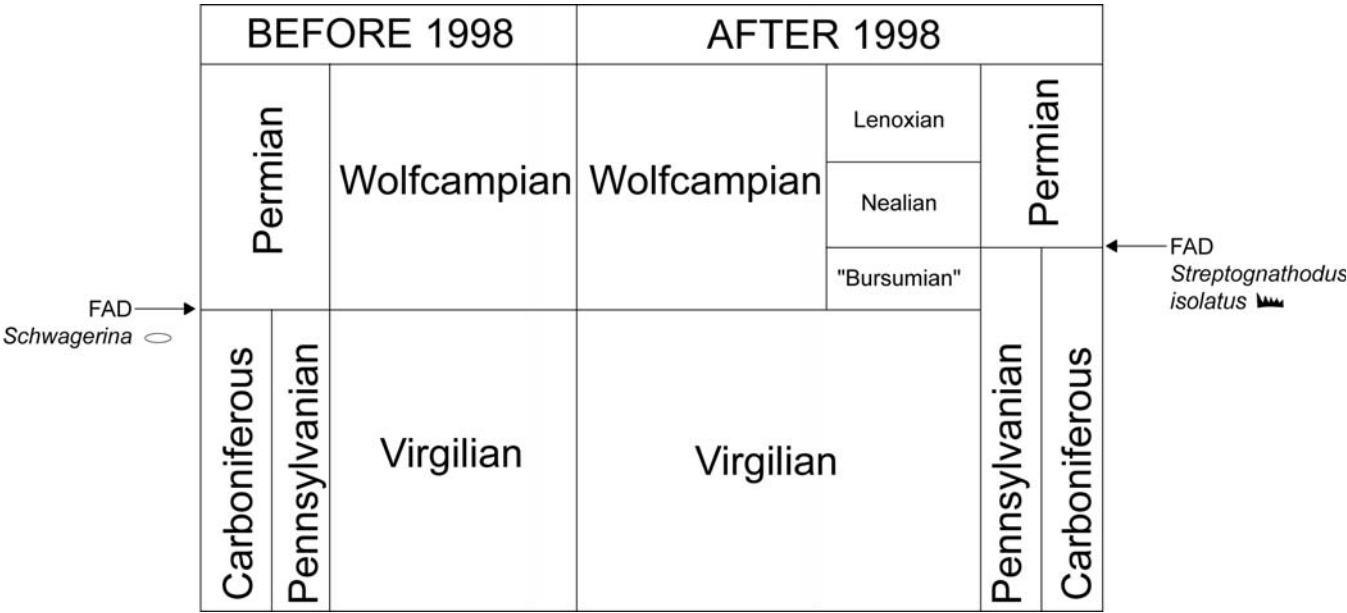
We do not advocate a solution to this issue of North American provincial chronostratigraphic nomenclature. Instead, our concern is clear understanding of differing definitions of the Perm-

ian base and 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 (text-figs. 3-4).

PREVIOUS CORRELATIONS

Introduction

When naming the Red Tanks Member of the Madera Limestone, Kelley and Wood (1946) first assigned it a Late Pennsylvanian age (text-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 Lime-



TEXT-FIGURE 4
The two different definitions of the Carboniferous-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" and Nealian fusulinid substages as used by some workers.

stone, 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; Jicha and Lochman-Balk 1958). This meant they considered the Red Tanks Member to be of Early Permian age (text-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 (text-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. Therefore, we review these age assignments in taxonomic order.

Palynomorphs

Two opinions as to the age of the Red Tanks Member at Carrizo Arroyo have been based on palynology. Traverse and Ash (1999) reported two palynological assemblages from the Red Tanks Member at Carrizo Arroyo: (1) a stratigraphically lower one from just below the coal bed in depositional sequence 2 (in horizon brackish A) dominated by monosaccates and judged by them to be Late Pennsylvanian in age, and (2) a stratigraphically higher assemblage from horizon nonmarine A dominated by bisaccate forms, including *Platysaccus* and *Limitisporites*, which they judged to be of Early Permian age (text-fig. 3). Traverse and Ash (1999) suggested that the presence of *Limitisporites monstruosus* (Luber and Waltz) Hart in the upper assemblage indicated a Permian age for part of the succession. They thus placed the Pennsylvanian-Permian boundary within the Red Tanks Member (text-fig. 3). However, as Utting et al. (2004) later noted, although *L. monstruosus* is a characteristic species of the Early Permian, it does occur rarely in Carboniferous strata, so its presence at Carrizo Arroyo is not definitively Permian.

In a more extensive palynological study, Utting et al. (2004) identified palynomorphs from ten stratigraphic levels in the Red Tanks Member at Carrizo Arroyo. The most prolific and diverse palynofloras came from units 17, 23 and 46 of the Krainer and Lucas (2004) section (text-fig. 2). They noted that most of the taxa identified in the Carrizo Arroyo section are stratigraphically long ranging and stressed that precise dating of rocks at the Carboniferous/Permian boundary based on palynology is problematic.

According to Utting et al. (2004), there are some minor qualitative differences in the assemblages from the lower and upper

parts of the Carrizo Arroyo section, but these differences may reflect changes in sedimentary facies rather than age differences. From their palynological data, they assigned a Virgilian age to essentially the entire Red Tanks section at Carrizo Arroyo (text-fig. 3). However, they also noted that a Wolfcampian age for the upper part of the Red Tanks Member, as suggested by Traverse and Ash (1999), cannot categorically be ruled out, though there are no conclusive palynological data to support it.

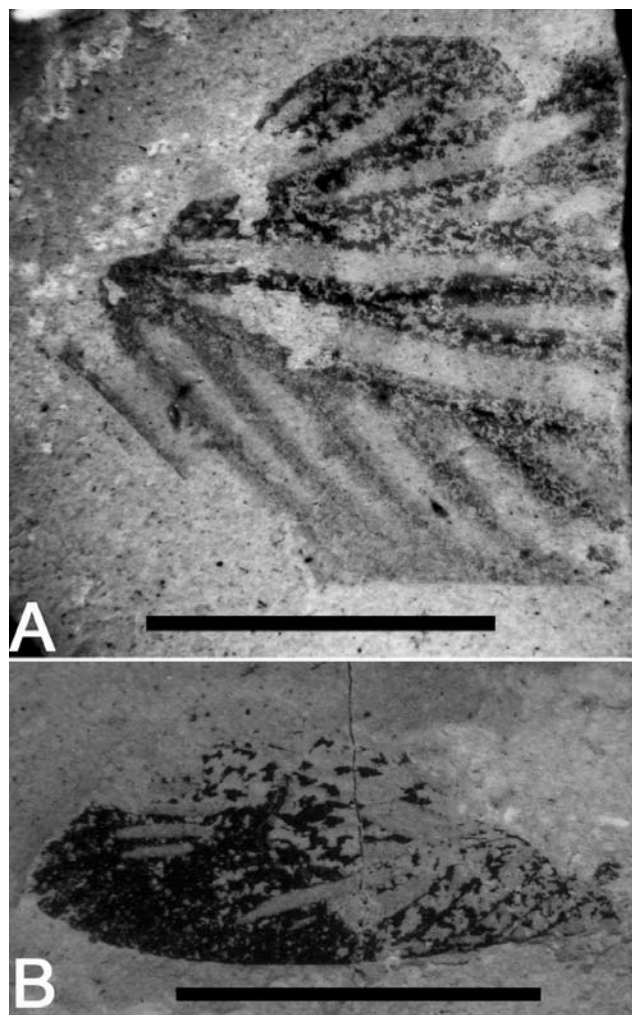
Plant Megafossils

Plant megafossils are found at three levels in the Carrizo Arroyo section: (1) horizon brackish A yields a low diversity assemblage from which no taxa other than the conifer *Walchia* have been published; (2) horizon nonmarine A has an extensive paleoflora documented by Ash and Tidwell (1982, 1986), Tidwell et al. (1999) and Tidwell and Ash (2004); and (3) horizon nonmarine B yields a similar but less well-studied paleoflora, partly documented by Knaus and Lucas (2004). The well-documented paleoflora from horizon nonmarine A is dominated by the conifer *Walchia pinniformis*, the callipterid peltasperms *Autunia conferta* and *Rhachiphyllum schenkii* and the pteridosperms *Sphenopteridium manzanum* and *Macro-neuropteris scheuchzeri*. DiMichele et al. (2004) regarded this paleoflora as representing a seasonally dry biome of the Pennsylvanian-Permian transition.

Ash and Tidwell (1982, 1986) considered the paleoflora of horizon nonmarine A to be of Wolfcampian age, as did Tidwell et al. (1999) (text-fig. 3). By that they meant that the flora is earliest Permian in age. However, citing Kues (2002), who concluded that the invertebrates in the limestone (marine D) overlying the principal leaf-bearing bed indicate that the Pennsylvanian-Permian boundary actually lies higher in the section, Tidwell and Ash (2004) concluded that the paleoflora is latest Pennsylvanian in age. Clearly, they had no strong allegiance to a strictly plant-megafossil-based age determination.

Non-fusulinid foraminifers (small foraminifers)

Limestone (skeletal wackestone, rare packstone and grainstone) of the uppermost Atlasado Formation (horizon marine A) contains a diverse assemblage of small foraminifers including calcivertellids, *Bradyina*, *Climacammina*, *Cornuspira*, *Deckerella*, *Diplosphaerina*, *Earlandia*, *Glomospira*, *Glomospiroides*, *Hemigordius/Lasiodiscus*, *Palaeonubecularia*, *Syzrania*, *Tetrataxis* and *Tuberitina* (Krainer and Lucas 2004). Limestone beds of the Red Tanks Member on top of depositional sequences 1, 2 and 3 (horizons marine B, C and D) are dominantly skeletal wackestone, but also include mudstone and packstone containing a foraminiferal assemblage similar to that of the topmost Atlasado Formation: calcivertellids, *Climacammina*, *Diplosphaerina*, *Earlandia* ex gr. *E. elegans*, *Globivalvulina bulloides*, *Globivalvulina* ex gr. *G. moderata*, *G. sp.*, *Glomospira*, *Nodosinelloides potievskayae*, *N. sp.*, *Palaeonubecularia*, *Spiretina conspecta*, *S. bella*, *S. sp.* and *Tuberitina*. On top of depositional sequence 2 a foraminiferal wackestone is present that contains abundant calcivertellid foraminifers (Krainer and Lucas 2004). Limestone on top of depositional sequence 4 (skeletal wackestone, packstone and mudstone) has a low-diversity foraminiferal assemblage containing *Earlandia* and *Palaeonubecularia*. Limestone on top of depositional sequence 5 (horizon marine E) lacks small foraminifers. The uppermost limestone beds on top of depositional sequence 6 are composed of skeletal wackestone and floatstone containing a low diversity foraminiferal assemblage with rare *Calcitornella*



TEXT-FIGURE 5

Spiloblattinid forewings from horizon nonmarine A (NMMNH locality 3437) at Carrizo Arroyo. A, Fragment of spiloblattinid forewing close to *Sysciophlebia ifeldensis*, wide dimorph; Kukalova-Peck collection No. 1. B, Fragment of spiloblattinid forewing close to *Spiloblattina weissigenis*; Kukalova-Peck collection No. 138. Scale bars = 5mm.

and *Syzrania* (Krainer and Lucas 2004). These genera of non-fusulinid foraminifers are stratigraphically long ranging, and do not support precise placement of the Pennsylvanian-Permian boundary in the Carrizo Arroyo section.

Fusulinids

Abundant, well-preserved fusulinids are only present in limestone beds of the uppermost Atlasado Formation of the Carrizo Arroyo section (horizon marine A). Wahlman and Kues (2004) concluded that the fusulinids from the uppermost Atlasado Formation indicate a late (but not latest, or “Bursumian”) Virgilian age based on the presence of *Tricittites* cf. *T. fresnalensis* Needham and *T. imperialis* Kauffman and Roth. The sparse fusulinids from horizon marine B, at the top of depositional sequence 2 of the Red Tanks Member, include small indeterminate *Triticites* specimens and a primitive *Leptotriticites* related to *L. eoextenta* Thompson. Wahlman and Kues (2004) suggested that although this horizon could be as young as early “Bursumian”

in age, a late Virgilian (sub-Bursumian) age was likely based on the features (small proloculus) of the *Triticites* specimens. Only rare, specifically unidentifiable juvenile fusulinids are present in horizon marine D at the top of depositional sequence 3 of the Red Tanks Member (text-fig. 3). Based on the small prolocular diameters, Wahlman and Kues (2004) indicated that this horizon was also probably sub-Bursumian in age. They thus placed the base of the Permian above horizon marine D (text-fig. 3).

Ostracods and conchostracans

The ostracods from the Red Tanks Member at Carrizo Arroyo have not been fully described and published. In an abstract, Kietzke (1983) claimed a change from Pennsylvanian ostracods in the Atrasado Formation to Permian ostracod taxa in the Red Tanks Member. Kietzke (1983) thus assigned the Atrasado Formation a Virgilian age and the Red Tanks Member a Wolfcampian (Early Permian) age based on ostracods (text-fig. 3).

We also note that extensive conchostracan assemblages are present (but largely unstudied) in horizons nonmarine A (unit 27 A and B) and nonmarine B (unit 37) in the Carrizo Arroyo section. Small (3 to 5mm long) *Lioestheria* is common (Schneider et al. 2004, text-fig. 8D-E). An unusual, large *Palaeolimnadiopsis* up to 30mm long is also present, but rare. A similar association is known from the late Stephanian in Central Europe with *Lioestheria* Form Schadewalde and *Palaeolimnadiopsis* Form Jessen (Schneider et al. 2005, figs. 1, 24, 25). But, because the stratigraphic ranges of conchostracan species are mostly unknown, their real biostratigraphic significance remains uncertain.

Insects

Scudder (1879, 1895) made the first serious attempt to use insect wings, especially of the common blattoids (cockroaches), for late Paleozoic biostratigraphy. Much later, Durden (1969, 1972, 1984a, b, 1988) delineated “blattoid assemblages” (Durden 1969), “North American provincial insect ages” (Durden 1984b) or simply “insect faunal ages,” supposedly analogous to the mammalian ages of the Tertiary (Durden 1984c) for the biostratigraphy of nonmarine Pennsylvanian and Permian deposits and their correlation with the marine standard scale. Methodologically, “each insect faunal age is characterized by a type assemblage of at least three finds at the same locality and horizon” but “age boundaries are not defined” (Durden 1984c, p. 175). Instead, each of Durden’s “insect ages” corresponds to a list of localities with all the insect taxa, mainly blattoids (cockroaches), that have been found at them (Durden 1984c) or, in the case of the “North American provincial insect ages,” a compilation of localities with the dominant blattoid families, in places completed by the names of selected genera such as *Brachymylacris*, *Spiloblattina* and *Anthracoblattina*. Nevertheless, for some of the “insect ages” a weak definition was given, such as defining an “age” by the first known occurrence of a blattoid family, the occurrence “of the first large Mylacridae” or simply, as in the case of the “Lawrencean provincial age,” “the species of *Spiloblattina* and *Anthracoblattina* are characteristic” (Durden 1984b, p. 611).

As a result of these imprecise definitions, Durden’s insect biostratigraphy has not been used by subsequent workers. In fact, many of his correlations remain doubtful because of inadequate taxonomy (Durden 1969; see Schneider and Werneburg 2006). For example, Durden (1984b, text-fig. 2, p. 609) correlated the German localities Breitenbach with the Stephanian B,

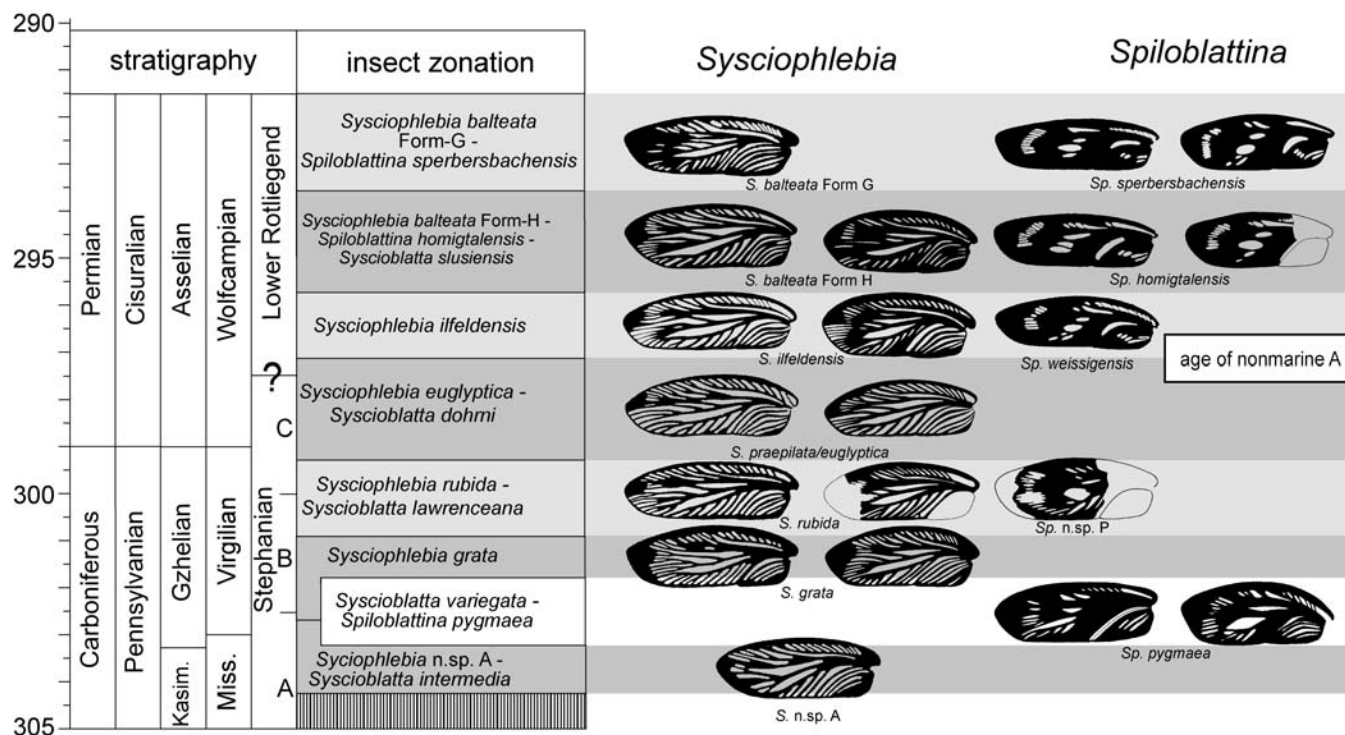
Wettin with the early Asselian, and Löbejün with the higher Sakmarian – but, in reality, Wettin and Löbejün belong both to the same lithostratigraphic level (the Wettin Subformation), and strata at all three localities belong to the same spiloblattnid biozone of Schneider and Werneburg (2006), the *Sysciophlebia euglyptica*-*Syscioblatta dohrni* Zone of Stephanian C age at the Gzhelian/Asselian transition.

The stratigraphic position of Durden’s insect ages was apparently often based on the paleobotanical age determination of the localities or on lithostratigraphic data. An anchor point for his stratigraphy was the first occurrence of the callipterid plant genus *Callipteris* at the base of the “Fairplayan” insect age, supposedly in the late Sakmarian (i.e., high above the top of the Stephanian). But, it remains unclear how this late Sakmarian age was determined, because the first occurrence of “*Callipteris*” (a genus that now includes *Autunia*) was long used to determine the Stephanian /Autunian boundary (Bouroz and Doubinger 1977). Furthermore, a much earlier occurrence in the Late Pennsylvanian is known for *Autunia* (see various references from Kozur 1978 to Hmich et al. 2006). Indeed, in the discussion of the age of the Hamilton (Kansas) insect fauna, Durden (1988, p. 120) downplayed the biostratigraphic significance of the first appearance of *Callipteris* as “more time-transgressive ... than had been hoped....”

Durden (1984b, p. 611) equated the insect fauna from Carrizo Arroyo (horizon nonmarine A) with that of the Fairplay locality in Colorado, as part of his “Fairplayan insect age,” which is defined as “...the first fauna with a generous diversity of ‘Permian’ aspect,” yet the Fairplay site contains both the last known members of several ‘Carboniferous’ families and the first of numerous ‘Permian’ families in the same horizon.” Indeed, abundant cockroaches, with the last Hemimylacridae present and Petrablattnidae predominant, give a decidedly “Carboniferous” aspect to the insect fauna. Durden (1988, p. 119-120) later changed this age estimate for Carrizo Arroyo in discussing the age of the Hamilton quarry insect fauna, which should be “definitely older than the Fairplay, Colorado, insect assemblage and may be close to the [age of the] Carrizo Arroyo... assemblage.”

Schneider et al. (2004) investigated cockroach samples from two horizons (nonmarine A and B) in the Red Tanks Member at Carrizo Arroyo. According to Schneider et al. (2004), the Carrizo Arroyo blattoid assemblages generally resemble those from the European Stephanian C to lowermost Rotliegend, which indicates a Gzhelian to Asselian age. However, they stressed that the guide forms of the Euramerican Spiloblattnidae insect zonation were not known at that time from Carrizo Arroyo, so this precluded a more precise correlation using blattoids (see below).

Rasnitsyn et al. (2004) undertook a detailed study of the non-blattoid insects from the nonmarine A and B horizons of the Carrizo Arroyo section. They observed no striking differences of chronostratigraphic significance between the two insect assemblages. Rasnitsyn et al. (2004) based their correlations of the Carrizo Arroyo insect assemblages primarily on information compiled by Rasnitsyn and Quicke (2002), noting that the vast majority of index taxa found at Carrizo Arroyo are known to cross the Carboniferous-Permian boundary. However, of the 28 insect genera identified (besides 3 transitional genera and 13 endemic genera), they considered 11 genera to be otherwise known only from the Permian, and only one a strictly Carbonif-



TEXT-FIGURE 6

Spiloblattnid insect-based age of horizon nonmarine A of the Carrizo Arroyo section. The spiloblattnid zonation of Schneider and Werneburg (2006) is used because of inconsistencies in correlations of the marine and the nonmarine scale based on numerical ages. The early to middle Asselian conodont age of horizon marine D at the top of depositional sequence 3 is in good agreement with an early Asselian age for the middle part of this sequence based on the spiloblattnid-insect zonation.

erous genus. This induced Rasnitsyn et al. (2004) to conclude that the Carrizo Arroyo insect assemblage has an essentially Permian composition and is of Early Permian age (text-fig. 3).

Shelly Marine Invertebrates

Kues (1983, 1984, 2002, 2004) documented the shelly marine invertebrates of the Red Tanks Member and uppermost Atrasado Formation at Carrizo Arroyo, assigning them to more than 120 species of brachiopods and molluscs. Most of these fossils come from horizon marine D (text-fig. 3). Kues (2004) concluded that only a few of the brachiopod taxa from the Red Tanks Member suggest a Permian instead of a Pennsylvanian age, but he also stressed that little, if any, change occurred in brachiopod species at the Pennsylvanian-Permian boundary in the Midcontinent to New Mexico region. Kues (2004) thus concluded that the brachiopods of the uppermost Atrasado Formation at Carrizo Arroyo are late Virgilian, but the most that can be said of the Red Tanks brachiopods is that they indicate a late Virgilian to early Wolfcampian age.

Kues (2004) also concluded that the gastropod taxa from the Red Tanks Member at Carrizo Arroyo are consistent with a latest Virgilian age, as most of them are either Pennsylvanian species or are new species that are clearly closely related to and probably derived from Late Pennsylvanian species. However, according to Kues (2004), the large gastropod *Omphalotrochus* from horizon marine D of the Red Tanks Member suggests that the upper half of the Red Tanks may be of earliest Wolfcampian

age, so he suggested that the base of the Permian is probably at or very close to horizon marine D (text-fig. 3). Earlier, Kues (1983) had simply termed the Red Tanks Member gastropods as of latest Pennsylvanian-earliest Permian age, though he did note their similarity to Bursum Formation gastropod assemblages in southern New Mexico.

Kues (2004) argued that the most useful age-diagnostic bivalve at Carrizo Arroyo is the large myalinid *Myalina* (*Orthomyalina*) *subquadrata* Shumard, which is limited to a dense concentration of shells in horizon brackish A. He considered this species to be an indicator of a late Virgilian age based on its stratigraphic range in the Kansas section (Mudge and Yochelson, 1962). Other well-documented bivalve taxa present in the Red Tanks Member have ranges that extend from Virgilian into Wolfcampian strata according to Kues (2004).

No ammonoids were identified in the Red Tanks fauna. The Red Tanks cephalopod fauna documented by Kues (2004) chiefly includes orthoconic nautiloids with long Pennsylvanian-Early Permian ranges. Kues (2004) attributed no precise biostratigraphic significance to the other kinds of shelly marine invertebrate taxa found in the Red Tanks Member at Carrizo Arroyo—bryozoans, echinoids, crinoids, rugose corals and trilobites. Indeed, he based his age assignments primarily on the fusulinids reported by Wahlman and Kues (2004), not on the shelly invertebrate macrofauna, so he placed the base of the Permian above horizon marine D (text-fig. 3).

Vertebrates

The only vertebrate fossils identified from the Red Tanks Member at Carrizo Arroyo are ichthyoliths—teeth, denticles and scales of fishes. Harris et al. (2004) documented tooth fragments of the chondrichthyans *Deltodus* and *Petalodus* from horizon marine D. Johnson and Lucas (2004) reported ichthyoliths of chondrichthyans (including *Orthacanthus*), acanthodians, sarcopterygians and actinopterygians? from bed 41 of the Krainer and Lucas (2004) section (text-fig. 2). None of these fossils has any precise significance for placement of the Carboniferous-Permian boundary (e. g., Johnson 1991).

South of Carrizo Arroyo, the middle and upper parts of the Red Tanks Member yield a much more extensive and diverse, tetrapod-dominated vertebrate fossil assemblage documented by Harris et al. (2004). Taxa present are the lungfish *Gnathorhiza bothrotreta* Berman, the temnospondyls *Eryops* sp. and *Trimerorhachis* sp., an anthracosaur (cf. *Archeria* sp.), a caseid pelycosaur, the eupelycosaur *Edaphosaurus* sp., *Sphenacodon* sp., and *Dimetrodon* cf. *D. milleri* Romer and an indeterminate bolosaurid. These taxa are readily assigned to the Coyotean land-vertebrate faunachron of Lucas (2005, 2006), which straddles the Virgilian-Wolfcampian boundary (also see Lucas et al. 2010). Therefore, the vertebrate fossil assemblage from the Red Tanks Member does not aid in placement of the Pennsylvanian-Permian boundary (text-fig. 3).

NEW INSECT-BASED CORRELATION

Excavations at Carrizo Arroyo supervised by one of us (JWS) in 2005, 2006 and 2009 have recovered a large number of insects, other arthropod and plant fossils, but regrettably not one specimen of the insect biozonal species used by Schneider and Werneburg (1993, 2006). In 2006, J. Kukalova-Peck provided her blattoid samples from nonmarine horizon A for investigation to one of us (JWS), which fortunately contain three spiloblattnid forewing fragments. Despite their incomplete preservation, two of them (text-fig. 5) can be assigned with confidence by the venation and color patterns to spiloblattnid genera and species.

One fragment (text-fig. 5A) is the middle part of a forewing with a piece of the CuP framed by a dark strip, which is typical of the genus *Sysciophlebia*. The reduced length of the bright fields between the CuA branches indicates a female forewing close to *S. ilfeldensis*. Because these bright fields are a bit longer than in *S. ilfeldensis* but definitely shorter than in the predecessor species *S. euglyptica*, this specimen represents a transitional form between the two species, but one closer to *S. ilfeldensis*. The latter is the zonal species of the homonymous spiloblattnid-biozone, which marks the lowermost part of the European Lower Rotliegend (text-fig. 6), and is correlated with the early Asselian of the marine standard scale (see below).

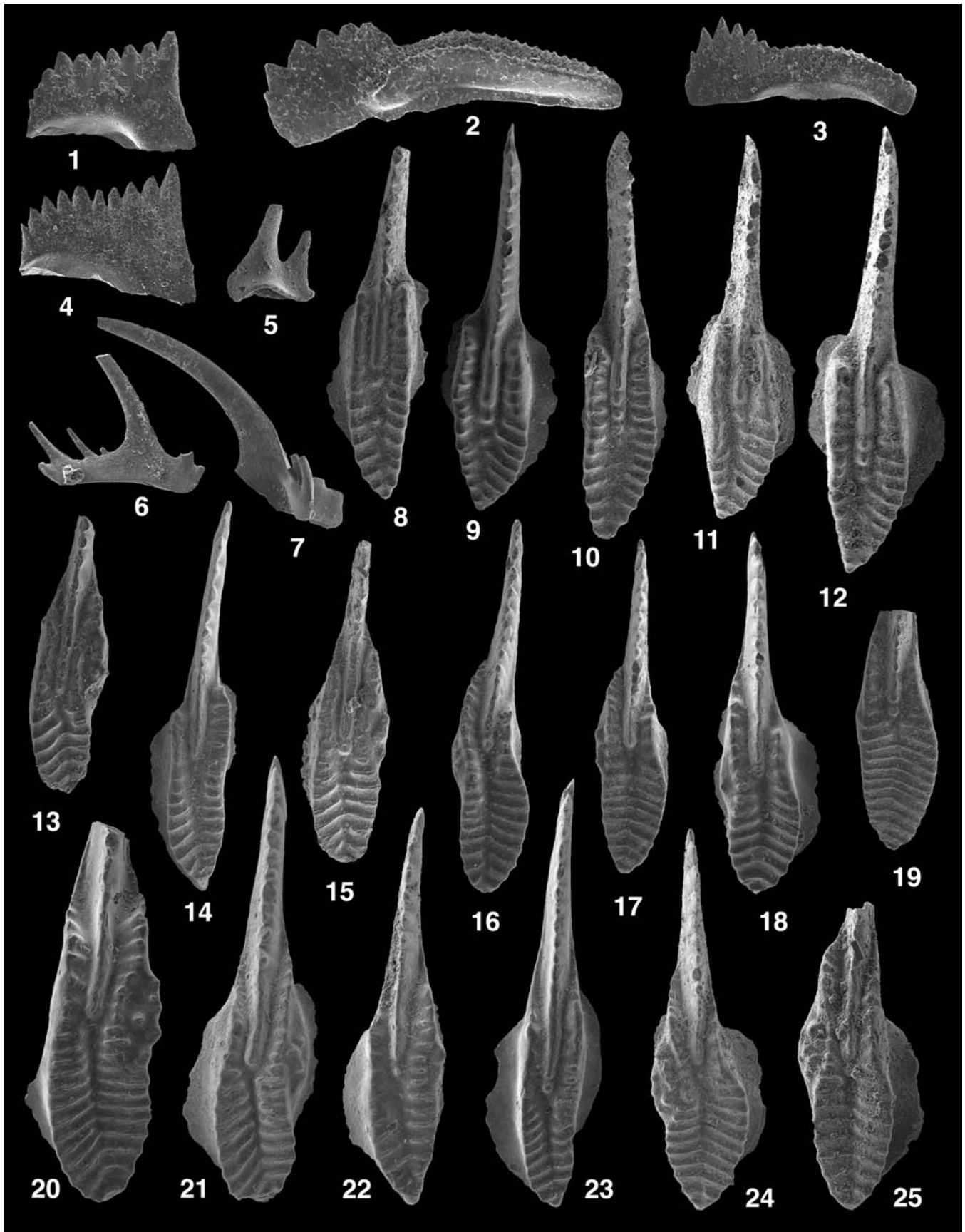
The other fragment (text-fig. 5B) shows the apical part of a forewing with a portion of the M and the CuA. It is compared with *Spiloblattina weissigensis* because of the arrangement and the small size of the bright spots on the dark wing surface. *Sp. weissigensis* is the forerunner species of *Sp. homigtalensis* in the *Spiloblattina* chronocline. The latter zone species co-occurs with *S. balteata* form H, which is the succeeding species of *S. ilfeldensis* in the *Sysciophlebia* chronocline (Schneider and Werneburg 2006, 2012). Because of this predecessor-successor relationships in both chronoclines, *Sp. weissigensis* is inferred as an accompanying species of the *S. ilfeldensis* Zone. *Sp. weissigensis* is known from the Early Rotliegend Weissig basin in Germany and from the Fairplay locality, Maroon Formation, Pony Spring Member, Colorado. Despite the very incomplete preservation, it confirms a lowermost Rotliegend age.

Based on the spiloblattnid insect zonation of Schneider and Werneburg (2006), the nonmarine horizon A at 43m belongs (with certain reservation because of fragmentary preservation of the diagnostic wings) in the upper part of the *S. euglyptica* zone close to the base of the *S. ilfeldensis* Zone (text-fig. 6). The *S. ilfeldensis* zone marks the base of the Lower Rotliegend in the European nonmarine scale. The base of the Rotliegend was correlated with the earliest Asselian at about 297-298 Ma by Roscher and Schneider (2005) and Lützner et al. (2007) based on a compilation of isotopic ages as well as the cross-correlation

TEXT-FIGURE 7

Conodonts from the uppermost part of the Atasado Formation and Red Tanks Member of the Bursum Formation at Carrizo Arroyo. All figures $\times 75$.

- | | |
|--|---|
| 1,4 <i>Hindeodus</i> sp., P ₁ elements, CA-05. | 15,20,24 <i>Streptognathodus invaginatus</i> Reshetkova and Chernykh 1986, P ₁ elements, CA-32. |
| 2,3 <i>Adetognathus</i> sp., P ₁ elements, CA-05. | |
| 5-7 <i>Ellisonia</i> sp., 5 - M element; 6, 7, - S elements, CA-32. | 17,21,25 <i>Streptognathodus isolatus</i> Chernykh, Ritter and Wardlaw 1997?, P ₁ elements, CA-32. |
| 8-12 <i>Streptognathodus virgilicus</i> Ritter 1995, P ₁ elements, CA-05. | 19 <i>Streptognathodus</i> sp., P ₁ element, CA-32. |
| 13 <i>Streptognathodus minacutus</i> Barskov and Reimers 1996?, P ₁ element, CA-32. | 23 <i>Streptognathodus postelongatus</i> Wardlaw, Boardman, and Nestell 2009, P ₁ element, CA-32. |
| 14,16 <i>Streptognathodus nevaensis</i> Wardlaw, Boardman and Nestell 2009, P ₁ element, CA-32. | |
| 18,22 | |



with biostratigraphic data from the Thuringian Forest basin and the Saar-Nahe basin in Germany. A crucial date for this compilation was the 300 ± 1.2 ($2\sigma = 2.4$) Ma date of Burger et al. (1997) for a volcanic ash horizon allegedly situated in the late Stephanian C upper Breitenbach Formation, which belongs to the *S. euglyptica* Zone. The position of this horizon was re-evaluated by Schindler (2007), who concluded that this age comes from a synsedimentary reworked volcanic ash in the basal Rotliegend lowermost Remigiusberg Formation (Boy et al. 2012), which overlies the Stephanian C Breitenbach Formation of the *S. euglyptica* Zone (text-fig. 6). If this age is correct, the error range of 2.4 Ma gives a time range of Gzhelian to early Asselian for the lowermost Remigiusberg Formation. Consequently, because of the succession *S. euglyptica*-*S. ilfeldensis* in a chronocline, a position of the *S. ilfeldensis* Zone above the Gzhelian/Asselian boundary can be assumed with confidence. This fits well with the conodont-based correlation (see below) of the upper part of the Atrasado Formation with the late Gzhelian *Streptognathodus virgilicus* Zone and horizon marine D at the top of depositional sequence 3 to the early to middle Asselian *S. nevaensis* Zone. The synthesis of the conodont and the insect ages assigns nonmarine horizon A, situated in the middle of depositional sequence 3, to the early Asselian.

CONODONT-BASED CORRELATION

Orchard et al. (2004) presented a preliminary study of conodonts from the Atrasado-Red Tanks section at Carrizo Arroyo extracted from small samples taken from horizons marine A, C and D of the section. Orchard et al. (2004) offered the preliminary conclusion that the conodonts indicated a late Virgilian age. We undertook more extensive sampling for conodonts at Carrizo Arroyo. Here, we report the results of this sampling.

Uppermost part of the Atrasado Formation (horizon marine A)

The conodont fauna from unit 5, near the top of the Atrasado Formation, is dominated by P_1 elements of *Streptognathodus* and smaller numbers of P_1 elements of *Adetognathus* and *Hindeodus*. A few ramiform elements of an *Ellisonia* species were also recovered. This association is characteristic of Late Pennsylvanian to Early Permian shallow water carbonate environments. The majority of the *Streptognathodus* P_1 elements are too small for confident species-level identification, but most of the larger specimens can be assigned to *S. virgilicus* Ritter 1995. The Atrasado specimens possess the V-shaped median trough and wide margins with transverse ridges that extend to near the middle of the trough that are characteristic of this species. A few small specimens have a wider more U-shaped trough and shorter transverse ridges like the closely related species *S. pawhuskaensis*. Ritter (1995) noted that in the upper part of the range of *S. virgilicus* forms occur that may be difficult to assign to one species or the other. Orchard et al. (2004) recovered a few small conodont elements from the uppermost part of the Atrasado Formation (units 3 and 6), which are like those reported here from unit 5.

In the Midcontinent region, *Streptognathodus virgilicus* ranges from the Virgilian Queen Hill sequence (Lecompton Limestone; Shawnee Group) into the Brownville sequence (Brownville Limestone) near the top of the late Virgilian Wabauensee Group (Ritter 1995; Boardman et al. 2009). Ritter (1995) defined the *S. virgilicus* Zone to range from the FAD of this species to the FAD of *S. brownvillensis* in the Brownville sequence. This zone includes much of the middle to upper portion of the Virgilian Stage. Boardman et al. (2006), however,

did not report *S. virgilicus* from the Lecompton-Queen Hill sequence, so the lower extent of the *S. virgilicus* Zone is unclear. Chernykh (2002) included a *S. virgilicus* Zone in his zonation of Gzhelian strata for the southern Urals, but assigned the zone to a more restricted interval above the occurrence of *S. vitali* Chernykh 2002, which has been reported as appearing in the Lecompton-Queen Hill sequence by Boardman et al. (2006).

The presence of *Streptognathodus virgilicus* in the uppermost part of the Atrasado Formation at this locality constrains its age to the middle to upper part of the Virgilian and to a comparable position in the Gzhelian. Uppermost Virgilian strata in North America and uppermost Gzhelian strata in Eurasia can be readily identified by the appearance of several species of *Streptognathodus* near and above the last occurrence of *S. virgilicus* (Chernykh 2005; Boardman et al. 2009), none of which were recovered from this unit. This conodont-based age determination is consistent with several other age determinations, including that based on fusulinids, which assign the strata of the uppermost part of the Atrasado Formation at Carrizo Arroyo to a late Virgilian age. Indeed, all biostratigraphic data have been interpreted to indicate a Late Pennsylvanian age for the uppermost beds of the Atrasado Formation at Carrizo Arroyo.
















Red Tanks Member

Just a few elements of *Adetognathus* and *Ellisonia* were obtained from near the top of depositional sequence 1 (horizon marine B, unit 15; text-figs. 2-3) and near the top of depositional sequence 2 (horizon marine C, unit 24; text-figs. 2-3) of the Red Tanks Member. Orchard et al. (2004) also recovered some specimens of *Adetognathus* from units 23 and 24. Samples from units 30 and 31 near the top of depositional sequence 3 (horizon marine D) were barren of conodonts, but unit 32 yielded a moderate number of conodont elements.

Small P_1 elements of *Streptognathodus* species dominate the fauna, and several *Ellisonia* elements and a few P_1 elements of *Adetognathus* were obtained. Orchard et al. (2004) reported a few small elements of *Streptognathodus* from unit 31. This typical shallow marine conodont fauna, and the presence of *Streptognathodus* elements, suggest a more marine setting for units 31 and 32 than that of the underlying beds of the Red Tank Member.

Many of the *Streptognathodus* P_1 elements are too small for species-level identification. The few larger specimens include the range of features that place most of them in the early to middle Asselian, earliest Permian, *S. isolatus* group of species. The FAD of *S. isolatus* Chernykh, Ritter and Wardlaw 1997 is the biostratigraphic indicator for the base of the Permian, but the diagnosis of this species has been modified since the GSSP was established. The original diagnosis emphasized that the nodose inner (caudal) accessory lobe was separated from the remainder of the platform by a narrow shallow groove and that a continuous adcarinal ridge (parapet) was present (Chernykh et al. 1997). Subsequently, Boardman et al. (2009), in their study of latest Pennsylvanian-earliest Permian stratigraphy and conodonts from the Midcontinent region, reassigned to at least three other species coeval morphotypes that may have been included in the original concept of *S. isolatus*.

In their range charts, Boardman et al. (2009, figs. 49 and 50) show that a group of five species, including *S. isolatus*, appears in the Bennett Shale in the Red Eagle fourth-order Sequence in

Stages		Conodont zones at Carrizo Arroyo	Carrizo Arroyo depositional sequences		North American Midcontinent cycles
Asselian	Wolfcampian	no conodonts	Red Tanks Member (Bursum Formation)	 5 and 6?	 Beattie
		<i>Streptognathodus nevaensis</i>		nonmarine B  4?	 Upper Grenola
				nonmarine A  3 marine D	 Lower Grenola
Gzhelian	Virgilian	no age-diagnostic conodonts		 ?	 Red Eagle
				 2 marine C	 Foraker
				 ?	 Five Point
				 1 marine B	 Falls City
					 1 marine A
		<i>Streptognathodus virgolicus</i>		Atrasado Formation	

TEXT-FIGURE 8

Correlation of Midcontinent cyclothem 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 cyclothem across the Pennsylvanian-Permian boundary.

the Midcontinent region, four of which range up into the Neva Limestone in the Upper Grenola (Neva) fourth-order Sequence. Three of these species were named prior to *S. isolatus*, and some specimens originally illustrated as *S. isolatus* by Chernykh et al. (1997), were reassigned to these species. *Streptognathodus isolatus* was restricted to P₁ elements in which the caudal lobe bears common accessory denticles and an adcarinal parapet that aligns with the posterior platform parapet (Boardman et al. 2009, p. 132-133). The most similar coeval species is *S. minacutus* Barskov and Reimers 1996, in which the caudal adcarinal parapet-posterior platform margin transition has a distinct gap (sinistral element) or the caudal parapet is aligned with the accessory denticles on the lobe (dextral element), as used by Boardman et al. (2009, p. 134-135). These authors note that small elements of *S. isolatus* and *S. minacutus* could not be differentiated in their material and that the larger dextral elements were only “subtly distinguishable” (Boardman et al. 2009, p. 133). Another coeval species, *S. invaginatus* Reshetkova and Chernykh 1986, possesses a more marked invagination of the caudal adcarinal ridge than *S. isolatus*, and a caudal accessory lobe that bears only one to three accessory denticles, at least one of which is large (Boardman et al. 2009, p. 132). The third species, *S. fuchengensis* Zhao 1982, appears to differ from *S. isolatus* by its more robust P₁ element and having only one to four accessory denticles on the caudal lobe (Boardman et al. 2009, p. 131). The P₁ elements of all of these

species have adcarinal ridges of similar length on both sides of the carina.

The unit 32 fauna includes nodose morphotypes with a pronounced invagination of the caudal adcarinal ridge and a lobe dominated by a single large denticle, which are assigned to *S. invaginatus* (text-figs. 7.15, 20, 24). Some morphotypes, however, possess a weaker invagination and several more evenly-sized accessory nodes on the caudal lobe, which are possibly examples of *S. isolatus* (text-figs. 7.17, 21, 25), or *S. fuchengensis*. At least one smaller sinistral specimen (text-fig. 7.13) possesses a gap in the transition from the caudal adcarinal ridge to the posterior platform and the adcarinal ridge merges with the caudal accessory denticles, which suggests *S. minacutus*. Many of the more numerous smaller specimens in the fauna are similar in morphology and are likely examples of one of these species.

Other P₁ elements from Unit 32 have a high caudal adcarinal ridge that extends much further along the blade (ventrally) than does the lower rostral (outer) adcarinal ridge (text-figs. 7.14, 16, 18, 22). These specimens may be assigned to *S. nevaensis* Wardlaw, Boardman and Nestell 2009, which appears slightly higher than, and, in the lower part of its range, occurs with the *S. isolatus* group of species, and ranges higher in the Midcontinent region (Lower Grenola (Burr) through Beattie fourth-order se-

quences: Boardman et al. 2009). One P₁ element is an elongate form that is likely *S. postelongatus* Wardlaw, Boardman and Nestell 2009, because it possesses at least one poorly developed denticle doublet on the caudal side (text-fig. 7.23). In the Midcontinent region, *S. postelongatus* is restricted to the Lower Grenola (Burr) and Upper Grenola (Neva) sequences (Boardman et al. 2009).

Based on the range overlaps of the species discussed above, unit 32 of the Red Tanks Member is probably equivalent in age to the *Streptognathodus nevaensis* Zone (Boardman et al. 2009) and corresponds in age to some part of the interval represented by the Lower Grenola (Burr) and Upper Grenola (Neva) sequences in the Midcontinent region (text-fig. 8). Because the *S. nevaensis* Zone overlies the basal Asselian *S. isolatus* Zone of the Red Eagle sequence in the Midcontinent region, unit 32 thus is early-middle Asselian in age. However, as Boardman et al. (2009) point out, the ranges of many latest Pennsylvanian and earliest Permian conodonts are not especially well known.

Orchard et al. (2004) tentatively attributed the small specimens they obtained from unit 31 to the latest Pennsylvanian species group that includes *S. wabaunsensis* Gunnell 1933, following the work of Ritter (1995). Boardman et al. (2009) indicated that in the P₁ element of *S. wabaunsensis* the adcarinal ridges do not join the posterior platform parapet smoothly, whereas in our unit 32 specimens, as well as those illustrated by Orchard et al. (2004) from unit 31, the transition is smooth, as is characteristic of the younger *S. isolatus* group. Also, we did not find *Streptognathodus* P₁ elements that could be assigned to any of the distinctive species described from the latest Pennsylvanian fourth-order sequences (Brownville, Falls City, Five Point and Foraker) in the Midcontinent region (e.g., *S. bellus* Chernykh and Ritter 1997, *S. binodosus* Wardlaw, Boardman and Nestell 2009, *S. conjunctus* Barskov, Isakova and Schastlivtseva 1981, *S. farmeri* Gunnell 1933, or *S. flexuosus* Chernykh and Ritter 1997).

Direct comparison with conodont faunas in the southern Urals (e.g., Chernykh 2005), including the Permian stratotype section at Aidaralash Creek (Chernykh and Ritter 1997), is difficult because of what are interpreted to be endemic species and differences in reported ranges for more widely distributed species (Boardman et al. 2009). The designation of several new species in latest Gzhelian to Asselian strata in the southern Urals (Chernykh 2005) also makes species-level correlation hazardous. However, the range of morphologic features seen in *Streptognathodus* P₁ elements from unit 32 of the Red Tanks Member appears to be similar to that illustrated from lower to middle Asselian strata assigned to the Uralian *S. isolatus*, *S. glenisteri*, *S. cristellaris* and *S. sigmoidalis* zones of Chernykh (2005), and unlike what is displayed in the older, latest Gzhelian faunas.

POSITION OF THE CARBONIFEROUS-PERMIAN BOUNDARY AT CARRIZO ARROYO

The new conodont data documented here provide firm biostratigraphic ages for two levels in the Carrizo Arroyo section (text-fig. 8). The upper beds of the Atasado 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 ex-

act position cannot be determined at Carrizo Arroyo with current data. A major complication is the presence of multiple unconformities 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.

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 *S. virgilicus* and *S. nevaensis* zones (Boardman et al. 2009), whereas only two depositional sequences are present that represent this time interval at Carrizo Arroyo (text-fig. 8). 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 non-marine Lagerstätte at 43m (horizon nonmarine A), which lies within depositional sequence 3, is probably early-middle Asselian in age, based on the *S. nevaensis* Zone conodont fauna obtained from the top of this sequence. The non-marine Lagerstätten at 68m (horizon nonmarine B), which occurs in the overlying depositional sequence 4, is middle Asselian by the new insect correlation presented here and stratigraphic position.

Most previous workers considered much or all of the Red Tanks Member to be Pennsylvanian, including those who before 1998 assigned part of it to the early Wolfcampian, which is Pennsylvanian by current definition of the base of the Permian. 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 Carboniferous-Permian boundary. Only the fusulinids, which indicate a Virgilian age for strata of the uppermost part of the Atasado Formation and lowermost part of the Red Tanks Member at Carrizo Arroyo, can be considered to have been reliable age indicators. 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 is between the two nonmarine Lagerstätten in the Red Tanks Member section (text-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.

Krainer and Lucas (2004, 2009) argued that cycles in the Bursum Formation are not strictly glacio-eustatic in origin, largely because of rapid lateral and vertical facies changes from marine to nonmarine (or the reverse). They thus suggested that tectonic movements of the ancestral Rocky Mountain (ARM) orogeny substantially influenced Bursum deposition. The Bursum Formation, in their view, reflects a series of tectonic pulses that affected large areas of New Mexico during the ARM

orogeny. The age data presented here provide the first close dating of strata within the Bursum lithosome, which allows us to correlate at least one Bursum depositional sequence with Midcontinent fourth-order sequences (cyclothems) by biostratigraphy. The fact that the Bursum Formation section at Carrizo Arroyo has too few cycles to be matched to the succession of Midcontinent cyclothems (text-fig. 8) is *prima facie* evidence that regional tectonic events of the ARM exerted a greater control over the creation and preservation of Bursum depositional sequences than did eustatic events.

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 43m and 68m above the base of the Carrizo Arroyo section are Lagerstätten of plants, insects, crustaceans, eurypterids and other fossils that form unique Late Paleozoic nearshore arthropod assemblages. New insect data indicate that the two Lagerstätten in the Red Tanks Member are of early Asselian age.

3. We also present new conodont data that include the presence of *Streptognathodus virgicus* in the uppermost part of the Atrasado Formation (immediately below the Bursum Formation), which constrains its age to the middle to upper part of the Virgilian (and to a comparable position in the Gzhelian). 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 A is not the latest Pennsylvanian and marine 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 at a major disconformity at the top of the Atrasado Formation and 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 was partly overprinted by local tectonics.

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