[American Journal of Science, Vol. 314, June, 2014, P. 981–1008, DOI 10.2475/06.2014.01]

American Journal of Science

JUNE 2014

REVISED CHRONOSTRATIGRAPHY OF THE LOWER CHINLE FORMATION STRATA IN ARIZONA AND NEW MEXICO (USA): HIGH-PRECISION U-Pb GEOCHRONOLOGICAL CONSTRAINTS ON THE LATE TRIASSIC EVOLUTION OF DINOSAURS

JAHANDAR RAMEZANI*,†, DAVID E. FASTOVSKY**, and SAMUEL A. BOWRING*

ABSTRACT. The early history of dinosaurs in North America is obscured by an incomplete fossil record, taxonomic uncertainties and speculative correlations of tetrapod-bearing rocks, as well as poor calibration of the Late Triassic time scale. High-precision U-Pb geochronology provides a reliable means of correlating terrestrial rock formations independent of equivocal lithostratigraphy or vertebrate biostratigraphy, and hence the possibility of properly evaluating models for the early radiation and diversification of Dinosauria. Here we present new, high-precision, U-Pb ID-TIMS zircon geochronology from the presumed lowermost strata of the Upper Triassic Chinle Formation of the Colorado Plateau in Southwest United States, including a mean $^{206}Pb/^{238}U$ date of 219.39 ± 0.16 Ma from the renowned *Placerias* Quarry Bone Bed in eastern Arizona. The new results prompt revisions to the chronostratigraphy of the lower Chinle and provide a new temporal context for its rich tetrapod fauna.

The oldest documented dinosaurs of North America coexisted with their non-dinosaurian near-relatives for a minimum of 12 m.y., from *ca.* 223 Ma to *ca.* 211 Ma, in the Norian. This early dinosauromorph record follows a *ca.* 6 m.y. period from which no tetrapod fossils have been documented and which was itself preceded by a *ca.* 10 m.y. depositional hiatus spanning nearly the entire Ladinian and Carnian stages of the terrestrial North America. The supposed late appearance of dinosauromorphs in North America compared to those in South America thus appears to be an artifact of incomplete preservation, as well as unsubstantiated age interpretations. This, together with the conspicuous biogeographic distinctions among the Triassic dinosauromorph assemblages, invalidates a simple diachronous model for the transcontinental radiation of early dinosaurs.

Key words: Late Triassic, Chinle Formation, U-Pb geochronology, *Placerias* Quarry, dinosaur evolution, North America

INTRODUCTION

The distribution in space and time of the earliest dinosaurs and their closest non-dinosaurian evolutionary relatives, known as basal dinosauromorphs, play a key role in understanding the early evolution of dinosaurs. Nevertheless, the great majority of the dinosauromorph-bearing deposits lack a reliable chronostratigraphy and in the absence of reliable radioisotopic dates, correlations have been historically based upon (paradoxical) tetrapod biostratigraphy, uncalibrated magnetostratigraphy or fossil palynomorphs. This has added to the difficulties of unravelling the mode and tempo of the early dinosaur evolution. Fossil occurrences of the earliest dinosaurs are limited to

---

* Department of Earth, Atmospheric and Planetary Sciences, Massachusetts Institute of Technology, 77 Massachusetts Avenue, Cambridge, Massachusetts 02139 USA

** Department of Geosciences, University of Rhode Island, 9 E. Alumni Avenue, Kingston, Rhode Island 02881 USA

† Corresponding author: ramezani@MIT.EDU; (617) 253 1384

a few Late Triassic continental basins scattered throughout the Pangean supercontinent. Significant occurrences include the Ischigualasto-Ville Union basin of northwestern Argentina, Paraná basin of southern Brazil, Karoo basin of South Africa, Pranhita-Godavari basin of peninsular India, Germanic basin of central Europe, Triassic basins of the British Isles and Normandy, and the Chinle-Dockum basin of southwestern US (see Brusatte and others, 2010a; Langer and others, 2010).

The Upper Triassic Chinle Formation of the Colorado Plateau in the southwestern United States preserves the earliest record of dinosaurs and their near-relatives in North America (for example Hunt and others, 1998; Nesbitt and others, 2007). Furthermore, its depositional history as well as the records of biotic and paleoenvironmental change it preserves have important implications for the early evolution of dinosaurs. Recent studies combining high-precision U-Pb zircon geochronology and high-resolution sequence stratigraphy have elucidated the depositional history of the Chinle Formation in eastern Arizona in unprecedented detail and have provided robust age constraints for its tetrapod assemblages (Ramezani and others, 2011; Atchley and others, 2013). Here we present new U-Pb geochronology for the presumed oldest fossil-bearing Chinle deposits in Arizona and New Mexico. A revised chronostratigraphy for the basal Chinle Formation is presented, proposed correlations with the South American dinosauromorph record are examined and implications for the early evolution of dinosaurs are discussed.

STRATIGRAPHY AND REGIONAL CORRELATION

Stratigraphic Subdivisions and Age of the Chinle Formation

The Chinle Formation is best exposed in the Petrified Forest National Park (PEFO) and vicinity in eastern Arizona (fig. 1A). There, the formation is generally subdivided into five members (fig. 2) that from bottom to the top are the Mesa Redondo, Blue Mesa (also known as Lower Petrified Forest), Sonsela, Petrified Forest (also known as Painted Desert) and Owl Rock Members (see reviews by Woody, 2006; Martz and Parker, 2010). The base of the Chile Formation is locally marked by a distinct conglomerate unit, known as the Shinarump Member, which underlies and/or intertongues with the Mesa Redondo Member (Akers and others, 1958; Cooley, 1958; Stewart and others, 1972a). Likely correlative with the Shinarump Member is a distinctive, pedoturbated, mudstone horizon (fig. 2B) known as the "mottled strata" (for example Stewart and others, 1972a). The topmost Chinle deposits are represented by the Rock Point Member (for example Harshbarger and others, 1957).

Based on the view that lithostratigraphic units of the Colorado Plateau are laterally continuous, correlatable and bounded by basin-wide unconformities, Lucas (1993) elevated the Chinle Formation to Group, in effect turning designated members or groups of members into formations (fig. 2B). This stratigraphic scheme, however, has not been widely adopted. We continue to refer to the lithostratigraphic subdivisions of the Chinle as members, despite our strong reservations as to their lateral continuity and correlatability across distant outcrops (see DISCUSSION below).

Previous geochronological investigations on the Chinle Formation largely focused on the age and provenance of detrital zircons in its tuffaceous sedimentary rocks (for example Riggs and others, 1996; Dickinson and Gehrels, 2008), or were restricted to individual dates from isolated Chinle beds (Riggs and others, 2003; Heckert and others, 2009; Irmis and others, 2011). A newly established, high-resolution chronostratigraphy for the Chinle Formation in the PEFO area (fig. 2A) based on U-Pb zircon geochronology (CA-TIMS method) of closely-spaced, tuffaceous interbeds (Ramezani and others, 2011; Atchley and others, 2013) has allowed integration of the Chinle into the marine-based, global Triassic, independent of controversial tetrapod biochronology or inconclusive magnetostratigraphy. Accordingly, the deposition of the Mesa

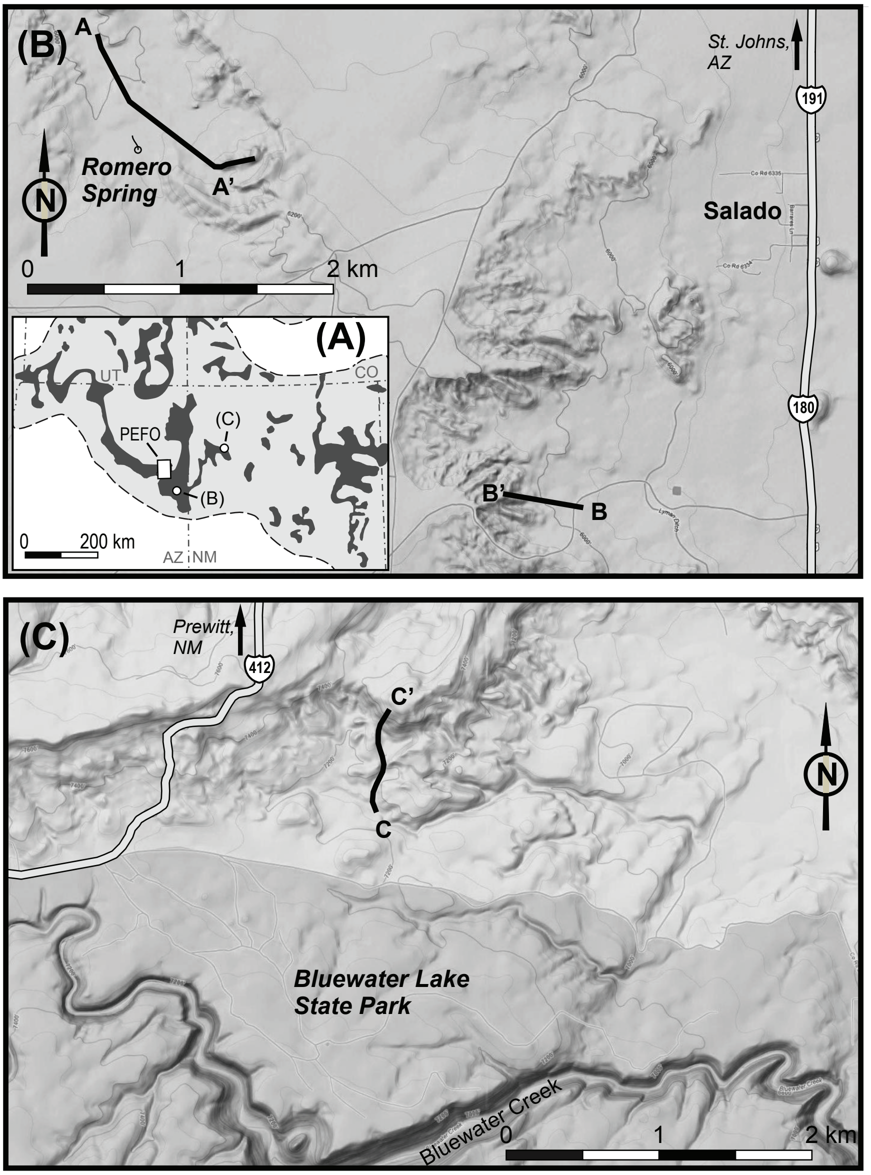

Fig. 1. (A) Geographic distribution of the Upper Triassic Chinle Formation (dark gray) and the extrapolated paleogeographic extent of the Chinle-Dockum Basin (light gray) throughout the states of Arizona and New Mexico, Southwest United States. PEFO—Petrified Forest National Park. (B) Salado—Romero Spring, AZ study area. (C) Bluewater Creek, NM study area. Labeled transects correspond to stratigraphic sections in figure 3. Shaded relief images from Google Maps.

Redondo Member started shortly before 227.604 ± 0.082 Ma (*ca.* 228.1 Ma by extrapolation), which coincides with the approximate Carnian–Norian boundary age based on the latest preferred calibration of the Triassic time scale (GTS2012: Gradstein and others, 2012). The Petrified Forest-Owl Rock Member boundary of the upper Chinle Formation is placed at *ca.* 207.2 Ma, corresponding to the early Rhaetian.

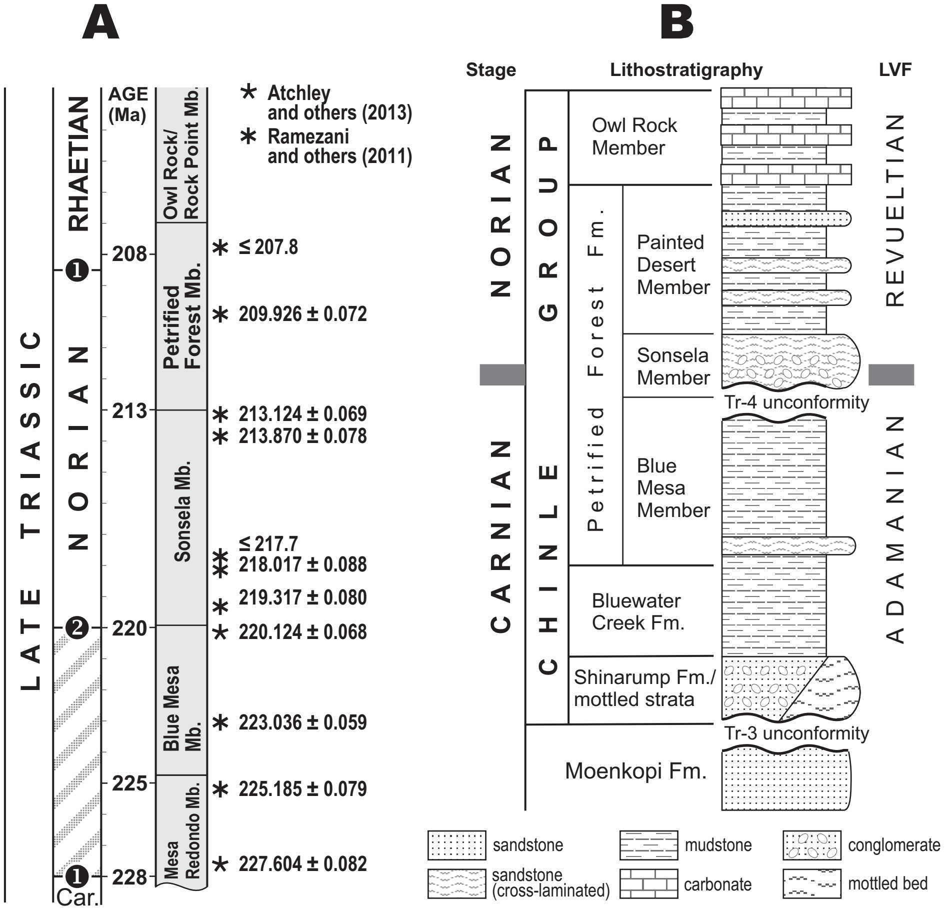

Fig. 2. (A) Modern, age-calibrated stratigraphy of the Chinle Formation based on U-Pb geochronology of Ramezani and others (2011) and Atchley and others (2013) from the Petrified Forest National Park (PEFO) and vicinity. Triassic time scale based on Gradstein and others (2012), showing both the "long Norian" (1) and "short Norian" (2) calibrations of the Late Triassic Epoch. (B) Example of traditional lithostratigraphy of the Upper Triassic strata in eastern Arizona and western New Mexico, as laid out by Heckert and Lucas (2002), showing two of the presumed basin-wide Triassic unconformities of the Colorado Plateau. Major Land Vertebrate Faunachrons (LVF) from Lucas (2010). Car. = Carnian, Fm. = Formation, Mb. = Member.

The Chinle Formation therefore spans nearly the entire final 26 m.y. of the Triassic Period.

Throughout much of the Colorado Plateau, the Chinle Formation is underlain by the predominantly siliciclastic and locally evaporate-bearing strata of the Moenkopi Formation (fig. 2B) that were deposited in transitional fluvial–to–flood plain and deltaic settings (McKee, 1954; Akers and others, 1958; Stewart and others, 1972b). A prominent unconformity marks the contact between the basal Shinarump Member of the Chinle and the topmost Holbrook Member of the Moenkopi (Tr-3 unconformity of Pipiringos and O'Sullivan, 1978); it has locally eroded the entire Moenkopi succession down to the underlying Permian strata. The Moenkopi Formation is thought to be Early-Middle Triassic based on ammonite fossils in its intraformational limestones (Poborski, 1954) and its vertebrate biostratigraphy (Welles, 1947; Camp and others, 1947; Lucas and Schoch, 2002; Heckert and others, 2005). Uranium-lead detrital zircon geochronology (*in situ* dating techniques), however, suggests that the topmost Holbrook Member of the Moenkopi Formation was deposited as late as the Anisian–Ladinian boundary (*ca.* 244-240 Ma) of the Middle Triassic (Dickinson and Gehrels, 2009). Similarly, detrital zircon age data from the overlying Shinarump Member in northeastern Arizona, southern Utah and eastern Nevada (Dickinson and Gehrels, 2008) indicate (maximum) ages of deposition in the *ca.* 234 to 229 Ma range. These suggest that an approximately 10 m.y. hiatus is associated with the sub-Chinle unconformity that spans nearly the entire Ladinian and Carnian Stages of the Triassic.

Regional Correlation of the Lower Chinle Formation

The Chinle lithostratigraphic scheme laid out in eastern Arizona has been applied to other Upper Triassic deposits, albeit different terminologies, throughout the Colorado Plateau (for example Cooley, 1959; Stewart and others, 1972a; Blakey and Gubitosa, 1983; Lucas and Heckert, 1996). These include the general tripartite subdivisions of the middle Chinle succession into Blue Mesa (Lower Petrified Forest), Sonsela and Petrified Forest (Upper Petrified Forest or Painted Desert) Members. More contentious however has been the correlation of deposits that occupy the lower interval of the Chinle Formation, immediately overlying the basal Shinarump Member and/or the mottled strata (fig. 2). These deposits have been assigned by various workers to the Lower Red, Mesa Redondo, Monitor Butte or Bluewater Creek Member (for example Cooley, 1958; Repenning and others, 1969; Stewart and others, 1972a; Lucas and Hayden, 1989).

The lower Chinle deposits are widely exposed in the area surrounding the town of St. Johns (Apache County, Arizona), 50 km southeast of the PEFO. Several detailed stratigraphic sections were measured in this area by Stewart and others (1972a) of which “Section B” is geographically closest and most relevant to our study area in Arizona (see *Lithostratigrahy* below and fig. 1B). Here, the Chinle strata have been ascribed from bottom to top to the mottled strata (5.1 m), Shinarump Member (10.2 m) and the Mesa Redondo Member (25.8 m), overlain by 8.2 meters of the Lower Petrified Forest (herein Blue Mesa) Member rocks. Farther west towards Salado and Romero Spring (fig. 1B), however, the relationship between Blue Mesa Member and the Mesa Redondo Member is obscure (Jacobs and Murry, 1980) and stratigraphy is difficult to resolve.

Lucas and others (1997b) and Heckert and Lucas (2003) incorporated a large part of the Chinle deposits in the vicinity of St. Johns, including those in the Salado and Romero Spring areas, to their Bluewater Creek Member (Formation), following the stratigraphic subdivisions of Lucas and Hayden (1989) laid out in western New Mexico. The Bluewater Creek Formation was introduced to occupy the lower Chinle interval between the basal Shinarump Member/mottled strata and the overlying Blue Mesa Member (fig. 2B) by substituting the Mesa Redondo, Monitor Butte and Lower Red Members altogether (Lucas and others, 1997a; Heckert and Lucas, 2002a; Heckert and Lucas, 2002b).

Accurate correlation of the lower Chinle deposits and fauna as discussed below bears important ramifications for the Late Triassic biostratigraphy of the Colorado Plateau.

Placerias Quarry

The highly fossiliferous *Placerias* and adjacent Downs Quarries of the Chinle Formation are located in the area of Romero Spring, 14 km to the southeast of St. Johns (fig. 1B). Their exact stratigraphic position has been difficult to determine because of poor exposure of subhorizontal beds in an area of shallow topography (for example Jacobs and Murry, 1980). However, they are surrounded by stretches of buttes and badlands that expose typical interstratified mudstones and sandstones of the Chinle Formation.

The rocks surrounding the *Placerias*-Downs Quarry have been traditionally mapped as part of the Lower Chinle or Lower Petrified Forest (Blue Mesa) Member of the Chinle Formation by most workers (for example Camp and Welles, 1956; Akers, 1964; Jacobs and Murry, 1980), noting insufficient exposure to allow detailed correlation to the nearby Chinle outcrops. However, Lucas and others (1997b) and Heckert and Lucas (2003) correlated the strata of the quarries and adjacent areas to the base of the Bluewater Creek Formation in western New Mexico, significantly lower in stratigraphy than previously recognized. The latter correlation was based entirely on lithologic evidence such as color, the presence of dark (anoxic) shales and crystalline gypsum closely associated with the *Placerias* Bone Bed, and the absence of Sonsela type lithologies from the overlying strata. In contrast, Parker and Martz (2011) and Irmis and others (2011) placed the *Placerias* Quarry in the upper part of the Blue Mesa Member, though without providing further supporting evidence.

Together, the two quarries have produced since 1930 one of the richest collections of Triassic fossil vertebrates in the Western Hemisphere, including up to eighty tetrapod taxa (Camp and Welles, 1956; Jacobs and Murry, 1980; Kaye and Padian, 1994; Lucas and others, 1997b). Large, disarticulated and variably fragmented fossil bones occur within two stratigraphic levels, 0.6 meters apart at the *Placerias* Quarry, with the lower (main) bone level characterized by the remarkable dominance of the large hippopotamus-like dicynodont *Placerias* (Camp and Welles, 1956; Jacobs and Murry, 1980). The Downs Quarry is located *ca.* 72 m to the east and is stratigraphically higher than the upper *Placerias* bone level by approximately 3.5 meters (fig. 3). Whereas a typical mid-Chinle tetrapod assemblage is dominated by metoposaurian amphibians and phytosaurs that inhabited a flood-plain depositional environment, the main bone bed of the *Placerias* Quarry preserves a largely terrestrial macrofauna represented by *Placerias*, aetosaurs and rauisuchian archosaurs (Jacobs and Murry, 1980; Kaye and Padian, 1994; Fiorillo and others, 2000). In contrast, the upper *Placerias* Bone Bed and the Downs Quarry display more typical Chinle macrofaunal compositions. The identifiable microvertebrates are represented about equally by tetrapods and non-tetrapods, with the latter dominated by ancient (freshwater) sharks and fishes (Jacobs and Murry, 1980; Kaye and Padian, 1994).

The matrix of the *Placerias* Bone Bed has been identified as a poorly consolidated, grayish, bentonitic clay, through which partly disintegrated skulls and other skeletal elements are scattered (Camp and Welles, 1956). Other distinctive features of the bone bed are the abundance of carbonate (mostly calcareous nodules), crystalline gypsum and sulfurous deposits, which were attributed to chemosynthetic bacterial action in a "soft, wet, vegetated pond bottom" environment, where tetrapods supposedly congregated and fed (Camp and Welles, 1956; Jacobs and Murry, 1980). Fiorillo and others (2000) reevaluated the depositional environment of the *Placerias* Bone Bed as palustrine deposits associated with ephermal freshwater springs, to which large numbers of animals were presumably drawn in times of seasonal dryness.

METHODS AND RESULTS

Lithostratigraphy

Stratigraphic sections were measured at three key Chinle outcrops where sedimentary strata attributed to the Bluewater Creek Formation are exposed. The first two outcrops are located in the hills surrounding the community of Salado, 5 km to the southwest of St. Johns in eastern Arizona (fig. 1B). One is 2.5 km southwest of Salado (herein referred to as the Salado Section) and nearly 10 km to the west of "St. Johns Section B" of Stewart and others (1972a). Another is located farther west at Romero

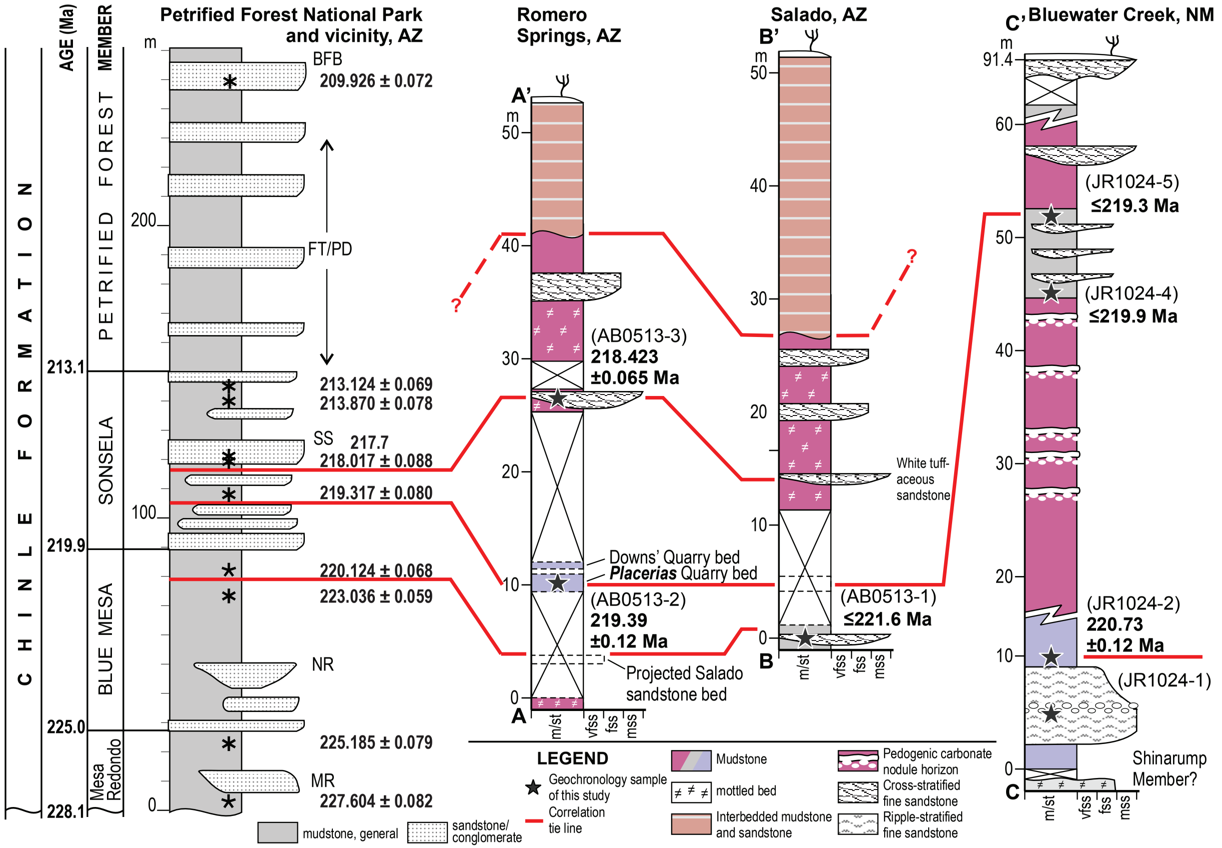

Fig. 3. Measured stratigraphic sections illustrating lithostratigraphy and age correlation of the lower Chinle successions in eastern Arizona and western New Mexico with respect to the PEFO reference section (see fig. 2 for references). BFB = Black Forest Bed, FT = Flattops sandstone beds, MR = Mesa Redondo conglomerate bed, NR = Newspaper Rock sandstone bed, PD = Painted Desert sandstone beds, SS = Sonsela sandstone/conglomerate bed.

TABLE 1

U-Pb data for analyzed zircon from tuffaceous rocks of the lower Chinle Formation

	Composition					Ratios[5]						Age (Ma)				
Sample Fraction [1]	Pb_c[2] (pg)	$\frac{Pb^*}{Pb_c}$[2]	$\frac{Th}{U}$	$\frac{^{206}Pb}{^{204}Pb}$[3]	$\frac{^{208}Pb}{^{206}Pb}$[4]	$\frac{^{206}Pb}{^{238}U}$	err (2σ%)	$\frac{^{207}Pb}{^{235}U}$	err (2σ%)	$\frac{^{207}Pb}{^{206}Pb}$	err (2σ%)	$\frac{^{206}Pb}{^{238}U}$	err (2σ)	$\frac{^{207}Pb}{^{235}U}$	$\frac{^{207}Pb}{^{206}Pb}$	corr. coef.
Salado/Romero Spring, Apache County, Arizona																
AB0513-3																
z5	0.7	49.2	1.57	2321.9	0.496	0.034945	(.07)	0.24353	(.45)	0.05057	(.43)	221.42	0.14	221.31	220.1	0.39
z3	0.6	18.5	1.47	901.4	0.466	0.034734	(.12)	0.24245	(1.14)	0.05065	(1.10)	220.11	0.26	220.4	224	0.39
z8	0.5	18.4	0.78	1043.6	0.248	0.034673	(.10)	0.24134	(1.20)	0.05051	(1.18)	219.73	0.21	219.5	217	0.29
z7	0.5	33.2	1.08	1743.3	0.343	0.034539	(.10)	0.24042	(.65)	0.05051	(.61)	218.89	0.21	218.8	217	0.46
z4	0.4	285	0.81	15822	0.257	0.034478	(.06)	0.24011	(.13)	0.05053	(.09)	**218.51**	**0.12**	218.51	218.5	0.66
z1	1.7	31.0	0.88	1708.4	0.277	0.034469	(.07)	0.24000	(.57)	0.05052	(.55)	**218.46**	**0.16**	218.4	218	0.31
z6	0.4	59.0	0.89	3227.0	0.283	0.034463	(.06)	0.23993	(.34)	0.05052	(.33)	**218.42**	**0.13**	218.37	217.8	0.28
z2	0.4	147	1.09	7663.8	0.345	0.034445	(.06)	0.23981	(.21)	0.05052	(.18)	**218.31**	**0.12**	218.26	217.7	0.52
AB0513-2																
z8	0.3	5.3	1.41	276.0	0.447	0.034857	(.36)	0.24203	(3.97)	0.05038	(3.85)	220.88	0.78	220.1	212	0.36
z10	0.4	5.9	1.38	304.6	0.438	0.034816	(.38)	0.24218	(4.75)	0.05047	(4.58)	220.62	0.82	220.2	216	0.48
z12	0.5	5.2	1.46	265.6	0.463	0.034807	(.40)	0.24628	(4.65)	0.05134	(4.47)	220.56	0.87	223.6	255	0.48
z5	0.4	16.6	1.29	844.7	0.408	0.034741	(.13)	0.24241	(1.29)	0.05063	(1.25)	220.15	0.29	220.4	223	0.38
z6	0.3	20.2	1.39	998.4	0.441	0.034720	(.11)	0.24217	(1.18)	0.05061	(1.14)	220.02	0.25	220.2	222	0.39
z7	0.5	22.4	0.70	1291.3	0.223	0.034642	(.09)	0.24138	(1.03)	0.05056	(1.02)	**219.53**	**0.20**	219.6	220	0.22
z2	0.3	43.9	1.18	2251.6	0.375	0.034615	(.10)	0.24127	(.55)	0.05057	(.54)	**219.37**	**0.22**	219.5	220	0.24
z4	0.4	15.8	1.18	823.8	0.373	0.034607	(.14)	0.24092	(1.43)	0.05051	(1.38)	**219.32**	**0.30**	219.2	218	0.45
z13	0.4	7.1	1.24	372.6	0.393	0.034589	(.36)	0.24090	(3.32)	0.05053	(3.19)	**219.21**	**0.78**	219.2	219	0.41
z1	0.3	39.3	0.95	2127.4	0.300	0.034576	(.18)	0.24124	(.63)	0.05062	(.57)	**219.13**	**0.38**	219.4	223	0.43
z3	0.3	25.5	1.30	1280.7	0.413	0.034384	(.09)	0.23962	(.84)	0.05057	(.80)	217.93	0.19	218.1	220	0.40
AB0513-1																
z6	0.3	53.0	0.45	3171.0	0.135	0.227633	(.11)	2.67225	(.27)	0.08518	(.23)	1322.1	1.4	1320.8	1318.8	0.55
z16	0.3	24.5	0.54	1454.9	0.164	0.174620	(.11)	1.77687	(.56)	0.07383	(.53)	1037.5	1.0	1037.04	1036	0.31
z5	0.3	68.5	0.70	3889.2	0.213	0.158110	(.16)	1.54092	(.26)	0.07072	(.21)	946.3	1.4	946.87	948.3	0.60
z7	0.7	8.5	1.18	450.7	0.367	0.096064	(.25)	0.78955	(1.9)	0.05964	(1.8)	591.3	1.4	590.92	589	0.24
z13	0.3	1.0	1.26	69.4	0.393	0.077908	(2.84)	0.59787	(21.2)	0.05568	(20.5)	484	13	476	439	0.32
z17	0.2	34.8	0.43	2140.5	0.136	0.065232	(.09)	0.49178	(.63)	0.05470	(.61)	407.37	0.37	406.12	399	0.32

TABLE 1

(continued)

	Composition					Ratios[5]						Age (Ma)				
Sample Fraction [1]	Pb_c[2] (pg)	Pb*[2] / Pb_c	Th / U	^{206}Pb[3] / ^{204}Pb	^{208}Pb[4] / ^{206}Pb	^{206}Pb / ^{238}U	err (2σ%)	^{207}Pb / ^{235}U	err (2σ%)	^{207}Pb / ^{206}Pb	err (2σ%)	^{206}Pb / ^{238}U	err (2σ)	^{207}Pb / ^{235}U	^{207}Pb / ^{206}Pb	corr. coef.
Salado/Romero Spring, Apache County, Arizona																
AB0513-1																
z3	0.3	16.1	0.39	1015.0	0.122	0.064126	(.33)	0.47533	(1.2)	0.05378	(1.1)	400.7	1.3	394.87	361	0.43
z10	0.4	4.5	0.40	296.9	0.126	0.062364	(.41)	0.46889	(3.79)	0.05455	(3.65)	390.0	1.5	390	393	0.39
z14	0.2	17.5	0.90	966.2	0.283	0.061135	(.16)	0.45087	(1.14)	0.05351	(1.11)	382.52	0.59	377.89	350	0.27
z9	0.4	4.3	0.38	286.0	0.121	0.054999	(.44)	0.40160	(3.83)	0.05298	(3.68)	345.1	1.5	343	327	0.37
z8	0.3	4.9	0.85	289.0	0.268	0.051333	(.61)	0.36364	(4.17)	0.05140	(4.01)	322.7	1.9	315	258	0.33
z4	0.5	26.1	1.01	1398.8	0.320	0.035157	(.09)	0.24512	(.78)	0.05059	(.75)	**222.74**	**0.19**	222.60	221	0.40
z1	0.5	2.6	1.20	149.6	0.379	0.034979	(.63)	0.24376	(7.33)	0.05056	(7.15)	**221.6**	**1.4**	221	220	0.33
Blue Water Creek, McKinley County, New Mexico																
JR1024-5																
z10	0.4	34.2	1.81	1545.7	0.550	0.173097	(.22)	1.75605	(.56)	0.07361	(.49)	1029.2	2.1	1029.4	1030	0.51
z14	0.3	52.6	0.48	3158.9	0.146	0.129521	(.34)	1.23876	(.47)	0.06940	(.30)	785.1	2.5	818.32	909.6	0.76
z5	0.4	6.6	0.99	370.3	0.309	0.067107	(.63)	0.50660	(2.86)	0.05478	(2.75)	418.7	2.6	416.16	402	0.28
z7	0.3	6.7	0.70	398.1	0.220	0.065555	(.30)	0.48963	(3.03)	0.05419	(2.94)	409.3	1.2	405	378	0.36
z9	0.3	15.4	0.51	940.2	0.159	0.062422	(.23)	0.46052	(1.08)	0.05353	(1.10)	390.34	0.88	384.62	350	0.04
z8	0.4	5.2	0.59	321.2	0.184	0.062360	(.63)	0.46180	(4.17)	0.05373	(4.01)	390.0	2.4	386	359	0.34
z13	0.5	3.9	0.10	276.4	0.031	0.062290	(.35)	0.47864	(3.94)	0.05575	(3.82)	389.5	1.3	397	442	0.39
z12	0.3	9.2	0.10	631.5	0.032	0.062277	(.27)	0.45960	(2.29)	0.05355	(2.18)	389.5	1.0	383.98	351	0.47
z2	0.3	5.4	0.39	354.2	0.123	0.061711	(.30)	0.45921	(3.44)	0.05399	(3.34)	386.0	1.1	384	370	0.39
z11	0.2	14.0	0.79	797.6	0.249	0.059098	(.30)	0.44285	(1.39)	0.05437	(1.31)	370.1	1.1	372.26	385	0.34
z1	0.3	12.1	0.91	671.8	0.288	0.034605	(.17)	0.24076	(1.58)	0.05048	(1.54)	**219.30**	**0.36**	219.05	216	0.29
z4	0.4	5.5	1.36	285.6	0.432	0.034591	(.43)	0.24184	(4.02)	0.05073	(3.90)	**219.22**	**0.92**	219.92	227	0.32
JR1024-4																
z7	0.3	11.0	1.95	495.7	0.604	0.101581	(.29)	0.84626	(1.80)	0.06045	(1.73)	623.7	1.7	622.6	619	0.31
z8	0.4	16.1	0.52	978.3	0.164	0.065688	(.31)	0.48783	(1.40)	0.05389	(1.26)	410.1	1.2	403.4	365	0.53
z3	0.4	10.1	0.38	644.3	0.119	0.065538	(.31)	0.49564	(1.84)	0.05487	(1.71)	409.2	1.2	408.7	406	0.49
z2	0.3	8.5	0.65	507.3	0.202	0.062594	(.23)	0.47287	(2.24)	0.05482	(2.18)	391.38	0.88	393.2	404	0.34
z1	0.4	6.6	0.51	414.4	0.160	0.062559	(.51)	0.45969	(2.89)	0.05332	(2.75)	391.2	1.9	384.0	341	0.35

TABLE 1
(continued)

	Composition					Ratios[5]						Age (Ma)				
Sample Fraction [1]	Pb_c[2] (pg)	Pb^*[2]/Pb_c	Th/U	^{206}Pb[3]/^{204}Pb	^{208}Pb[4]/^{206}Pb	^{206}Pb/^{238}U	err (2σ%)	^{207}Pb/^{235}U	err (2σ%)	^{207}Pb/^{206}Pb	err (2σ%)	^{206}Pb/^{238}U	err (2σ)	^{207}Pb/^{235}U	^{207}Pb/^{206}Pb	corr. coef.
Blue Water Creek, McKinley County, New Mexico																
JR1024-4																
z4	0.3	14.1	0.42	877.6	0.133	0.061496	(.12)	0.45698	(1.31)	0.05392	(1.28)	384.72	0.43	382.2	367	0.24
z5	0.2	32.2	0.76	1828.3	0.239	0.046481	(.08)	0.33411	(.69)	0.05216	(.67)	292.88	0.23	292.7	291	0.24
z6	0.3	20.7	0.88	1148.3	0.278	0.034704	(.09)	0.24150	(.89)	0.05049	(.86)	**219.92**	**0.19**	219.7	217	0.34
JR1024-2																
z4	0.6	37.8	0.26	2386.8	0.077	0.208208	(.16)	2.32443	(.37)	0.08101	(.31)	1219.3	1.7	1219.8	1220.7	0.56
z1	0.3	8.3	0.59	502.7	0.185	0.063016	(.36)	0.46900	(2.34)	0.05400	(2.22)	393.9	1.4	390.5	370	0.40
z7	0.7	6.7	0.44	424.6	0.138	0.061778	(.30)	0.44165	(2.46)	0.05187	(2.39)	386.4	1.1	371.4	279	0.29
z5	1.0	2.2	0.43	155.6	0.134	0.057956	(.70)	0.43353	(7.26)	0.05428	(7.03)	363.2	2.5	365.7	382	0.37
z2	0.3	32.1	1.28	1617.2	0.404	0.034847	(.08)	0.24321	(.75)	0.05064	(.72)	**220.81**	**0.18**	221.0	223	0.33
z3	0.3	42.1	1.26	2120.4	0.399	0.034826	(.08)	0.24269	(.60)	0.05056	(.58)	**220.68**	**0.17**	220.6	220	0.29
z6	0.9	18.0	0.81	1016.6	0.256	0.034804	(.19)	0.24261	(.97)	0.05058	(.91)	**220.55**	**0.42**	220.6	221	0.39
JR1024-1																
z1	0.3	7.2	0.44	454.9	0.138	0.070972	(.36)	0.54803	(3.16)	0.05603	(2.98)	442.0	1.5	444	452	0.54
z2	0.4	16.2	0.63	958.5	0.200	0.058423	(.16)	0.43272	(1.01)	0.05374	(.96)	366.03	0.56	365.1	359	0.37
z4	0.4	63.9	1.31	3179.9	0.412	0.051156	(.07)	0.37271	(.39)	0.05287	(.37)	321.61	0.21	321.7	322.0	0.38

Notes: Corr. coef. = correlation coefficient. Age calculations are based on the decay constants of Jaffey and others (1971).

[1] All analyses are single zircon grains and pre-treated by the thermal annealing and acid leaching (CA-TIMS) technique. Data used in age calculations are in bold.

[2] Pb_c is total common Pb in analysis. Pb* is radiogenic Pb concentration.

[3] Measured ratio corrected for spike and fractionation only.

[4] Radiogenic Pb ratio.

[5] Corrected for fractionation, spike, blank, and initial Th/U disequilibrium in magma. Mass fractionation correction of 0.25%/amu ± 0.04%/amu (atomic mass unit) was applied to single-collector Daly analyses. All common Pb is assumed to be blank. Total procedural blank was less than 0.1 pg for U. Blank isotopic composition: ^{206}Pb/^{204}Pb = 18.42 ± 0.35, ^{207}Pb/^{204}Pb = 15.36 ± 0.23, ^{208}Pb/^{204}Pb = 37.46 ± 0.74.

Spring (4 km west of Salado), where the renowned *Placerias* and Downs quarries are located. The third outcrop is located in the Zuni Mountains of northwestern New Mexico, south of the town of Prewitt (McKinley County) and near the northern boundary of the Bluewater Lake State Park (fig. 1C), where the type section of the Bluewater Creek Formation is located (Lucas and Hayden, 1989). Lithology, grain size, thickness and sedimentary structures were recorded in each locality and stratigraphic columns were constructed (fig. 3). Samples were collected for zircon geochronology from potentially tuffaceous mudstones and sandstones within the stratigraphic context of the three measured stratigraphic sections.

The Chinle strata of the Salado and Romero Spring sections are lithologically similar, though variable in thickness, and consist of a) a partially exposed lower interval of gray to grayish purple mudstones, b) a middle interval of purple, mottled mudstones and siltstones intercalated with beds of white to buff, cross-stratified, tuffaceous sandstone, and c) an upper interval of interbedded sandstone and tan mudstone forming the hilltop slopes (fig. 3). The lower mudstone interval exposed at Romero Spring contains the *Placerias* and Downs bone beds. The upper interval is lithologically more uniform and rests disconformably on the middle interval. Its affinity is unclear, but likely correlates with the upper Sonsela and/or Petrified Forest Member of the Chinle Formation.

The Bluewater Creek section (figs. 1C and 3) consists of the Chinle strata exposed throughout the northern tributaries and headwaters of the Bluewater Creek. The section is slightly over 90 meters thick and is dominated by a variety of dark-purple, purple-red and gray, silty mudstones with isolated sandstone beds only near the base and top of the section. Multiple indurated, nodular, carbonate beds interlayered with purple mudstone form a set of stacked paleosols in the lower-middle part of the section (fig. 3), resembling the typical landscape of the Petrified Forest (Painted Desert) Member of the Chinle Formation exposed throughout the northern PEFO. The lowermost Chinle strata in the Bluewater Creek area are underlain unconformably by the red sandstones of the Moenkopi Formation. The contact is marked by a variably thick interval of the highly indurated "mottled strata" (Stewart and others, 1972a; Heckert and Lucas, 2002a) (fig. 3).

U-Pb Geochronology

Sixty-two single zircons from 7 rock samples were analyzed by the U-Pb ID-TIMS method following the procedures described in Ramezani and others (2011). All zircons were pre-treated by a chemical abrasion (CA-TIMS) technique modified after Mattinson (2005) and spiked with the EARTHTIME ET535 mixed ^{205}Pb-^{233}U-^{235}U tracer prior to dissolution and analysis. Data reduction including date calculation and propagation of uncertainties was carried out using applications Tripoli and U-Pb Redux developed as part of the EARTHTIME initiative (Bowring and others, 2011; McLean and others, 2011). Complete U-Pb data appear in table 1.

The tuffaceous sample dates interpreted as maximum depositional ages are calculated based on the weighted mean ^{206}Pb/^{238}U date of a coherent cluster of the youngest zircon analyses from the sample, provided that there are at least 3 precise analyses to form a cluster, and are reported at 95 percent confidence level. Uncertainties in the calculated sample dates are reported as ±X/Y/Z Ma, where X is the internal (analytical) uncertainty in the absence of all external errors, Y incorporates the U-Pb tracer calibration error and Z includes the latter as well as the decay constant errors of Jaffey and others (1971). Calculated sample dates and detailed uncertainties are listed in table 2 and illustrated in date distribution plots of figure 4A. Since the high-resolution Chile Formation geochronology presented in Ramezani and others (2011), Atchley and others (2013) and this study were all produced using the same U-Pb tracer, only the analytical uncertainties (X) need to be considered here.

Table 2

Summary of calculated U-Pb dates and their uncertainties

Sample	Location	$\frac{^{206}\mathrm{Pb}}{^{238}\mathrm{U}}$ date (Ma)	error (2σ)			MSWD	*n*
			X	Y	Z		
AB0513-3	Romero Spring, AZ	218.423	0.065	0.11	0.26	1.9	4
AB0513-2	Romero Spring, AZ	219.39	0.12	0.16	0.28	1.1	5
AB0513-1	Salado, AZ	≤ 221.6	-	-	-	-	1
JR1024-5	Blue Water Creek, NM	≤ 219.3	-	-	-	-	2
JR1024-4	Blue Water Creek, NM	≤ 219.9	-	-	-	-	1
JR1024-2	Blue Water Creek, NM	220.73	0.12	0.16	0.28	0.98	3

Note: Sample locations are shown on figure 3.

X—internal (analytical) uncertainty in the absence of all external or systematic errors; Y—incorporates the U-Pb tracer calibration error; Z—includes X and Y, as well as the uranium decay constant errors.

MSWD—mean square of weighted deviates.

n—number of analyses included in the calculated date.

A set of high-precision U-Pb dates from successive tuffaceous beds in stratigraphic sequence is considered a geologically meaningful approximation of the depositional age when the dates are mutually distinct outside 2σ (analytical) uncertainty and they are consistent with stratigraphic order (see Ramezani and others, 2011).

Results

Romero Spring, Arizona.—Sample AB0513-2 was collected from the actively quarried *Placerias* Bone Bed (fig. 3). The rock has the appearance of a loosely consolidated, gray mudstone that has been extensively weathered due to meteoric water seepage, such that its original composition cannot be identified. Nevertheless, it yielded a significant quantity of multifaceted, acicular, zircon crystals with elongate melt inclusions (fig. 4B) common to many felsic volcanic (pyroclastic) rocks. This is consistent with the matrix of the bone bed being largely of tuffaceous origin. Ten single zircons analyzed from this sample ranged in ^{206}Pb/^{238}U dates from 220.88 Ma to 219.13 Ma (table 1), whereas the youngest 5 analyses form a coherent cluster with a weighted mean ^{206}Pb/^{238}U date of 219.39 ± 0.12/0.16/0.28 Ma and a mean square of weighted deviates (MSWD) of 1.1 (table 2 and fig. 4A). This date serves as the best estimate for the maximum age of deposition of the *Placerias* bed. One outlier analysis (z3) yielded a significantly younger date of 217.93 ± 0.19 Ma, probably due to the effects of persistent Pb loss.

A 0.8 meters-thick bed of distinctly white, cross-stratified, sandstone with abundant lithic grains (for example, chert) in a clay-rich matrix is exposed stratigraphically 14 meters above the *Placerias* Bone Bed (fig. 3). The white sandstone bed forms a stratigraphic horizon marking the base of the middle interval (see *Lithostratigraphy*) which is observed in the Salado section, as well. Eight zircons from a sample (AB0513-3) of this bed were analyzed, from which the youngest 4 form a coherent cluster (table 2 and fig. 4A) with a weighted mean ^{206}Pb/^{238}U date of 218.423 ± 0.065/0.11/0.26 Ma (MSWD = 1.9), interpreted as the best estimate for the maximum depositional age of the tuffaceous sandstone.

Salado, Arizona.—The lowermost exposures of the Salado section (figs. 1B and 3) consist of a *ca.* 0.2 meters-thick, poorly exposed, greenish-gray, ripple-laminated sandstone in an apparently mudstone-dominated interval. The sandstone falls approximately 6 meters below the *Placerias* Quarry Bed in Romero Spring by way of stratigraphic projection (fig. 3). A sample of the Salado basal sandstone (AB0513-1) yielded

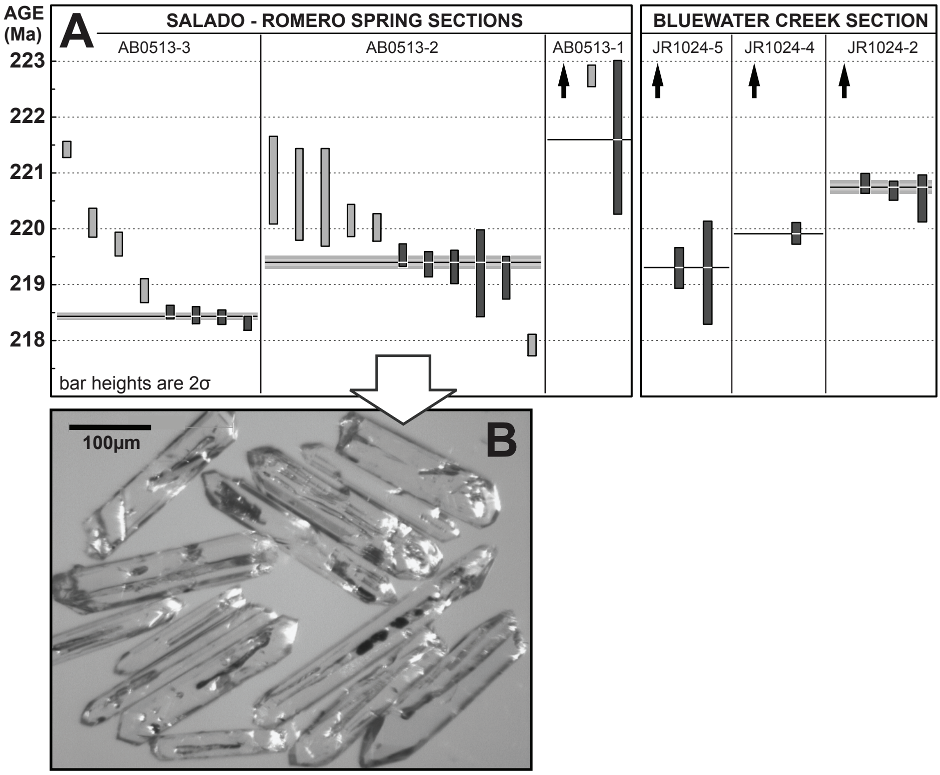

Fig. 4. (A) Date distribution plots of analyzed zircons of this study. Bar heights are proportional to 2σ analytical uncertainty of individual analyses; solid bars are analyses used in age calculation. Horizontal lines signify calculated sample dates and the width of the shaded band represents internal uncertainty in weighted mean at 95% confidence level, where applicable. Solid arrows point to additional analyses plotting outside the diagram. See table 1 for complete analytical data and table 2 for a list of sample ages and detailed uncertainties. (B) Photomicrograph of zircon from the sample of *Placerias* Bone Bed matrix.

a highly mixed population of small and predominantly detrital zircon. Thirteen zircon analyses from this sample ranged in ^{206}Pb/^{238}U dates from 1322.1 ± 1.4 Ma to 221.6 ± 1.4 Ma (table 1 and fig. 4A). The latter represents a crude estimate for the maximum depositional age of the sandstone bed, consistent with its stratigraphic position.

Bluewater Creek, New Mexico.—A climbing-ripple-stratified, ridge-forming, sandstone up to 8 meters in thickness occurs near the base of the exposed Chinle Formation strata at Bluewater Creek (figs. 1C and 3). Only three zircons were analyzed from a sample of the sandstone (JR1024-1), which yielded Paleozoic ^{206}Pb/^{238}U dates ranging from 442.0 ± 1.5 Ma to 321.61 ± 0.21 Ma, reflecting the dominant detrital origin of zircon in this rock.

A sample of purple mudstone approximately 1 meter above the massive sandstone (JR1024-2) produced a more coherent set of zircon analyses. Of 7 analyzed zircon grains from this sample, the youngest three yield a weighted mean ^{206}Pb/^{238}U date of 220.73 ± 0.12/0.16/0.28 Ma (MSWD = 0.98), which we interpret as the maximum depositional age of the bed (fig. 4A).

Two samples of clay-rich siltstone, stratigraphically 7 meters apart, collected from the middle of the Bluewater Creek section and above the stacked paleosol interval (fig. 3) produced zircon analyses with a significant scatter in their ^{206}Pb/^{238}U dates (table 1). Eight analyses from the lower sample (JR1024-4) range in ^{206}Pb/^{238}U dates from

623.7 ± 1.7 Ma to 219.92 ± 0.19 Ma, with the latter representing our best estimate of the maximum depositional age. Similarly, the youngest two (out of 12) zircon ^{206}Pb/^{238}U dates from the upper siltstone sample (JR1024-5) are 219.30 ± 0.36 Ma and 219.22 ± 0.92 Ma, which overlap within uncertainty and provide a provisional estimate for the maximum age of deposition of the bed.

DISCUSSION

New Correlation of the "Lower Chinle" Strata in Arizona and New Mexico

Our new U-Pb zircon dates from each of the Romero Spring or Bluewater Creek sections of the Chinle Formation are mutually resolvable outside the (2σ) analytical uncertainty and obey the observed stratigraphic superposition (fig. 3). Therefore, we consider them to be reliable estimates of the depositional ages of the associated strata. When placed in the broader Chinle Formation geochronologic framework (see *Stratigraphic Subdivisions and Age of the Chinle Formation*), the new results indicate that the package of sedimentary rocks assigned to the Bluewater Creek Formation has a stratigraphic position that occupies the uppermost Blue Mesa Member to the middle Sonsela Member of the Chinle Formation at the PEFO. This is at odds with the lithostratigraphic interpretation of Heckert and Lucas (2002b) and Heckert and Lucas (2003), which places the Bluewater Creek Formation stratigraphically above the Shinarump/mottled strata and below the Blue Mesa Member (fig. 2). Our results indicate that the basal, supra-Shinarump, Chinle deposits are genuinely represented only by the Mesa Redondo Member in eastern Arizona, whereas an unconformity separates the (upper) Blue Mesa Member from the Shinarump/mottle strata in western New Mexico. We therefore suggest that a) the term Bluewater Creek be abandoned as a lithostratigraphic unit or, b) that it refer informally to only the correlative strata of the combined Blue Mesa and Sonsela Members exposed in western New Mexico.

According to the lithostratigraphic correlation of Heckert and Lucas (2002a) the Chinle strata exposed at Bluewater Creek underlie (and partially overlap) those in the Sixmile Canyon, some 40 km to the west-northwest. Previous U-Pb zircon geochronology from a tuffaceous sandstone key bed interpreted to mark the base of the Blue Mesa Member in the Sixmile Canyon produced dates of 220.9 ± 0.6 Ma (Heckert and others, 2009) and 218.1 ± 0.7 Ma (Irmis and others, 2011). Our new geochronology is generally consistent with the above correlation between the Chinle strata exposed at Bluewater Creek and Sixmile Canyon in the Zuni Mountains, but it does not support any correlation scheme that recognizes the Bluewater Creek as a distinct lithostratigraphic unit underlying the Blue Mesa Member of the Chinle, even if a time-transgressive boundary relationship is hypothesized (for example Irmis and others, 2011).

The new geochronologic results highlight drastic changes in fluvial lithofacies on geographic scales shorter than 50 km. Whereas the predominantly white, medium- to coarse-siliciclastic deposits of the lower Sonsela Member in PEFO (Camp Butte, Lot's Wife and Jasper Forest beds of Martz and Parker, 2010) are readily identified as a lithologically distinct stratigraphic interval, they surprisingly show almost no lithologic resemblance to their age-equivalent, mudstone-dominated beds in the nearby St. John-Salado area (fig. 1A). This further emphasizes the complex, horizontally discontinuous and vertically repetitive depositional architecture of the fluvial deposits in extensional continental settings (for example Miall, 1983; Kraus and Middleton, 1987; Dubiel and others, 1991) and warns against any method that relies exclusively upon lithologic characteristics (for example, color, mineralogy, grain size, fabric) for correlation in the absence of outcrop continuity. The presence of otherwise undetectable hiatuses in fluvial successions such as that underlying the Blue Mesa Member strata at Bluewater Creek (see above) also challenges the efficacy of magnetostratigraphy as a correlation tool in this type of setting. We therefore suggest that geochronologic correlation independent of conventional stratigraphic methods is the only viable means for deciphering the depositional history of rock similar to the Chinle Formation.

The anomalously high abundances of carbonate, gypsum and native sulfur associated with the *Placerias* Quarry Bone Bed have been interpreted to reflect the paleoenvironmental conditions of sediment accumulation and/or pedogenesis (Camp and Welles, 1956; Fiorillo and others, 2000) and have been utilized by some workers as lithologic markers for stratigraphic correlation (Lucas and others, 1997a; Lucas and others, 1997b). Our observations, however, recognize the *Placerias* Bone Bed as a zone of active groundwater seepage (for example the Romero Spring), where the differential permeability of the bone bed has facilitated the near-surface water discharge in modern times. We interpret the abundant gypsum, sulfur deposits and possibly carbonate nodules as Quaternary groundwater precipitates, largely unrelated to the Triassic sedimentation or subsequent diagenetic processes. It is also possible that the internal deformation of the bone bed as a result of clay expansion/contraction and sediment liquefaction may have contributed to the post-depositional disarticulation and scattering of the fossil bones. Consequently, the textural and compositional features of the *Placerias* Bone Bed matrix are of dubious stratigraphic significance.

The conspicuous abundance of a morphologically uniform, acicular population of zircon with no physical signs of reworking in the *Placerias* Bone Bed matrix (fig. 4B) is a strong indication that the origin of the bed is predominantly tuffaceous.

Late Triassic Non-marine Biostratigraphy and Land Vertebrate Faunachrons

The Chinle Formation preserves a rich record of non-marine, tetrapod fauna that consists primarily of suchian archosaurs and basal members of the archosauriformes (=Crurotarsi; Nesbitt, 2011), along with less abundant dicynodont therapsids, temnospondyl amphibians, basal dinosauromorphs, primitive theropod dinosaurs and a variety of microvertebrates (for example Lucas, 2010; Parker and Martz, 2011 and references therein). The crurotarsans are predominated by Phytosauria and Aetosauria. The tetrapod assemblages of the Chile Formation and its presumed correlatives have been used to construct a Late Triassic, non-marine biostratigraphy that consists in its modern version of four land-vertebrate faunachrons (LVFs); namely the Otischalkian, Adamanian, Revueltian and Apachian (Lucas, 1998; Lucas, 2010). The LVFs are defined by characteristic faunal assemblages and first appearance datums (FADs) of tetrapod "index" taxa, along the lines of the Cenozoic North American Land Mammal Ages (Savage and Russell, 1983), and have been used for stratigraphic correlation as an alternative to the marine-based Triassic timescale. The so-called Triassic nonmarine, tetrapod biochronology is based upon correspondence between the latter four LVFs, respectively, and the early to late Carnian, late Carnian, early-middle Norian (fig. 2B) and late Norian to Rhaetian stages of the Late Triassic (for example Lucas and Huber, 2003; Lucas, 2010; Lucas and others, 2012). However, the global utility of these faunachrons has been disputed, chiefly based on endemism and/or uncertain temporal ranges of the designated index taxa (for example Rayfield and others, 2009; Irmis and others, 2010). The results reported here further underscore key problems with the Late Triassic, none-marine biochronology.

Lucas and others (1997b) assigned the *Placerias*-Downs quarries assemblage to the Adamanian LVF, despite the widespread presence of Otischalkian faunal elements (for example phytosaur *Paleorhinus*, dicynodont *Placerias*, and the basal archosauromorph *Trilophosaurus*) in that locality. The latter faunal elements were regarded as "holdover" from the Otischalkian (Heckert and Lucas, 2003). This assignment appeared consistent with the occurrence of the diagnostic Adamanian phytosaur *Rutiodon* in the

Placerias Quarry (Camp and Welles, 1956; Jacobs and Murry, 1980). However, an Adamanian (or even Otischalkian) assignment for the *Placerias*-Downs quarries is further contradicted by the reported presence there of *Revueltosaurus callenderi*[1] (Kaye and Padian, 1994) which is considered to be an exclusively Revueltian (or younger) taxon (Lucas, 2010; Parker and Martz, 2011). Therefore, it would seem that an age for the *Placerias* Quarry based on the Triassic non-marine biochronologic scheme remains ambiguous.

In contrast, U-Pb geochronology allows unambiguous correlation of the *Placerias*-Downs quarries with the lower Sonsela Member of the Chinle Formation at the PEFO (see above and fig. 3). In addition, our revised chronostratigraphy makes the fossiliferous beds of the upper Blue Mesa Member at PEFO the oldest documented tetrapod-bearing horizon of the Chinle Formation (fig. 5), pending reliable geochronologic data from the type Otischalkian of western Texas.

The new Chinle geochronology (Ramezani and others, 2011; Atchley and others, 2013) incorporates dated tuffaceous beds collected directly from the Blue Mesa and Sonsela Members exposed in the PEFO (that is, type Adamanian: Lucas, 2010) and thus places reliable constraints on the age and duration of the Adamanian LVF. Combined with the known stratigraphic ranges of fauna at PEFO (compilation of Parker and Martz, 2011) the U-Pb geochronology places the lowest occurrence of *Leptosuchus* (incorporating *Rutiodon*) between 223.036 ± 0.059 Ma and 225.185 ± 0.079 Ma (*ca.* 223 Ma by stratigraphic extrapolation). This age is early Norian according to the preferred Late Triassic time scale calibration of Gradstein and others (2012). With the main *Placerias* Quarry Bone Bed now constrained at a maximum of 219.39 ± 0.12 Ma, the lowest occurrence of *Leptosuchus* at the PEFO marks the most basal Chinle tetrapod record, below which no tetrapod fossils have been documented (fig. 5). This suggests that the complete temporal range of Adamanian taxa may not be represented in the lower Chinle Formation.

Parker and Martz (2011) recognized the Adamanian and Revueltian as biostratigraphic units (biozones), but of limited temporal significance due to fossil preservation/collection biases. Nonetheless, they reiterated the explicitly diachronous characterization of the two zones and hypothesized an environmentally-driven, faunal turnover associated with the Adamanian-Revueltian boundary. The boundary is thought to be represented by a distinct stratigraphic marker, a persistent red silcrete bed, within the Sonsela Member (Parker and Martz, 2011) with an approximate age between 218.017 ± 0.088 Ma and 213.124 ± 0.069 Ma based on the U-Pb geochronology of Ramezani and others (2011). Assuming that the Adamanian-Revueltian boundary is conceivably isochronous throughout the Chinle Basin, our geochronology bounds the entire Adamanian biozone at its type locality (fig. 5) to *ca.* 60 meters of the Chinle strata (upper Blue Mesa and lower Sonsela Members) spanning a *ca.* 8 m.y. period in the Late Triassic (223 Ma-215 Ma). Accordingly, there would be at least some overlap of the Adamanian with the Norian stage, even if the "short Norian" Late Triassic time scale of Lucas and others (2012) is adapted.

The Triassic Rise of Dinosaurs

The Late Triassic witnessed the prominent rise of a "modern" fauna that consisted of crocodyliforms, lepidosaurs, mammaliforms, turtles, pterosaurs and dinosaurs, many of whom have close associations to principal extant groups (for example Fraser and Sues, 2010). Triassic dinosaurs were comparatively low in abundance and diversity;

---

[1] Kaye and Padian (1994) identified *Revueltosaurus callenderi* as an ornithischian dinosaur, but it has since been reclassified as a pseudosuchian archosaur (for example Nesbitt, 2011).

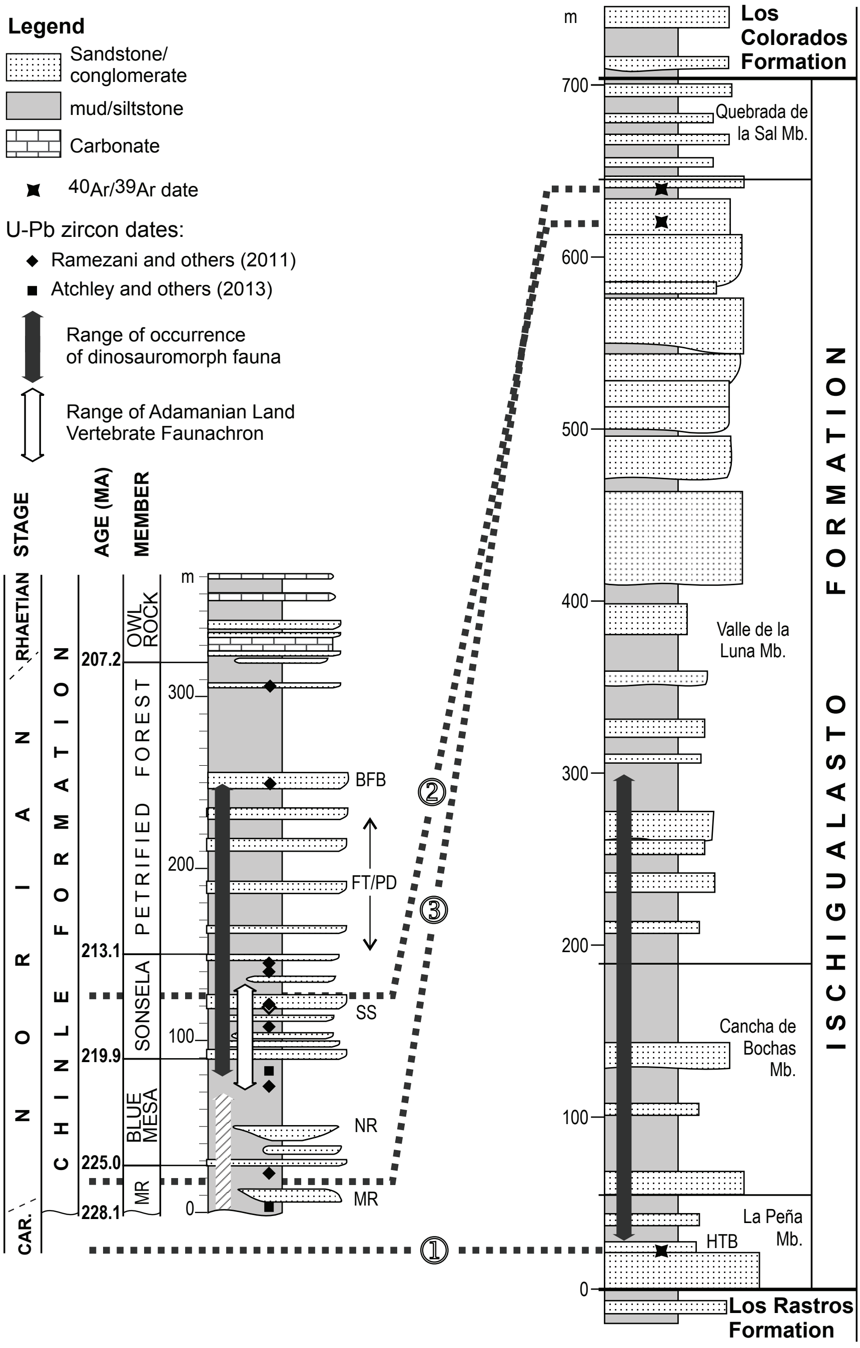

Fig. 5. Age correlation between Chinle Formation of the Colorado Plateau and Ischigualasto Formation of northwestern Argentina (equal elevation scales), based on the available radioisotopic data. Chinle chronostratigraphy based on Ramezani and others (2011) and Atchley and others (2013). Ischigualasto stratigraphy is from Martinez and others (2011). Dashed lines represent correlation models based on ^{40}Ar/^{39}Ar geochronology of the Ischigualasto Formation: (1)—Rogers and others (1993), (2)—Shipman (ms, 2004) and (3)—Martinez and others (2011). Solid bars signify the stratigraphic ranges of early dinosaurs in the Chinle (Parker and Martz, 2011; Irmis and others, 2011) and in the Ischigualasto (Martinez and others, 2011). Hachures mark the basal Chinle interval with no tetrapod record. HTB = Herr Toba bentonite. All other abbreviations as in figure 3.

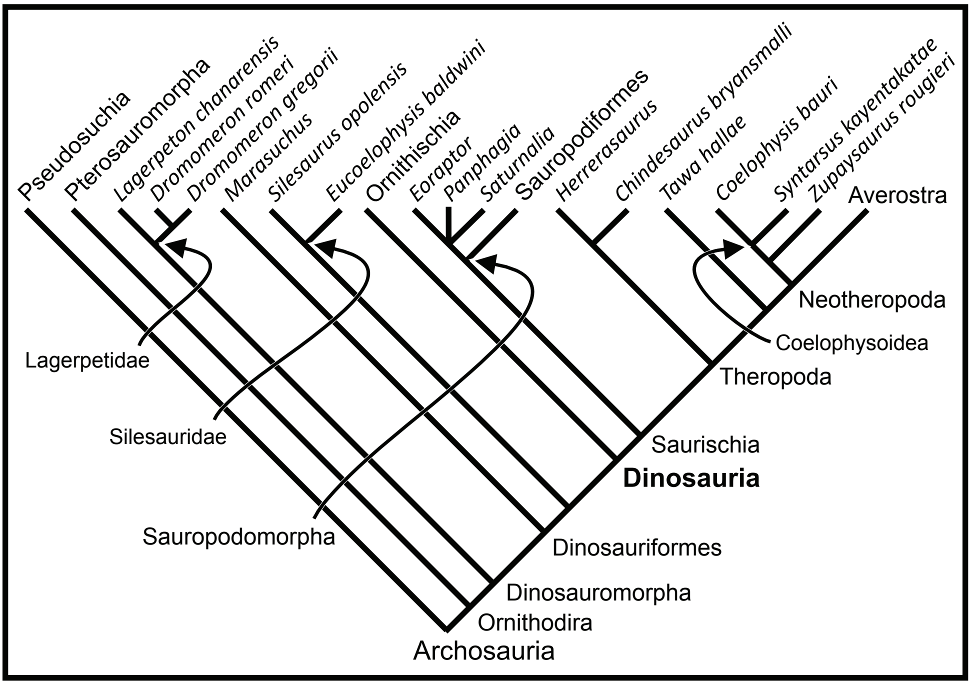

Fig. 6. Phylogenetic relationships of basal dinosauromorph and early dinosaur taxa discussed here. Cladogram based on Nesbitt and others (2009a), Langer and others (2010), Martinez and others (2011), and Langer and others (2013).

they did not become significant components of tetrapod paleocommunities until the end of the epoch (Langer and others, 2010).

The Late Triassic rise of dinosaurs was closely associated with, and preceded by, an extensive radiation of non-dinosaurian dinosauromorphs (Langer and others, 2013). Dinosauromorpha (*sensu* Sereno, 1991) is defined as a clade that incorporates all known dinosaurs, as well as their phylogenetically closest, non-dinosaur, ornithodiran relatives commonly referred to as basal dinosauromorphs (fig. 6). The latter group has a body fossil record that ranges from Anisian to at least late Norian (for example Langer and others, 2013), with ichnological evidence for possible basal dinosauromorphs as old as Olenekian (Brusatte and others, 2010b). The geographic and temporal associations of basal dinosauromorph and early dinosaur communities are crucial to our understanding of the early evolution and diversification of Dinosauria. Yet, unraveling this early evolutionary history has been hindered by a) the sparse and largely fragmentary fossil record of the Triassic dinosauromorphs, b) disputed phylogenetic positions within the clade, and c) uncertain age relationships among the corresponding fossil-bearing formations, often determined speculatively based on tetrapod biostratigraphy.

Dinosauromorph record of the Chinle Formation.—Investigations into the non-marine Triassic of North America originally promised an extensive dinosaur record (Hunt and others, 1998), including ornithischians and possible sauropodomorphs, from the Chinle Formation of eastern Arizona and northern New Mexico, as well as the presumed equivalent Dockum Group of eastern New Mexico and western Texas. However, more recent apomorphy-based analyses (for example Nesbitt and others, 2007) suggested a much more limited dinosaur fauna for the American Southwest, belonging mainly to the basal theropodan clades of the saurischian dinosaurs. Among the North American theropods, coelophysoids (basal neotheropods) are particularly common (fig. 6). The coelophysoids include indeterminate taxa from the *Placerias* Quarry and PEFO in Arizona, the Snyder Quarry in New Mexico (Hunt and others, 1998; Heckert and others, 2005; Parker and Martz, 2011) and the Post Quarry in western Texas (Nesbitt and Chatterjee, 2008), as well as *Coelophysis bauri* and from the *Coelophysis* Quarry at Ghost Ranch, New Mexico (Colbert, 1989). A theropod from the Dinosaur Hill locality of PEFO has also been assigned to *Coelophysis bauri* (Padian, 1986; Spielmann and others, 2007), although it may represent a new taxon (Parker and Martz, 2011). The more basal (non-coelophysoid) theropods are represented by *Tawa hallae* from the Hayden Quarry, New Mexico (Nesbitt and others, 2009b) and *Chindesaurus bryansmalli* from the Dinosaur Hollow locality of PEFO (Long and Murry, 1995) and from the Hayden Quarry of New Mexico (Irmis and others, 2007), a basal saurischian from the Post Quarry (Nesbitt and Chatterjee, 2008), as well as other possibly related specimens from the Dockum Group of Texas (Hunt and others, 1998).

Of the basal (non-dinosaurian) dinosauromorphs, lagerpetid and silesaurid groups are both represented in the Triassic of North America (fig. 6). The former includes *Dromomeron romeri* from the Chinle Formation of the Hayden Quarry (Irmis and others, 2007) and *Dromomeron gregorii* from the Colorado City Formation (Dockum Group) of the Otis Chalk Quarry, western Texas and from the *Placerias* Quarry (Nesbitt and others, 2009a). The best-documented silesaurids are *Eucoelophysis baldwini* from the Orphan Mesa near Ghost Ranch (reassigned by Sullivan and Lucas, 1999; Nesbitt and others, 2007) and from the Hayden Quarry (Irmis and others, 2007), and *Technosaurus smalli* from the Bull Canyon Formation (Dockum Group) of western Texas (Chatterjee, 1984; reassigned by Nesbitt and others, 2007). In addition, non-dinosaurian dinosauriform specimens from the Otis Chalk Quarry (Nesbitt, 2011), Post Quarry (Nesbitt and Chatterjee, 2008), Dying Grounds locality of the PEFO (Parker, 2006) and the Eagle Basin of central Colorado (Small, 2009) have been mostly assigned to Silesauridae.

The rich tetrapod assemblage of the *Placerias* Quarry (see *Placerias Quarry*) has been regarded as containing some of the oldest dinosauromorphs documented from North America and was reported to include the oldest (late Carnian) confirmed theropod yet found (Nesbitt and others, 2007; Nesbitt and others, 2009b), based on its presumed stratigraphic position near the base of the Mesa Redondo (Bluewater Creek) Member of the Chinle Formation (see *Regional Correlation of the Lower Chinle Formation*). Our U-Pb geochronologic framework, including a zircon date directly from the main *Placerias* Bone Bed, however, places its associated fauna at a significantly younger age of 219.4 Ma (Norian) and well within the range of dinosauromorph assemblages of the PEFO (fig. 5).

The stratigraphically lowest occurrence of a basal dinosauromorph at the PEFO is from the highly fossiliferous "Dying Grounds" locality, close to the top of the Blue Mesa Member, where remains similar to that of *Silesaurus* have been recovered (Parker and Martz, 2011). A sample of green, tuffaceous sandstone from the same horizon was dated by the U-Pb zircon (CA-TIMS) method and yielded a weighted mean ^{206}Pb/^{238}U date of 220.124 ± 0.068/0.12/0.26 Ma (Atchley and others, 2013), which directly constrains the age of the fossil. This occurrence is presently the oldest documented basal dinosauromorph from North America. An unpublished report of a dinosauriform femur from the Black Forest Bed pointed out in Parker and Martz (2011) marks the highest occurrence of basal dinosauromorphs in the PEFO. The U-Pb zircon date of 209.926 ± 0.072/0.13/0.26 Ma for the Black Forest Bed (Ramezani and others, 2011) thus constrains the range of documented basal dinosauromorphs from the Chinle Formation to between 220.1 and 209.9 Ma.

The full stratigraphic range of dinosaurs at PEFO is bound at its base to a probable theropod femur recovered from the upper Blue Mesa Member of the Chinle Formation in the Billings Gap area, and at its top to a theropod specimen (referred to *Coelophysis bauri*) from the Dinosaur Hill fossil locality below the Black Forest Bed (see above; Parker and Martz, 2011). Although no direct radioisotopic dates are available from these two localities, the corresponding stratigraphic horizons are well-bracketed by previously published U-Pb dates of tuffaceous beds from the PEFO (Ramezani and others, 2011; Atchley and others, 2013); their depositional ages thus can be plausibly estimated by linear extrapolation (fig. 5). Accordingly, the first appearance of a true dinosaur at PEFO is constrained between 223.036 ± 0.059 Ma and 220.124 ± 0.068 Ma. Considering uncertainties associated with stratigraphic positions, our best estimate for the age of this dinosaur locality is *ca.* 223 Ma. Similarly, the stratigraphically highest documented dinosaur occurrence is constrained between 213.870 ± 0.078 Ma and 209.926 ± 0.072 Ma, with an estimated age of *ca.* 211 Ma. The lowest theropod occurrence is only a short interval (*ca.* 8 m) above the lowermost fossil horizon of the PEFO, suggesting that the stratigraphic range of the Triassic dinosaurs in the Chinle Formation is truncated at its base due to lack of preservation.

Irmis and others (2011) reported a U-Pb date (ID-TIMS method) of 211.9 ± 0.7 Ma for the maximum age of the dinosauromorph assemblage of the Hayden Quarry in northern New Mexico, based on the youngest zircon analysis from a sample described as an "intraformational conglomerate" in the quarry section. This date falls within the range of the dinosauromorph record of the PEFO and is more than 10 m.y. younger than the earliest documented theropod dinosaur from the Chinle Formation. The Hayden Quarry date has been considered as geochronologic evidence in support of the model of diachronous radiation of the early dinosaurs in the Triassic (see below).

Was the early dinosaur radiation diachronous?—The Triassic record of basal dinosauromorphs and primitive dinosaurs in South America is particularly diverse and better known than elsewhere in Pangea (for example Novas, 2009; Langer and others, 2013). The Chañares Formation of the Ischigualasto-Villa Unión Basin in northwestern Argentina (fig. 7) has produced some of the earliest documented basal dinosauromorphs (fig. 6), including the lagerpetid *Lagerpeton chanarensis* (Romer, 1971), the dinosauriform *Marasuchus lilloensis* (Sereno and Arcucci, 1993), as well as the silesaurid *Pseudolagosuchus major* (Arcucci, 1987). This formation is believed to be Middle Triassic (Ladinian?) in age, chiefly based on its stratigraphic position below the Los Rastros and Ischigualasto Formations (Rogers and others, 2001; fig. 2).

Some of the most complete and best-studied basal dinosaurs have been discovered in the fluvial strata of the overlying Ischigualasto Formation (figs. 5 and 7), including the basal saurischians *Herrerasaurus ischigualastensis* (Sereno and Novas, 1992) and *Eoraptor lunensis* (Sereno and others, 1993), as well as the basal ornithischian *Pisanosaurus mertii* (fig. 6; Casamiquela, 1967; Butler and others, 2008). Comparable taxa such as *Staurikosaurus pricei* (Colbert, 1970) and *Saturnalia tupiniquim* (Langer and others, 1999) have also been recovered from the presumed coeval (based on biostratigraphy; Langer, 2005) but yet undated upper Santa Maria Formation of southern Brazil. Recent studies have described the most primitive members of Sauropodomorpha (*Panphagia protos*: Martinez and Alcober, 2009) and Theropoda (Eodromaeus murphi: Martinez and others, 2011) known from the lower Ischigualasto Formation. Only two basal dinosauromorphs are known from the Ischigualasto Formation; specimens of an unnamed lagerpetid and the silesaurid *Ignotosaurus fragilis* (Martínez and others, 2012), suggesting that the basal dinosauromorphs were significantly diminished in numbers by that time. Taken together, these discoveries indicate that the diversification of the major clades of Dinosauria was well underway by the time that the lower Ischigualasto Formation and its correlatives were deposited. The exact timing of that

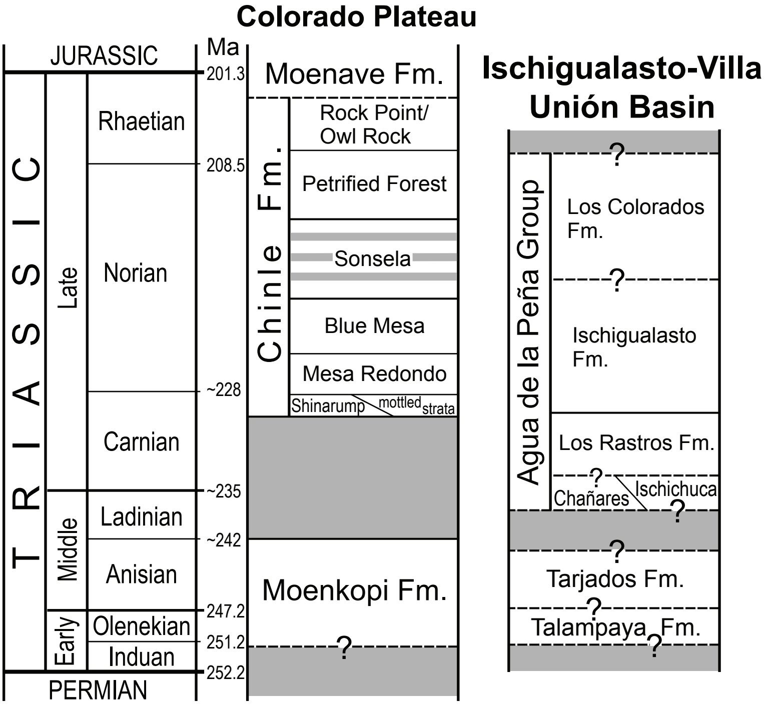

Fig. 7. Triassic chronostratigraphy of the Colorado Plateau of Southwest United States (see text for references) and of the Ischigualasto-Villa Unión Basin of northwestern Argentina (modified after Rogers and others, 2001). Time scale based on the preferred calibration of the Late Triassic in Gradstein and others (2012); Permo-Triassic boundary age from Shen and others (2011). Dashed lines signify boundaries of uncertain age. Depositional hiatuses are shown with gray shading.

crucial diversification, however, remains unclear because of uncertainties associated with the age of the Ischigualasto and related formations.

Rogers and others (1993) reported an $^{40}Ar/^{39}Ar$ plateau date of 227.78 + 0.30 Ma (1σ internal error only) from a bentonite bed named Herr Toba from the basal La Peña Member of the Ischigualasto, about 20 m above the base of the formation (fig. 5). The date was produced by incremental laser heating of sanidine and calculated at the time using the ^{40}K decay constants of Steiger and Jaeger (1977) and an age of 27.84 Ma for the Fish Canyon sanidine fluence monitor standard. Later revisions to the ^{40}K decay constants (Min and others, 2000) and the age of the Fish Canyon Tuff (28.201 Ma: Kuiper and others, 2008) prompted a recalculation of the above date to 230.8 ± 4.5 Ma (1σ total error) (see Ramezani and others, 2011) which includes contribution from large uncertainties associated with the ^{40}K decay constants. The application of $^{40}Ar/^{39}Ar$ statistical optimization approach of Renne and others (2010) that empirically reduces the ^{40}K decay constant uncertainties resulted in a recalculated date of 231.4 ± 0.3 Ma (1σ total error) (see Martinez and others, 2011) with significantly smaller error for the Herr Toba bentonite. Regardless of its uncertainty, the Herr Toba $^{40}Ar/^{39}Ar$ date places the overlying dinosauromorph assemblages of the Ischigualasto Formation at the latest Carnian–earliest Norian time interval, based on the GTS 2012 preferred calibration of the Triassic timescale (Gradstein and others, 2012).

Obtaining $^{40}Ar/^{39}Ar$ geochronology from the upper Ischigualasto Formation has proven difficult due to complex samples that yield excess data scatter. Shipman (ms,

2004) reported in an unpublished dissertation an $^{40}Ar/^{39}Ar$ feldspar date of 217.0 ± 1.7 Ma (cited in Currie and others, 2009) from the upper Valle de la Luna Member (fig. 5), although no supporting analytical data were presented. A more recent $^{40}Ar/^{39}Ar$ feldspar date of 225.9 ± 0.9 Ma was reported by Martinez and others (2011) from the topmost Valle de la Luna Member (fig. 5). The latter date was calculated by combining six weighted mean dates from relatively low-precision, incremental heating analyses (five) and of more precise, total fusion analyses (one) on single feldspars (both plagioclase and K-feldspar), after discarding data for grains the authors interpreted as xenocrystic. The five (out of 24) incremental heating analyses used in age calculation gave nominal $^{40}Ar/^{39}Ar$ plateau dates ranging from 226 ± 6.46 Ma to 218.07 ± 6.72 Ma (Martinez and others, 2011: online supporting material) that highlight the complex underpinnings of the preferred 225.9 ± 0.9 Ma date. A recent magnetostratigraphic study and correlation to the Newark Basin astronomical polarity time scale (Santi Malnis and others, 2011) suggested a 227.5 to 215 Ma age for the overlying Los Colorados Formation (fig. 5) that, if correct, reduces the duration of the Ischigualasto Formation to less than 4 m.y., in contradiction to the previously published $^{40}Ar/^{39}Ar$ geochronology. These conflicting results make it difficult to precisely constrain the age and duration of the Ischigualasto fauna. An unequivocal chronostratigraphy for the Ischigualasto-Villa Unión Basin must await further reliable geochronology.

The apparent age disparity between the Chinle Formation of the North American Southwest and the South American Ischigualasto Formation has formed the basis for the model of diachronous evolution of early dinosaurs. Irmis and others (2007) observed that the transition from assemblages of dinosaur precursors to those consisted exclusively of dinosaurs that presumably began in the Carnian in South America was a protracted process that persisted well into the Norian elsewhere, as evidenced by the significantly younger Hayden Quarry fauna of the Chinle Formation in New Mexico. Nesbitt and others (2009b) further elaborated that the Chinle dinosaur assemblage was qualitatively more similar to that of the Ischigualasto Formation, despite their apparent contemporaneity with that of the overlying Los Colorados Formation. These authors concluded that the evolution of Triassic dinosaurs must have been diachronous across Pangea. A reported U-Pb date from the Hayden Quarry in northern New Mexico (see *Dinosauromorph record of the Chinle Formation*) and its correlation to South America broadened the occurrence of the basal dinosauromorphs to at least 30 m.y. and suggested that the herrerasaurid theropod dinosaurs of North America were 10 to 15 m.y. younger than their South American counterparts. These were interpreted as evidence in support of the diachronous nature of the early dinosaur evolution (Irmis and others, 2011).

Figure 5 illustrates possible correlations between the Chinle and Ischigualasto Formations, including the ranges of their dinosaur faunas, based on available geochronologic data. A temporal overlap is strongly supported by the data, the extent of which is nevertheless poorly understood due to the large uncertainties associated with the duration of the Ischigualasto Formation (see above). Most significantly, the most likely interval of overlap between the two formations lacks any dinosaur record that would allow a direct comparison of the two fauna. The geologic stage most relevant to the emergence of basal dinosaurs—the Carnian through earliest Norian—are either absent from the North American Triassic due to non-deposition and/or erosion or, where present, preserves no tetrapod fossil record (see *Stratigraphic Subdivisions and Age of the Chinle Formation* and fig. 7). An extensive tetrapod preservational hiatus in North America coeval with the deposition of Chañares, Los Rastros and lower Ischigualasto Formations in South America (fig. 7), hampers an understanding of possible transcontinental variations in the earliest dinosaur assemblages.

Irmis and others (2011) pointed out significant quantitative differences between the North and South America Triassic dinosaurs in terms of species richness and relative abundance, which they took as supportive of the diachronous rise of dinosaurs across paleolatitudes. However, comparisons between the North and South American Triassic faunal assemblages are complicated by their biogeographic dissimilarities. Three significant qualitative characteristics distinguish the earliest North American dinosaur-bearing assemblages from their South American counterparts. First, the earliest documented dinosaurs of North America are dominated by taxa such as *Tawa hallae* and *Coelophysis bauri* that are well nested within Theropoda (fig. 6). This is in contrast to the more primitive, basal-saurischian-dominated taxa in South America whose taxonomic assignments (for example, theropod versus sauropodomorph) have been problematic. Second, undisputed sauropodomorphs or ornithischians have not been reported from the Chinle assemblages (for example Nesbitt and others, 2007). Lastly, the Chinle Formation dinosaurs coexisted with basal dinosauromorphs for their entire documented range (*ca.* 223-211 Ma; see *Dinosauromorph record of the Chinle Formation*) without unequivocal indications of any faunal transition. In contrast, the basal dinosauromorphs and early dinosaurs of the South American Agua de la Peña Group occur, respectively, in stratigraphically separate Chañares-Los Rastros and lower Ischigualasto Formations, without evidence for extensive mixing of the two faunas (for example Rogers and others, 1993; Martinez and others, 2011). The phylogenetically closest dinosaur to *Coelophysis bauri* documented from South America is the basal neotheropod *Zupaysaurus rougieri* (a coelophysoid; Ezcurra and Novas, 2007) that occurs in the Los Colorados Formation (figs. 6 and 7). No basal dinosauromorph has been reported from the latter unit, suggesting a complete transition to a dinosaur-only assemblage throughout the Agua de la Peña Group. In the absence of any clear evidence in support of a taphonomic bias, we interpret the early dinosaur record of the Chinle Formation to be qualitatively different compared to that of South America, independent of their respective ages.

In conclusion, the lack of an undisputed evolutionary relationship between the documented earliest North and South American dinosaurs, along with the nearly 16 m.y. gap in the North American Triassic depositional and/or tetrapod record (see above), suggest that comparisons between the North and South American early dinosaur assemblages at their present state are of only limited paleobiologic significance. Pending a more complete fossil record augmented by a robust geochronologic framework, the present faunal comparisons cannot provide a firm basis for any model for the global radiation and diversification of dinosaurs in the Triassic.

CONCLUSIONS

New U-Pb ID-TIMS geochronology from what was considered to be the lowermost strata of the Upper Triassic Chinle Formation of the Colorado Plateau in eastern Arizona and western New Mexico places them in the mid-Chinle interval instead, prompting revisions to the regional Chinle chronostratigraphy. A zircon date of 219.39 ± 0.16 Ma from the highly fossiliferous *Placerias* Quarry in eastern Arizona provides a new temporal context for the Chinle faunal record and reveals a *ca.* 6 m.y. tetrapod preservational gap associated with the basal Chinle deposits. The latter was preceded by a *ca.* 10 m.y. hiatus, concomitant with the Ladinian and Carnian stages of the Late Triassic, in the sedimentary record of the Colorado Plateau.

The new Chinle chronostratigraphy constrains the appearance of the oldest documented dinosaurs of North America to *ca.* 223 Ma, immediately following the Triassic depositional/preservational gap. The early dinosaur record of the Chinle Formation is neither complete, nor primitive—it uniquely exhibits the coexistence of basal dinosauromorphs, basal saurischians and more advanced theropodan dinosaurs in a mixed assemblage that persisted for at least 12 m.y. This assemblage has no equivalent in the fossil-rich, South American, Triassic record and thus does not readily lend itself to the construction of any global model of early dinosaur evolution.

ACKNOWLEDGMENTS

This study was supported by a National Science Foundation grant EAR-024196/1023788 to Bowring and Fastovsky. We are grateful to Andy Heckert and Vince Schneider for providing access to the *Placerias* Quarry through permits from the Arizona State Museum and the Arizona State Lands Department (issued for the North Carolina State Museum of Natural Sciences), and to Bill Parker for access to the Salado section. Alissa Becker assisted in measuring sections and sample collection in Arizona. Reviews by Max Langer of an early draft of the manuscript are gratefully acknowledged. We thank George Gehrels, an anonymous reviewer and Associate Editor Peter Reiners for their helpful comments.

REFERENCES

Akers, J. P., 1964, Geology and ground-water in the central part of Apache County, Arizona: Reston, Virginia, U.S. Geological Survey, Water Supply Paper W 1771, p. 107.

Akers, J. P., Cooley, M. E., and Repenning, C. A., 1958, Moenkopi and Chinle formations of Black Mesa (Arizona) and adjacent areas: New Mexico Geological Survey, 9th Field Conference Guidebook, p. 88–94.

Arcucci, A., 1987, Un nuevo Lagosuchidae (Thecodontia-Pseudosuchia) de la fauna de Los Chanares (Edad Reptil Chanarense, Triasico Medio), La Rioja, Argentina: Ameghiniana, v. 24, n. 1–2, p. 89–94.

Atchley, S. C., Nordt, L. C., Dworkin, S. I., Ramezani, J., Parker, W. G., Ash, S. R., and Bowring, S. A., 2013, A linkage among Pangean tectonism, cyclic alluviation, climate change, and biologic turnover in the Late Triassic: The Record From The Chinle Formation, Southwestern United States: Journal of Sedimentary Research, v. 83, n. 12, p. 1147–1161, http://dx.doi.org/10.2110/jsr.2013.89

Blakey, R. C., and Gubitosa, R., 1983, Late Triassic paleogeography and depositional history of the Chinle Formation, southern Utah and northern Arizona, *in* Reynolds, M. W., and Dolly, E. D., editors, Rocky Mountain paleogeography symposium; Mesozoic paleogeography of the West-Central United States: Denver, Colorado, Rocky Mountain Symposium 2, p. 57–76.

Bowring, J. F., McLean, N. M., and Bowring, S. A., 2011, Engineering cyber infrastructure for U-Pb geochronology: Tripoli and U-Pb_Redux: Geochemistry, Geophysics, Geosystems, v. 12, n. 6, p. Q0AA19, http://dx.doi.org/10.1029/2010GC003479

Brusatte, S. L., Nesbitt, S. J., Irmis, R. B., Butler, R. J., Benton, M. J., and Norell, M. A., 2010a, The origin and early radiation of dinosaurs: Earth-Science Reviews, v. 101, n. 1–2, p. 68–100, http://dx.doi.org/10.1016/j. earscirev.2010.04.001

Brusatte, S. L., Niedzwiedzki, G., and Butler, R. J., 2010b, Footprints pull origin and diversification of dinosaur stem lineage deep into Early Triassic: Proceedings of the Royal Society B: Biological Sciences, v. 278, n. 1708, p. 1107–1113, http://dx.doi.org/10.1098/rspb.2010.1746

Butler, R. J., Upchurch, P., and Norman, D. B., 2008, The phylogeny of the ornithischian dinosaurs: Journal of Systematic Palaeontology, v. 6, n. 1, p. 1–40, http://dx.doi.org/10.1017/S1477201907002271

Camp, C. L., and Welles, S. P., 1956, The North American genus Placerias (Arizona), Part 1 of Triassic dicynodont reptiles: University of California Memoirs, v. 13, p. 255–348.

Camp, C. L., Colbert, E. H., McKee, E. D., and Welles, S. P., 1947, A guide to the continental Triassic of northern Arizona: Plateau, v. 20, p. 1–9.

Casamiquela, R. M., 1967, Un nuevo dinosaurio ornitisquio triasico (Pisanosaurus mertii; ornithopoda) de la formacion Ischigualasto, Argentina. A new Triassic ornithischian dinosaur (Pisanosaurus mertii; Ornithopoda) from the Ischigualasto formation, Argentina: Ameghiniana, v. 5, p. 47–58.

Chatterjee, S., 1984, A new ornithischian dinosaur from the Triassic of North America: Naturwissenschaften, v. 71, n. 12, p. 630–631, http://dx.doi.org/10.1007/BF00377897

Colbert, E. H., 1970, A saurischian dinosaur from the Triassic of Brazil: American Museum Novitates, v. 2405, p. 1–39, http://hdl.handle.net/2246/2615

——— 1989, The Triassic dinosaur Coelophysis: Museum of Northern Arizona Bulletin, v. 57, p. 160.

Cooley, M. E., 1958, The Mesa Redondo member of the Chinle Formation, Apache and Navajo counties, Arizona: Plateau, v. 31, n. 1, p. 7–15.

——— 1959, Triassic stratigraphy in the state line region of west-central New Mexico and east-central Arizona, *in* Weir, J. E., Jr., and Boltz, E. H., editors, Tenth Field Conference: Albuquerque, New Mexico, New Mexico Geological Society, p. 66–73.

Currie, B. S., Colombi, C. E., Tabor, N. J., Shipman, T. C., and Montañez, I. P., 2009, Stratigraphy and architecture of the Upper Triassic Ischigualasto Formation, Ischigualasto Provincial Park, San Juan, Argentina: Journal of South American Earth Sciences, v. 27, n. 1, p. 74–87, http://dx.doi.org/10.1016/j.jsames.2008.10.004

Dickinson, W. R., and Gehrels, G. E., 2008, U-Pb ages of detrital zircons in relation to paleogeography: Triassic paleodrainage networks and sediment dispersal across Southwest Laurentia: Journal of Sedimentary Research, v. 78, n. 12, p. 745–764, http://dx.doi.org/10.2110/jsr.2008.088

——— 2009, Use of U-Pb ages of detrital zircons to infer maximum depositional ages of strata: A test against a Colorado Plateau Mesozoic database: Earth and Planetary Science Letters, v. 288, n. 1–2, p. 115–125, http://dx.doi.org/10.1016/j.epsl.2009.09.013

Dubiel, R. F., 1991, Architectural-facies analysis of nonmarine depositional systems in the Upper Triassic Chinle Formation, southeastern Utah, *in* Miall, A. D., and Tyler, N., editors, The Three-Dimensional Facies Architecture of Terrigenous Clastic Sediments and Its Implications for Hydrocarbon Discovery and Recovery: SEPM, Concepts in Sedimentology and Paleontology, v. 3, p. 103–110.

Ezcurra, M. D., and Novas, F. E., 2007, Phylogenetic relationships of the Triassic theropod *Zupaysaurus rougieri* from NW Argentina: Historical Biology, v. 19, n. 1, p. 35–72, http://dx.doi.org/10.1080/08912960600845791

Fiorillo, A. R., Padian, K., and Musikasinthorn, C., 2000, Taphonomy and depositional setting of the *Placerias* Quarry (Chinle Formation: Late Triassic, Arizona): PALAIOS, v. 15, n. 5, p. 373–386, http://dx.doi.org/10.1669/0883-1351(2000)015⟨0373:TADSOT⟩2.0.CO;2

Fraser, N. C., and Sues, H.-D., 2010, The beginning of the "Age of Dinosaurs": a brief overview of terrestrial biotic changes during the Triassic: Transactions of the Royal Society of Edinburgh: Earth and Environmental Science Transactions of the Royal Society of Edinburg, v. 101, n. 3–4, p. 189–200, http://dx.doi.org/10.1017/S1755691011020019

Gradstein, F. M., Ogg, J. G., Schmitz, M. D., and Ogg, G. M., 2012, The Geologic Time Scale 2012: Oxford, Elsevier, p. 1144.

Harshbarger, J. W., Repenning, C. A., and Irwin, J. H., 1957, Stratigraphy of the uppermost Triassic and the Jurassic rocks of the Navajo Country: Reston, Virginia, U.S. Geological Survey, Geological Survey Professional Paper 291, p. 74.

Heckert, A. B., and Lucas, S. G., 2002a, Lower Chinle Group (Upper Triassic, Carnian) stratigraphy in the Zuni Mountains, west-central New Mexico: Bulletin—New Mexico Museum of Natural History and Science, v. 21, p. 51–72.

——— 2002b, Revised Upper Triassic stratigraphy of the Petrified Forest National Park, Arizona, U.S.A: Bulletin—New Mexico Museum of Natural History and Science, v. 21, p. 1–36.

——— 2003, Stratigraphy and paleontology of the lower Chinle Group (Adamanian; latest Carnian) in the vicinity of St. Johns, Arizona: New Mexico Geological Society Field Conference Guidebook, v. 54, p. 281–288.

Heckert, A. B., Lucas, S. G., and Hunt, A. P., 2005, Triassic vertebrate fossils in Arizona: Bulletin—New Mexico Museum of Natural History and Science, v. 29, p. 16–44.

Heckert, A. B., Lucas, S. G., Dickinson, W. R., and Mortensen, J. K., 2009, New ID-TIMS U-Pb ages for Chinle Group strata (Upper Triassic) in New Mexico and Arizona, correlation to the Newark Supergroup, and implications for the "long Norian": Geological Society of America Abstracts with Programs, v. 41, p. 123.

Hunt, A. P., Lucas, S. G., Heckert, A. B., Sullivan, R. M., and Lockley, M. G., 1998, Late Triassic dinosaurs from the Western United States: Geobios, v. 31, n. 4, p. 511–531, http://dx.doi.org/10.1016/S0016-6995(98)80123-X

Irmis, R. B., Nesbitt, S. J., Padian, K., Smith, N. D., Turner, A. H., Woody, D., and Downs, A., 2007, A late Triassic dinosauromorph assemblage from New Mexico and the rise of dinosaurs: Science, v. 317, n. 5836, p. 358–361, http://dx.doi.org/10.1126/science.1143325

Irmis, R. B., Martz, J. W., Parker, W. G., and Nesbitt, S. J., 2010, Re-evaluating the correlation between Late Triassic terrestrial vertebrate biostratigraphy and the GSSP-defined marine stages: Albertiana, v. 38, p. 40–52.

Irmis, R. B., Mundil, R., Martz, J. W., and Parker, W. G., 2011, High-resolution U-Pb ages from the Upper Triassic Chinle Formation (New Mexico, USA) support a diachronous rise of dinosaurs: Earth and Planetary Science Letters, v. 309, n. 3–4, p. 258–267, http://dx.doi.org/10.1016/j.epsl.2011.07.015

Jacobs, L. L., and Murry, P. A., 1980, The vertebrate community of the Triassic Chinle Formation near St. Johns, Arizona, *in* Jacobs, L. L., editor, Aspects of vertebrate history; essays in honor of Edwin Harris Colbert: Flagstaff, Arizona, Museum of Northern Arizona Press, p. 55–71.

Jaffey, A. H., Flynn, K. F., Glendenin, L. E., Bentley, W. C., and Essling, A. M., 1971, Precision measurement of half-lives and specific activities of ^{235}U and ^{238}U: Physical Review C, v. 4, n. 5, p. 1889–1906, http://dx.doi.org/10.1103/PhysRevC.4.1889

Kaye, F. T., and Padian, K., 1994, Microvertebrates from the Placerias Quarry; a window on Late Triassic vertebrate diversity in the American Southwest, *in* Fraser, N. C., and Sues, H.-D., editors, In the Shadow of the Dinosaurs; Early Mesozoic Tetrapods: Cambridge, United Kingdom (GBR), Cambridge University Press, p. 171–196.

Kraus, M. J., and Middleton, L. T., 1987, Dissected paleotopography and base-level changes in a Triassic fluvial sequence: Geology, v. 15, n. 1, p. 18–21, http://dx.doi.org/10.1130/0091-7613(1987)15⟨18:DPABCI⟩2.0.CO;2

Kuiper, K. F., Deino, A., Hilgen, F. J., Krijgsman, W., Renne, P. R., and Wijbrans, J. R., 2008, Synchronizing rock clocks of Earth history: Science, v. 320, n. 5875, p. 500–504, http://dx.doi.org/10.1126/science.1154339

Langer, M. C., 2005, Studies on continental Late Triassic tetrapod biochronology. I. The type locality of *Saturnalia tupiniquim* and the faunal succession in south Brazil: Journal of South American Earth Sciences, v. 19, n. 2, p. 205–218, http://dx.doi.org/10.1016/j.jsames.2005.04.003

Langer, M. C., Abdala, F., Richter, M., and Benton, M. J., 1999, A sauropodomorph dinosaur from the Upper Triassic (Carnian) of southern Brazil: Comptes Rendus de l'Academie des Sciences, Series IIA-Earth and Planetary Sciences, v. 329, n. 7, p. 511–517, http://dx.doi.org/10.1016/S1251-8050(00)80025-7

Langer, M. C., Ezcurra, M. D., Bittencourt, J. S., and Novas, F. E., 2010, The origin and early evolution of dinosaurs: Biological Reviews, v. 85, n. 1, p. 55–110, http://dx.doi.org/10.1111/j.1469-185X.2009.00094.x

Langer, M. C., Nesbitt, S. J., Bittencourt, J. S., and Irmis, R. B., 2013, Non-dinosaurian Dinosauromorpha:

Geological Society, London, Special Publications, v. 379, p. 157–186, http://dx.doi.org/10.1144/SP379.9

Long, R. A., and Murry, P. A., 1995, Late Triassic (Carnian and Norian) tetrapods from the Southwestern United States: Bulletin—New Mexico Museum of Natural History and Science, v. 4, p. 254.

Lucas, S. G., 1993, The Chinle Group; revised stratigraphy and biochronology of Upper Triassic nonmarine strata in the Western United States: Museum of Northern Arizona Bulletin, v. 59, p. 27–50.

——— 1998, Global Triassic tetrapod biostratigraphy and biochronology: Palaeogeography, Palaeoclimatology, Palaeoecology, v. 143, n. 4, p. 345–382, http://dx.doi.org/10.1016/S0031-0182(98)00117-5

——— 2010, The Triassic timescale based on nonmarine tetrapod biostratigraphy and biochronology: Geological Society, London, Special Publications, v. 334, p. 447–500, http://dx.doi.org/10.1144/SP334.15

Lucas, S. G., and Hayden, S. N., 1989, Triassic stratigraphy of west-central New Mexico, *in* Anderson, O. J., Lucas, S. G., Love, D. W., and Cather, S. M., editors, Guidebook: Socorro, New Mexico, New Mexico Geological Society, p. 191–211.

Lucas, S. G., and Heckert, A. B., 1996, Stratigraphy and correlation of Triassic strata around the Nacimiento and Jemez uplifts, northern New Mexico: Guidebook—New Mexico Geological Society, v. 47, p. 199–204.

Lucas, S. G., and Huber, P., 2003, Vertebrate biostratigraphy and biochronology of the nonmarine Late Triassic, *in* LeTourneau, P. M., and Olsen, P. E., editors, The Great Rift Valleys of Pangea in Eastern North America: New York, New York, Columbia University Press, p. 143–191.

Lucas, S. G., and Schoch, R. R., 2002, Triassic temnospondyl biostratigraphy, biochronology and correlation of the German Buntsandstein and North American Moenkopi Formation: Lethaia, v. 35, n. 2, p. 97–106, http://dx.doi.org/10.1111/j.1502-3931.2002.tb00071.x

Lucas, S. G., Heckert, A. B., and Anderson, O. J., 1997a, Triassic stratigraphy and paleontology on the Fort Wingate Quadrangle, west-central New Mexico: New Mexico Geology, v. 19, n. 2, p. 33–42.

Lucas, S. G., Heckert, A. B., and Hunt, A. P., 1997b, Stratigraphy and biochronological significance of the Late Triassic Placerias Quarry, eastern Arizona (U.S.A.): Neues Jahrbuch fuer Geologie und Palaeontologie Abhandlungen, v. 203, n. 1, p. 23–46.

Lucas, S. G., Tanner, L. H., Kozur, H. W., Weems, R. E., and Heckert, A. B., 2012, The Late Triassic time scale: Age and correlation of the Carnian-Norian boundary: Earth-Science Reviews, v. 114, n. 1–2, p. 1–18, http://dx.doi.org/10.1016/j.earscirev.2012.04.002

Martinez, R. N., and Alcober, O. A., 2009, A basal sauropodomorph (Dinosauria: Saurischia) from the Ischigualasto Formation (Triassic, Carnian) and the early evolution of Sauropodomorpha: PLoS ONE, v. 4, p. e4397, http://dx.doi.org/10.1371/journal.pone.0004397

Martinez, R. N., Sereno, P. C., Alcober, O. A., Colombi, C. E., Renne, P. R., Montañez, I. P., and Currie, B. S., 2011, A basal dinosaur from the dawn of the dinosaur era in southwestern Pangaea: Science, v. 331, n. 6041, p. 206–210, http://dx.doi.org/10.1126/science.1198467

Martínez, R. N., Apaldetti, C., Alcober, O. A., Colombi, C. E., Sereno, P. C., Fernandez, E., Malnis, P. S., Correa, G. A., and Abelin, D., 2012, Vertebrate succession in the Ischigualasto Formation: Journal of Vertebrate Paleontology, v. 32, Supplement 1, p. 10–30, http://dx.doi.org/10.1080/02724634.2013.818546

Martz, J. W., and Parker, W. G., 2010, Revised lithostratigraphy of the Sonsela Member (Chinle Formation, Upper Triassic) in the southern part of Petrified Forest National Park, Arizona: PLoS ONE, v. 5, p. e9329, http://dx.doi.org/10.1371/journal.pone.0009329

Mattinson, J. M., 2005, Zircon U/Pb chemical abrasion ("CA-TIMS") method: Combined annealing and multi-step partial dissolution analysis for improved precision and accuracy of zircon ages: Chemical Geology, v. 220, n. 1–2, p. 47–66, http://dx.doi.org/10.1016/j.chemgeo.2005.03.011

McKee, E. D., 1954, Stratigraphy and history of the Moenkopi Formation of Triassic age: Geological Society of America Memoirs, v. 61, p. 1–126, http://dx.doi.org/10.1130/MEM61-p1

McLean, N. M., Bowring, J. F., and Bowring, S. A., 2011, An algorithm for U-Pb isotope dilution data reduction and uncertainty propagation: Geochemistry, Geophysics, Geosystems, v. 12, n. 6, p. Q0AA18, 10.1029/2010GC003478

Miall, A. D., 1983, Basin analysis of fluvial sediments, *in* Collinson, J. D., and Lewin, J., editors, Second international conference on fluvial sedimentology: Keele, United Kingdom, Special Publication of the International Association of Sedimentologists 6, p. 279–286.

Min, K., Mundil, R., Renne, P. R., and Ludwig, K. R., 2000, A test for systematic errors in ^{40}Ar/^{39}Ar geochronology through comparison with U/Pb analysis of a 1.1-Ga rhyolite: Geochimica et Cosmochimica Acta, v. 64, n. 1, p. 73–98, http://dx.doi.org/10.1016/S0016-7037(99)00204-5

Nesbitt, S. J., 2011, The early evolution of archosaurs: relationships and the origin of major clades: Bulletin of the American Museum of Natural History, n. 352, p. 292, http://hdl.handle.net/2246/6112

Nesbitt, S. J., and Chatterjee, S., 2008, Late Triassic dinosauriforms from the Post Quarry and surrounding areas, west Texas, U.S.A: Neues Jahrbuch für Geologie und Paläontologie—Abhandlungen, v. 249, n. 2, p. 143–156, http://dx.doi.org/10.1127/0077-7749/2008/0249-0143

Nesbitt, S. J., Irmis, R. B., and Parker, W. G., 2007, A critical re-evaluation of the Late Triassic dinosaur taxa of North America: Journal of Systematic Palaeontology, v. 5, n. 2, p. 209–243, http://dx.doi.org/10.1017/S1477201907002040

Nesbitt, S. J., Irmis, R. B., Parker, W. G., Smith, N. D., Turner, A. H., and Rowe, T., 2009a, Hindlimb Osteology and Distribution of Basal Dinosauromorphs from the Late Triassic of North America: Journal of Vertebrate Paleontology, v. 29, n. 2, p. 498–516, http://dx.doi.org/10.1671/039.029.0218

Nesbitt, S. J., Smith, N. D., Irmis, R. B., Turner, A. H., Downs, A., and Norell, M. A., 2009b, A complete skeleton of a Late Triassic saurischian and the early evolution of dinosaurs: Science, v. 326, n. 5959, p. 1530–1533, http://dx.doi.org/10.1126/science.1180350

Novas, F. E., 2009, The age of dinosaurs in South America: Blomington, Indiana, Indiana University Press, p. 452.

Padian, K., 1986, On the type material of Coelophysis Cope (Saurischia; Theropoda), and a new specimen from the Petrified Forest of Arizona (Late Triassic; Chinle Formation), *in* Padian, K., editor, The Beginning of the Age of Dinosaurs: Cambridge, Cambridge University Press, p. 45–60.

Parker, W., 2006, The stratigraphic distribution of major fossil localities in Petrified Forest National Park, Arizona: Museum of Northern Arizona Bulletin, v. 62, p. 46–61.

Parker, W. G., and Martz, J. W., 2011, The Late Triassic (Norian) Adamanian-Revueltian tetrapod faunal transition in the Chinle Formation of Petrified Forest National Park, Arizona: Transactions of the Royal Society of Edinburgh: Earth and Environmental Science, v. 101, n. 3–4, p. 231–260, http://dx.doi.org/10.1017/S1755691011020020

Pipiringos, G. N., and O'Sullivan, R. B., 1978, Principal unconformities in Triassic and Jurassic rocks, Western Interior United States; a preliminary survey: U.S. Geological Survey Professional Paper 1035-A, p. 1–29.

Poborski, S. J., 1954, Virgin Formation (Triassic) of the St. George, Utah, area: Geological Society of America Bulletin, v. 65, n. 10, p. 971–1006, http://dx.doi.org/10.1130/0016-7606(1954)65[971:VFTOTS]2.0.CO;2

Ramezani, J., Hoke, G. D., Fastovsky, D. E., Bowring, S. A., Therrien, F., Dworkin, S. I., Atchley, S. C., and Nordt, L. C., 2011, High-precision U-Pb zircon geochronology of the Late Triassic Chinle Formation, Petrified Forest National Park (Arizona, USA): Temporal constraints on the early evolution of dinosaurs: Geological Society of America Bulletin, v. 123, n. 11–12, p. 2142–2159, http://dx.doi.org/10.1130/B30433.1

Rayfield, E. J., Barrett, P. M., and Milner, A. R., 2009, Utility and validity of Middle and Late Triassic 'land vertebrate faunachrons': Journal of Vertebrate Paleontology, v. 29, n. 1, p. 80–87, http://dx.doi.org/10.1671/039.029.0132

Renne, P. R., Mundil, R., Balco, G., Min, K., and Ludwig, K. R., 2010, Joint determination of ^{40}K decay constants and ^{40}Ar/^{40}K for the Fish Canyon sanidine standard, and improved accuracy for ^{40}Ar/^{39}Ar geochronology: Geochimica et Cosmochimica Acta, v. 74, n. 18, p. 5349–5367, http://dx.doi.org/10.1016/j.gca.2010.06.017

Repenning, C. A., Cooley, M. E., and Akers, J. P., 1969, Stratigraphy of the Chinle and Moenkopi formations, Navajo and Hopi Indian reservations; Arizona, New Mexico, and Utah, *in* Hydrogelogy of the Navajo and Hopi Indian Reservations, Arizona, new Mexico and Utah: U.S. Geological Survey Professional Paper 521-B, p. 34.

Riggs, N. R., Lehman, T. M., Gehrels, G. E., and Dickinson, W. R., 1996, Detrital zircon link between headwaters and terminus of the Upper Triassic Chinle-Dockum paleoriver system: Science, v. 273, n. 5271, p. 97–100, http://dx.doi.org/10.1126/science.273.5271.97

Riggs, N. R., Ash, S. R., Barth, A. P., Gehrels, G. E., and Wooden, J. L., 2003, Isotopic age of the Black Forest Bed, Petrified Forest Member, Chinle Formation, Arizona; An example of dating a continental sandstone: Geological Society of America Bulletin, v. 115, n. 11, p. 1315–1323, http://dx.doi.org/10.1130/B25254.1

Rogers, R. R., Swisher, C. C., III, Sereno, P. C., Monetta, A. M., Forster, C. A., and Martinez, R. N., 1993, The Ischigualasto tetrapod assemblage (Late Triassic, Argentina) and ^{40}Ar/^{39}Ar dating of dinosaur origins: Science, v. 260, n. 5109, p. 794–797, http://dx.doi.org/10.1126/science.260.5109.794

Rogers, R. R., Arcucci, A. B., Abdala, F., Sereno, P. C., Forster, C. A., and May, C. L., 2001, Paleoenvironment and taphonomy of the Chañares Formation tetrapod assemblage (Middle Triassic), northwestern Argentina: Spectacular preservation in volcanogenic concretions: PALAIOS, v. 16, n. 5, p. 461–481, http://dx.doi.org/10.1669/0883-1351(2001)016⟨0461:PATOTC⟩2.0.CO;2

Romer, A. S., 1971, The Chanares (Argentina) Triassic reptile fauna; X, Two new but incompletely known long-limbed pseudosuchians: Breviora, v. 378, p. 1–10.

Santi Malnis, P., Kent, D. V., Colombi, C. E., and Geuna, S. E., 2011, Quebrada de la Sal magnetoestratigraphic section, Los Colorados Formación, Upper Triassic Ischigualasto-Villa Unión basin, Argentina: Latinmag Letters, v. 1, Special Issue B15, p. 1–7.

Savage, D. E., and Russell, D. E., 1983, Mammalian paleofaunas of the world: Reading, Massachusetts, Addison-Wesley Publishing Co., p. 432.

Sereno, P. C., 1991, Basal archosaurs: phylogenetic relationships and functional implications: Journal of Vertebrate Paleontology, v. 11, p. 1–53, http://dx.doi.org/10.1080/02724634.1991.10011426

Sereno, P. C., and Arcucci, A. B., 1993, Dinosaurian precursors from the Middle Trirassic of Argentina: Lagerpeton chanarensis: Journal of Vertebrate Paleontology, v. 13, n. 4, p. 385–399, http://dx.doi.org/10.1080/02724634.1994.10011522

Sereno, P. C., and Novas, F. E., 1992, The complete skull and skeleton of an early dinosaur: Science, v. 258, n. 5085, p. 1137–1140, http://dx.doi.org/10.1126/science.258.5085.1137

Sereno, P. C., Forster, C. A., Rogers, R. R., and Monetta, A. M., 1993, Primitive dinosaur skeleton from Argentina and the early evolution of Dinosauria: Nature (London), v. 361, p. 64–66, http://dx.doi.org/10.1038/361064a0

Shen, S.-z., Crowley, J. L., Wang, Y., Bowring, S. A., Erwin, D. H., Sadler, P. M., Cao, C.-q., Rothman, D. H., Henderson, C. M., Ramezani, J., Zhang, H., Shen, Y., Wang, X.-d., Wang, W., Mu, L., Li, W.-z., Tang, Y.-g., Liu, X.-l., Liu, L.-j., Zeng, Y., Jiang, Y.-f., and Jin, Y.-g., 2011, Calibrating the end-Permian mass extinction: Science, v. 334, n. 6061, p. 1367–1372, http://dx.doi.org/10.1126/science.1213454

Shipman, T. C., ms, 2004, Links between sediment accumulation rates and the development of alluvial architecture; Triassic Ischigualasto Formation, northwestern Argentina: Tucson, Arizona, University of Arizona, Unpublished Ph. D. thesis, 187 p.

Small, B., 2009, A Late Triassic dinosauromorph assemblage from the Eagle Basin (Chinle Formation), Colorado, U.S.: Journal of Vertebrate Paleontology, v. 29, p. 182A.

Spielmann, J. A., Lucas, S. G., Rinehart, L. F., Hunt, A. P., Heckert, A. B., and Sullivan, R. M., 2007, Oldest records of the Late Triassic theropod dinosaur Coelophysis bauri: Bulletin—New Mexico Museum of Natural History and Science, v. 41, p. 384–401.

Steiger, R. H., and Jaeger, E., 1977, Subcommission on geochronology: Convention on the use of decay constants in geo- and cosmochronology: Earth and Planetary Science Letters, v. 36, n. 3, p. 359–362, http://dx.doi.org/10.1016/0012-821X(77)90060-7

Stewart, J. H., Poole, F. G., and Wilson, R. F., 1972a, Stratigraphy and origin of the Chinle Formation and related Upper Triassic strata in the Colorado Plateau region: U.S. Geological Survey Professional Paper 690, p. 336.

Stewart, J. H., Poole, F. G., Wilson, R. F., and Cadigan, R. A., 1972b, Stratigraphy and origin of the Triassic Moenkopi Formation and related strata in the Colorado Plateau region, with a section on sedimentary petrology: U.S. Geological Survey Professional Paper, v. 691, p. 195.

Sullivan, R. M., and Lucas, S. G., 1999, *Eucoelophysis baldwini*, a new theropod dinosaur from the Upper Triassic of New Mexico, and the status of the original types of *Coelophysis*: Journal of Vertebrate Paleontology, v. 19, n. 1, p. 81–90, http://dx.doi.org/10.1080/02724634.1999.10011124

Welles, S. P., 1947, Vertebrates from the upper Moenkopi Formation of northern Arizona: University of California Publications in Geological Sciences, v. 27, p. 241–294.

Woody, D. T., 2006, Revised stratigraphy of the lower Chinle Formation (Upper Triassic) of Petrified Forest National Park: Museum of Northern Arizona Bulletin, v. 62, p. 17–45.