

The age of North America's youngest Paleozoic continental vertebrates: a review of data from the Middle Permian Pease River (Texas) and El Reno (Oklahoma) Groups

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Abstract – The youngest Paleozoic vertebrate-bearing continental deposits of North America are Middle Permian (Guadalupian) in age and occur in the Chickasha Formation (El Reno Group) of central Oklahoma and the lithostratigraphically lower San Angelo Formation (Pease River Group) of North-Central Texas. Although regarded originally as Guadalupian, these deposits have been assigned recently to the Early Permian on the basis of marine fossils and questionable lithostratigraphic correlations between marine and continental strata. A review of ammonoid genera recovered from the Blaine Formation, which overlies both the Chickasha and San Angelo in Oklahoma and Texas, shows that they range globally in age from the Early to Late Permian, but most occur in the Guadalupian or Middle Permian. A modest but intensively studied paleobotanical record of compression fossils from the San Angelo, as well as palynomorphs in rocks associated with the Chickasha, presents an unquestionably Middle to Late Permian flora dominated by voltzian conifers. The Chickasha and San Angelo vertebrate assemblages are overwhelmingly dominated by large caseid synapsids and indicate a biostratigraphic signal of early Guadalupian. The occurrence of the tupilakosaurid temnospondyl *Slaughenhopia*, the parareptile *Macroleter*, and the eureptile *Rothianiscus* suggests a Roadian age (lowermost Guadalupian) given the global records of closely related forms. These plant and vertebrate assemblages contrast sharply with those of underlying Cisuralian rocks of the Hennessey Formation of Oklahoma and the Clear Fork Formation of Texas, both of which are much more fossiliferous than those of the Guadalupian in the region. A barren interval of up to 300 m in thickness separates these fossil-bearing intervals. This true void in the late Kungurian was first reported a half century ago but has not been recognized in recent biochronology studies. Our findings, as well as those of other vertebrate paleontologists who have evaluated the San Angelo and Chickasha data by other means, strongly refute the current notion of “Olson’s Gap” as spanning most of the Roadian.

Keywords: biostratigraphy / geochronology / Kungurian / Roadian / San Angelo Formation / Chickasha Formation

Résumé – L'âge des plus jeunes vertébrés continentaux paléozoïques d'Amérique du Nord : un examen des données des groupes du Permien moyen de Pease River (Texas) et d'El Reno (Oklahoma). Les plus jeunes dépôts continentaux vertébrés paléozoïques de l'Amérique du Nord datent du Permien moyen (Guadalupien) et se trouvent dans la Formation Chickasha (Groupe El Reno) de l'Oklahoma central et dans la Formation San Angelo (Groupe Pease River) lithostratigraphiquement plus basse du Texas central du nord. Bien que considérés à l'origine comme Guadalupiens, ces dépôts ont été récemment assignés au Permien précoce sur la base de fossiles marins et de corrélations lithostratigraphiques douteuses entre strates marines et continentales. Un examen des genres d'ammonoïdes provenant de la formation Blaine, qui recouvre les formations Chickasha et San Angelo en Oklahoma et au Texas, montre que leur âge varie globalement du Permien précoce au Permien tardif, mais que la plupart se trouvent dans le Guadalupien ou le Permien moyen. Un registre paléobotanique modeste mais intensivement étudié de fossiles de compression de San Angelo, ainsi que des palynomorphes dans les roches associées à la

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Chickasha, présente une flore incontestablement du Permien moyen à tardif dominée par des conifères voltziens. Les assemblages de vertébrés des formations Chickasha et San Angelo sont dominés de façon écrasante par de grands synapsides caséidés et présentent un signal biostratigraphique du Guadalupien précoce. La présence du temnospondyle tupilakosauridé *Slaugenhopia*, du parareptile *Macroleter* et de l'eureptile *Rothianiscus* suggère un âge Roadien (Guadalupien inférieur) étant donné l'âge de formes étroitement apparentées sur d'autres continents. Ces assemblages de plantes et de vertébrés contrastent fortement avec ceux des roches cisuraliennes sous-jacentes de la formation Hennessey de l'Oklahoma et du groupe Clear Fork du Texas, qui sont tous deux beaucoup plus fossilifères que ceux du Guadalupien dans la région. Un intervalle stérile d'une épaisseur pouvant atteindre 300 m sépare ces intervalles fossilifères. Cette véritable lacune dans le Kungurien tardif, signalée pour la première fois il y a un demi-siècle, n'a pas été reconnue dans les études récentes de biochronologie. Nos résultats, ainsi que ceux d'autres paléontologues vertébristes qui ont évalué les données de San Angelo et de Chickasha par d'autres moyens, réfutent fermement la notion de « lacune d'Olson », qui est censée occuper la plus grande partie du Roadien.

Mots clés : biostratigraphie / géochronologie / Kungurien / Roadien / formation San Angelo / formation Chickasha

1 Introduction

An understanding of ancient terrestrial biotas, environments, and ecological changes requires a stratigraphic framework that is built upon a judicious assessment of all available data. In the case of the continental Permian of North America, this foundation relies upon biostratigraphic and lithostratigraphic data because few radiometric dates have been recovered from these rocks. Although some magnetostratigraphic refinements have appeared recently, and isotope geochemistry may provide significant advances in chemostratigraphy, comparatively low-resolution data remain the basis for estimating the ages of these rocks. The reliance upon such data is complicated further by the fact that several sedimentary basins are involved and that conventional biostratigraphy is based upon marine rocks. Thus, in the specific example of the continental lower-to-middle Permian strata of the Texas-Oklahoma region of the United States, it is not surprising that there is a lack of agreement on the age of terrestrial fossil assemblages that are the youngest known from the Paleozoic of North America.

These records are critical to the documentation of the transition from Early Permian terrestrial faunas dominated by Permo-Carboniferous synapsids and captorhinid eureptiles to Middle Permian faunas dominated by therapsids and parareptiles, a transition that may have been accelerated by one of the three or four mass extinction events that have been argued to have taken place in the Permian (Olson and Beerbower, 1953; Olson, 1962; Olson and Barghusen, 1962; Reisz and Laurin, 2001, 2002; Benton, 1985, 1989, 2012; Brocklehurst *et al.*, 2013; Brocklehurst, 2020; Didier and Laurin, 2021). An apparent gap (but emphasizing great and apparently rapid faunal changes rather than a genuine stratigraphic gap) in the Permian continental fossil record was mentioned first by Milner (1993a: 344–345) based upon his review of the paleontological literature:

“Upper Permian tetrapod faunas show a quantum change from those of the Lower Permian, although there are some conservative elements in Russia (Ivakhnenko, 1990). It is increasingly clear that the best known Lower Permian faunas are mostly Asselian-Sakmarian and that the Artinskian and Kungurian are poorly represented outside Texas. The dramatic

faunal changes represent a late Lower Permian-early Upper Permian ‘gap’ in the record.”

Several years later, Lucas (2001) highlighted Milner's observation in a newsletter submission, which was the first of many contributions that elaborated the notion (Lucas, 2002a, 2002b, 2004, 2005a, 2005b, 2006, 2013, 2017, 2018; Lucas and Golubev, 2019). However, Lucas went much farther than Milner (1993a) in arguing that there was a temporal separation between the latest North American amniote-bearing strata, which he initially placed in the Roadian (or possibly late Kungurian), and the oldest Russian Middle Permian strata (zones I and II), which he initially placed in the mid- and late Wordian (Lucas 2001: fig. 1). Lucas (2001) thus placed the gap in the late Roadian and early Wordian. Subsequently, Lucas, 2002b, 2004, 2005a, 2005b, 2006, and most of his more recent papers argued for an older, late Cisuralian age for the North American deposits, thus shifting the gap down to occupy all of the Roadian, minimally. As a result, the suggestion of a global hiatus, termed “Olson's Gap” by Lucas, has taken root in global Permian correlations (e.g. Ogg *et al.*, 2016) even though vertebrate paleontologists have repeatedly challenged the concept (Reisz and Laurin, 2002; Lozovsky, 2005; Sahney and Benton, 2008; Benton, 2012, 2013; Brocklehurst *et al.*, 2017; Brocklehurst, 2020). Whereas Lucas has relied mainly upon marine fossils and lithostratigraphic extrapolations to assert that Permian terrestrial vertebrates are restricted to the Early Permian in North America, his critics have focused on the terrestrial record itself to assign one or more of the youngest North American tetrapod assemblages to the Middle Permian.

The latest North American Permian terrestrial vertebrates occur in the coeval Pease River Group of North-Central Texas and the El Reno Group of central Oklahoma but at different stratigraphic intervals (Figs. 1 and 2). These vertebrate-bearing sediments, which occur in comparatively small areas (Figs. 3 and 4), accumulated on the Eastern Shelf of the Midland Basin and on the Northern Shelf of the Anadarko Basin, respectively. The Texas material, collected first in 1950 by E.C. Olson and his students, came from the San Angelo Formation, the basal division of the Pease River Group (Fig. 3). In Oklahoma, Middle Permian vertebrates were discovered in 1959 by geologist R.O. Fay (Olson and Barghusen, 1962) in the Chickasha Formation (Fig. 4), a unit that Olson's field parties

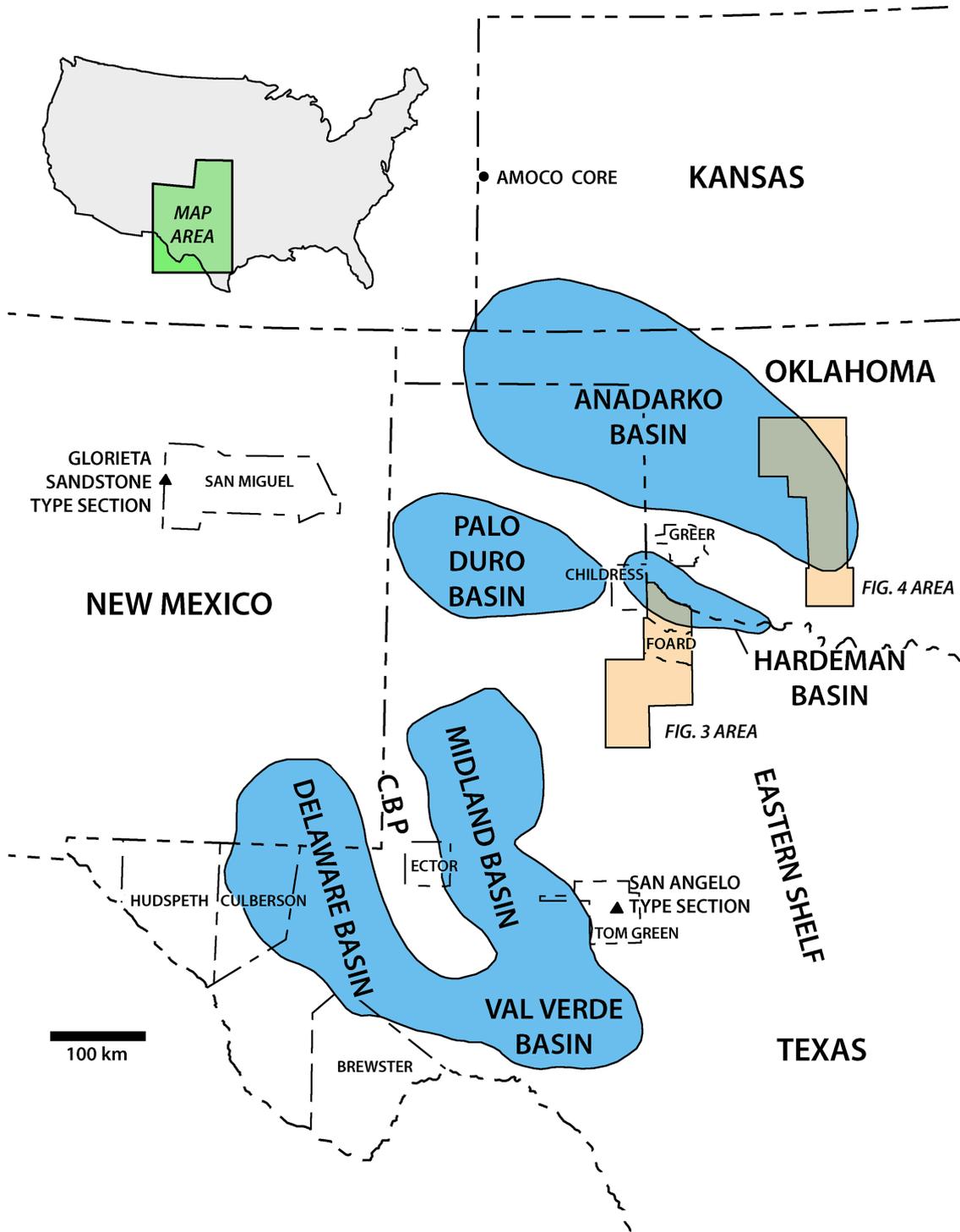


Fig. 1. Map of Texas, Oklahoma, New Mexico, and Kansas to illustrate areas, counties, and localities mentioned in the text as well as locations of Figures 3 and 4. Abbreviation: CBP: Central Basin Platform. Inset at upper left shows map location in the United States.

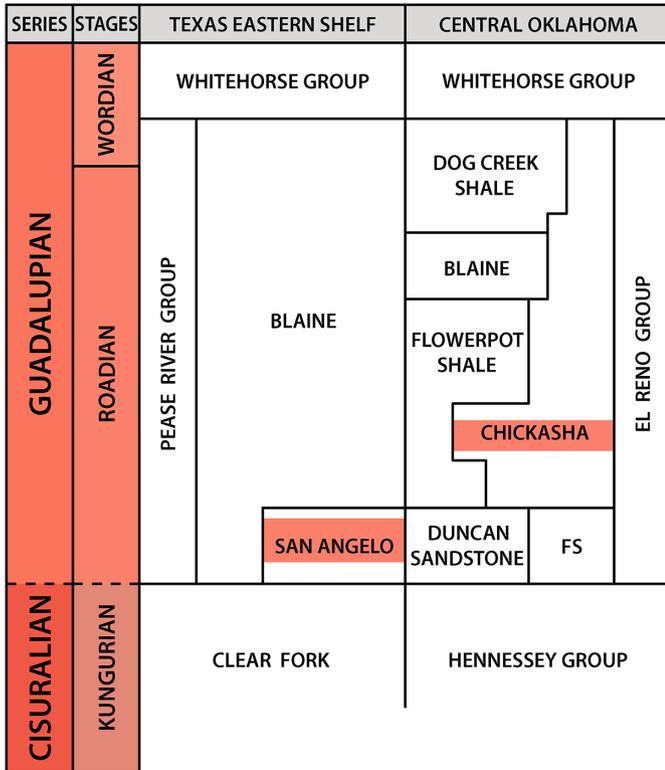


Fig. 2. Schematic stratigraphic chart of Permian rocks discussed in this paper. The tetrapod-bearing parts of the San Angelo and Chickasha formations are highlighted. Although no overall vertical scale is implied, the relative thicknesses of the El Reno formations are adapted from [Fay \(1962\)](#). Abbreviation: FS: Flowerpot Shale Formation. The age of the Dog Creek Shale shown here assumes a mid-Wordian age of the Illawarra reversal; see text for details.

consequently would investigate and collect for several years. Olson’s descriptions of these vertebrate assemblages convinced other paleontologists (e.g., [Chudinov, 1965](#)) that the San Angelo Formation extended into the basal “Upper Permian” as then conceptualized (Roadian) and that the Chickasha Formation (erroneously called the Flowerpot by Chudinov; see [Sect. 2.1](#) about this confusion) was slightly younger still. The geological attributes and vertebrate assemblages of these two formations are reviewed below.

Finally, because much of this paper involves stratigraphy, it is important to note that the current three-fold division of the Permian into, from bottom to top, Cisuralian, Guadalupian, and Lopingian series was adopted by the International Commission on Stratigraphy (ICS) in the 1990s ([Jin et al., 1997](#)). These divisions should not be confused with the formerly accepted bipartite system of Lower and Upper Permian found in older papers and maps.

2 Lithostratigraphy

2.1 Nomenclatural problems

The use and meaning of stratigraphic terms can change over time. [Clifton \(1942, 1944, 1946\)](#), for instance, regarded ammonoids (discussed below in [Sect. 4.2](#)) from the Blaine

Formation and the Dog Creek Shale as Leonardian and Middle Permian simultaneously. Another example is the previous use of Leonardian, which once included some West Texas and New Mexico rocks now considered to be Guadalupian. On the institutional side, various geological agencies and organizations, including the U.S. Geological Survey, the Texas Bureau of Economic Geology, the West Texas Geological Society, the Oklahoma Geological Survey, the Kansas Geological Survey, and the New Mexico Bureau of Geology and Mineral Resources, have modified their classifications of Permian rocks over time, and these entities have never been in close agreement. An additional fact that obfuscates Permian Basin stratigraphy in particular was decried by [Nelson et al. \(2013b: 312\)](#): “Names based on fully terrestrial outcrops more than 300 km away from the basin have been applied to totally dissimilar marine rocks that may not even be the same age as their terrestrial namesakes. This practice falsely implies that accurate correlations have been achieved from the outcrop to the subsurface.” The last point is particularly relevant in the assessment of literature-based correlations between marine and terrestrial sections over considerable geographic distances.

2.2 The Pease River Group of Texas and the El Reno Group of Oklahoma

The lithostratigraphic relationships within and between major rock units of the Pease River Group in North-Central Texas and the El Reno Group of central Oklahoma are shown in [Figure 2](#). Because the Pease River Group was reviewed by [Nelson and Hook \(2005\)](#), emphasis is placed on clarifying aspects of the El Reno Group.

In southwestern Oklahoma, the El Reno Group consists of, from bottom to top, the Duncan Sandstone, Flowerpot Shale, Blaine Formation, and Dog Creek Shale, each of which has a checkered history in the literature (see [Davis, 1955](#)). The Duncan Sandstone was named for rocks that form a modest escarpment near Duncan in Stephens County, Oklahoma ([Fig. 4](#)), and has been accepted as a lithostratigraphic correlative of the San Angelo of Texas since its introduction ([Gould, 1924](#)). In fact, a 1:250,000-scale geological map of southwestern Oklahoma ([Havens, 1977](#)) identified the “San Angelo Sandstone” in the southwestern part of the quadrangle. Similarly, on the Texas side of the state line, the basal part of the San Angelo Formation in North-Central Texas is the informal (unmapped) Duncan Member, and the finer-grained, upper part of the same formation is the informal (unmapped) Flowerpot Member ([Smith, 1974; Hentz and Brown, 1987](#)). The units overlying the Duncan Sandstone in southwestern Oklahoma are equivalent to the Blaine Formation of North-Central Texas ([Roth, 1945; Pendery, 1963; Jones, 1971](#)).

The El Reno Group of central Oklahoma differs from that of the southwestern part of the state in the development of the Chickasha Formation, a siliciclastic unit named for exposures near Chickasha, in central Grady County, Oklahoma ([Figs. 2 and 4](#)). It was introduced somewhat informally by [Gould \(1924\)](#) and investigated later by [Becker \(1927\), Freie \(1930\), Davis \(1955\), and Fay \(1962, 1964\)](#). The formation conformably overlies the Duncan Sandstone where both have been mapped (Stephens, Grady, Canadian, and Kingfisher counties) and is intercalated from north-to-south along the

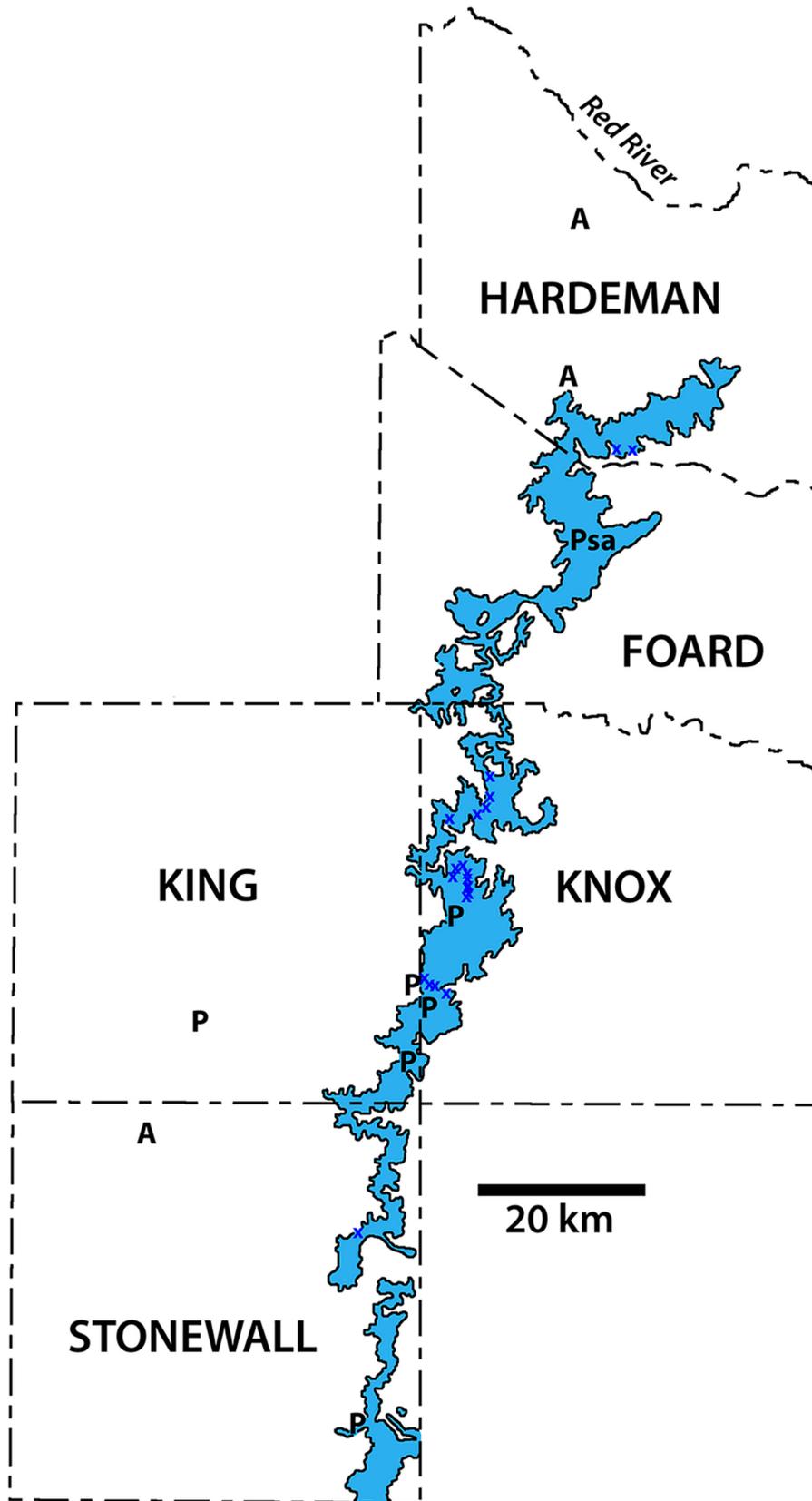


Fig. 3. Schematic map of the northern part of the San Angelo (Psa) outcrop in North Central Texas. Abbreviations: X: vertebrate localities of Olson (1962); P: plant collections reported by DiMichele *et al.* (2001, 2004); A: ammonoid localities of Clifton (1942). Outcrop adapted from Hentz and Brown (1987) and Eifler *et al.* (1993, 1994).

outcrop with the Flowerpot Shale (in Blaine and Kingfisher counties), Blaine Formation (in Canadian and Grady counties), and Dog Creek Shale (in Grady County). In the southern-most part of the Chickasha Formation outcrop, it forms the upper-most part of the El Reno Group and is overlain by the Whitehorse Group. From the northwestern corner of Stephens County, the El Reno Group is mapped as an undifferentiated unit, in part because of poor exposures. Where formation divisions have been mapped again, approximately 70 km to the northwest, the Chickasha Formation is not recognized, and the El Reno Group consists of the Duncan Sandstone, Flowerpot Shale, Blaine, and Dog Creek Shale (Carr and Bergman, 1976). Both the Duncan and Chickasha pinch-out in North-Central Oklahoma and are thought to have been derived mainly from the Arbuckle Mountains and the Ouachita uplift with only very minor input from the Wichita Mountains and other sources (Freie, 1930; Fay, 1964). The Chickasha Formation is more persistent to the north than is the Duncan Sandstone, and where the latter is absent, the former is underlain by rocks mapped as the Flowerpot Shale Formation (Fig. 2 based upon the mapping of Carr and Bergman, 1976).

Two additional points require discussion. Although the Chickasha Formation has not been the subject of recent surface or subsurface work known to us, it has been misrepresented in paleontological literature as a lithostratigraphic equivalent of the San Angelo Formation of Texas (Lucas 2002b, 2004, 2017, 2018; Marchetti *et al.*, 2021). This overlooks the fact that superposition places the Chickasha Formation above the Duncan Sandstone and that only the latter is regarded as a lithostratigraphic equal to the San Angelo Formation. Secondly, the paleontological literature indicates that some vertebrate remains came from the Flowerpot Shale. Such statements were based upon preliminary interpretations (Olson, 1962; Olson and Barghusen, 1962) and an ignorance of primary geological reports, such as Fay (1962, 1964) and Smith (1974). Olson initially followed the regional stratigraphy of Roth (1945) in his use of the term Flowerpot (or Flower Pot) in Texas. This was subsequently shown to be inappropriate by Smith (1974), who was the first to do detailed mapping of the San Angelo Formation in North-Central Texas and who regarded the Flowerpot as a transitional lithofacies within the upper part of the San Angelo. In Oklahoma, Olson followed Fay (1962), who initially used the phrase “Chickasha Tongue of the Flowerpot Formation” instead of the simpler Chickasha Formation, which he adopted shortly afterwards (Fay, 1964). Thus, the assignment of vertebrate remains from either Texas or Oklahoma to the Flowerpot is inappropriate given current lithostratigraphy.

2.3 The San Angelo Formation of Texas and the Glorieta Sandstone of New Mexico

Because the San Angelo Formation of Texas and the Glorieta Sandstone of New Mexico occur in similar rock sequences, albeit on widely separated, opposite sides of the Permian Basin, they have been considered as lithostratigraphic equivalents (Fig. 1). This assumption has promoted the use of biostratigraphic data from marine rocks in New Mexico and West Texas to constrain the age of the Pease River Group in North-Central Texas and even the El Reno Group in Oklahoma. Whereas lithostratigraphic correlations between the latter two areas are straightforward,

those involving New Mexico and West Texas are complicated by paleogeographic and paleoenvironmental differences. The following considers lithostratigraphic data related to the supposed San Angelo-Glorieta tie.

The San Angelo Formation was founded upon exposures of very coarse-grained alluvial rocks just south of the town of that name in Tom Green County, Central Texas (Beede and Christner, 1926). The unit extends northward along a narrow outcrop belt and becomes finer grained in North-Central Texas and southwestern Oklahoma. The San Angelo lacks an appreciable subsurface record because it does not persist as a clastic unit into the Midland Basin (Mear, 1963; Smith, 1974; Nelson and Hook, 2005).

The Glorieta Sandstone Formation was established for exposures in San Miguel County, north-central New Mexico, on the basis of rocks that are predominantly eolian in origin and related lithogenetically to much thicker eolian deposits of northern Arizona (Needham and Bates, 1943; Mack and Bauer, 2014; Krainer and Lucas, 2015; Ruppel, 2020). In contrast to the San Angelo, the Glorieta is exposed over a large part of central New Mexico and also is known in the subsurface of west-central, northeastern, and southeastern New Mexico, as well as parts of West Texas and the Texas Panhandle. Unfortunately, the name Glorieta has been applied liberally to supposedly correlative coastal and marine deposits, including carbonates, at the surface and in the subsurface of southeastern New Mexico and adjoining areas of West Texas (Kelley, 1971; Milner, 1978; Kerans and Ruppel, 2020). In addition, rocks attributed to sabkha environments in the Texas Panhandle have qualified for the name Glorieta because of correlations between the type area and subsurface evaporites (Handford, 1981; Presley, 1981; Presley and McGillis, 1982; Fracasso and Hovorka, 1986). As such, it is difficult to judge if the name Glorieta is a legitimate lithostratigraphic unit or a chimera that includes undoubtedly diachronous desert, coastal, evaporite, shallow marine, and even basin deposits.

Despite these uncertainties, Lucas (2004: 50) claimed that a lithostratigraphic correlation between the San Angelo and the Glorieta is “well represented” in the literature. The six papers (Page and Adams, 1940; Hills, 1942, 1972; King, 1942; Mear 1963, 1984) that he cited to support this assertion are discussed below in chronologic order.

Page and Adams (1940) presented an approximately 355 km long, northeast-to-southwest cross section based upon cuttings and/or drillers’ logs from 27 cable-tool wells. The section extends through eight Texas counties from the Eastern Shelf to the southern Midland Basin. Only the northern-most 10 wells include the San Angelo, and the Glorieta is absent altogether because the section does not extend far enough to the west. Yet, Page and Adams (1940: 58) stated: “In the northern, shallower portions of the South Permian basin, the San Angelo can be traced westward in the subsurface to correlation with the Glorieta sandstone of New Mexico.” No data or references are provided to support this claim.

Hills (1942: fig. 7) presented nine well records and two surface sections in a cross section that extends west-to-east from central New Mexico to North-Central Texas, or from the southeast end of the Sacramento Uplift, across the Palo Duro Basin, to the west side of the Hardeman Basin. The west end of the cross section included a thick Glorieta surface section that was detailed later by Milner (1978). The east end is a composite

surface section from Childress and Foard counties, Texas, that has a very thin interval labeled as San Angelo at its base. These Texas data cannot be assessed critically because (1) the section lacks a vertical scale, (2) Childress and Foard counties are proximal to each other but not contiguous, (3) there are no San Angelo exposures in Childress County and those in Foard County are approximately 23 km distant, and (4) the section is attributed to a 1939 AAPG field trip guidebook that is no longer available. Moreover, the regional correlation chart offered by Hills (1942: fig. 1) does not include the Glorieta.

Next chronologically is King (1942), which remains a great synthesis of early work in the Permian of West Texas and southeastern New Mexico. But it contains no primary data on the relationship between the San Angelo and the Glorieta. The statement (p. 693), “The Glorieta sand at the base apparently passes into the San Angelo sandstone of central Texas”, refers to Page and Adams (1940), see above, and, thus, is unsupported by data. Shortly after P.B. King (1942), his brother R.E. King (1945) published data in the form of cross sections based upon well cuttings and concluded that the Glorieta either pinched-out into the lower San Andres or interfingered with the underlying Yeso Formation in southeastern-most New Mexico. Thus, King (1945) did not endorse a Glorieta-San Angelo correlation.

Mear (1963) presented a chart that shows the San Angelo and Glorieta as equals at the base of the Guadalupian. No data or explanation accompany the chart.

Hills (1972) was an update of his 1942 paleogeographic narrative critiqued above. It contains no relevant data.

Mear (1984) is a very brief paper in a fieldtrip volume. On the basis of a personal communication, he states that the San Angelo may be correlative to the subsurface Glorieta. There are no actual data.

In summary, these six papers do not substantiate a San Angelo-Glorieta correlation. To the contrary, this question was a matter of contention during the first half of the last century when geologists spurred by oil exploration started to study the Delaware Basin and surrounding exposures. Differences over Permian correlations in the Midland and Delaware basins, and especially on the Central Basin Platform, filled many pages of the American Association of Petroleum Geologists Bulletin in the late 1930s and early 1940s (e.g., King, 1945 discussed above). The waning of such papers was not because a consensus was ever reached but because exploration efforts shifted to deeper reservoirs. Or, as T.S. Jones, Chairman of the Stratigraphic Problems Committee of the West Texas Geological Society (WTGS), wrote in notes that accompany one of the WTGS Permian Basin cross sections:

“Vigorous discussion during the many meetings required to construct the cross section made obvious certain facts which had been only dimly realized before, the most important of which was the amount of disagreement on many matters. The Permian is evidently the most difficult period to understand in West Texas, for it caused the most trouble, due largely to the change in facies. The chief economic interest is shifting to the pre-Permian, and therefore many of the newcomers have not been able to acquaint themselves with the Permian rocks. This is a deplorable tendency in view of the many unsolved problems” (WTGS, 1949: 29).

Nelson and Hook (2005) considered a San Angelo-Glorieta correlation on the basis of a west-to-east cross section across

the Palo Duro Basin (Fracasso and Hovorka, 1986, pl. 4). They observed that the two units occupy the same stratigraphic interval but qualified this conclusion by noting that most lithostratigraphic contacts in this part of the section were problematic because of lithofacies changes and dissolution of evaporite-rich intervals. Further study of more detailed cross sections in this same area (Presley, 1981; McGookey *et al.* 1988) shows a lack of coarse clastics in the supposed San Angelo interval, which was called the Flowerpot Shale. These more complete sections also identified zones of evaporite dissolution that were not presented in the Fracasso and Hovorka sections. As shown dramatically by Benison *et al.* (2015: fig. 10), dissolution is a major factor that hampers both surface and subsurface correlations of evaporite-bearing Permian rocks.

A San Angelo-Glorieta correlation also has been promoted on the grounds of a supposed unconformity at the base of both units and the perceived significance of such to sequence stratigraphy models developed in the Delaware Basin. As shown in Figure 1, the type areas of these two units are approximately 500 km apart, a distance that encompasses a considerable range of depositional environments and lithostratigraphic conventions. The contact between the San Angelo Formation and the underlying Clear Fork Formation (*sensu* Nelson *et al.*, 2013a) has been described as unconformable, disconformable, and conformable. Authors of early county reports in Central Texas characterized the contact as disconformable or unconformable (e.g., Beede and Bentley, 1918; Beede and Christner, 1926; Henderson, 1928; Patton, 1930). Somewhat later, as drilling records accumulated from oil exploration in the Midland Basin and the Eastern Shelf, Page and Adams (1940: 58) concluded: “It is probable, however, that the importance of the unconformity at the base of the San Angelo formation has been greatly over-estimated.” Smith (1974) and Nelson and Hook (2005) relied upon surface observations to conclude that, although locally erosive alluvial channels marked the contact, it was conformable regionally. Likewise, the base of the Glorieta Sandstone at its type section was described as one of “evident conformity” (Kraimer and Lucas, 2015: 206), and the contact was described as “mostly gradational, but sharp contacts are locally present” (Milner, 1978: 8) in south-central New Mexico. Given reports from several parts of New Mexico and North-Central Texas of no unconformity based upon field investigations, there is no reason to adopt correlations that are predicated upon presumed unconformities or the tenets of sequence models.

Without sufficient evidence of close lithogenetic or lithostratigraphic ties between the San Angelo Formation and the Glorieta Sandstone, their postulated correlation should be viewed as a proxy at best. Although this level of resolution is acceptable for regional correlation charts, fieldtrip reports, conference papers, in-house publications, newsletters, and other informal venues, it is hardly the basis for derivative biostratigraphic interpretations and does not merit a finite chronostratigraphic assignment at this time.

2.4 Thickness of stratigraphic units and ages

In addition to other assertions, Lucas (2004: 50) stated the following:

“In conclusion, ammonoid biostratigraphy indicates a Leonardian age for the Blaine Formation. This means that the vertebrate fossils of the San Angelo, Flowerpot and Chickasha formations cannot be younger than Leonardian. Given that these units overlie a thick section of Leonardian strata (upper Wichita Group and Clear Fork Group), a late Leonardian age for the Blaine, San Angelo, Flowerpot and Chickasha formations seems certain.”

Whereas the claim pertaining to ammonoid biostratigraphy is addressed critically in [Section 4.2](#) below, and the misrepresentations of the vertebrate record are treated in [Section 5](#), the suggestion that the thickness of subjacent rock units (“thick section of Leonardian”) is a valid criterion for assessing the stratigraphy of overlying rock units is sophistry. Using the same approach, an early Guadalupian age for the San Angelo, Duncan, Flowerpot, Chickasha, and Blaine “seems certain” because these rocks are overlain by a thick Guadalupian section.

3 Magnetostratigraphy and chemostratigraphy

Magnetostratigraphic analysis of a 1,600 m continuous core drilled in 1988 by Amoco Production Company in western Kansas ([Fig. 1](#)) indicated that the end of the Kiaman Superchron, a long period of reversed polarity that extended from the late Carboniferous to part of the Guadalupian, was nearly coincident with the Dog Creek Shale-Whitehorse formational contact ([Foster et al., 2014](#)). Integration of these findings with stratigraphic and sedimentological studies of excellent Dog Creek, Blaine, and Flowerpot exposures in Blaine County, Oklahoma ([Sweet et al., 2013](#); [Foster et al., 2014](#); [Soreghan et al., 2015](#)) places the Dog Creek in the lower Wordian to upper Roadian, the Blaine in the upper half of the Roadian, and the Flowerpot almost entirely in the lower half of the Roadian, if we accept a mid-Wordian age for the Illawarra reversal. Although no paleomagnetic data constrain the lower part of this interval, one of the main Blaine County exposures, Cat Canyon ([Fig. 4, C](#)), which was studied by [Foster et al. \(2014\)](#), is less than 5 km away from some of the Chickasha vertebrate sites, which are intercalated with the middle part of the Flowerpot Shale Formation. Whereas we provisionally accept a mid-Wordian age of the Illawarra reversal, we agree with [Schneider et al. \(2020\)](#) that it could range from about mid-Roadian to early Capitanian (see also [Lanci et al., 2013](#); [Canile et al., 2016](#); [Rocha-Campos et al., 2019](#); [Wu et al., 2020](#); [Aragão and Scardia, 2021](#)).

[Denison et al. \(1998\)](#) performed chemostratigraphy on the Blaine Formation on the basis of strontium isotopic data of gypsum. Their results are problematic, however, because the isotopic ratios obtained from various levels of the Blaine Formation in Blaine County, Oklahoma, are highly variable and inconsistent both between and within various gypsum beds. Furthermore, [Denison et al. \(1998: 9–10\)](#) recognized that the lower levels of the Blaine Formation were “profoundly affected by a meteoric contribution” and admitted that “these models all show that there were locations and times when continental waters dominated the Blaine salinas”. Nevertheless, they concluded that the upper Blaine samples were marine and inferred a mid-Leonardian age for the Blaine

Formation in Blaine County. Yet, they also recognized that the Sr isotopic signatures for samples of the Blaine Formation from other localities outside Blaine County (sample sites in Oklahoma and Texas) suggested an early Roadian age, which is congruent with the other lines of evidence mentioned above and below.

The traditional paleoenvironmental interpretation of the Blaine and Flowerpot formations of Blaine County as marine to brackish settings was largely dismissed by [Sweet et al. \(2013\)](#), who presented sedimentological data indicative of eolian origins for most of these rocks. Unfortunately, they did not integrate their findings with precedent paleontological reports. The most common metazoan taxon known from these rocks is the bivalve *Permophorus* Chavan, 1954, which [Fay \(1964: 83\)](#) considered to form part of an assemblage characteristic of brackish-marine conditions, an interpretation confirmed by more recent studies (e.g., [Harris et al., 2004](#); [Kues 2004](#)). These fossil-bearing units are, however, a very minor part of the section and in no way diminish the conclusions of [Sweet et al. \(2013\)](#). We conclude that the chemostratigraphic study of [Denison et al. \(1998\)](#) yielded dubious results on the Blaine Formation of Blaine County because the formation is not a fully marine unit, because its chemistry has been differentially overprinted by groundwater, or because of a combination of these factors.

Lastly, [Roth \(1945\)](#) reported an ash bed in the Blaine Formation of North-Central Texas. As reported previously ([DiMichele et al., 2004](#)), USNM field parties sampled this approximately 1.5-m thick unit at several exposures in hope of obtaining material for isotopic age data. Subsequent thin section and X-ray diffraction analyses showed no volcanic components. The conclusion was that this fairly widespread, flat-bedded deposit originated as wind-blown silt that collected in standing water.

4 Palynomorphs and megascopic plant fossils

Paleobotanical collections from the Pease River and El Reno groups are few. As a rule, however, they are characterized by the presence of taxa known otherwise from Middle to Upper Permian and lower Mesozoic rocks of Europe and China ([Wilson, 1962](#); [Clapham, 1970a, 1970b](#); [DiMichele et al., 2001, 2004, 2011](#); [Looy, 2007](#); [Looy and Stevenson, 2014](#); [Looy and Duijnste, 2020](#)).

The most diverse Pease River assemblage is a compression flora reported by [DiMichele et al. \(2001\)](#), who summarized collections made at seven San Angelo Formation deposits in three North-Central Texas counties ([Fig. 3](#)). The fossiliferous deposits originated as copper-bearing fills of shallow tidal channels in the upper part of the informal Flowerpot Shale Member and are regarded as roughly contemporaneous based upon field mapping and core descriptions ([Stroud et al., 1970](#)). Voltzian conifers, the dominant taxa in Late Permian Zechstein floras of Europe, are the most common fossils in this Flowerpot Shale assemblage ([Looy, 2007](#); [Looy and Stevenson, 2014](#)).

[Wilson \(1962\)](#) reported a fairly diverse palynomorph assemblage in the upper Flowerpot Shale Formation on the basis of samples taken along the Salt Fork of the Red River in Greer County, southwestern Oklahoma ([Fig. 1](#)). He placed the

Flowerpot Shale in the early Guadalupian and concluded that the most similar Permian palynoflora was from the Zechstein of Europe (Uhl, 2013), which extends from the mid- or basal late Wuchiapingian to a bit below the Permo-Triassic boundary (Szurlies, 2013, 2020). Whereas it is now clear that the Flowerpot Shale is not that recent, Wilson based his age assignment partly on *Lueckisporites virkkiae* Potonié and Klaus, 1954, which is known to appear in the basal Kazanian (Stephenson, 2018), hence in the early Roadian (Golubev, 2005, 2015; Davydov *et al.*, 2018). *L. virkkiae* was, in fact, the most abundant taxon in Wilson's collection, comprising 68.10% of the assemblage. This formerly enigmatic, bisaccate pollen grain recently has been assigned recently to voltzian conifers (Gibson *et al.*, 2020). Thus, the dominant plant type of both the San Angelo compression assemblage of North-Central Texas and the nearly coeval Flowerpot Shale palynoflora of southwestern Oklahoma is unambiguously Middle to Late Permian.

Clapham (1970a, 1970b) later sampled the upper part of the Flowerpot Shale Formation for palynomorphs in an area that covered four north-central Oklahoma counties, including Blaine County (Fig. 4). His findings confirmed the abundant occurrence of *L. virkkiae*. He also reported *Falcisporites zapfei* Leschik, 1956 as abundant, which is significant because Zhu *et al.* (2005: 189) stated that, "the combined presence of *L. virkkiae*, *K[lausipollenites]. schaubergeri*, *S[cutasporites]. xinjiangensis* and *F. zapfei* is of vital importance because they are generally taken as indices of the Upper Permian", a conclusion that was accepted by Stephenson (2018).

Olson and Barghusen (1962) and Olson (1965) noted abundant plant remains at the Chickasha vertebrate site called Omega Quarry (see Sect. 5.2), which is the northern of the two localities along the Kingfisher-Blaine county line as shown in Figure 4. It appears that the collection does not survive based upon recent exchanges with the Field Museum of Natural History, which acquired the University of Chicago's Walker Museum paleobotanical holdings in 1965. Otherwise, we know of no significant megascopic plants from the El Reno Group.

The youngest plant assemblage from the Pease River interval is South Ash Pasture, in King County, Texas (Fig. 3). This is another channel fill in a lower coastal plain setting, but it is much younger, occurring in the upper part of the Blaine Formation at the level of the Aspermont Dolomite (DiMichele *et al.*, 2004). Although this locality yielded a low-diversity assemblage, it is distinctly Middle to Late Permian (DiMichele *et al.*, 2011; Looy and Duijnste, 2020).

These plant records, though few, differ substantially from the much-collected plant-bearing rocks of the lower and middle Clear Fork Formation in North-Central Texas (Chaney and DiMichele, 2007). The Clear Fork is assigned to the Cisuralian Series on the basis of marine fossils from Central Texas exposures and surface and subsurface samples from West Texas.

5 Marine fossils

5.1 Fusulinid data

Fusulinids from marine rocks of the Permian Basin have been used to approximate the age of the vertebrate-bearing continental formations on the Eastern Shelf since at least the

time of Romer (1935). Such early work concentrated on an Upper Carboniferous-Permian division and revealed major differences in how micropaleontologists and vertebrate paleontologists, as well as paleobotanists, perceived the Texas record. Although this era preceded the discovery of middle Permian vertebrates in the San Angelo Formation of North-Central Texas by nearly two decades, there are similarities between the uncertainties that arose in the Permo-Carboniferous and what can be reported today for the middle Permian.

The San Angelo Formation is limited to the Eastern Shelf, unquestionably continental, and devoid of marine fossils. Yet, the name has been misapplied to a great variety of rocks in the Midland Basin, the Central Basin Platform (CBP), and even the Delaware Basin (Fig. 1). Early stratigraphic syntheses, such as Skinner (1946), mentioned the occurrence of marine fossils in well cuttings or cores samples that had been correlated to the San Angelo or Glorieta. In most cases, no geographic details or well names were provided, but one, the "Holt Pay" or zone, is fairly well documented and has taken on a life of its own. This informal name was introduced for a producing reservoir composed of massive limestone that was reached in a deep well (Gulf No. 1 Holt) drilled on the margin of the CBP in north-central Ector County, Texas (Anonymous, 1940; Manulik, 1976). Skinner (1946: 1863) mentioned that it "underlies the San Andres and overlies the San Angelo", which has little basis in fact given that the San Angelo does not occur on the CBP, and regarded it as Leonard in age based upon the occurrence of *Parafusulina fountaini* Dunbar and Skinner, 1937. A few years later, the "Holt Pay" was assigned to the Guadalupe Series without any explanation (WTGS, 1949), but the same ghost author subsequently reported that the zone was "about 140 feet above the top of the subsurface Glorieta" and mentioned the presence of an assemblage dominated by *Parafusulina rothi* Dunbar and Skinner, 1935 and *Parafusulina maleyi* Dunbar and Skinner, 1937, which indicated a Guadalupe assignment (Jones, 1953). This report placed the "Holt Pay" in the lowermost San Andres, but, once again, no data were presented to substantiate the claim.

In assessing the age of plant-bearing channel deposits in the San Angelo Formation mentioned above (Sect. 4), DiMichele *et al.* (2001) cited Skinner (1946) and the Ector County record, as well as other marine fossil occurrences, without a full understanding of prior stratigraphic malpractices that were discussed later by Nelson *et al.* (2013b). The same year, Wilde *et al.* (2001) contributed a brief paper on the "Holt Pay" to a WTGS field guide. This note introduced fusulinids from the Apache Mountains on the southwest side of the Delaware Basin, some 200 km removed from Ector County (Fig. 1), but almost no fusulinids from Ector County were illustrated, and those that were shown are poorly rendered. Without any taxonomic descriptions or sound illustrations, this curious paper concluded that the "Holt Pay" was late Leonardian.

The shortcomings of Wilde *et al.* (2001) were overlooked in a subsequent discussion of fusulinid occurrences and the age of the San Angelo (Lucas, 2004). Lucas did not address lithostratigraphic problems and was inaccurate in stating, "Wilde *et al.* (2001) have recently documented the middle-upper Leonardian fusulinid *Parafusulina brooksensis* Ross, 1960 from the 'Holt Pay'" (Lucas, 2004: 50). This is an overstatement given what actually was published by Wilde

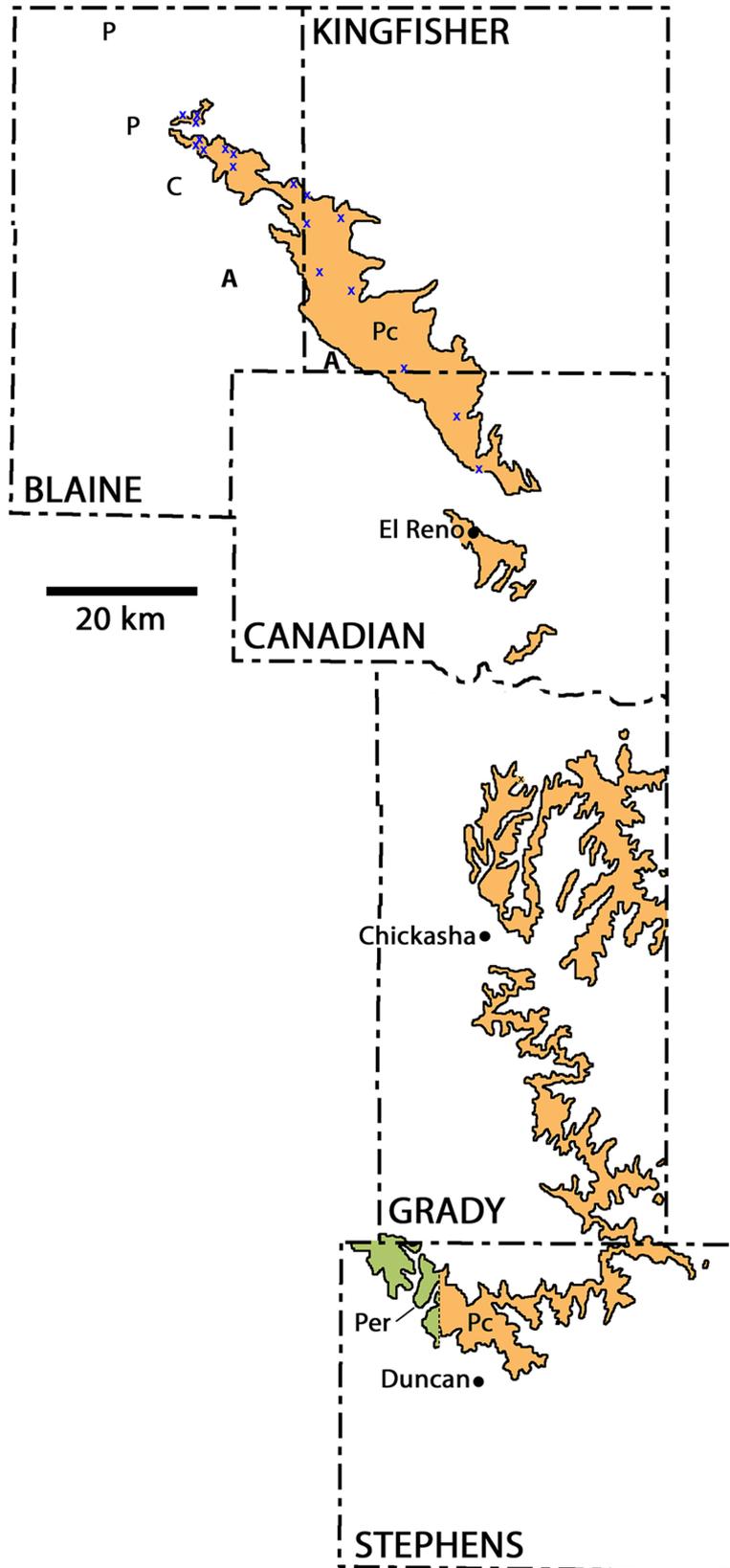


Fig. 4. Schematic map of the Chickasha (Pc) and undifferentiated El Reno Group (Per) outcrop in central Oklahoma. Abbreviations: X: vertebrate localities modified from [Olson \(1965\)](#); P: palynological sample sites of [Clapham \(1970a, 1970b\)](#); A: ammonoid localities of [Clifton \(1942\)](#); C, Cat Canyon field area of [Sweet *et al.* \(2013\)](#) and [Foster *et al.* \(2014\)](#). Outcrop adapted from [Hart \(1974\)](#), [Bingham and Moore \(1975\)](#), [Carr and Bergman \(1976\)](#), and [Morton \(1980\)](#).

et al. (2001): “However, enough data is available to identify the material as similar to *Parafusulina brooksensis* Ross” (Wilde *et al.*, 2001: 252). Indeed, “similar to” does not equal “documented” and given the superficial nature of Wilde *et al.* (2001), it should not be the basis of sweeping conclusions regarding the age of any rock units.

Recently, the term “Holt”, appropriated from the “Holt Pay” of Ector County, Texas, has been applied by sequence stratigraphers for rocks on the Eastern Shelf that they characterized as “San Andres Deep” and “Shallow shelf carbonates” without any explanation (Kerans and Ruppel, 2020: fig. 3). This follows an unfortunate practice noted by Nelson *et al.* (2013b) in which conventional lithostratigraphic strictures are ignored and illegitimate names introduced in sequence stratigraphic schemes. Simply stated, the “Holt”, like its namesake “Holt Pay”, is not well documented biostratigraphically or lithostratigraphically and has no proven relationship to rocks on the Eastern Shelf.

In Oklahoma, fusulinids, ammonoids, and a lithostratigraphic correlation between the Duncan Sandstone, the San Angelo Formation, and the Glorieta Sandstone have been the basis for correlating much of the El Reno Group with the San Andres Formation of West Texas (Fay, 1962). As noted above, a correlation of the Duncan Sandstone and San Angelo Formation is proven, but a San Angelo-Glorieta equivalency is less so. Because the San Andres Formation was considered Guadalupian on the basis of marine fossils (King, 1942), Fay (1962) regarded the Flowerpot Shale Formation and vertebrate-bearing Chickasha “Tongue” as Guadalupian. Most of the *Parafusulina* Dunbar and Skinner, 1931, species used by P.B. King to justify a Guadalupian age (*P. rothi* Dunbar and Skinner, 1935, *P. lineata* Dunbar and Skinner, 1937, *P. sellardsi* Dunbar and Skinner, 1937, *P. maleyi* var. *referta* Dunbar and Skinner, 1937) remain valid Guadalupian index fossils today (Nestell *et al.*, 2019; Wahlman *et al.*, 2020).

5.2 Ammonoid data

Ammonoid fossils were among the first to be used biostratigraphically in the Texas Permo-Carboniferous, starting with Böse (1919), who described specimens from the Glass Mountains of Brewster County in West Texas. Somewhat later, two ammonoid-rich deposits were reported on the Eastern Shelf from exposures of the Blaine Formation (Plummer and Scott, 1937; Miller and Furnish, 1940). The most productive locality had been discovered many years earlier by W.F. Cummins of the Second Geological Survey of Texas at the Falls of Salt Croton Creek (Cummins, 1891; Fig. 3, A) in northwestern Stonewall County. The other locality was discovered near Quanah by C.N. Gould of the Oklahoma Geological Survey in the early 20th century (Fig. 3, A in north-central Hardeman County). These two localities are referred to as “the Falls” and “Quanah” in the following. Clifton (1942, 1944, 1945, 1946) studied these marine assemblages and investigated coeval deposits in Oklahoma, West Texas, and New Mexico. Although Clifton’s descriptions are brief and based generally upon fragmentary remains, he consulted with W.M. Furnish, who was a leading ammonoid specialist of the time. Thus, Clifton’s contributions should not be discounted.

As in the case of fusulinid data from the basin, DiMichele *et al.* (2001: 450) used precedent ammonoid data, mainly

Clifton’s, from the Eastern Shelf to bracket the age of the San Angelo plant assemblage and suggested that the overlying Blaine Formation “is largely Guadalupian in age, but may include the latest Leonardian at its base”. Because the last 20 years have seen considerable research on Permian ammonoids (e.g. Leonova, 2002, 2007, 2011, 2018; Furnish *et al.*, 2009; Leonova and Boiko, 2015; Zhou, 2017), it is appropriate to revisit Clifton’s taxa (Tab. 1) and compare their stratigraphic ranges at the generic level (Tab. 2).

Although *Eumedlicottia* Spath, 1934 was considered a junior synonym of *Medlicottia* Waagen, 1880 by Miller and Furnish (1940), it was reinstated by Leonova (2002) (see also Leonova, 2019). Miller and Furnish (1940: 52–53) also had difficulties differentiating fragmentary remains of the Texas species *M. whitneyi* (Böse, 1919) and *M. burckhardtii* (Böse, 1919) and, “as a matter of expediency”, referred specimens from rocks assigned to the Leonard series to the former species and those from the Word Formation to the latter. Unfortunately, this practice of stratigraphy-based species is not uncommon, which is why the ranges of genera, not species, are depicted in Table 2.

Perrinites hilli (Smith, 1903) is by far the most common ammonoid known from the Blaine Formation (Clifton, 1942). Once regarded as a Leonardian (Cisuralian) index fossil, it is now known to occur in Roadian (Guadalupian) rocks (Leonova, 2007, 2011). Leonova (2002: 71) suggested that “the genus needs further study and subdivision” based upon the findings of Tharalson (1984). We are not aware of any major revisions.

Bamyaniceras knighti (Miller and Furnish, 1940) is the current name for what was described originally as *Propinaceras knighti*. The material introduced by Miller and Furnish (1940) was from West Texas (Apache Canyon, Sierra Diablo, Hudspeth County; Finlay Mountains, Hudspeth County; Glass Mountains, Brewster County). Clifton (1942) recorded it at both the Falls and at Quanah as a rarity. The generic-level synonymy was published by Leonova (2002), who also showed that *Bamyaniceras* ranges from Artinskian through Capitanian.

More problematic is *Pseudogastrioceras texanum* Clifton, 1942, which was reported as common at Quanah and the Falls. Lozovsky (2005) referenced a personal communication with T. B. Leonova, who suggested that the poorly preserved material may pertain to *Altudoceras* Ruzhencev, 1940, which ranges from the Roadian through the Wuchiapingian. Even though Lucas (2004) dismissed Clifton’s use of *Pseudogastrioceras* Spath, 1936 as archaic and obsolete, Lucas (2005a) responded to Lozovsky (2005) by resurrecting *P. texanum* as a valid taxon based upon his (Lucas, 2005a) interpretation of specimen photographs in the literature. We are more inclined to accept the identification of Leonova, an ammonoid specialist who doubtlessly has seen some of the Texas material. Furnish *et al.* (2009: 170) did not recognize *Pseudogastrioceras* in Texas but noted that it “resembles and intergrades with” *Altudoceras* and *Roadoceras*, which are common Texas taxa. Thus, this material is posted in the tables as *Altudoceras*.

The status of *Pseudogastrioceras roadense* (Böse, 1919) also is unclear. After Miller and Furnish (1940) reported material from the Glass Mountains (Brewster County) and the Delaware and Guadalupe mountains (Culberson County), Clifton (1946) described and figured two specimens from the

Table 1. Blaine ammonoid taxa of Texas and Oklahoma.

Original taxa	Current name	Additional references
<i>Eumedlicottia crotonensis</i> Plummer and Scott, 1937	<i>Eumedlicottia whitneyi</i> (Böse, 1919)	Miller and Furnish (1940) , Leonova (2002, 2019)
<i>Eumedlicottia burckhardti</i> (Böse, 1919)	<i>Eumedlicottia burckhardti</i> (Böse, 1919)	Plummer and Scott (1937) , Clifton (1945) , Leonova (2002)
<i>Perrinites gouldi</i> Plummer and Scott, 1937	<i>Perrinites hilli</i> (Smith, 1903)	Miller and Furnish (1940) , Tharalson (1984)
<i>Perrinites hilli</i> (Smith, 1903)	<i>Perrinites hilli</i> (Smith, 1903)	Plummer and Scott (1937) , Tharalson (1984) , Leonova (2002, 2011)
<i>Propinacoceras knighti</i> Miller and Furnish, 1940	<i>Bamyaniceras knighti</i> (Miller and Furnish, 1940)	Clifton (1942) , Leonova (2002)
<i>Pseudogastrioceras texanum</i> Clifton, 1942	<i>Altudoceras texanum</i> (Clifton, 1942)	Leonova in Lozovsky (2005)
<i>Adrianites newelli</i> Miller and Furnish, 1940	<i>Metacrimites newelli</i> (Miller and Furnish, 1940)	Clifton (1942) , Ruzhencev (1950) , Leonova (2002) , Leonova and Boiko (2015)
<i>Agathiceras girty</i> Böse, 1919	<i>Agathiceras girty</i> Böse, 1919	Clifton (1942) , Leonova (2002) , Zhou (2017)
<i>Pseudogastrioceras roadense</i> (Böse, 1919)	<i>Roadoceras roadense</i> (Böse, 1919)	Clifton (1944, 1946) , Zhou (1985) , Leonova (2002)

Table 2. Stratigraphic ranges of Blaine ammonoid genera. See text for references.

Series	Stages	Genera						
		<i>Agathiceras</i>	<i>Altudoceras</i>	<i>Bamyaniceras</i>	<i>Eumedlicottia</i>	<i>Metacrimites</i>	<i>Perrinites</i>	<i>Roadoceras</i>
Lopingian	Changhsingian				X			
	Wuchiapingian		X		X			X
Guadalupian	Capitanian		X	X	X	X		X
	Wordian	X	X	X	X	X		X
Cisuralian	Roadian	X	X	X	X	X	X	X
	Kungurian	X		X	X	X	X	
	Artinskian	X		X	X		X	
	Sakmarian	X						
	Asselian	X						

Falls as *P. roadense*. [Zhou \(1985\)](#) transferred the species to a new genus, *Roadoceras* [Zhou, 1985](#), which ranges from Roadian to Wuchiapingian, but did not mention any Blaine specimens. [Leonova \(2002\)](#) agreed with Zhou's synonymy but only cited the West Texas material. The assignment of Clifton's *P. roadense* to *Roadoceras* is provisional, much like the referral of his *P. texanum* to *Altudoceras*, which is why [Tables 1 and 2](#) show *Roadoceras* for this record.

Adrianites newelli [Miller and Furnish, 1940](#) was based upon material from Coahuila, northern Mexico, and the Glass Mountains of Brewster County, Texas. [Clifton \(1942\)](#) noted that it was scarce at the Falls. The species was transferred to *Metacrimites* [Ruzhencev, 1950](#) ([Leonova, 2002](#)), which was later synonymized with *Neocrimites* [Ruzhencev, 1940](#) ([Furnish et al., 2009](#)). Because this synonymy was addressed and rejected by [Leonova and Boiko \(2015\)](#), the genus *Metacrimites* is used here even though [Zhou \(2017\)](#) followed

[Furnish et al. \(2009\)](#) without addressing [Leonova and Boiko's](#) work. *Metacrimites* ranges from Kungurian to Wuchiapingian.

Agathiceras girtyi [Böse, 1919](#) has survived as a valid binomen for material known from both the Falls and Quanah. [Zhou \(2017\)](#) reported a global stratigraphic range for *Agathiceras* [Gemmellaro, 1887](#) as Moscovian through Wordian.

In summary, of the seven ammonoid genera considered above, three are known from Cisuralian and Guadalupian deposits, two are reported to extent from the Cisuralian to Lopingian, and two are recorded in Guadalupian to lower Lopingian rocks ([Tab. 2](#)). This broad stratigraphic distribution refutes frequent and emphatic claims that ammonoid data relegate the Blaine Formation to the Leonardian, Kungurian, Cisuralian, or Lower Permian ([Lucas, 2002b, 2004, 2005a, 2013, 2017](#); [Lucas and Golubev, 2019](#)). On the contrary, the only age assignment for the Blaine that is consistent with all ammonoid taxa is the Roadian ([Tab. 2](#)).

Table 3. San Angelo Formation vertebrates.

Taxa	Additional references
TEMNOSPONDYLI Cope, 1868	
<i>Slaugenhopia texensis</i> Olson, 1962	Milner and Sequeira (2004)
AMNIOTA Haeckel, 1866	
Eureptilia Olson, 1962	
<i>Kahneria seltina</i> Olson, 1962	
<i>Rothianiscus multidontus</i> (Olson and Beerbower, 1953)	
Synapsida Osborn, 1903	
<i>Angelosaurus dolani</i> Olson and Beerbower, 1953	Olson (1962, 1968)
<i>Angelosaurus greeni</i> Olson, 1962	Olson (1968)
<i>Caseoides sanangeloensis</i> Olson and Beerbower, 1953	Olson (1962, 1968)
<i>Caseopsis agilis</i> Olson, 1962	Olson (1968)
<i>Cotylorhynchus hancocki</i> Olson and Beerbower, 1953	Olson (1962, 1968)
<i>Dimetrodon angelensis</i> Olson, 1962	

6 Vertebrate fossils

6.1 Introduction

Our summary of the San Angelo and Chickasha vertebrate assemblages (Tabs. 3 and 4) is based upon the literature, the fieldnotes of E.C. Olson, limited study of specimens, and field work. Because the two assemblages have been discussed in tandem rarely and because such treatments are for the most part dated, our objectives are (1) to provide information on how Olson, who was responsible for both assemblages, pursued field work, (2) to update taxonomic data, and (3) to assess the biostratigraphic significance of these assemblages. Oloyd and Sidor (2017, table 16 of their supplementary information) offered a synopsis of both assemblages but overlooked a number of taxonomic points that are rectified below.

The taxonomy and nomenclature of the relevant vertebrate taxa remain to an extent unsettled. Although most of these uncertainties have no bearing on the stratigraphic significance of these assemblages, for the sake of clarity, we provide a brief explanation of hypothesized phylogeny and the nomenclature used herein. This approach is based to a large extent upon the work of the senior author.

The origin of extant amphibians, usually considered to form a clade called “Lissamphibia” that excludes all Paleozoic taxa, remains controversial. The most popular hypothesis asserts an origin among temnospondyls, and more specifically, among dissorhophoids. This is by far the oldest hypothesis, which can be traced back to Cope (1888), who suggested that the rhachitinous centrum represented the initial stage in the increasing dominance of the intercentrum in some taxa, which culminated in batrachians (he did not comment on gymnophionans, which are usually not considered batrachians), which he believed had lost the pleurocentrum. In the same paper, he also identified embolomeres as the first representatives of an opposite tendency in another taxon, which culminated with amniotes, in which the pleurocentrum expanded as the intercentrum dwindled.

A more recent hypothesis is that extant amphibians originated among “lepospondyls”, a taxon that is probably paraphyletic because it includes extant amphibians (Laurin, 1998), or that may even be polyphyletic (e.g., Clack

et al., 2019). Even though this hypothesis has not been endorsed by many paleontologists, we follow it here because it has been supported by reanalyses of the largest relevant dataset of morphological (Marjanović and Laurin, 2019) and developmental (Laurin et al., 2022) data, as well as by a tip-dating analysis (Pyron, 2011).

Amniote phylogeny likewise is controversial. While the Captorhinomorpha was dismantled long ago and replaced by Eureptilia (e.g., Laurin and Reisz, 1995), the basic division of sauropsids into Parareptilia and Eureptilia, and even the synapsid status of varanopids, has been challenged by recent studies (Laurin and Piñeiro, 2017, 2018; MacDougall et al., 2018; Ford and Benson, 2020). These works suggest that varanopids could be basal eureptiles or diapsids, and parareptiles may be stem-diapsids. We provisionally consider varanopids to be synapsids and similarly accept the Parareptilia/Eureptilia dichotomy.

We use principles of phylogenetic nomenclature as implemented in the PhyloCode (Cantino and de Queiroz, 2020) to assign low-ranking taxa to higher-ranking taxa, at least when relevant taxa have been established under that code. Thus, the definition of Amphibia that we use follows Laurin et al. (2020), which specifies that the name Amphibia applies to the largest clade that includes various extant amphibians but not amniotes. Under the lepospondyl hypothesis (our working hypothesis), temnospondyls are stem-tetrapods, and thus do not belong to Amphibia.

6.2 San Angelo Formation

In prospecting and reporting the San Angelo Formation in the 1950s and early 1960s, Olson used aerial photographs from the U.S. Department of Agriculture because almost no topographic maps of appropriate scale were available for the region. Though such an approach seems crude by modern standards, he was expert in using aerial photography and coauthored a book on the topic for the military during World War II (Maclean and Olson, 1943). He also successfully used such methods during his work in the Clear Fork after the war (see Olson, 1948). Significant parts of his collection of aerial photographs are archived at the University of Chicago Library.

Table 4. Chickasha Formation vertebrates.

Taxa	Additional references
CHONDRICHTHYES Huxley, 1880	
Xenacanthiformes Berg, 1940	
<i>Orthacanthus</i> cf. <i>O. platypternus</i>	Johnson (1999), Olson (1965)
OSTEICHTHYES Huxley, 1880	
Actinopterygii Cope, 1887	
Undescribed scales	Olson (1965)
STEGOCEPHALI Cope, 1868	
Temnospondyli Zittel, 1888	
<i>Noxobeia gracilis</i> Gee <i>et al.</i> , 2018	Olson (1972a)
AMPHIBIA Linnaeus, 1758	
Nectridea Miall, 1875	
<i>Diplocaulus parvus</i> Olson, 1972b	
AMNIOTA Haeckel, 1866	
Eureptilia Olson, 1947	
<i>Rothianiscus robusta</i> (Olson, 1965)	
Parareptilia Olson, 1947	
<i>Macroleter agilis</i> Olson, 1980	Reisz and Laurin (2001)
Synapsida Osborn, 1903	
<i>Angelosaurus romeri</i> Olson and Barghusen, 1962	
<i>Cotylorhynchus bransoni</i> Olson and Barghusen, 1962	
<i>Varanodon agilis</i> Olson, 1965	
<i>Watongia meieri</i> Olson, 1974	Reisz and Laurin (2004)

Vertebrate fossils are exceedingly rare in the San Angelo Formation even though exposures are better than most in the underlying lower Clear Fork and Wichita, which are renowned for their productivity. Nearly all of Olson's San Angelo field work was on large ranches in Knox County, Texas (Fig. 3), and he reported these properties and the localities found within each (Olson, 1962). The localities, however, actually were collecting areas of some size, whose boundaries were defined arbitrarily by factors such as accessibility and topography. Some localities contained more than one collecting site, and nearly all sites produced single individuals that were neither well preserved nor complete. The very noteworthy exception was Kahn Quarry, which furnished nearly half of the approximately 120 specimens recovered from the San Angelo. Olson's four- to five-man field parties excavated the site for parts or all of seven field seasons from 1956 to 1962 and in 1971 (Olson, 1962, 1990). Most specimens occurred in an approximately 2-m thick by 3-m wide channel-form deposit that was traced for nearly 27 m (Olson, 1962). By far the most common taxon in the deposit is the gigantic caseid *Cotylorhynchus hancocki* Olson and Beerbower 1953, which is represented by fairly complete material (Olson, 1968).

Olson (1962) presented the San Angelo vertebrate assemblage (Tab. 3) in a vaguely stated stratigraphic framework in which he reported middle San Angelo, upper San Angelo, and Flower Pot occurrences; he also noted that no fossils were found in the lower San Angelo. He later observed (Olson and Chudinov, 1992) that it was difficult to marry his three divisions to the geological mapping of Smith (1974), who regarded such divisions as lithofacies variations. Therefore, as noted above, all of the Texas material is assigned to the San Angelo Formation (Fig. 2).

The assemblage is dominated by large terrestrial amniotes, with only one temnospondyl, *Slaughenhopia texensis* Olson, 1962, present. This is the oldest known tupilakosaurid, a group known otherwise from Guadalupian, Lopingian, and Early Triassic rocks of Europe, Russia, Greenland, India, and South Africa (Milner and Sequeira, 2004; Schoch and Milner, 2014). Outside of the San Angelo, the oldest tupilakosaurid is an unnamed taxon from the La Lieude Formation (Lodève Basin, France) that was described by Werneburg *et al.* (2007). The age of the La Lieude Formation is poorly constrained, but it has usually been considered to date from the Wordian to the early Lopingian. Werneburg *et al.* (2007) stated that the La Lieude Formation was above the Illawarra reversal, which they assumed dated from the Wordian/Capitanian transition (but see Sect. 3). These authors considered that its age is Lopingian, but other more recent studies reached differing conclusions. For instance, Schneider *et al.* (2020: fig. 2) assigned a Capitanian age to it, but this seems to rest on the assumption that caseids became extinct in the Guadalupian. We prefer to follow the more conservative opinion of Romano *et al.* (2017), who considered that the La Lieude Formation may range from Wordian to early Lopingian.

Other terrestrial vertebrates of the San Angelo include two captorhinids, *Rothianiscus multidontus* (Olson and Beerbower, 1953) and the smaller *Kahneria seltina* Olson, 1962, both of which are known from several collecting areas. Sumida (pers. com. in Lucas, 2006) asserted that some of specimens described as *Rothianiscus* Kuhn, 1961 pertained to an older multitooth-row captorhinid, *Labidosaurikos* Stovall, 1950, but has not, to our knowledge, published supporting data. A tooth plate from the San Angelo that Seltin (1959) reported as a possibly new *Labidosaurikos* species was later attributed to *Kahneria* (Olson, 1962).

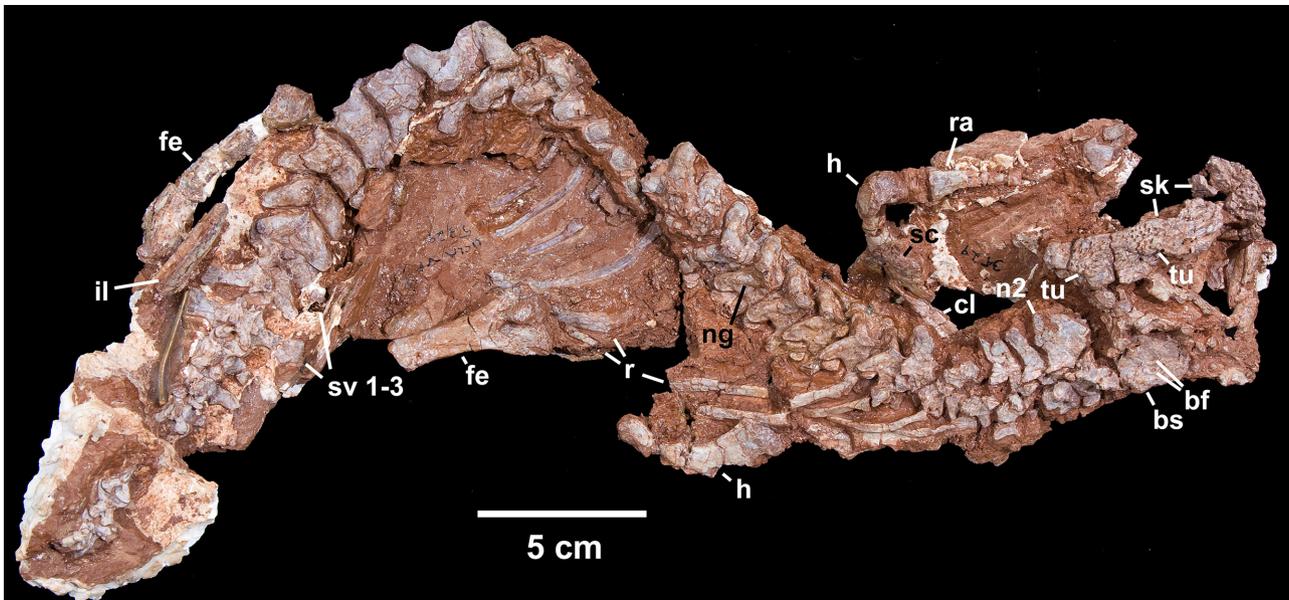


Fig. 5. UCMP 143 277, holotype of *Macroleter agilis* (Olson, 1980) in dorsal view. Anatomical abbreviations: bf: basisphenoid foramen; bs: basisphenoid; cl: clavicle; fe: femur; h: humerus; il: ilium; n: neural arch; ng: anterior groove on the postzygapophyseal buttress; r: ribs; ra: radius; sc: scapula; sk: dermal skull elements; sv: sacral vertebrae; tu: tuberosities on dermal skull elements. Diane Scott, photographer.

Determining the biostratigraphic significance of *Rothianiscus* and *Kahneria* requires a proper phylogenetic background. Because phylogenetic analyses of captorhinids yield less congruent results for *Kahneria* than for *Rothianiscus*, the latter genus is discussed first. Modesto *et al.* (2018a: figs. 7 and 8) concluded that *Rothianiscus* was the sister group of *Gansurhinus* from China and that this clade was the sister group of *Moradisaurus* from Niger. Brocklehurst (2017) found a compatible topology but added an unnamed captorhinid taxon represented by MBCN (Museu Balear de Ciencies Naturals, Sóller, Mallorca, Spain) 15730 from Mallorca, which appears to be more closely related to *Rothianiscus* than to *Gansurhinus* and which appears to be Guadalupian or Lopingian (Liebrecht *et al.*, 2017). *Gansurhinus* is known from the Xidagou and the lower part of member II of the Naobaogou formations (Reisz *et al.*, 2011). Whereas the Xidagou Formation probably is Wordian (Olroyd and Sidor, 2017: 588; Fig. 6), the Naobaogou Formation appears to be of Changhsingian age (Liu and Chen, 2021); in any case, a clearly post-Wordian age of its member II is suggested by the presence of the pareiasaur *Elginia* in that member (Liu and Bever 2018). *Elginia* is from deposits that Spencer and Lee (2000) indicated have been correlated with the Tatarian, which according to more recent works corresponds to the Capitanian to Changhsingian (Sennikov and Golubev, 2017; Fig. 6). However, the elginids from Russia date from the Vyatkian Russian regional stage (Bulanov and Yashina, 2005), which is correlated with the late Wuchiapingian and the Changhsingian (Sennikov and Golubev, 2017). Finally, *Moradisaurus* is from the Moradi Formation, which is often considered as Changhsingian (e.g., Modesto *et al.*, 2018b) but that can be more conservatively dated from the Guadalupian or Lopingian (Taber *et al.*, 2011). More precisely, the presence of a pareiasaur in the Moradi Formation (Turner *et al.*, 2015) suggests a Capitanian or Lopingian age. The closest Cisuralian

relatives of *Moradisaurus* are the Kungurian *Labidosaurikos meachami* from the Hennessey Formation of Oklahoma (Dodick and Modesto, 1995) and *Captorhinikos valensis* from the middle Clear Fork Formation of Texas (Modesto *et al.*, 2014; Nelson *et al.*, 2013a), but these are more distant relatives of *Rothianiscus* under all recently published captorhinid phylogenies. Thus, the captorhinid *Rothianiscus* from the San Angelo Formation belongs to a clade that is known only in the Guadalupian and Lopingian, and whose well-dated taxa are Wordian and younger. Because this clade has not been formally named as far as we know, we formally recognize Moradisaurini de Ricqlès and Taquet 1982 (ranked as a tribe; by virtue of the principle of coordination in the Zoological Code, the author of the tribe is the same as that of the subfamily based on the same type-genus; see Article 36.1 of the code) for the smallest clade that includes *Moradisaurus*, *Gansurhinus*, and *Rothianiscus*. Moradisaurini is characterized by a greatly laterally expanded cheek and a straight skull table occipital margin, according to the data matrix used by Brocklehurst (2017). It follows that *Rothianiscus* is by far the oldest Moradisaurini.

The affinities of *Kahneria* have been assessed by two studies. Matamales-Andreu *et al.* (2021) produced a parsimony analysis of captorhinids, which placed *Kahneria* in a trichotomy with *Captorhinikos valensis* (Kungurian) and a clade that includes *Labidosaurikos* (also Kungurian) and Moradisaurini (known from the Guadalupian and Lopingian [see above]). A possible exception is the poorly dated captorhinid material from the Balearic islands, which this analysis places among the Moradisaurini. This topology constrains weakly the age of *Kahneria* to Kungurian to Lopingian but is not robust: all the clades discussed above have a Bremer (decay) index of 1 and many have a bootstrap frequency below 50%. Matamales-Andreu *et al.* (2021) also left all characters unordered, a common but problematic

Table 5. Stratigraphic distribution of relevant vertebrate taxa in the San Angelo Formation. None of the taxa shown here extend beyond the Olenekian.

Geological timescale		Taxa			
Series	Stages	Tupilakosauridae	Moradisaurini	Caseinae	Sphenacodontidae
Triassic	Olenekian	?			
	Induan	X			
Lopingian	Changhsingian	X	X		
	Wuchiapingian	X	X		
Guadalupian	Capitanian	X	X		?
	Wordian	X	X		?
	Roadian	SA	SA	X	SA
Cisuralian	Kungurian			X	X
	Artinskian				X
	Sakmarian				X
	Asselian				X

Abbreviations: SA: present only in the San Angelo (and eventually in the Chickasha); ?: presence suggested by some studies but based upon fragmentary material of uncertain attribution or material from inadequately dated rocks.

procedure, given that simulations show that this leads to suboptimal results (Rineau *et al.*, 2015, 2018). The other analysis that assessed the affinities of *Kahneria* is Brocklehurst (2020), which used Bayesian tip dating with a fossilized birth-death model. The obtained topology is incompatible with that of Matamales-Andreu *et al.* (2021) because it places *Kahneria* as the sister-group of *Gansurhinus*, which is known from the Wordian and, probably, the Changhsingian (see above). The sister-group of that clade is the Kungurian *Captorhinikos valensis*. Thus, this topology suggests a Guadalupian age for *Kahneria*, but this result is less robust than for *Rothianiscus*.

The San Angelo caseids reported first by Olson and Beerbower (1953) and Olson (1962) and revisited by Olson (1968) are known from numerous collecting areas, with *Cotylorhynchus hancocki* Olson and Beerbower, 1953 accounting for approximately 90% of all San Angelo fossil occurrences. Other less common San Angelo caseids include *Angelosaurus dolani* Olson and Beerbower, 1953, *Angelosaurus greeni* Olson, 1962, *Caseoides sanangeloensis* Olson and Beerbower, 1953, *Caseopsis agilis* Olson, 1962, and *Cotylorhynchus hancocki* Olson and Beerbower, 1953. Because all these taxa are found only in the San Angelo and, in some cases (*Angelosaurus* and *Cotylorhynchus*), the Chickasha, they do not help constrain the age of these formations. However, *Cotylorhynchus romeri* Stovall, 1937 is known from the Kungurian Hennessey Formation (Olson, 1968; Reisz, 1986). The sister group of *Cotylorhynchus*, *Alierasaurus ronchii* Romano and Nicosia, 2014, from the Cala del Vino Formation, also dates from the late Kungurian or Roadian (Romano *et al.*, 2017).

Taking into consideration taxonomic affinities of the San Angelo caseids does not clarify matters. *Angelosaurus* appears to form a clade with *Alierasaurus* Romano and Nicosia, 2014 and *Cotylorhynchus* Stovall, 1937 (Berman *et al.*, 2020). In fact, an even more inclusive clade, which we will here formally recognize as Caseinae Williston, 1911 (also attributed to Williston by virtue of the principle of coordination of the code), also includes the Roadian *Ennatosaurus tecton* Efremov, 1956 and the Kungurian *Euromycter rutenus*

(Sigogneau-Russell and Russell, 1974), *Casea nicholsi* Olson 1954, *Trichasaurus texensis* (Williston, 1910), and *Casea broilii* Williston, 1910; Caseinae is restricted to the late Kungurian and Roadian (Tab. 5; Brocklehurst and Fröbisch, 2017: fig. 5). Caseinae is characterized by the posteroventral inflexion of the temporal bar (compared to the tooth row) and the low number (fewer than 15) of maxillary teeth, according to the data matrix and of Berman *et al.* (2020) and their majority-rule consensus tree.

Caseoides Olson and Beerbower, 1953 and *Caseopsis* are represented by fragmentary remains known only from the San Angelo Formation. *Caseopsis* was integrated into the analysis of Brocklehurst *et al.* (2016), which is based on an update of the matrix published by Benson (2012). Neither study constrains well the position of *Caseopsis*, even though Brocklehurst *et al.* (2016: fig. 10C) yielded slightly higher resolution. This tree features a polytomy that includes *Caseopsis*, the three species of *Cotylorhynchus* (two of which are Kungurian and the other, from the San Angelo Formation), and the two species of *Angelosaurus* included in the analysis (*A. romeri*, from the Chickasha Formation, and *A. dolani*, from the San Angelo Formation). This topology only suggests a Kungurian to Roadian age for *Caseopsis*. Thus, despite the fact that caseids extend down into the late Carboniferous (Reisz and Fröbisch, 2014), all data are congruent with a late Kungurian/early Roadian age of the caseids of the San Angelo Formation.

Sphenacodontids are represented by *Dimetrodon angelensis* Olson, 1962, which appears to be the most recent representative of this clade (Didier and Laurin, 2021). The oldest known sphenacodontids are *Cryptovenator hirschbergi* Fröbisch *et al.*, 2011 and *Sphenacodon ferox* Marsh, 1878, both of which date from the latest Carboniferous or the earliest Permian (Spielmann *et al.*, 2010; Fröbisch *et al.*, 2011); the enigmatic "*Macromerion*" *schwarzenbergii* Fritsch, 1879 may be of comparable age (Spindler, 2020). Other than *D. angelensis*, the most recent sphenacodontids include *Dimetrodon giganhomogenes* Case, 1907 and *D. grandis* (Case, 1907), which both occur in the Kungurian Clear Fork

Formation (Olson, 1948; Rega *et al.*, 2012). However, the FBD (Fossilized Birth and Death) analysis of Didier and Laurin (2021: fig. 8) suggests that Sphenacodontidae Marsh, 1878 probably became extinct between the late Kungurian (only if we assume a late Kungurian age for the San Angelo) and the early Capitanian (given the incompleteness of the fossil record). Indeed, a preliminary report of undescribed Late Permian “sphenacodontid-like forms” from South America (Spindler *et al.*, 2013), if confirmed, would suggest an even later extinction. This material is from the Yaguari Formation (G. Piñeiro, pers. comm. January 21st, 2022), which has recently been dated either as Lopingian (Ernesto *et al.*, 2020) or late Guadalupian-early Lopingian (Piñeiro *et al.*, 2022). Such a long range extension in South America of a Euramerican Permo-Carboniferous taxon is not unprecedented: putative diadectomorph vertebrae were described (Piñeiro, *et al.*, 2015) from the Late Permian or early Triassic Sanga do Cabral Formation (Brazil), and the Wuchiapingian (lower Lopingian or Late Permian) occurrence of diadectomorphs in China attests to a comparable record (Laurin, 2015; Liu and Bever, 2015).

Eight more amniote taxa are of uncertain affinities. Three were erected by Olson and Beerbower (1953): *Steppesaurus gurleyi*, which they interpreted as a sphenacodontid, *Tappenosaurus magnus*, which they considered a sphenacodontian but placed in the new (redundant) family Tappenosauridae, and *Dimacrodon hottoni*, which they interpreted as a therapsid of uncertain affinities. Subsequently, Olson (1962) regarded *Steppesaurus* and *Tappenosaurus* as therapsids (as a phthinosuchid eutheriodont and an eodinocephalian dinocephalian, respectively). Olson (1962) also erected several new taxa that he considered to be therapsids: *Eosyodon hudsoni*, a presumed brithopodid eutheriodont, *Gorgodon minutus*, interpreted as a phthinosuchid eutheriodont, *Knoxosaurus niteckii*, a possible phthinosuchid eutheriodont, and two presumed eodinocephalians, *Driveria ponderosa*, and *Mastersonia driverensis*. In an abstract, Sidor and Hobson (1995) dismissed these eight possible San Angelo therapsid taxa. All were based upon fragmentary remains, and five of the eight are known from only one or two specimens. Although additional details were never presented by Sidor and Hobson, this abstract has become a convenient touchstone for rejecting many of Olson’s San Angelo conclusions, most notably his Guadalupian age assignment. Because we have not studied this material, we are agnostic about these taxa, and they are not included in Tables 3 and 5. Renewed study of this material by modern methods is very much needed.

6.3 Chickasha Formation

Unlike North-Central Texas, central Oklahoma was surveyed on a township and range plan, and much of it is crisscrossed by a network of section-line roads, which greatly facilitates field work. But topographic relief is less, and average precipitation more, which results in Chickasha exposures of only a few meters in height and of generally limited lateral extent, especially in mudstone-rich areas. After an initial reconnaissance of the region in 1960, Olson focused on two adjacent counties, Blaine and Kingfisher (Fig. 4), and continued to use the term locality for what most often were collecting areas, not individual fossil-producing deposits. Over

the course of several field seasons in the early 1960s, Olson’s field crews discovered 19 localities that produced significant specimens (Olson, 1965). Although he did no further exploration of Chickasha exposures after the early 1960s, he would return for brief visits to known sites in Blaine County during the 1970s and 1980s and collected additional material that substantially enhanced what is known about the assemblage (Olson, 1972a, 1972b, 1974, 1980). Whereas the initial collections are held by the Field Museum in Chicago, as are nearly all of Olson’s San Angelo specimens, the later Chickasha collections made originally for UCLA are now housed at the Museum of Paleontology, University of California, Berkeley (UCMP).

Chickasha vertebrates are rare, mostly fragmentary to partially articulated, and scattered. The notable exception is Omega Quarry in western-most Kingfisher County, which yielded approximately 100 specimens taken in plaster jackets from a channel deposit that was roughly 1.5 m thick and 4.6 m wide. It is difficult to estimate the extent of the deposit, but because the deposit was traversed by a local road that may have been removed and subsequently restored, it was at least 25 m in length.

The Chickasha tetrapod assemblage as presently understood includes a temnospondyl, an amphibian (a “lepospondyl”, a paraphyletic group), one or two eureptiles, a parareptile, and four synapsids (Tab. 4). Several Chickasha temnospondyl and “lepospondyl” specimens described by Olson that were based upon fragmentary specimens have been reassessed. The holotype and lone specimen of *Cymatorhiza kittsi* Olson and Barghusen, 1962 is a small jaw fragment that was described as a “microsaur” (also a paraphyletic group) amphibian, a notion dismissed by Carroll and Gaskill (1978), who regarded the fragment as indeterminable. Despite this, Lucas (2006: 79) erroneously claimed that *Cymatorhiza* Olson and Barghusen, 1962 was “widely distributed in Texas-Oklahoma” and considered the taxon as a “relatively robust index fossil” of his “Littlecrotonian” land-vertebrate faunachron. Fragmentary postcranial material described as a possible trimerorhachid, *Nannospondylus stewarti* Olson, 1965 was found later to be undiagnostic and, therefore, a *nomen dubium* (Schoch and Milner, 2014). In addition, the holotype of *Fayella chickashaensis* Olson, 1965, a weathered partial neurocranium that was believed to be a dissorophid, likewise is regarded as a *nomen dubium*, and a referred specimen that consists of cranial fragments probably is a captorhinid (Gee *et al.*, 2018).

An additional and far more substantial temnospondyl specimen referred to *Fayella* by Olson (1972a) has been redescribed as a new dissorophid taxon, *Noxobeia gracilis* Gee *et al.*, 2018. Gee *et al.* mentioned that this may well be the one of the geologically most recent dissorophids. However, *Kamacops acervalis* Gubin, 1980, is a bit more recent because it occurs in the Belebey Formation, which is late Kazanian (late Roadian) according to Gubin (1980). The presence of a dissorophid (*Noxobeia*) does not constrain the age of the Chickasha Formation because according to Milner (1993b), the Dissorophidae Boulenger, 1902, ranges from the Moscovian to the Roadian.

The best-preserved amphibian from the Chickasha Formation is *Diplocaulus parvus* Olson, 1972b. Although this neotridean species is known only from the Chickasha Formation, the genus itself has a much broader stratigraphic

distribution. *Diplocaulus* is known with certainty from the Abo Formation in New Mexico, which indicates that this taxon appeared no later than Sakmarian (Berman, 1993), and is common in the Clear Fork (Kungurian) of Texas. The youngest record attributed to *Diplocaulus* is *D. minimus* Dutuit, 1988, from the Ikakern Formation of the Argana Basin (Morocco), which is currently thought to be of Lopingian age (Germain, 2010). Thus, the stratigraphic range of the clade extends from the Sakmarian to the Lopingian and, like the Chickasha dissorophoid, does not constrain the age of the assemblage.

Although appendix A of Olson and Chudinov (1992) recorded both *Rothianiscus* and *Kahneria* in the Chickasha, we believe the mention of *Kahneria* in this context was unintended because it is not noted in the text; the only captorhinid that has been documented so far in the Chickasha is *Rothianiscus*. Years earlier, in his description of *Rothia* [= *Rothianiscus*] *robusta*, Olson (1965) mentioned *Kahneria*, a smaller but similar captorhinid, but did not mention that it was present in the Chickasha. Moreover, the UCMP online fossil vertebrate catalog does not include any *Kahneria* entries as would be the case if Olson had discovered such material in the Chickasha later in his career. See Section 6.2 “San Angelo Formation” for the stratigraphic significance of *Rothianiscus*.

The Chickasha vertebrate taxon of greatest stratigraphic significance was described as *Seymouria agilis* Olson, 1980. The single specimen was collected in 1978 in Blaine County and supposedly “extended the stratigraphic range of the genus into the lower part of the Upper Permian, early Guadalupian” (Olson, 1980: 139). Olson (1980: 142) obviously based his identification mostly on the swollen neural arches but he had reasons to doubt this assignment, noting: “Although the presacral vertebrae and ribs are virtually indistinguishable from those of *S. baylorensis* in form, the shoulder girdle, sacral ribs, and limb elements are strikingly different.”

An explanation for this strange mix of features was provided by Reisz and Laurin (2001: 1231), who pointed out that affinities of UCMP 143 277 to the parareptiles found in Kazanian strata of Russia were supported by “overwhelming evidence”, such as neural arches that are narrow and tall in the cervical region but swollen in the dorsal region, an anterior groove on the postzygapophyseal buttress (Fig. 5, ng), the presence of three sacral ribs (Fig. 5, sv 1–3), and a T-shaped interclavicle with a deep anterior groove into which fits the narrow clavicular head. They also emphasized five synapomorphies that link the Chickasha specimen to *Macroleter*, including: (1) the peculiar dermal sculpturing, which consists of deep circular depressions separated by broad, flat areas, and a few tuberosities (Fig. 5, tu); (2) an elongate basisphenoid (Fig. 5, bs) that bears a broad, shallow, paired foramen on either side of its dorsal sagittal ridge (Fig. 5, bf); (3) a prominent median ridge on the parasternal (posterior) process of the interclavicle; (4) a horizontal dorsal edge of the expanded iliac blade (Fig. 5, il); (5) a long, slender humeral shaft.

The identification of UCMP 143 277 as *Macroleter* Tverdochlebova and Ivakhnenko, 1984 was accepted in several subsequent studies (e.g., Müller and Tsuji, 2007; Cisneros and Tsuji, 2009; Benton, 2012; Tsuji et al., 2012) but was questioned by Olroyd and Sidor (2017: 591), who stated:

“Five features were used by Reisz and Laurin (2001) to support the assignment of the Chickasha fossil to *Macroleter*. Of these, the two cranial features were not listed as diagnostic in Tsuji’s (2006) comprehensive revision of the genus. The utility of the three postcranial characters is difficult to evaluate because of a lack of parareptile, and especially nycteroleterid, postcranial research. Thus, the strongest piece of vertebrate evidence supporting a Guadalupian age for the Chickasha Formation is not as unambiguous as might be hoped.”

The absence of some characters from a diagnosis does not invalidate them because diagnoses are short and designed to differentiate a taxon from its closest relative. This does not imply that Tsuji contested the identification of UCMP 143 277 as *Macroleter*; on the contrary, the following quote implies that she accepted this identification: “Until a misidentified specimen from the Chickasha Formation in Oklahoma was recognized as a species of *Macroleter* (Reisz and Laurin, 2001), the genus was monospecific, and was restricted to the localities within the Mezen Basin” (Tsuji, 2006: 849–850). Also, even though sculpturing and ornamentation were not retained by Tsuji (2006) in her diagnosis of *Macroleter*, this character, which had been used by Reisz and Laurin (2001) to reassign UCMP 143 277 to *Macroleter*, was emphasized by Tsuji (2006) in her description as shown by the fact that these words occur 16 and six times, respectively, in her paper. Similarly, Tsuji (2006) described in detail the aspect and distribution of the tuberosities (another peculiar aspect of the dermal sculpturing of *Macroleter*), which she mentioned 13 times as “tubercle(s)” and twice as “tuberosities”. Olroyd and Sidor’s (2017: 591) statement that “the utility of the three postcranial characters is difficult to evaluate because of a lack of parareptile, and especially nycteroleterid, postcranial research” is baseless because the postcranium of *Emeroleter levis* was described in detail by Tsuji et al. (2012). Indeed, Tsuji et al. (2012) compared extensively *Emeroleter* with *Macroleter* (the latter is mentioned 76 times in the paper, six of which are in the description of the postcranium).

Olroyd and Sidor (2017) may also have overlooked the statement by Reisz and Laurin (2001: 1231):

“In fact, UCMP 143 277 is almost indistinguishable from *M. poezicus* on the basis of its morphology. Detailed comparisons between the North American and Russian specimens reveal a remarkable level of similarity; the only distinguishing feature is the large size of the third sacral rib (s3), which is slightly broader than the second (s2) in UCMP 143 277... This evidence leads us to reassign UCMP 143 277 to the genus *Macroleter*, **tentatively retaining the specific designation of *M. agilis*** on the basis of the single recognizable autapomorphy of the large size of the third sacral rib” [bold print added for emphasis].

The presence of *Macroleter* in the Chickasha suggests a Guadalupian age because in Russia it is known only from the late Kazanian Mezen assemblage and the Ocher “subassemblage” (Ivakhnenko, 2003; confirmed by a search in the Paleobiology Database on September 22nd, 2021), and this translates into late Roadian and Wordian (Sennikov and Golubev, 2017; Davydov et al., 2018; Fig. 6).

The caseids *Angelosaurus romeri* Olson and Barghusen, 1962, and *Cotylorhynchus bransoni* Olson and Barghusen, 1962, are present in the Chickasha Formation. See the analysis

Table 6. Stratigraphic distribution of relevant vertebrate taxa in the Chickasha formation. None of the taxa shown here extend beyond the Changhsingian.

Geological timescale		Taxa					
Series	Stages	Dissorophidae	<i>Diplocaulus</i> + <i>Diploceraspis</i>	Moradisaurini	<i>Macroleter</i>	Caseinae	Varanopidae
Lopingian	Changhsingian		?	X			
	Wuchiapingian		?	X			
Guadalupian	Capitanian			X			X
	Wordian			X	X		X
Cisuralian	Roadian	X	Ch	Ch	X	X	Ch
	Kungurian	X	X			X	X
	Artinskian	X	X				X
	Sakmarian	X	X				X
Pennsylvanian	Asselian	X	X				X
	Gzhelian	X	X				X
	Kasimovian	X					X
	Moscovian	X					X

Abbreviations: Ch: present in the Chickasha (and also, in some cases, in the San Angelo); ?: presence suggested by some studies but based upon fragmentary material of uncertain attribution or material from inadequately dated rocks.

of the San Angelo caseids (Sect. 6.2) above for an assessment of their stratigraphic significance.

The Chickasha Formation also yielded remains of two varanopids, *Varanodon agilis* Olson, 1965 and *Watongia meieri* Olson, 1974, the latter of which Olson interpreted as a therapsid (Reisz and Laurin, 2004). Both occur only in the Chickasha and are of little biostratigraphic utility. Expanding the analysis to other varanopids does not help because the stratigraphic distribution of Varanopidae is too broad, from the Moscovian (Maddin *et al.*, 2020) to the Capitanian (Modesto *et al.*, 2011).

6.4 Comparison of the San Angelo and Chickasha assemblages and their biostratigraphic significance

Because the San Angelo and Chickasha continental vertebrate assemblages are known from comparably sized areas (Figs. 3 and 4) and samples – the former from 20 collecting areas and the latter from 19, with each formation yielding one quarry site – a comparison of the two is straightforward. If the San Angelo “therapsids” that have been questioned are omitted, both assemblages consist of eight genera with three in common. Approximately half the taxa known from each formation is known from only one or two specimens, and most of these are fragmentary. Even without the rich records of Kahn and Omega quarries, both assemblages are dominated by large terrestrial forms, namely caseid synapsids and, a distant second, eureptiles. The middle Permian forms of both groups are believed to be herbivores (Hotton *et al.*, 1997).

The Kahn and Omega quarry sites in the San Angelo and Chickasha are benchmark deposits that share many similarities: (1) both originated as channel deposits, the exact nature of which cannot be determined; (2) both produced otherwise rare, well-preserved and/or articulated but incomplete specimens; (3) both collections are heavily dominated by caseids; (4) both yielded rare aquatic forms that are almost unknown otherwise in both formations; (5) both are reported to have produced abundant plant fossils that, if collected, have never

been described and may no longer exist; (6) both were thought to have been exhausted or nearly so by Olson, who also noted that in the case of Kahn Quarry further work would require heavy equipment and explosives to remove overburden.

The vertebrate assemblages of both formations suggest a Roadian age (Tabs. 5 and 6). In the San Angelo, *Slaughenhopia texensis* and *Rothianiscus multidontus* are the oldest representatives of Tupilakosauridae Kuhn, 1960 and Moradisaurini de Ricqlès and Taquet, 1982, respectively, both of which are not known elsewhere before the Wordian. The Chickasha Formation has not yielded tupilakosaurids, but it has produced remains of *Rothianiscus*, and it has remains of the parareptile *Macroleter*, which is otherwise known only from the late Roadian and Wordian of Russia. Both formations include caseine synapsids, a clade that is restricted elsewhere to the Kungurian and Roadian. The other synapsids from these formations differ; the San Angelo has the geologically most recent indubitable sphenacodontine (*Dimetrodon angelensis*), a clade elsewhere documented throughout the Cisuralian (and possibly in the Capitanian or early Lopingian Yaguari Formation in Uruguay; see Sect. 6.2), whereas the Chickasha includes varanopids, which have an even broader stratigraphic distribution (Cisuralian and Guadalupian). The vertebrates of both formations thus provide reasonably compelling evidence of a Roadian age, supported mostly by the stratigraphic distribution of Tupilakosauridae and Moradisaurini for the San Angelo, and the latter plus *Macroleter* for the Chickasha Formation.

7 The real gap in the Permian fossil record of continental vertebrates

In the course of his extensive work in the Clear Fork of North-Central Texas, Olson delimited the vertebrate-bearing parts of the section (Olson, 1958). Subsequent field investigations by Murry and Johnson (1987) and by U.S. National Museum (USNM) field parties confirmed Olson’s findings. Among these is that no fossils, animal or plant, are known from the uppermost part of the Clear Fork, some 120 m of evaporite-

bearing red mudstone that Olson inappropriately assigned to the Choza Formation (see [Nelson et al., 2013a](#)). Even though this paleontological void has been attributed to paleoclimatic factors, it fundamentally was the result of the filling of the Midland Basin, which left the equatorial coastal plains of the Eastern Shelf and similar environments in the Palo Duro and Anadarko basins to host evaporite-rich environments that were not conducive to preservation of organic remains. If the nonfossiliferous basal part of the San Angelo section (estimated at 2 to 8 m by [Olson, 1962](#)) is added, the barren interval approaches 130 m, which is greater than the bone-bearing part of either the San Angelo or the Chickasha.

Although the middle to upper Clear Fork of Texas is impossible to correlate precisely with Oklahoma because of poor exposures and a lack of persistent units in the subsurface that could serve as mapping datums, it appears that a similar void is present in the Hennessey Group, which underlies the El Reno Group in Oklahoma ([Fig. 2](#)). All the reported Hennessey vertebrate localities are low in the section ([Olson 1967, 1970; Simpson, 1979](#)) and cannot be regarded as filling the barren interval. As [Olson \(1967: 91\)](#) emphasized: “The upper part of the Hennessey Formation has yielded no fossils, although it has been explored rather thoroughly... there remains a large gap, ranging from several hundred to nearly 1,000 feet of section between the Hennessey beds and the fossiliferous Chickasha beds.”

In summary, geological data and extensive field work undertaken by a number of individuals working independently indicate a significant non-fossiliferous interval in the upper Clear Fork and Hennessey. This is not a hypothetical gap based upon a review of the literature. Nor does it involve far-reaching correlations to other basins or “cross correlations” between terrestrial and marine lithofacies. Although it was first noted over 50 years ago, we have never seen it considered in any discussion of Permian biostratigraphy, be it based on plant, animal, or trace fossils. This real gap in the fossil record coincides with a division between the Clear Fork/Hennessey assemblages and those of the Pease River/El Reno, which have long been known to be dissimilar.

8 Discussion

8.1 Other perspectives on the age of the Chickasha and San Angelo Formations

Our study is not the first attempt at dating the San Angelo and Chickasha Formations, nor the first review of previous work on this topic. Thus, [Lozovsky \(2005: 182\)](#) concluded that:

“Recently, closer similarity of the Russian fauna with the North American fauna has been established: the holotype of *Seymouria agilis* (Olson) from the Chickasha Fm. of Oklahoma is in reality a parareptile *Macroleter*, a typical taxon of the Mezen fauna, which is found together with a form like *Mesenosaurus* from Oklahoma but much larger (*Varanodon*), and caseids like *Ennatosaurus* (*Cotylorhynchus*). So not only the same animal is present in North America and European Russia (which is the best evidence for correlation), but also similarities in faunal composition support their simultaneity ([Reisz and Laurin, 2001](#)). This provides direct evidence of tetrapod faunal interchange between North

America and Russia in the Late Permian, and supports ideas that North America was connected to Europe at that time ([Scotese and McKerrow, 1990](#)).”

[Lozovsky \(2005\)](#) rejected [Lucas' \(2004\)](#) arguments that the Blaine ammonoids indicate a Leonardian age (the assemblage is Roadian, according to [Lozovsky](#)), and was similarly unconvinced by [Lucas' \(2004\)](#) argument about the San Angelo fusulinids. [Lozovsky \(2005: 182\)](#) thus concluded that: “Being based on the new data stated above, I believe that a break in the tetrapod fauna in the Middle Permian actually did not exist. Between the Permian of Russia and North America, intercontinental communications on the bridge named here ‘Olson’s bridge’ were carried out.”

[Benton \(2012\)](#) also accepted a Roadian age for the Chickasha Formation based upon its faunal similarities with the Mezen complex in Russia and work by Russian geologists who assigned the Kazanian to the Roadian. In his reply to [Lucas' comments \(Lucas, 2013\)](#), [Benton \(2013: e294\)](#) summarized the relevant issues: “He [Lucas] says that the uppermost tetrapod-bearing terrestrial Permian beds in Oklahoma and Texas (United States) are Early Permian in age, and that the oldest Russian tetrapod-bearing beds are post-Roadian, so leaving a temporal gap of 2–3 m.y. On the first point, his view is not accepted by the majority of researchers, although the biostratigraphic evidence is far from watertight, and on the second, he is opposed by the majority of experts.” We agree with [Benton](#) and have further substantiated his conclusions in the current paper.

Most recently, [Brocklehurst \(2020\)](#) used tip dating in a novel way to assess the age of these formations. His analyses relied on three previously published datasets: one on Paleozoic amniotes ([Ford and Benson, 2020](#)), one on caseids ([Romano et al., 2017](#)), and one on captorhinids ([Modesto et al., 2018a](#)). Normally, tip dating is used to infer topology and branch lengths (hence, nodal ages, too) from a dataset consisting of character data and geological ages of extinct taxa. Because the latter can incorporate uncertainty, [Brocklehurst \(2020: 3\)](#) indicated that “age priors were represented by a uniform distribution between the lowermost and uppermost age of each formation”. However, instead of using a single set of age priors as is typically done, he considered three sets of age priors, which differ by the assumed age of the San Angelo and Chickasha Formations. One set, called “extinction hypothesis”, placed these formations in the early Roadian with their base at the Kungurian/Roadian boundary and with the top of the Chickasha extending higher than the San Angelo, as it does in all three sets. The second set, called “gap A hypothesis”, placed these formations in the late Kungurian with the top of the Chickasha Formation extending to the Kungurian/Roadian boundary; this matches the ages suggested by [Lucas](#) until recently (*e.g.*, [Lucas 2002b, 2004, 2018: fig. 8](#)). The third set, called “gap B hypothesis”, placed the San Angelo and Chickasha formations at the bottom of the Kungurian with their bases at the Artinskian/Kungurian boundary; this matches the ages suggested recently by [Lucas and Golubev \(2019\)](#) and accepted by [Schneider et al. \(2020\)](#).

[Brocklehurst \(2020\)](#) then performed three sets of tip-dating analyses on the three datasets, one for each set of age priors. He used Bayes factors ([Kass and Raftery, 1995](#)) to evaluate relative support for each set of age priors. Bayes factor is a measure of relative support and is typically used to compare

Series	Stages	Russia			South Africa			Niger	France	Germany	China	Brazil
		Series	Stage	Fa. As.	Gr.	Fm.	AZ.	Fm.	Fm.	Gr.	Fm.	Fm.
Guadalupian	Lopi.			Ilinskoe						Zechstein		
	Wuchi.			Kotelnich								
	Capitanian	Tatarian	Severodvinian	Sundyr	Abrahamskraal	Te.	Tapinocephalus	Moradi	La Lieude	Rotliegend	Xidagou	Rio do Rasto
				Isheevo								
Wordian	Biramanian	Urzhumian	Ocher	Ecca	Waterford	Eodicynodon						
Roadian	Kazanian	Golyusherma	Mezen							Salagou		
												Serra Alta

Fig. 6. Schematic stratigraphic chart of Guadalupian strata outside North America discussed in this paper. A few early Lopingian units discussed in the text are also shown. Only about the lower two-thirds of the Wuchiapingian is shown. Russian stratigraphy follows [Golubev \(2015\)](#) and [Sennikov and Golubev \(2017\)](#) for faunal assemblages and [Davydov et al. \(2018\)](#) for the correlations between the Russian regional scale and the international time scale. For South African, the age of the *Eodicynodon* Assemblage Zone follows [Rubidge and Day \(2020\)](#) and [Day et al. \(2022\)](#). The *Tapinocephalus* Assemblage Zone has now been divided into the *Eosimops-Glanosuchus* and the *Diictodon-Styracocephalus* subzones ([Day and Rubidge, 2020](#)). No faunal zones are currently recognized in the Waterford Formation, just under the *Eodicynodon* Assemblage Zone ([Smith et al. 2020](#)). The age of the Abrahamskraal-Teekloof contact follows [Day et al. \(2015\)](#). Brazilian geochronology follows [Canile et al. \(2016\)](#) and references cited therein. The age of the Moradi Formation is poorly constrained (only to Capitanian or Lopingian). The base of the Zechstein Group may date from mid- to late Wuchiapingian, and this group extends to just below the Permo-Triassic boundary ([Szurlies, 2013, 2020](#)). Abbreviations: AZ.: Assemblage Zones and subzones; Fa. As.: faunal assemblages; Fm.: formation; Gr.: group; Lopi.: Lopingian; Te.: Teekloof; Wuchi.: Wuchiapingian.

support for two models, much like the classical log-likelihood ratio test ([Woolf, 1957](#)), but the Bayes factor differs from the latter by integrating over all possible parameter values of the compared models, whereas the log-likelihood ratio compares two models with sets of estimated parameter values. Unsurprisingly, the hypothesis best supported by Bayes factors is overwhelmingly the “extinction hypothesis” that assumes a Roadian age for both formations. Indeed, for the amniote dataset, the Bayes factor of the extinction hypothesis compared to the gap A hypothesis is 244, and that of the extinction hypothesis compared to the gap B hypothesis is 580. It is generally considered that the evidence in favor of a model over an alternative one is substantial when the Bayes factor is 3 to 20, strong for values of 20 to 150, and decisive for values >150 ([Kass and Raftery, 1995: 777](#)). The other two datasets appear to offer less discrimination between hypotheses, but they still favor strongly the extinction hypothesis, with Bayes factors ranging from 26 to 106 ([Brocklehurst, 2020: table 1](#)). Thus, taken together, tip dating of these three datasets provides decisive support for a Roadian age of the San Angelo and Chickasha formations.

8.2 The Roadian record

The San Angelo and Chickasha assemblages must be considered in the larger context of Roadian tetrapod occurrences globally (e.g., [Modesto and Rybczynski, 2000](#); [Abdala et al., 2008](#)). These records can be divided into three categories: those from Russia, from South Africa, and scattered records from various other locations ([Fig. 6](#)).

The Russian Permian has a continuous record of tetrapods from the Kungurian (the oldest assemblage is represented by Inta, which is Kungurian), through the Capitanian, and possibly the Triassic ([Sennikov and Golubev, 2006](#); [Golubev, 2015](#)). It is now reasonably well-established that the Kazanian, which has yielded fairly rich tetrapod assemblages ([Tatarinov, 1999](#); [Tsuji, 2006](#); [Tsuji et al., 2012](#)), is probably coeval with the Roadian ([Leven and Bogoslovskaya, 2006](#); [Leonova, 2007](#); [Davydov et al., 2018](#)), a conclusion accepted by [Golubev \(2005, 2015\)](#). Thus, [Lozovsky \(2005\)](#) concluded that the Russian Roadian tetrapod fossil record constituted a connection to the San Angelo and Chickasha data, which he termed “Olson’s Bridge” rather than a gap. By contrast, [Lucas](#)

(2018) suggested that the Russian Kazanian fossil record starts in the mid-Roadian.

The other Guadalupian section that has yielded a rich record of tetrapods is the Karoo Basin of South Africa. This interval may begin in the late Roadian or early Wordian and thus be slightly later than the Roadian of Russia (Golubev, 2000; Brocklehurst and Fröbisch, 2017; Olroyd and Sidor, 2017). This is consistent with the absence of caseids in the Karoo, unless *Eumotosaurus* is a caseid (Lee, 1995; Lichtig and Lucas, 2021). The last known undisputed caseids date from the Roadian. The most recent, *Ennatosaurus tecton* from Moroznitsa (Russia), was assigned a Capitanian age by Maddin *et al.* (2008), but more recently, Golubev (2015) assigned a Roadian age to this locality. Karoo tetrapods extend from the *Eodicynodon* Assemblage Zone through the Triassic. The age of the *Eodicynodon* Assemblage Zone is difficult to assess (Rubidge *et al.*, 2013); a late Roadian or early Wordian age has been suggested (Lucas, 2018), or it could occupy most of these two stages (Rubidge, 2005). Rubidge and Day (2020) suggested a Wordian age for the *Eodicynodon* Assemblage Zone but also accepted that it was more or less synchronous with the Ocher subassemblage and Mezen assemblage of Russia. However, the Mezen assemblage appears to span the parts of the Roadian and Wordian and could conceivably extend into the late Kungurian (Sennikov and Golubev, 2006; Golubev, 2015; Davydov *et al.*, 2018). We thus conclude provisionally that the *Eodicynodon* Assemblage Zone probably represents at least parts of the Roadian and the Wordian. In contrast, Lucas (2018: fig. 9) suggested that the base of the *Eodicynodon* Assemblage Zone dates from the early Wordian to the early Capitanian; the upper end of this range seems too recent, considering recent works summarized by Rubidge and Day (2020) and Day *et al.* (2022).

A number of other formations that include Middle Permian tetrapod-bearing localities provide other records that are less temporally extensive. These formations, reviewed by Olroyd and Sidor (2017), are found in Tanzania (Ruhuhu Formation), Zambia (lower Madumabisa Mudstone Formation), Zimbabwe (middle Madumabisa Mudstone Formation), Niger (Moradi Formation), Brazil (Rio do Rasto Formation), China (Xidagou Formation), Turkey (Kas Formation), and France (La Liuede Formation). Many of these (like the La Liuede Formation) are Wordian or Capitanian, but some could possibly be Roadian, notably the Madumabisa Mudstone Formation from Zimbabwe (Lepper *et al.*, 2000).

In summary, the Roadian does have a tetrapod fossil record, minimally in Russia, in the USA (the Chickasha and possibly the San Angelo formations), and possibly in South Africa and in a few other countries.

8.3 The Kungurian record

Whereas we question the concept of “Olson’s Gap” on a variety of grounds, a recent newsletter suggestion that the supposed hiatus should be moved downward into the Kungurian (Lucas and Golubev, 2019) requires discussion, especially because it was accepted by Schneider *et al.* (2020), a more formal publication. Specifically, it (1) placed the entire Clear Fork (and presumably other coeval amniote fossil-bearing strata, such as the Garber Sandstone and Hennessey

Group of Oklahoma) in the uppermost Artinskian; (2) placed the erroneously correlated Chickasha and San Angelo formations at the base of the Kungurian; and (3) placed all of the Blaine in the Kungurian. These dramatic shifts were said to be justified by studies of marine fossils mainly from Russia and by stratigraphic revisions made by Russians. Lucas and Golubev (2019) further evoked the suppression of the Ufimian Russian regional stage (between the Russian stages Kungurian [not to be confused with the IGS Kungurian] and Kazanian) to justify these changes in the age of North American strata. They also assigned the base of the Blaine Formation to the *Neostreptognathodus prayi* conodont zone and supported this by a reference to Kerans *et al.* (1993), which is odd because there is no mention of the Blaine in this brief field-conference paper. Nor is there any conodont content other than a chart (their fig. 7) captioned “Evolution of stratigraphic nomenclature...” that has a column headed “Conodont zonation Wardlaw (pers. comm., 1992).” Nor, to our knowledge, are there any conodonts known from the Blaine of either Texas or Oklahoma.

There are several problems with these suggestions, which we will address in stratigraphic order, starting with the oldest geological units. A Leonardian or Kungurian age for the North-Central Texas Clear Fork redbeds has long been accepted on the basis of intercalated fossiliferous marine rocks exposed in Central and West Texas, a convention that was endorsed previously by Lucas several times (Lucas, 2005a, 2006, 2017, 2018). In addition, a recent summary of Permian Basin biostratigraphy based upon foraminifera placed the fossil-bearing marine rocks of the upper Albany Group in the Kungurian (Wahlman, 2019). The Albany Group is the marine equivalent of the Wichita Group on the Eastern Shelf of the Midland Basin, and both groups immediately underlie the Clear Fork (Hentz and Brown, 1987). Aside from the fact that the age of the Clear Fork has never been assessed through putative correlations with the distant Russian Permian, how could the recognition of an equivalency between the bases of the Kazanian and Roadian (Leonova, 2007, 2011) and nomenclatural changes (linked to the suppression of the Ufimian) in the Russian Permian justify dropping the Clear Fork Formation into the Artinskian? Furthermore, (1) the Ufimian is not part of the International Geological Time Scale, (2) geochronological units of the international time scale are defined by their base and by the base of the superjacent unit of the same scale (Gradstein *et al.*, 2004), and (3) the length of the Kungurian in the IGS scale is unaffected by the suppression of the Ufimian regional stage. That is, the Kungurian still extends from the base of its proposed GSSP (Chernykh *et al.*, 2020) to that of the Roadian (Glenister *et al.*, 1999).

A recent appraisal of freshwater conchostracans found in association with classical vertebrate-bearing localities of the lower to middle Clear Fork Formation (sensu Nelson *et al.*, 2013a) places them entirely within the Kungurian (Martens 2020). These data are more reliable to date the vertebrate-bearing Clear Fork than fossils found in distant marine rocks that are often not lithologically similar and may not be synchronous (Nelson *et al.*, 2013b). Moreover, the conchostracans were discovered in deposits that yield fossil plants of a distinctly Late Permian aspect (e.g. Chaney *et al.*, 2009; Mamay *et al.*, 2009).

Placing the Blaine in the last two-thirds of the Kungurian as suggested by Lucas and Golubev (2019) also is groundless. Based upon the data (marine fossils, continental vertebrates, plant fossils, as well as lithostratigraphy and magnetostratigraphy) that we have reviewed above, the Blaine clearly is Roadian with its top probably extending into the basal Wordian.

Because the possibility that practically all of the Kungurian represents a gap in the tetrapod fossil record as suggested by Lucas has even less empirical support than placing this gap in the Roadian, this hypothesis will be disregarded until credible evidence is produced to support it. Even Lucas *et al.* (2022), another newsletter contribution, ignored the ages proposed by Lucas and Golubev (2019) and moved the entire Clear Fork Group back up into the Kungurian, where it clearly belongs.

9 Conclusions

The evidence described in this review leads to the following conclusions:

1. Lithostratigraphic data show that the vertebrate-bearing San Angelo Formation of North-Central Texas is not an equivalent of the Chickasha Formation of central Oklahoma. This was never suggested in the initial geological or paleontological studies but has been misrepresented often in interpretive reports over the past 20 years. The San Angelo occupies a lower stratigraphic position in the Pease River Group of Texas than does the Chickasha in the coeval El Reno Group of Oklahoma.
2. There are no unambiguous lithostratigraphic data to support an equivalency between the widely separated San Angelo Formation of Texas and the Glorieta Sandstone of New Mexico. Historically, this correlation was based upon marine fossils and the position of these units on opposite sides of the Permian Basin. More recently, it has been predicated upon misconceptions introduced by sequence stratigraphy models.
3. A nonfossiliferous interval from approximately 130 m to possibly 300 m in thickness occupies the upper part of the Clear Fork of Texas and the Hennessey of Oklahoma, respectively. Though reported over a half century ago by E.C. Olson, this barren section has never been acknowledged or addressed in recent biochronologic reports. This real paleontological void separates the well-known Clear Fork and Hennessey vertebrate assemblages from those of the overlying Pease River and El Reno Groups.
4. Magnetostratigraphic analysis of a continuous core drilled in western Kansas places the end of the Kiaman Superchron near the top of the Dog Creek Shale, which, in turn, places the Blaine and nearly all of the Flowerpot of Oklahoma in the Roadian. Because the vertebrate-bearing levels of the Chickasha Formation are intercalated with the Flowerpot, it appears that these levels of the Chickasha are Roadian and Guadalupian.
5. A small but much-studied paleobotanical record including palynomorphs clearly signals a Guadalupian age for both the Pease River and El Reno groups. This fact is significant because many of the paleobotany/palynology collections were made in proximity to vertebrate-bearing exposures.
6. The seven ammonoid genera reported from the Blaine of Texas range in age from the Cisuralian to the Lopingian, with Guadalupian occurrences being the most common. These findings refute any ammonoid-based notion that relegates the Blaine to the Lower Permian.
7. The Chickasha vertebrate assemblage of Oklahoma is assigned to the Roadian on the basis of several criteria. The stratigraphic position of the San Angelo assemblage of Texas is slightly less certain because much of this material (Olson's "therapsids") requires reexamination and because the lower Pease River Group lacks any paleomagnetic markers. However, plant assemblages recovered from these same rocks have an unquestionably Guadalupian aspect, as do some of the vertebrates. Pending further work, we return the San Angelo to the basal Guadalupian (early Roadian), its traditional assignment and most plausible age based on the evidence that we reviewed. However, this formation could possibly date from the very end of the Kungurian, or more likely, straddle the Kungurian/Roadian boundary.
8. Our findings agree with those of Benton (2012), Brocklehurst (2020), and others who have rejected the notion of "Olson's Gap".

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