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TRIASSIC STRATIGRAPHY IN THE ZUNI MOUNTAINS, WEST-CENTRAL NEW MEXICO

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Abstract.—The Triassic System in the Zuni Mountains consists of one Middle Triassic unit, the Moenkopi Formation, the Upper Triassic Chinle Group, and the Upper Triassic-Lower Jurassic(?) Wingate Sandstone. The Chinle Group in the Zuni Mountains consists of six formations, in ascending order: Zuni Mountains (named here; = "mottled strata" of previous workers), Shinarump, Bluewater Creek, Petrified Forest, Owl Rock, and Wingate formations. The Moenkopi Formation rests on an unconformable surface that represents the compound Tr-0 through Tr-2 unconformities, and Moenkopi strata locally rest on either the San Andres or Glorieta formations, both of Early Permian age. Moenkopi strata in the Zuni Mountains are relatively thin (< 25 m thick) sequences of thinly bedded sandstone, siltstone, and conglomerate, overlain by the Zuni Mountains and/or Shinarump formations, which lie on a surface corresponding to the Tr-3 unconformity. The Moenkopi Formation in the Zuni Mountains is lithologically identical to the Anton Chico Member of the Moenkopi Formation in eastern New Mexico, and is presumably correlative to both that unit and the Holbrook Member in western Arizona, and is thus of Perovkan (early Anisian) age.

We coin the term Zuni Mountains Formation to replace the long-used informal term "mottled strata." Zuni Mountains Formation strata are color-mottled siliciclastics that record pedogenic modification of strata associated with development of the Tr-3 unconformity. Shinarump Formation strata are principally conglomerates and sandstone that represent channel deposits of a fluvial system that aggraded in Tr-3 paleotopography during early Late Triassic time. Bluewater Creek Formation strata are present across the Zuni Mountains and are typically 50-60 m thick. These strata primarily record floodplain deposition, including both proximal (coarse-grained, crevasse-splay) and more distal (fine-grained, floodplain) deposits. In the western two-thirds of the Zuni Mountains, the contact between the Bluewater Creek Formation and the overlying Petrified Forest Formation is defined by a bright white, tuffaceous sandstone that appears to represent a reworked ashfall from a discrete volcanic event. This horizon is not evident in the eastern third of the unit's outcrop area, where the contact between the two units is a more arbitrary mudstone-on-mudstone contact. Strata of the Blue Mesa Member of the Petrified Forest Formation are primarily highly bentonitic mudstone with well-developed calcrete (siderite) nodules that record floodplain deposition and paleosol development.

The Blue Mesa Member is overlain disconformably by the Sonsela Member on a surface corresponding to the Tr-4 unconformity. Sonsela strata are broadly similar to Shinarump Formation strata but are considerably more extensive in outcrop area and form the prominent cuesta south of Interstate 40 between Gallup and Bluewater. Erosion associated with the development of the Tr-4 unconformity generated at least 20 m of paleotopography across the study area that was subsequently filled by Sonsela Member fluvial deposits. The Sonsela grades upward into predominantly fine-grained strata of the Painted Desert Member, which represents a somewhat drier floodplain environment than the Blue Mesa Member. Across the Zuni Mountains, the Perea Bed is a prominent bench-forming, sandstone-dominated unit stratigraphically low in the Painted Desert Member that represents the deposits of a low-sinuosity fluvial system. The Painted Desert Member is overlain conformably by the Owl Rock Formation, as much as 25 m of siltstone, sandstone, and largely pedogenic calcrete that forms persistent benches across the northern edge of the Triassic outcrop belt in the Zuni Mountains.

The Owl Rock Formation is disconformably overlain by the Wingate Sandstone, which some workers formerly (and incorrectly) included in the Entrada Sandstone. The surface separating the Owl Rock Formation from the Wingate Sandstone is the Tr-5 unconformity. These outcrops of the Wingate Sandstone in the Zuni Mountains are relatively thin (~35 m) and represent a mix of eolian and water-lain or water-reworked strata and are the only strata assigned to the Wingate Sandstone in the type area.

INTRODUCTION

Triassic strata in the Zuni Mountains in Cibola and McKinley counties, west-central New Mexico, crop out extensively along the northern edge of the Zuni uplift, with complete stratigraphic sections of this interval readily measured in a few transects. Most of these section are on the northern limb of the Triassic outcrop belt in the Zuni Mountains, where the Sonsela Member of the Petrified Forest Formation forms an elongate northwest-trending cuesta between Grants and Fort Wingate (Fig. 1). Beneath the Sonsela Member escarpment the lower Chinle Group and Moenkopi Formation crop out as topographically low exposures of rolling badlands. Stratigraphically above the Sonsela Member dip slope the Painted Desert Member and lower Owl Rock Member form a largely covered strike valley that is traversed by both Interstate 40 and the historic Atcheson Topeka and Santa Fe (now Burlington Northern and Santa Fe) railroad. Beneath the massive Middle Jurassic Entrada Sandstone cliffs on the north side of this valley, the uppermost Owl Rock Formation and, locally, the Wingate Sandstone crop out as thin ledges (Owl Rock Formation) and low cliffs and ridges (Wingate Sandstone). The stratigraphy and paleontology described here are based on numerous measured sections along the north flank of the Zuni Mountains because, farther south, outcrops of Triassic strata are more sparse, generally poorly exposed, and often structurally complicated.

The history of stratigraphic study of Triassic strata in the Zuni Mountains spans more than a century. One of the principal aims of this paper is to provide a comprehensive review of these previous studies. In addition, we record our observations of each stratigraphic unit and describe our interpretations of these units. We have integrated the fossil record into this study as much as possible, thereby providing age control for the Triassic section.

HISTORY OF STUDY

Triassic outcrops in the Zuni Mountains were first studied by Marcou (1858) and Dutton (1885; see also Lucas, 2003), who noted their probable Triassic age, although Dutton (1885) considered all rocks below the Sonsela Member of this paper to be of Permian age (Fig. 2). Darton (1910, 1928) modified this interpretation, and while he also equated the Sonsela Member with the Shinarump Formation (Shinarump Conglomerate of Dutton's

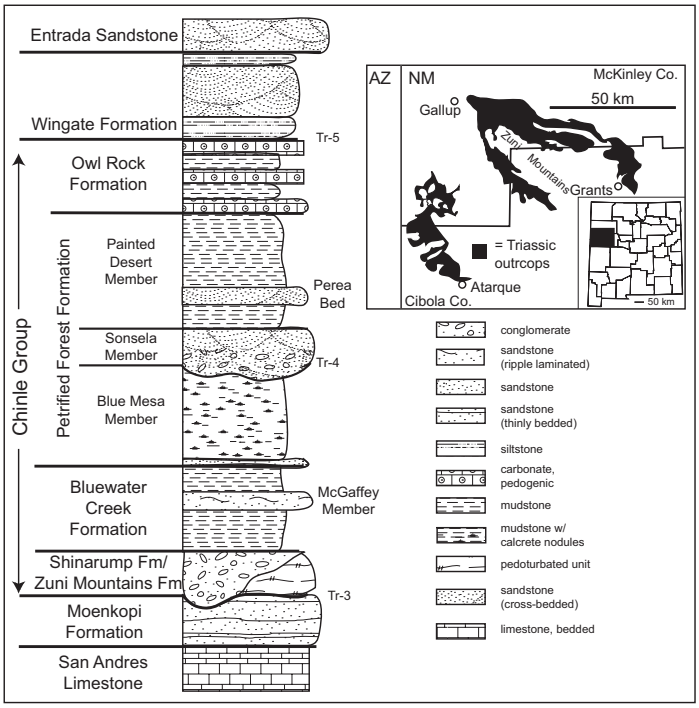

FIGURE 1. Index map and generalized stratigraphic section showing Triassic strata in west-central New Mexico.

usage), he considered lower Chinle beds to be part of the Moenkopi Formation. By 1928, he had adopted Gregory's (1917) term "Chinle" for all units above the Sonsela and below the Entrada. However, he still considered the lower Chinle to be Permian in age and therefore assigned strata of the lower Chinle Group (below the Sonsela Member of modern usage) to his concept of Moenkopi Formation. Between Darton's studies, however, Mehl et al. (1916) had reported the first tetrapod fossils from the Fort Wingate area, including a pelvis of an aetosaur and the snout of a phytosaur, both from below the Sonsela Member and indicating a Late Triassic age for these strata. Mehl et al. (1916) thus were the first to establish a Late Triassic age for most of the well-exposed red-bed badlands of the lower Chinle Group in the Zuni Mountains.

This stratigraphy remained relatively unstudied and unchanged until the 1950s, when uranium exploration spurred additional research, principally that of Smith (1954, 1957, 1958a,b), Cooley (1957, 1959a,b), and much of the USGS work published by Stewart et al. (1972a,b). Smith (1954) was the first to subdivide the Chinle of the Zuni Mountains into lower, middle, and upper members, with his informal "lower member" including all Triassic strata below the Sonsela Member, a lithostratigraphy he followed in a summary article on the Zuni Mountains (1957) and in later published mapping (1958a,b). He was also the first to recognize the distinct stratigraphic positions of the Sonsela (higher)

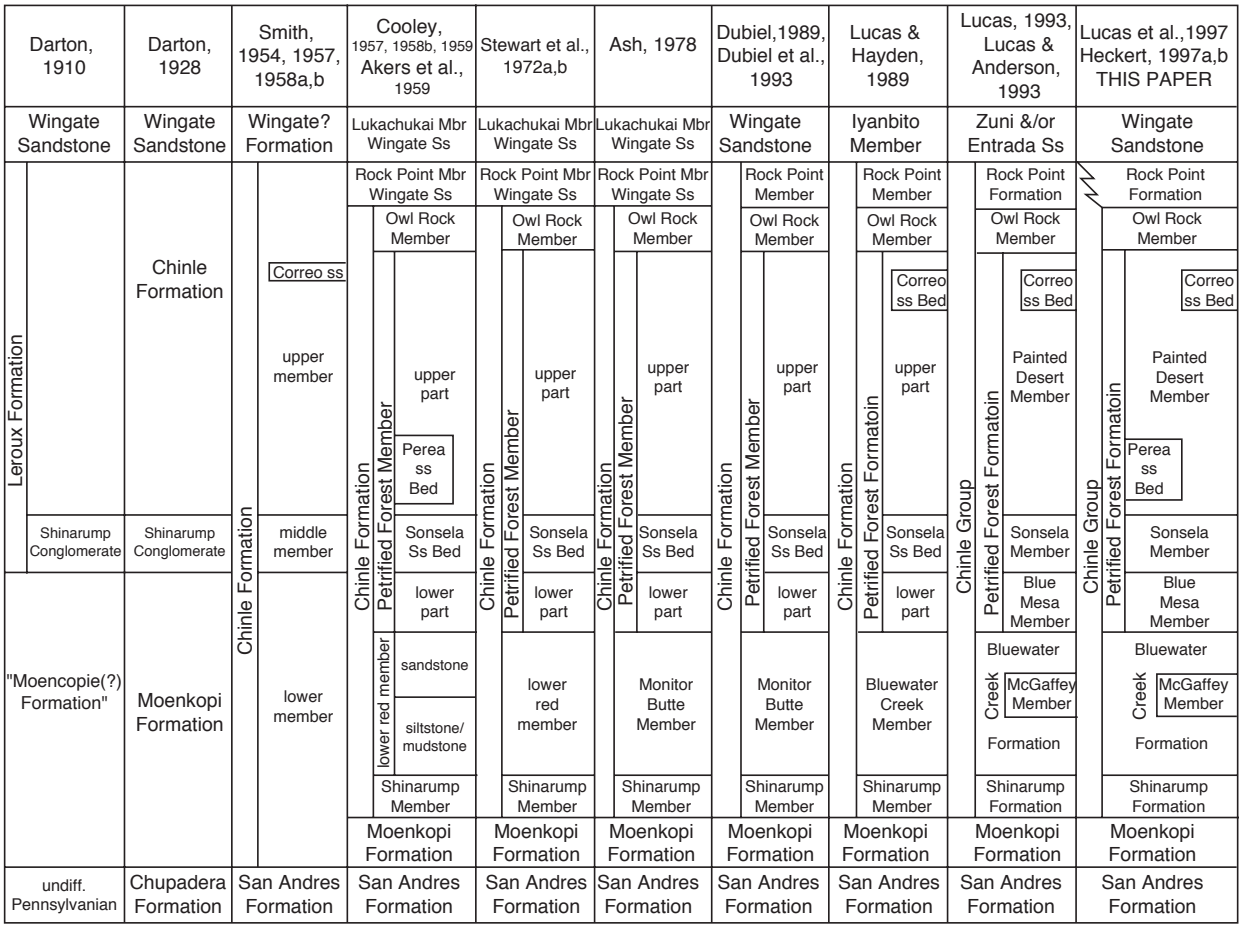

FIGURE 2. Evolution of Triassic stratigraphic nomenclature in the Zuni Mountains region. See text for discussion, especially of the uppermost interval. Rock Point Formation strata are not exposed in the Zuni Mountains (or are else interbedded within the Wingate Sandstone).

and the Shinarump (basal), designating the as-yet-unnamed former unit as an informal "middle" member of the Chinle Formation (Smith, 1954, 1957).

Cooley's (1957) master's thesis and subsequent publications (1959a,b) were the first to utilize an essentially modern stratigraphic nomenclature for the Triassic section in west-central New Mexico parallel to that used here (Fig. 2). Cooley followed the early insights of Darton (1910, 1928) in recognizing the Moenkopi Formation in western New Mexico, but improved upon Darton's work by restricting that term to the lowest sandstones and siltstones of the Triassic System. Above the Moenkopi, Cooley recognized scattered outcrops of the Shinarump and assigned overlying strata to the "lower red member" of the Chinle Formation, which were in turn overlain by the lower part of the Petrified Forest Member. Cooley (1957) also named a sandstone unit in the "upper Petrified Forest Member" the "Perea Sandstone bed" in his master's thesis, but did not use the term in his publications (Cooley, 1959a,b). Akers et al. (1958) named the Sonsela Sandstone Bed for outcrops of that unit in the Defiance uplift in northeastern Arizona, and Cooley (1959a) extended the term "Sonsela Sandstone Bed" to the Zuni Mountains.

Foster (1957) summarized stratigraphic work in west-central New Mexico and followed Smith's (1954) nomenclature for the Triassic System. Repenning et al. (1969) chose to lump together numerous informal Chinle units long recognized by the USGS and thus replaced the use of "lower red member" in the Zuni Mountains with "Monitor Butte Member," a term which had been used for correlative strata in the Four Corners region (Akers et al., 1958; Cooley, 1959a). However, in their summary of Chinle stratigraphy and sedimentology, Stewart et al. (1972a) followed the conclusions of Cooley (1958, 1959a) and Akers et al. (1958) and identified the "lower red member" as a unit distinct from the Monitor Butte Member. Stewart et al. (1972a) also introduced the informal term "mottled strata" to describe the thick, extensively pedoturbated paleosols at the base of the Chinle and formally included the Shinarump in the Chinle as a member.

Following these investigations, the work of Ash (1967, 1968, 1970a,b, 1978) focused on the lower Chinle in the vicinity of Fort Wingate. Ash (1978) followed Repenning et al. (1969) and applied the term Monitor Butte Member to strata identified by Cooley (1957, 1959a), Akers et al. (1958), and Stewart et al. (1972a) as the "lower red member." Ash (1989) continued this usage, even though lower Chinle Group strata near Fort Wingate are quite distinct from the type Monitor Butte Member in southeastern Utah (Stewart et al., 1972a; Blakey and Gubitosa, 1983; Dubiel, 1989a,b). Ash (1978) also recognized 2.1 m of gray and green shales low in the Chinle as the Ciniza Lake Beds of the Monitor Butte Member. Dubiel (1989a,b), Hasiotis and Dubiel (1993), and Hasiotis et al. (1994) followed Ash in identifying the unit above the "mottled strata" in the Zuni Mountains as the Monitor Butte Member. None of these workers modified the existing stratigraphic nomenclature above this interval.

Lucas and Hayden (1989) introduced the basic Triassic stratigraphic nomenclature advocated here, and essentially followed Cooley (1957, 1959a) in recognizing the Moenkopi Formation at the base of the Triassic System in the Zuni Mountains (Fig. 2). They also named the "lower red member" (as used by Cooley [1957, 1959a], Akers et al. [1958], and Stewart et al. [1972a]) the Bluewater Creek Member of the Chinle Formation, designating a type section at the eastern edge of the Chinle outcrop belt in the Zuni Mountains (Lucas and Hayden, 1989). Later Lucas (1993) elevated the Chinle to group status, likewise promoting member-rank units of previous authors to formation rank. Lucas (1993) also introduced formal names and type sections for the informal "lower" and "upper" members of the Petrified Forest Formation as the Blue Mesa and Painted Desert Members, respectively (Fig. 2). Mapping projects undertaken by Orin Anderson of the NMBMMR in the Upper Nutria (Anderson, 1997) and Fort Wingate (Anderson et al., 2003) 7.5-minute quadrangles resulted in further refinements in the stratigraphic column. As a result of observations made during these projects, Anderson and Lucas (1993) identified the McGaffey Member of the Bluewater Creek Formation as a distinct lithostratigraphic unit in the upper half of the formation. Lucas et al. (1997a) described the Triassic stratigraphy of the Fort Wingate quadrangle near the western edge of the Zuni Mountains. Lucas et al. (1997a) designated a type section and formally named Cooley's (1957) Perea Bed, noting its stratigraphic position in the Painted Desert Member of the Petrified Forest Formation.

Heckert's (1997a) master's thesis and related publications (Heckert and Lucas, 1996, 1997, 2002a) focused on the lower Chinle Group, applying the stratigraphy of Lucas and Hayden (1989) and Anderson and Lucas (1993) within the context of Lucas' (1993) elevation of the Chinle to group rank. Heckert and Lucas (1998a) briefly addressed the possibility of a new type section of the Wingate Sandstone where Green (1974) had measured his type "Iyanbito Member of the Entrada Sandstone." This abstract was the focus of a paper by Robertson and O'Sullivan (2001) claiming that the "Iyanbito" was in fact part of the Entrada, a contention rejected by Lucas et al. (2001). Heckert (2001) also completed a dissertation on microvertebrate paleontology in the lower Chinle Group of the southwestern U.S.A., including a site in the Zuni Mountains.

STRATIGRAPHY

There are three distinct Triassic units in the Zuni Mountains: A thin (< 25 m thick) Moenkopi Formation, a much thicker (as much as 600 m thick) Chinle Group section, and a relatively thin (~40 m thick), and only locally exposed, Wingate Sandstone, part of which may be of Jurassic age (Fig. 1). The Chinle Group succession in the Zuni Mountains consists of (ascending) Zuni Mountains Formation (= "mottled strata" of previous workers), Shinarump Formation, Bluewater Creek Formation, and Blue Mesa Member of the Petrified Forest Formation (Fig. 1). Most recent workers recognize the base of the Chinle as the first deposits above the Lower-Middle Triassic Moenkopi Formation, the top of which is the surface representing the Tr-3 unconformity of Pipiringos and O'Sullivan (1978). In the Zuni Mountains, the base of the Chinle Group generally consists of pedogenically modified siliciclastic deposits traditionally assigned to the "mottled strata" that we now identify as the Zuni Mountains Formation. Locally, channel-fill conglomerates of the Shinarump Formation overlie

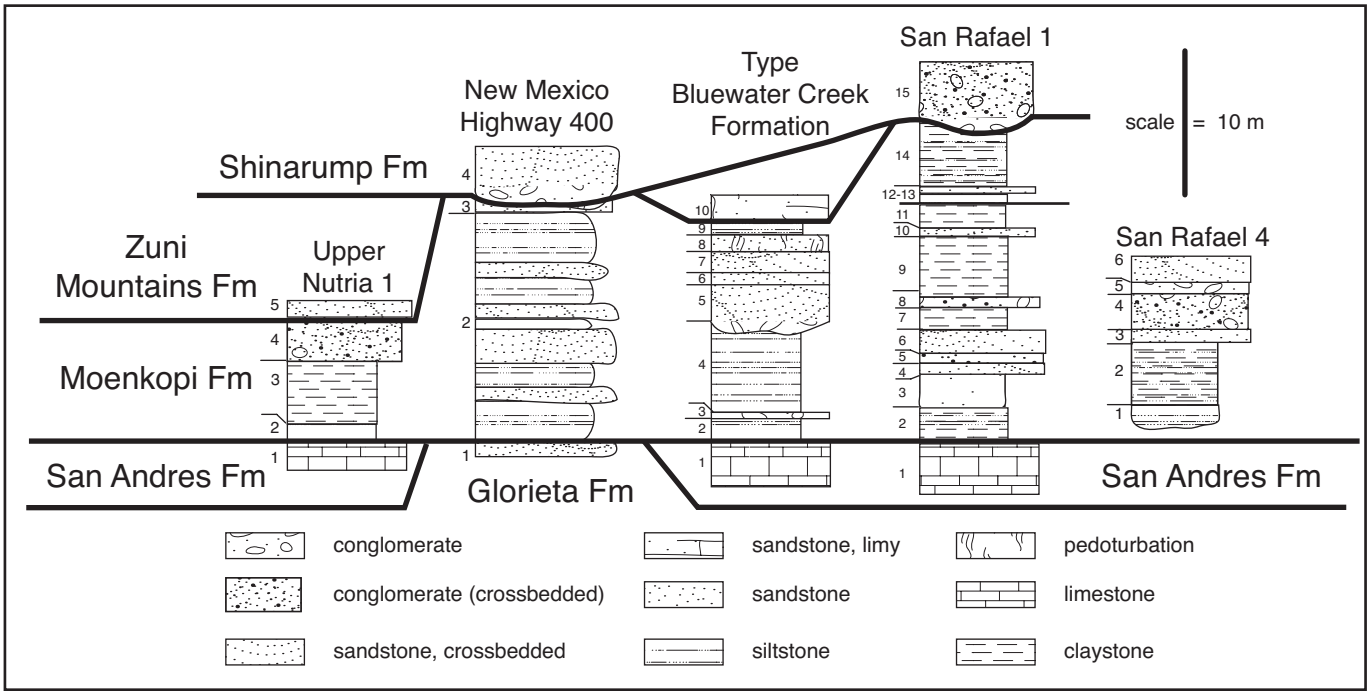

FIGURE 3. Measured stratigraphic sections of the Moenkopi Formation in western New Mexico. All but NM Highway 400 from Lucas and Hayden (1989). Highway 400 is after Heckert and Lucas (2002a).

either the Zuni Mountains Formation or the Moenkopi Formation. Red beds of the Bluewater Creek Formation conformably overlie these units throughout the Zuni Mountains.

Within the Bluewater Creek Formation, the McGaffey Member crops out as a regionally persistent, bench-forming ripple-laminated sandstone, 4-20 m thick in the upper half of the formation. The Bluewater Creek Formation is conformably overlain by muddy sandstones and highly bentonitic mudstones of the Blue Mesa Member of the Petrified Forest Formation. The Tr-4 unconformity of Lucas (1993) is expressed as an erosional surface between the Sonsela Member and the underlying Blue Mesa Member, which thins eastward from 45 to 22 m as a result of erosion during that hiatus (Heckert and Lucas, 1996).

Moenkopi Formation

Throughout the Zuni Mountains the stratigraphically lowest strata of the Triassic System pertain to the Middle Triassic Moenkopi Formation. Moenkopi strata in the Zuni Mountains consist of thin (< 25-m-thick) sections of grayish-red sandstone, siltstone, and conglomerate that overlie the Permian San Andres Formation or, locally, the Permian Glorieta Formation (Fig. 3). The surface underlying the Moenkopi Formation is thus the compound Tr-0 through Tr-2 unconformities of Pipiringos and O'Sullivan (1978). This surface reveals substantial paleotopographic relief, as the San Andres is missing locally, as in the NM-400 highway cut section we measured (Fig. 3). The Moenkopi Formation is overlain disconformably by basal Chinle deposits, either the Zuni Mountains Formation or Shinarump Formation.

Moenkopi Formation strata in the Zuni Mountains consist of thinly interbedded sandstone, siltstone, and conglomerate with minor amounts of mudstone (Fig. 3). Moenkopi strata are typically shades of grayish red with minor amounts of reddish purple, pale green, and shades of orange and brown (Stewart et al., 1972b; Hayden and Lucas, 1989; Lucas and Hayden, 1989). Sandstones are typically compositionally immature, and consist primarily of lithic arenites and lithic wackes that are nevertheless relatively well-sorted. Fine-grained strata are principally muddy siltstones and, locally, silty/sandy mudstones. Conglomerates are typically dominated by intraformational clasts but can include limestone and chert pebbles presumably derived from the underlying San Andres Formation. Moenkopi Formation strata are generally thinly bedded, with most sets much less than 0.5-m-thick, so many outcrops are partially covered slopes in spite of the relatively coarse-grained nature of the strata. Both sandstones and the thin lenses of conglomerate may be trough-crossbedded. Otherwise, most Moenkopi Formation strata are laminar bedded.

Moenkopi Formation strata clearly represent the onset of nonmarine deposition after a substantial hiatus dating to the end of San Andres Formation in Early Permian (Leonardian) time. In spite of this long hiatus (approximately 25-40 million years), relatively little paleotopography is evident at the base of the Moenkopi Formation. Locally, the San Andres Formation is absent, presumably as a result of channel development, as it is thick and well-exposed less than 2 km south of the NM 400 highway cut (see second day road log, this volume). Furthermore, the Moenkopi Formation, while thin, is never completely absent in the Zuni Mountains, so the ~25 m of Moenkopi Formation strata were adequate to

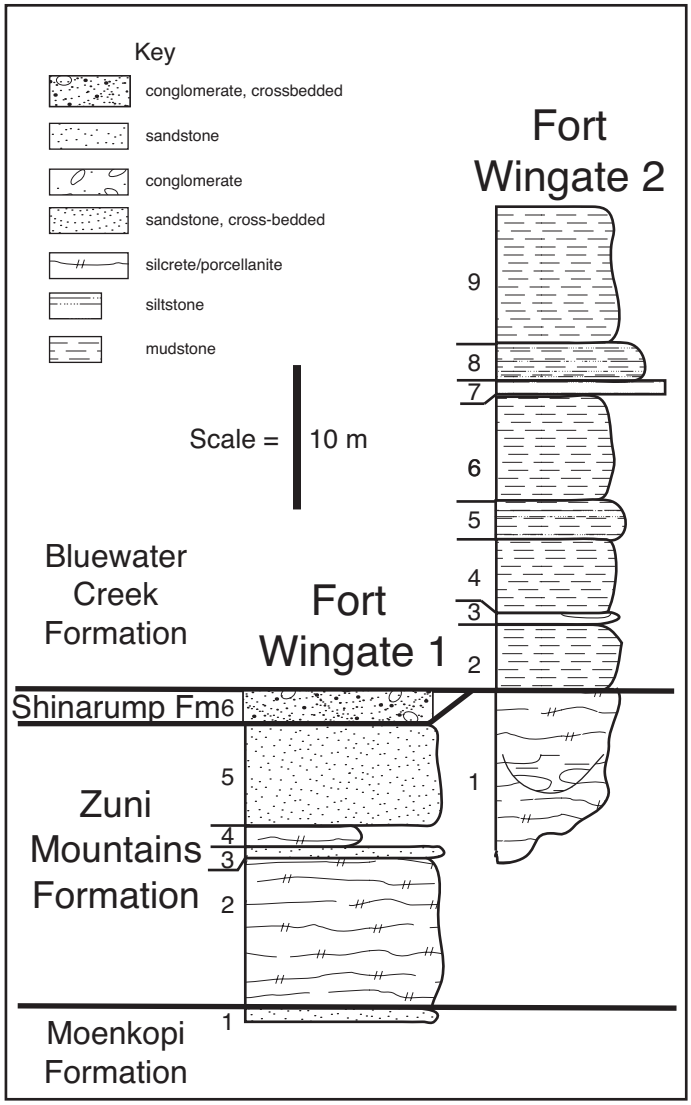

FIGURE 4. Type section of the Zuni Mountains Formation (Fort Wingate 1) and nearby section (Fort Wingate 2), showing that the Zuni Mountains Formation is overlain by either the Shinarump or the Bluewater Creek Formation. Detailed descriptions are in Lucas and Hayden (1989). See also Stop 1, Day 2, this guidebook.

completely fill the paleotopography generated during the hiatus represented by the Tr-0 through Tr-2 unconformities.

Zuni Mountains Formation

Here we designate units 2-5 of Lucas and Hayden's (1989) FW-1 (Fort Wingate 1) section the type section of the Zuni Mountains Formation, a name we use to replace the informal term "mottled strata," (Fig. 4). Stewart et al. (1972a) coined the term "mottled strata" to describe a variety of pedogenically altered sediments that appear at the base of the Chinle regionally. Since that time, various workers have used this unit to denote paleosols overlying Moenkopi or older strata on the Colorado Plateau that are in turn overlain by younger Chinle Group units (e.g., Ash, 1978; Dubiel, 1989a,b; Lucas and Hayden, 1989; Heckert, 1997a,b; Lucas et al., 1997a,b; Heckert and Lucas, 2002a). In the Zuni Mountains, the Zuni Mountains Formation is usually overlain by the Bluewater Creek Formation, although the Shinarump Formation overlies or is sharply incised into the Zuni Mountains Formation locally. Zuni Mountains Formation deposits vary widely in composition and color from outcrop to outcrop and are seldom thick enough to be mappable, yet are consistent enough and persistent enough to recognize formally. In west-central New Mexico, the Zuni Mountains Formation encompasses some of its thickest known sections, up to 25 m near Fort Wingate, although the unit may be locally absent, as in the NM-400 section (Figs. 4, 5). Notably, the Zuni Mountains Formation is so prevalent relative to the Moenkopi Formation in the Fort Wingate 7.5-minute quadrangle that Anderson et al. (2003) were unable to map the two units separately at the 1:24000 scale. Robeck (1957) named lithologically similar strata in south-central Utah the "Temple Mountain Member" but we refrain from using that term for Zuni Mountains Formation strata in the Zuni Mountains at this time.

In general, Zuni Mountains Formation strata are extensively pedoturbated siliciclastics that are color mottled shades of purple, red, yellow, white, blue, and gray and crop out in beds 1 to 25 m thick (Stewart et al., 1972a; Lucas and Hayden, 1989; Heckert, 1997a; Figs. 4, 5). All Zuni Mountains Formation lithologies indicate some degree of pedogenesis, sometimes to the extent that accurately describing them in the field is challenging. This pedogenesis and, in places, arthropod (crustacean?) bioturbation (Hasiotis and Dubiel, 1993), has obliterated most original bedding features of these deposits. Thus, throughout the Zuni Mountains, most mottled strata conglomerates and sandstones lack distinct primary bedforms, or else contain abundant rhizoliths and/or arthropod burrows (Lucas and Hayden, 1989). Hasiotis et al. (1998) interpreted these deposits as a mix of gleysols and alfisols. Tanner (2003) considered the Zuni Mountains Formation a composite paleosol, noting that it probably had a complex history of formation under subhumid conditions with fluctuating water tables. We note that there is no constraint on the timescale of these fluctuations, and that the observation of fluctuating water tables does not necessarily imply seasonal variation, and could instead be a result of longer-term (e.g., decade- or longer-term events). Consequently, soils formed under the influence of fluctuating water tables do not necessarily support "megamonsoonal" models of Chinle paleoclimate (e.g., Parrish, 1993a,b).

Locally, arcuate stringers of chert and jasper pebbles mark the remnants of trough crossbeds in the Zuni Mountains Formation. At least some of these probably represent pedogenically modified Shinarump Formation deposits. Many Zuni Mountains Formation sandstones are heavily calcified, and some of these strata are so highly silicified that they are best classified as silcretes or porcellanites. Mudrocks are considerably less common, but still exhibit color mottling and bio- or pedoturbation similar to that of the coarser-grained rocks. Locally, the mudstones of the Zuni Mountains Formation may include numerous nodules and veins of secondary gypsum, some as large as 20 cm in diameter. Flaggy sandstones and mudstones that exhibit similar color mottling and occur at or near the base of the Zuni Mountains Formation are probably pedogenically altered Moenkopi Formation sediments and should be considered part of that unit.

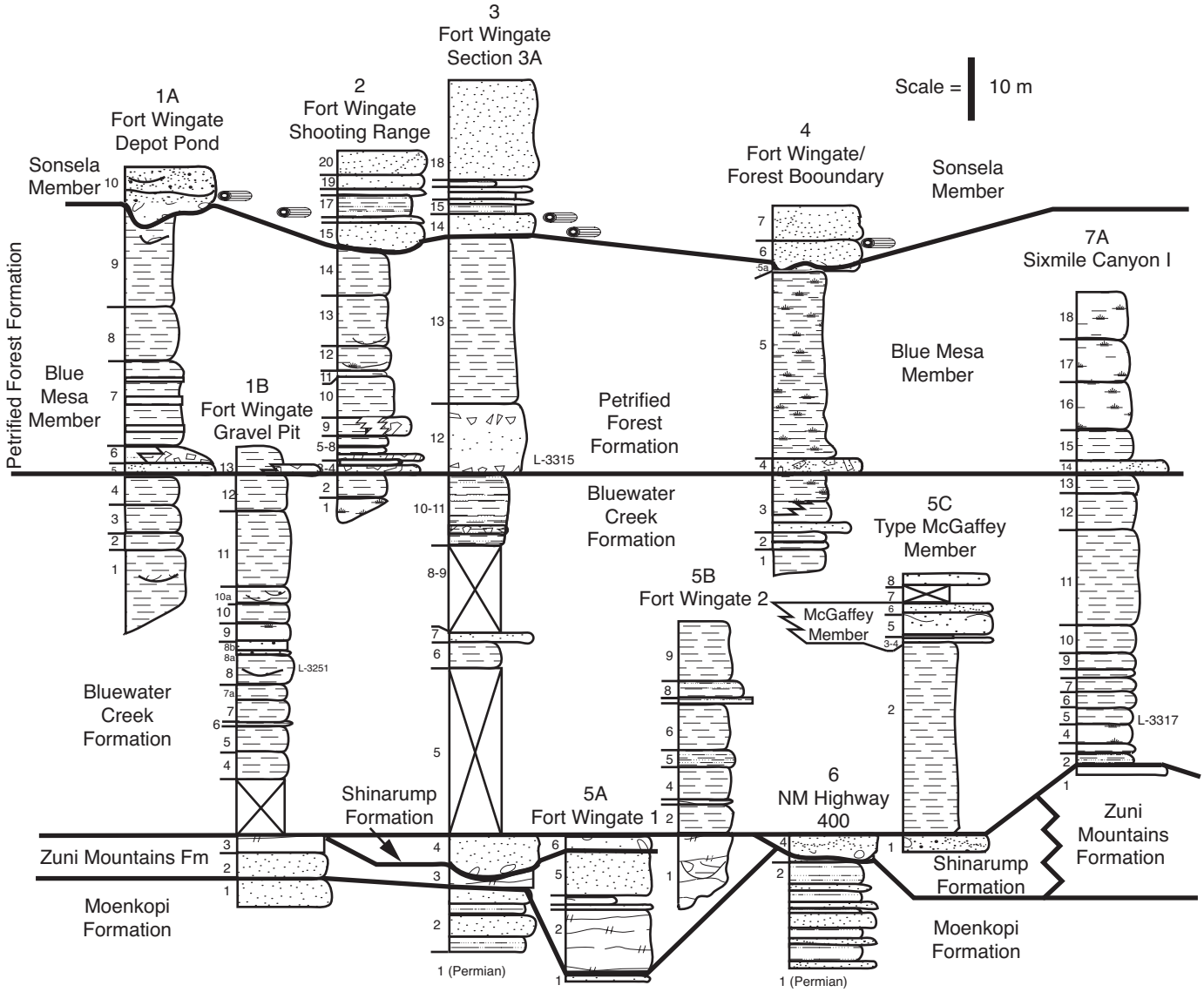

FIGURE 5. Measured stratigraphic sections of lower Chinle Group strata. Sections come from Lucas and Hayden (1989), Heckert (1997a) and Heckert and Lucas (2002a).

Shinarump Formation

The Zuni Mountains lie near the southern terminus of Shinarump Formation deposition (Evensen, 1958; Stewart et al., 1972a), and outcrops of the unit are relatively sparse throughout the region (Lucas and Hayden, 1989; Heckert, 1997a). The thickest unambiguous measured Shinarump Formation deposits are 7 m of trough-crossbedded extrabasinal conglomerate and conglomeratic sandstone near the entrance to the Cibola National Forest on NM-400 (Lucas et al., 1997a; Fig. 5).

Where present the Shinarump Formation consists of well-indurated conglomerates, conglomeratic sandstones, and sandstones that are dominantly quartzose. Conglomerate clasts are principally large (up to cobble-sized) extrabasinal chert and quartzite clasts, with some additional Paleozoic limestone cobbles but few, if any, intraformational clasts. Typically, conglomerates grade upward to finer, quartzose sandstones in large troughs that may be truncated by additional conglomerate-sandstone sets. Petrified wood is rare and occurs primarily as shattered log fragments generally less than 0.5 m long, unlike the complete logs found higher in the Chinle.

Shinarump Formation sediments were deposited in response to an initial base-level rise at the onset of Chinle deposition after development of the Tr-3 unconformity of Pipiringos and O'Sullivan (1978), and thus represent channel-fill in an incised topography. The primary Chinle drainage was to the northwest, roughly parallel to the Zuni Mountain outcrop belt (Stewart et al., 1972a). Therefore, most Shinarump outcrops in the Zuni Mountains probably represent subsidiary drainages to the main river, itself represented by the thicker Shinarump (=Agua Zarca) Formation deposits in northern New Mexico (Lucas and Hunt, 1992;

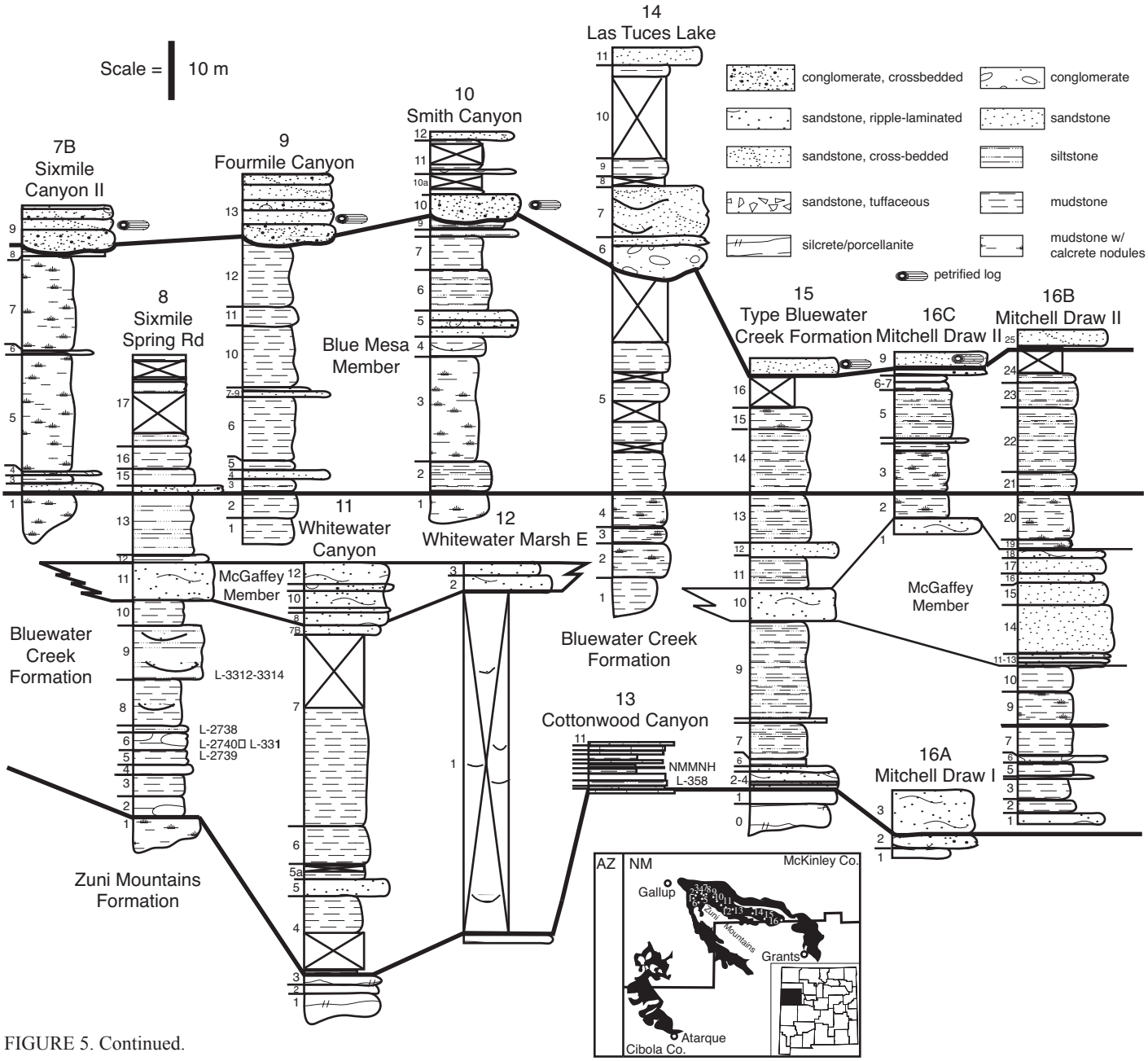

FIGURE 5. Continued.

Marzolf, 1993; Lucas et al., 1999; Lucas et al., 2003a). Therefore, tracing the outcrop and subsurface distribution of the Shinarump Formation should delineate paleovalleys that were first incised during the interval represented by the Tr-3 unconformity and then filled by channel-drowning associated with post-incision base-level rise.

Bluewater Creek Formation

The Zuni Mountains contain extensive outcrops of the Bluewater Creek Formation, with a nearly continuous outcrop belt from the type section near the community of Bluewater in the east to Fort Wingate in the west (Figs. 5, 6). To the south, outcrop is considerably more sparse. Throughout this region the Bluewater Creek Formation is consistently 50-60 m thick and consists of up to three distinct siliciclastic lithofacies assemblages (Heckert, 1997a). These assemblages are, in order of frequency of occurrence: (1) interbedded mudstone and siltstone with scattered calcrete nodule horizons, (2) ripple laminated to plane-bedded sandstone with minor intraformational conglomerate, and (3) greenish bentonitic mudstone and black shale. Also present in the Bluewater Creek Formation in the Zuni Mountains is at least one limestone that, when present, occurs coincident with the third lithofacies assemblage. Figure 6 documents correlations of these lithofacies assemblages in a schematic fashion across the Zuni Mountains.

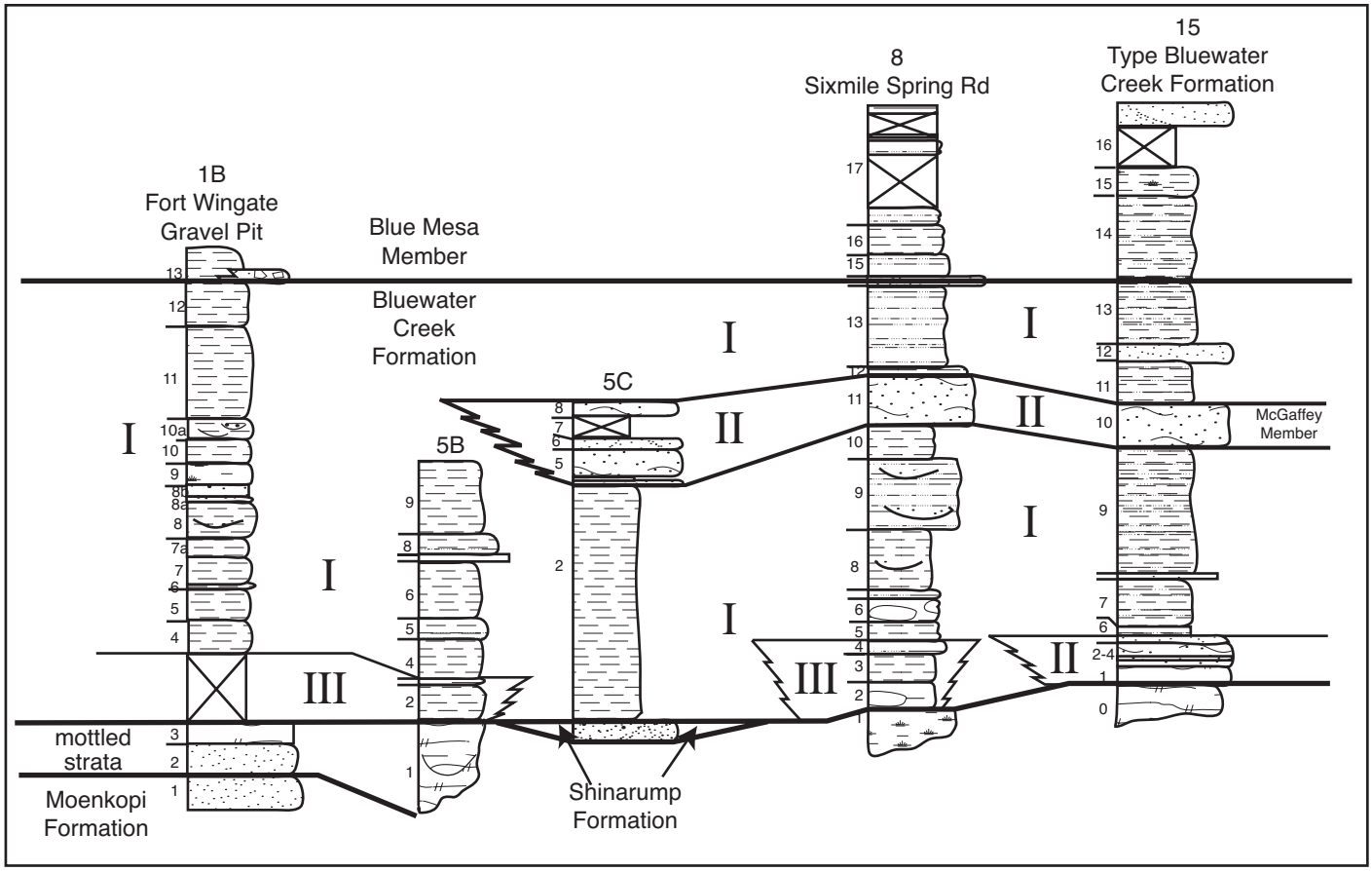

FIGURE 6. Correlation of lithofacies assemblages of the Bluewater Creek Formation in the Zuni Mountains.

First lithofacies assemblage

The dominant feature of the Bluewater Creek Formation throughout the Zuni Mountains is a succession of reddish-brown, bluish gray, and grayish purple mudstones with minor siltstones that crop out as brilliantly colored badlands: the first lithofacies assemblage. Most mudstones are silty to sandy and only slightly bentonitic, as expressed by a low percentage of smectite and mixed layer smectite-illite (Heckert and Lucas, 2002a). Stringers of reddish-brown siltstone, 0.1-0.5 m thick, are common in these mudstones. Grayish-brown and yellowish-brown calcrete and siderite nodules occur sporadically in thin, widely separated horizons throughout the section, representing limited soil development in an otherwise aggradational fluvial complex dominated by crevasse splay and overbank deposits. Deposits of this lithofacies assemblage are the single thickest package of sediments in the formation, and occur throughout the section (Fig. 6). Sediments of this type are only occasionally present at the base of the unit, but ubiquitous throughout the rest of the unit up to the base of the McGaffey Member. Above the McGaffey Member, this is the only lithofacies assemblage present in the Bluewater Creek Formation.

Second lithofacies assemblage

Ripple-laminated to laminated and plane-bedded sandstones in the Bluewater Creek Formation occur primarily at two stratigraphic levels: (1) in discontinuous lenses at or near the base of the unit and (2) within the McGaffey Member, in the upper half of the formation. The sandstone bodies of this lithofacies assemblage are usually thin, typically 4-6 m thick, but locally reach 20 m in thickness. Individual sets are generally 1 to 1.5 m thick. These sandstones are predominantly fine-to-medium-grained, well-rounded, well-sorted, micaceous sublitharenites and lithic arenites. Quartz is considerably more common than feldspar in these sandstones. In the eastern Zuni Mountains one prominent horizon of this lithofacies assemblage several meters thick marks the base of the Bluewater Creek Formation. There, gray, yellowish gray, and yellowish brown ripple-laminated sandstones are as much as 8 m thick and occur above the Zuni Mountains Formation at the base of the type section and farther east near Mitchell Draw (Figs. 5, 6). These micaceous sandstones, with abundant lithic fragments and no significant conglomerate clasts, are too immature and fine-grained to assign to the Shinarump Formation, which commonly occurs at a similar stratigraphic position in the Chinle. Instead we assign these strata to the Bluewater Creek Formation, based on their conformable relationship with overlying red-beds and high degree of lithologic similarity to other Bluewater Creek Formation sandstone bodies, such as the McGaffey Member.

The most prevalent occurrence of the sandy lithofacies assemblage is in the McGaffey Member of the Bluewater Creek Formation (Figs. 5, 6). Thin, intraformational conglomerates of cannibalized calcrete pebbles are locally present at the base of the

McGaffey Member, but the rest of the unit is dominated by ripple-laminated sandstones that are more typical of the second lithofacies assemblage. These can be seen both at the type section (Anderson and Lucas, 1993) and in the numerous McGaffey sections described here (Fig. 5). The McGaffey Member represents the most widespread and highest occurrence of the second lithofacies assemblage of the Bluewater Creek Formation. McGaffey Member strata are present throughout much of the Zuni Mountains.

Third lithofacies assemblage

Isolated outcrops of the third lithofacies assemblage occur low in the Bluewater Creek Formation, primarily in the western Zuni Mountains. These deposits are typically only 5 to 10 m thick. The third lithofacies assemblage of the Bluewater Creek Formation consists of interbedded bentonitic mudstones and dark shales. Mudstones are shades of greenish gray with locally abundant lignitic plant debris and numerous slickensides from shrinking and swelling of bentonitic clays. Shales are both rarer and thinner than mudstones and are very dark gray to black with abundant plant debris and microfossils (Ash, 1978, 1989). This lithofacies assemblage is only locally present at the base of the Bluewater Creek Formation and appears to represent various lowland and pond deposits in the poorly drained paleotopography that was present at the onset of Bluewater Creek Formation deposition. These deposits give way upward to the red-beds facies as base-level continued to rise and true fluvial depositional systems established themselves.

Ash (1978) termed 2.1 m of dark shales from the third lithofacies assemblage the "Ciniza Lake Beds," with his type section of that unit measured through a particularly fossiliferous plant- and microfossil horizon near Fort Wingate. He also diverged from the stratigraphy of Stewart et al. (1972a) and assigned the strata of the Bluewater Creek Formation to the Monitor Butte Member because of the similarity of the third lithofacies assemblage to that unit. Although sediments of the third lithofacies assemblage can be as much as 10 m thick they consist of discontinuous lenses, both across the Zuni Mountains (Fig. 6) and in other outcrop belts. Lucas and Hayden (1989), Anderson and Lucas (1993), Heckert and Lucas (1996), and Lucas et al. (1997a) considered the term "Ciniza Lake Beds" superfluous. Certainly, the unit is not mappable at the 1:24000 scale, even on the Fort Wingate quadrangle, where outcrops of greenish-gray bentonitic mudstones and dark gray to green shales are most prevalent (Anderson et al., 2003). Therefore, the utility of the name "Ciniza Lake Beds" is debatable, and appears at best to be a way of applying a formal name to the discontinuous third lithofacies assemblage.

The nature of the third lithofacies assemblage has been used both by Ash (1978, 1989) and by some later workers (Dubiel, 1989a,b; Dubiel et al., 1993; Hasiotis and Dubiel 1993) as justification for referring to the entire Bluewater Creek Formation as the "Monitor Butte Member" of the Chinle Formation. While the third lithofacies assemblage of the Bluewater Creek Formation is grossly similar to the Monitor Butte Formation in lithology, these greenish-gray bentonitic mudstones and dark shales have neither the lateral extent nor the stratigraphic thickness to merit identification as a formation-rank unit. Indeed, mapping on the Fort Wingate quadrangle, where extensive outcrops of this lithofacies assemblage occur east of NM-400 south of the village of Fort Wingate, reveals that this unit is too inconsistent to merit recognition as even a member-rank unit (Anderson and Lucas, 1993; Anderson et al., 2003). Rather, this lithofacies assemblage is seldom, if ever, more than 10 m thick, and never represents more than 15-20% of the total thickness of the Bluewater Creek Formation. Further, it is not ubiquitous at the base of the Bluewater Creek Formation, and is instead absent locally, as in the Sixmile Canyon I section (Fig. 5) and where flaggy, ripple-laminated sandstones of the second lithofacies assemblage mark the base of the formation (e.g., the type and Mitchell Draw sections—Figs. 5, 6).

Because of these lithologic differences in the first two lithofacies and the spotty outcrop pattern of the third lithofacies, parsimony dictates its inclusion in the Bluewater Creek Formation as local facies of that unit rather than trying to recognize its scattered occurrences as outliers of the Monitor Butte Formation. Certainly, to identify the entire Bluewater Creek Formation as the Monitor Butte, as done by Repenning et al. (1969), Ash (1978, 1989) or Dubiel (1989a,b), contradicts long-standing observations regarding lithologies, bedforms, and depositional environments such as those made by Cooley (1957, 1959a), Akers et al. (1958), and Stewart et al. (1972a) as well as those made later by Lucas and Hayden (1989), Anderson and Lucas (1993), Heckert and Lucas (1996), Lucas et al. (1997a,b), and Anderson et al. (2003).

Bluewater Creek Formation limestones

A thin bed of limestone that crops out very low in the Bluewater Creek Formation in the vicinity of Cottonwood Canyon has been problematic for years. The best outcrops of this limestone occur in the W1/2 NW1/4 SW1/4 SW1/4, sec. 19, T13N, R13W, although the unit as a whole is considerably more extensive, occurring as a mostly covered, very-low-angle dipslope in sections 19 and 20, and farther down the valley in sec. 13, T13N R14W. Cooley (1959b) proposed that this limestone was a cave developed in the Permian San Andres Formation and subsequently infilled by Triassic sediments. Lucas and Hayden (1989) revisited the area, measured a section, and concluded that the siliciclastics involved were a terrestrial facies of the San Andres Formation, to which they assigned the limestone. Since that time we have returned to Cottonwood Canyon and concluded that almost all of the exposed strata belong to the Bluewater Creek Formation.

The lowest exposures in Lucas and Hayden's (1989) Cottonwood Creek section (Fig. 5) are massive, highly bioturbated sandstones that only crop out in the floor of the wash. Above these are 6.2 m of lignitic shales, mudstones and siltstones that contain numerous plant fossils and coprolites in addition to the single tetrapod fossil fragment reported by Lucas and Hayden (1989). Here, we assign these strata to the third lithofacies assemblage of the Bluewater Creek Formation. Above these deposits is a single bench of micritic limestone that is typically less than 1 m thick. This limestone lacks the extensive nodular textures and pedogenic alteration found in Chinle Group limestone deposits, which typically represent paleosols, such as those of the Owl Rock Member (Lucas and Anderson, 1993; Tanner, 200). Instead, this limestone is micritic and lacks silica replacement. There does appear to be minor gypsum replacement,

and the limestone is overlain by (mostly covered) bentonitic mudstones. Some bioturbation in the form of thin (< 5 mm diameter) burrows is present, but rare. This unit lacks even fragmentary Paleozoic fossils, unlike many San Andres Formation limestone deposits in the area (e.g., Kues and Lucas, 1989). All of these features indicate that this limestone bed is one of the rare Chinle lacustrine limestones (Heckert and Lucas, 1997, 2002a), and probably formed in a poorly drained lowland area as is typical of third lithofacies assemblage deposits in the Bluewater Creek Formation.

McGaffey Member

Anderson and Lucas (1993) named the McGaffey Member of the Bluewater Creek Formation for a 4-12-m-thick sequence of ripple laminated sandstones with minor intraformational conglomerates in the Bluewater Creek Formation near Fort Wingate, New Mexico. With the exception of some local pinch-outs, this unit crops out extensively throughout the entire outcrop belt of the Bluewater Creek Formation (Fig. 5). Its upper and lower contacts are conformable. McGaffey Member sediments are primarily subangular, moderately- to well-sorted, micaceous sublitharenites and quartzarenites. Locally, it is conglomeratic with most clasts consisting of cannibalized calcrete-pebble or, rarely, mudstone rip-up clasts. These strata are typically shades of pale red and gray and crop out as persistent bench-formers. This unit forms numerous cuestas near NM-400, (at the type section), the low sandstone knobs south of the shooting range section on Fort Wingate, and a persistent ledge well below the Sonsela throughout much of the Zuni Mountains, including at the Mitchell Draw and type Bluewater Creek Formation sections (Fig. 5).

The thickness of the McGaffey Member is highly variable. Where present, its thickness varies from as little as 4 m to as much as 20 m. Locally, such as just south of the Sixmile Canyon I section (Fig. 5), it pinches out entirely. The McGaffey Member is well-indurated in most places, and forms a persistent bench throughout much of the northern Zuni Mountains, with particularly prominent ridges in Los Tuces Valley and overlooking the village of Bluewater. Although it appears to represent a period of increased lateral migration of Bluewater Creek Formation fluvial sands that might be interpreted as a time of low subsidence versus sediment supply (Blakey and Gubitosa, 1983), it is not immediately clear how to characterize the McGaffey Member in terms of regional base level. It may represent an interval of temporarily lowered, then recovering base-level coincident with a lower-order sequence than those responsible for the Tr-3 and Tr-4 unconformities. Little, if any, paleotopography is evident at the base of the McGaffey Member at the outcrop scale. However, its thickness variations (Fig. 5) may be at least partially explained by McGaffey Member sediments filling regional paleotopography that was generated during a base-level fall.

Petrified Forest Formation

The Petrified Forest Formation in the Zuni Mountains consists of all three members, the Blue Mesa, Sonsela, and Painted Desert members, in ascending order. The Blue Mesa Member conformably overlies the Bluewater Creek Formation throughout the study area, and the Sonsela disconformably overlies the Blue Mesa Member. The Painted Desert Member conformably overlies the Sonsela Member throughout the Zuni Mountains.

Blue Mesa Member

Throughout much of the Zuni Mountains region, the contact of the Petrified Forest Formation and the Bluewater Creek Formation is marked by a white, tuffaceous sandstone of the Blue Mesa Member that rests on uppermost red-beds of the Bluewater Creek Formation (Fig. 5). In the easternmost Zuni Mountains, the contact is more difficult to distinguish, but the fact that the Blue Mesa Member is dominated by purplish and greenish, highly bentonitic mudstones with abundant calcrete pebble horizons allows the careful observer to separate the two units (Fig. 5). This unit varies from 45 m thick in the western Zuni Mountains to as little as 21 m above the type Bluewater Creek Formation section. This change in thickness can be attributed to erosion during development of the Tr-4 unconformity before the onset of deposition of the overlying Sonsela Member (Heckert and Lucas, 1996).

Above the basal tuffaceous sandstone, the Blue Mesa Member consists primarily of stacked, highly bentonitic, paleosols. On a fresh vertical surface, significant pedogenesis is apparent, and numerous reduction spots and calcrete pebble horizons indicate soil formation. Clastic input was principally mud- and clay-sized particles, presumably from flood events. Mudrocks in the Blue Mesa Member are generally higher in smectite and mixed-layer smectite-illite than their Bluewater Creek Formation counterparts at the expense of quartz and other coarser materials (Heckert and Lucas, 2002a). Red-beds are rare in the Blue Mesa Member and generally less than 4 m thick (e.g., unit 11, Fourmile Canyon section). These probably represent occasional unchannelized flow. Clay sample 3 was taken from such a deposit, and its mineralogy is similar to that of the Bluewater Creek Formation mudstones (see Heckert and Lucas, 2002a).

In general, the Blue Mesa Member represents a very stable depositional environment, with distal floodplain and paleosol deposits accumulating during flood (floodplain) and normal (paleosol) conditions as basin accommodation permitted. Tanner (2003) interprets the paleosols of the Blue Mesa Member as stacked profiles preserving both A and B horizons in the mudstone intervals. He (Tanner, 2003) also considers the incipient carbonate (siderite) horizons developed in the Blue Mesa Member as stage I to stage II calcretes of Gile et al. (1966).

The Blue Mesa Member thins markedly across the outcrop belt from approximately 45 m in the western Zuni Mountains to a mere 21 m at the eastern terminus of Chinle Group outcrops. This marked change in thickness appears to be more closely related to base level fall and subsequent erosion as a result of the Tr-4 unconformity than it is to original basin parameters (Heckert and Lucas, 1996). For example, the Bluewater Creek Formation maintains a relatively constant thickness underneath the Blue Mesa Member both in the Zuni Mountains and along the southern edge of the Colorado Plateau (Fig. 5). The presence of abundant, thicker Blue Mesa deposits in Arizona, the generally inconsistent nature of this thinning (as seen in Fig. 5), and the absence of the Blue Mesa Member in the Lucero uplift to the east

all point to erosion and incision of Sonsela channels in the Blue Mesa Member as the most likely explanation for thickness variations of the Blue Mesa Member in the Zuni Mountains.

Sonsela Member

The Sonsela Member crops out most prominently in the Zuni Mountains as the heavily vegetated, bench-forming unit holding up the dipslope south of I-40 in the strike valley between Gallup and Grants. Throughout the Zuni Mountains the Sonsela Member rests disconformably on the Blue Mesa Member and is conformably overlain by the Painted Desert Member. The Sonsela Member generally crops out as two distinct benches, each 8-12 m thick, with an intervening mudstone interval up to 10 m thick between them.

The Sonsela Member is dominated by conglomeratic sandstones with lenses of true conglomerates and thin, scattered mudstone intervals. Locally, the conglomerates consist of trough-crossbedded channel lags of cobble-sized extraformational clasts. The cobbles are primarily chert and quartzite, with higher beds having a greater proportion of intraformational mudstone and calcrete pebble clasts. Above the Sixmile Canyon I section, the Sonsela includes banks of unionid bivalves in a coquina or packstone. Petrified wood is abundant in conglomeratic strata, and usually consists of large silicified logs several meters in length and up to 1 m in diameter. Indeed, the Sonsela Member is the primary petrified wood-bearing stratigraphic unit in both the Zuni Mountains and the Petrified Forest National Park (Heckert and Lucas, 1998b, 2002b).

Sonsela Member sandstones are generally trough-crossbedded, yellow to gray sublitharenites and subarkoses. The basal surface is commonly covered but, where exposed, is sharp and highly irregular. Although the Sonsela is a cliff-former, it is not a massive unit, displaying instead fine-grained breaks between depositional units. Sandstone beds typically occur in sets 1.5 to 3 m thick. Generally, two to four such beds are present in the basal Sonsela below a mudstone interval that closely resembles the Blue Mesa Member in color but appears less bentonitic and is generally covered. Upper Sonsela Member deposits are very similar to the lower sandstones and conglomerate, although extrabasinal clasts are much less common. Deacon (1990) reported paleocurrents in the Sonsela Member in the Zuni Mountains that are predominantly to the north or northeast at Fort Wingate, Continental Divide, and Bluewater. A section Deacon (1990) measured at Thoreau has easterly to southeasterly paleocurrents.

Heckert and Lucas (2002a) recognized three beds within the Sonsela in the Petrified Forest National Park in east-central Arizona. These beds are, in ascending order, the Rainbow Forest, Jim Camp Wash, and Agate Bridge beds. The Rainbow Forest and Agate Bridge beds consist of typical Sonsela lithologies, principally sandstone, conglomerate, and conglomeratic sandstone. The Jim Camp Wash Bed is a mudstone-dominated interval separating the two beds, and is also evident at the type section of the Sonsela, where upper and lower sandstone beds are separated by a finer-grained interval (Lucas et al., 1997b). The three beds are more difficult to distinguish in the Zuni Mountains, in large part because the finer-grained Jim Camp Wash Bed is thin and, often, covered.

Painted Desert Member

Painted Desert Member outcrops in the Zuni Mountains are relatively rare, with much of the unit covered in the broad strike valley running from northwest to southeast between Gallup and Grants. The Painted Desert Member conformably overlies the Sonsela Member, although the contact is commonly concealed by colluvium, whereas the Sonsela typically crops out as a heavily vegetated dipslope. Painted Desert Member deposits are typically brownish-red bentonitic mudstones and brownish red and reddish purple micaceous sandstones, both of which superficially resemble the Bluewater Creek Formation. Lucas et al. (1997a) described the Painted Desert Member on the Fort Wingate quadrangle in some detail, including naming the Perea Bed, a sandstone-dominated unit first described (and named informally) by Cooley (1957).

Lucas et al. (1997a) identified unit 12 of Stewart et al.'s (1972a) NM-3b section as the type section of the Perea Bed (Fig. 7). Interestingly, Cooley (1957) did not actually measure the Perea near the type area, and instead relied on descriptions provided to him by J.W. Harshbarger (Cooley, 1957, p. 108). The type section is part of a persistent cuesta arcing around the northern flanks of the Chinle outcrop belt on the Fort Wingate Army Depot. Perea itself is an abandoned railway station just north of Interstate 40 approximately 10 mi (6 km) to the east. Stewart et al. (1972a) measured 7 m of Perea Bed strata at the type section, and Lucas et al. (1997a) measured 4 m at another section on the type Fort Wingate Army Depot.

The Perea Bed typically consists of fine- to medium-grained sublitharenites that are banded reddish brown and pale green. Conglomerates are relatively uncommon in the Perea Bed and are generally restricted to mudstone and calcrete rip-ups < 2 cm in diameter flooring individual crossbed sets. There are both planar- and trough-crossbed sets in the Perea, but planar crossbeds predominate. The Perea is generally similar to the sandstones low in the Painted Desert Member in the Petrified Forest National Park (Heckert and Lucas, 2002b). Consequently, we interpret them similarly, and consider the Perea to represent the deposits of a high-sinuosity fluvial system.

We have not investigated the lithofacies assemblages of the Painted Desert Member to the same extent as Heckert (1997a) did for the Bluewater Creek Formation. However, it appears that the Painted Desert Member, while broadly similar to the Bluewater Creek Formation, has a somewhat simpler lithofacies assemblage. One lithofacies is broadly similar to the first lithofacies of the Bluewater Creek Formation and is dominated by the red-bed mudstones that are generally exposed as badlands slopes beneath bench-forming sandstones. These bench-forming sandstones, including outcrops of the Perea Bed, are grossly similar to the second lithofacies of the Bluewater Creek Formation, but preserve much more planar crossbedding and far less ripple lamination. Our preliminary interpretation is that the mudstone-dominated lithofacies of the Painted Desert Member represent floodplain deposits, whereas the sandstone-dominated lithofacies are the channel and bank deposits of river systems. In general, the Painted Desert Member appears to record a higher-sinuosity fluvial system than the Bluewater Creek Formation.

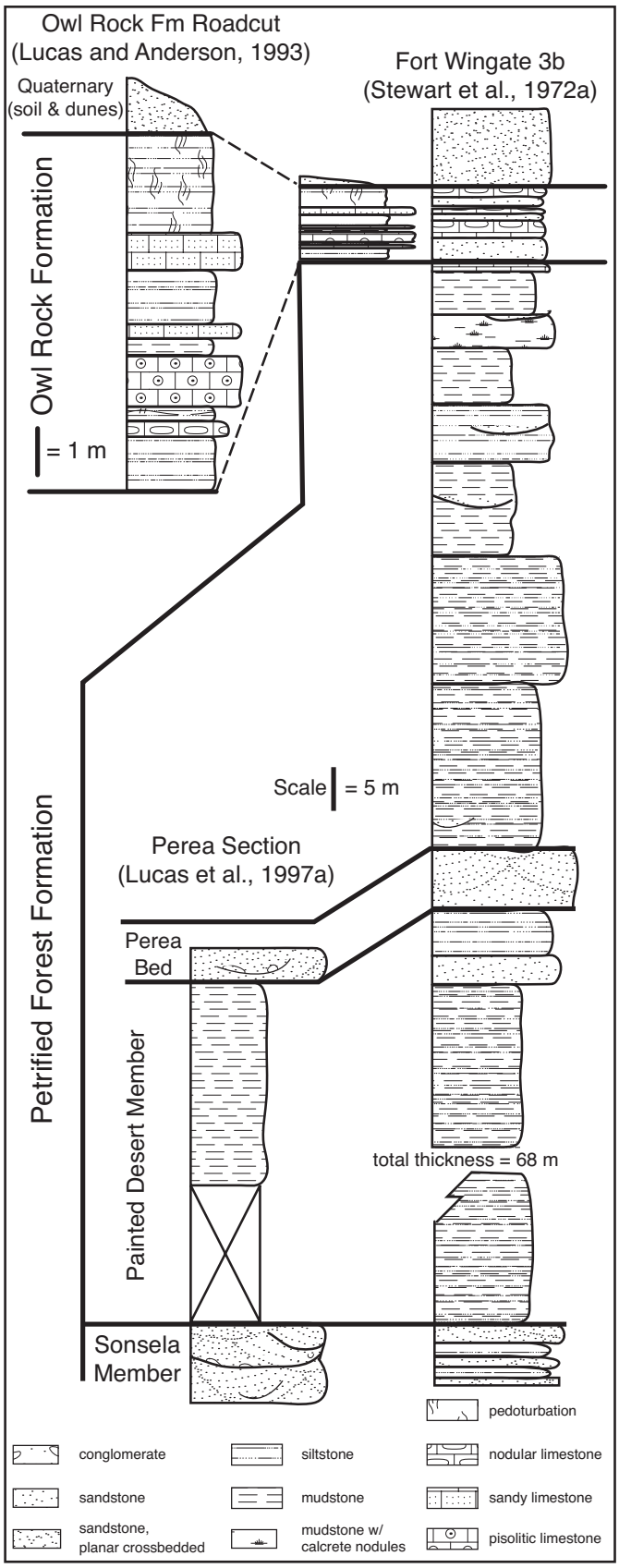

FIGURE 7. Measured stratigraphic sections of the upper Chinle Group in the Zuni Mountains. See cited sources for detailed descriptions of each section.

Tanner (2003) noted that Painted Desert Member paleosols (developed in the mudstone-dominated lithofacies) tended to preserve vertisols *sensu* Hasiotis et al. (1998). Calcrete horizons in the Painted Desert Member in eastern Arizona include more- and better-developed calcrete horizons, corresponding to stage II or stage III calcretes of Gile et al. (1966) (Tanner, 2003). These features record a general drying trend in the Chinle section over time (e.g., Lucas, 2001).

Owl Rock Formation

The Owl Rock Formation crops out as low benches and rounded slopes topographically below the massive cliffs of Entrada Sandstone on the north flank of the Zuni Mountains. Owl Rock Formation strata in the Zuni Mountains region are relatively thin (~25 m) and lie conformably on the Painted Desert Member (Fig. 7). The Owl Rock Formation is overlain unconformably by the Triassic-Jurassic Wingate Sandstone or Middle Jurassic Entrada Sandstone.

Owl Rock Formation strata are typically laterally persistent beds of pale red and pale reddish-brown, calcareous siltstone, thin-bedded sandy siltstone and light greenish-gray limestone and nodular limestone. Owl Rock Formation limestones are locally thick (up to 4 m) and are extremely indurated with tabular to platy structures, pisolitic and multilaminar fabrics, secondary silica and zones of dissolution, brecciation and recementation. Many vertical, tube-like structures Dubiel (1989a,b) and others have identified as lungfish or other animal burrows are, in fact, rhizoliths (Lucas and Hayden, 1989; Tanner, 2000, 2003). Consequently, we follow Lucas and Anderson (1993) and interpret most Owl Rock limestones as stage III to stage VI calcretes (e.g., Gile et al., 1966; Bachman and Machette, 1977). Tanner (2003) concurs, and notes that mudstone-hosted calcareous nodule horizons range from stage II to stage IV calcretes.

There is thus no reason to consider Owl Rock Formation limestones the deposits of a large lake, as argued by Blakey and Gubitosa (1983) and Dubiel (1989a,b). Indeed, Tanner (2000), in a regional study of the Owl Rock Formation, further undermined this interpretation and concluded that Owl Rock deposition took place in a low-gradient floodplain during a period of increasing aridity. Tanner (2000, 2003) further interpreted most Owl Rock Formation limestones as pedogenic calcretes and palustrine-lacustrine limestones formed in ponds and ephemeral lakes that developed in topographic lows on the floodplain. Some of the best exposures of Owl Rock Formation strata demonstrating the characteristics of the Owl Rock Formation documented here are the road cuts on both sides of Interstate 40 just outside of Gallup (mile 48.9 in Second-day road log of this volume; Fig. 7).

Wingate Sandstone

Dutton (1885) really only coined two stratigraphic names for sedimentary strata in the vicinity of the Zuni Mountains: the Jurassic Zuni Sandstone and the ?Triassic-Jurassic Wingate Sandstone (see also Lucas, 2003; Lucas and Heckert, 2003). Much of the type Wingate Sandstone in western New Mexico

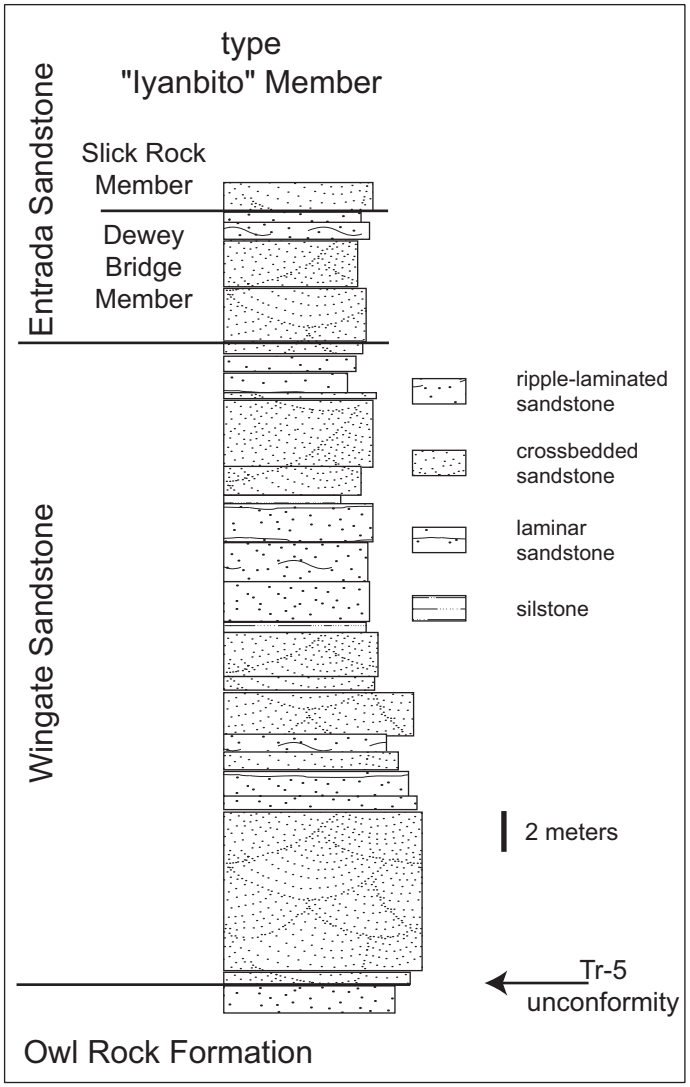

FIGURE 8. Measured stratigraphic section of the Wingate Sandstone in the type area (= "Iyanbito Member" of the Entrada Sandstone of Green, 1974). See Lucas and Heckert (2003) for detailed description.

was reassigned to the Middle Jurassic Entrada Sandstone in the middle of the 20th century, and the stratigraphically lowest eolian sandstones in the Gallup area were assigned to the "Iyanbito Member" of the Entrada in the 1970s (Green, 1974). We have restudied the type section of Green's (1974) "Iyanbito Member" of the Entrada and conclude that, as Harshbarger et al. (1957) argued, it more likely represents a southern tongue of the Upper Triassic-Lower Jurassic Wingate Sandstone as the unit is now construed in eastern Arizona.

The type section of the "Iyanbito Member" is 39.8 m thick and consists primarily of pale reddish brown to moderate reddish orange, very fine- to medium-grained, subangular to rounded, moderately sorted, silty quartzarenite with occasional thin (<0.03 m) shale partings (Fig. 8; measured section is described in Lucas and Heckert, 2003). Some of these quartzarenites are locally conglomeratic, with very coarse-grained to pebbly (2-4 mm diameter) clasts of chert, quartz, and clay. Most sandstones preserve faint, high-angle trough crossbeds and other features characteristic of eolianites (66%), whereas other sandstones are ripple laminated, laminated, or bioturbated, and thus probably are water-lain and/or water reworked (34%). In general, all "Iyanbito" strata are coarser-grained and more poorly sorted than overlying rock types of the Entrada Sandstone.

We agree with previous work that demonstrated that the "Iyanbito" rests disconformably on the Upper Triassic Owl Rock Formation of the Chinle Group (e.g., Green, 1974; Dubiel, 1989a,b). However, we argue that this erosional surface developed during latest Triassic through Early Jurassic time and was infilled and covered by sandstone deposits of the Wingate Sandstone (= "Iyanbito Member"). The upper contact of the Wingate Sandstone is not conformable with the medial silty (Dewey Bridge) member of the Entrada Sandstone, but is everywhere disconformable and expressed as an interval of uneven color-mottling (pale reddish brown to yellowish gray and bluish gray) and irregular topography where the base of the medial silty member fills fissures in the "Iyanbito" as much as 0.3 m deep.

LITHOSTRATIGRAPHIC CORRELATION

Moenkopi Formation strata in the Zuni Mountains were first recognized by Darton (1910, 1928), and our understanding of these strata has changed little since Stewart et al. (1972a,b). Lucas and Hayden (1989) noted that Moenkopi Formation strata in the Zuni Mountains pertained to the Anton Chico Member, as defined by Lucas and Hunt (1987). Based on the presence of the capitosaurid amphibian *Eocyclotosaurus*, the Anton Chico Member is of Perovkan (Middle Triassic: Anisian) age (Lucas and Morales, 1985; Morales, 1987; Lucas, 1998; Lucas and Schoch, 2002). The Anton Chico Member in the Zuni Mountains is thus a correlative of the Holbrook Member of the Moenkopi Formation in eastern Arizona (Lucas and Hayden, 1989). Consequently, the thin Moenkopi section in the Zuni Mountains postdates the vast majority of Moenkopi Formation deposition in Arizona and Utah, as it is stratigraphically higher, and therefore younger, than the Wupatki, Moqui, and correlative members (Stewart et al., 1972b).

The lower Chinle Group stratigraphy of the Zuni Mountains is relatively straightforward and can be readily correlated both across the outcrop belt and to other outcrop belts to the east and west. The Zuni Mountains Formation is nearly ubiquitous, and commonly underlies the Shinarump Formation when the latter is present. Shinarump Formation deposits are, as discussed previously, very patchy and scarcely mappable at the 1:24,000 scale, although they are of some importance in understanding the paleotopography generated during the Tr-3 unconformity. Both the Zuni Mountains Formation and the Shinarump Formation are readily correlated to lithologically similar units in outcrop belts to the east and west. Northward, Shinarump Formation deposits are much thicker and were formerly termed the Agua Zarca Formation in northern New Mexico (Lucas and Hunt, 1992; Lucas et al., 1999; Lucas et al., 2003a). The Shinarump Formation in the Zuni Mountains is thus the deposits of northward-draining tributaries of the trunk drainage of the Chinle during Carnian time.

Correlation of the Bluewater Creek Formation across the Zuni Mountains is easily achieved upon recognition of the three primary siliciclastic lithofacies assemblages. Numerous problems of local and regional correlation succumb to a basic understanding of the interrelationships of these lithofacies assemblages. For example, the third lithofacies assemblage of the Bluewater Creek Formation only occurs at the base of the formation, where there was significant ponding in the incised paleotopography. Ripple-laminated micaceous litharenites of the second lithofacies assemblage usually correlate either to outcrops of the McGaffey Member high in the Bluewater Creek Formation or, in the eastern Zuni Mountains, may persist near the base of the unit. The Bluewater Creek Formation is also readily recognized to the west in the vicinity of St. Johns (Lucas et al., 1997c) and to the east in the Lucero uplift (Lucas and Heckert, 1994; Heckert, 1997a).

The purplish- and greenish-gray highly bentonitic mudstones of the Blue Mesa Member are readily correlated across the Zuni Mountains, particularly west of Bluewater Lake, where an ashy sandstone marks the base of the Petrified Forest Formation. The Blue Mesa Member thins substantially across the Zuni Mountains, however, and varies from as much as 45 m in the western Zuni Mountains to a mere 20-24 m at the eastern terminus of Chinle outcrops. These mudstones are readily correlated to lithologically identical strata in the vicinity of St. Johns to the west, but the Blue Mesa Member is absent to the east in the Lucero uplift. This is a result of erosion associated with the Tr-4 unconformity (Lucas and Heckert, 1994; Heckert and Lucas, 1996, 2002a; Heckert, 1997a, 1999).

The Sonsela Member can be quite thick, as much as 20 m or more, in the Zuni Mountains and is readily correlated across the regional hogback south of Interstate 40. The Sonsela is typically thicker than it is to the west in Arizona, but this thickening does not appear to come at the expense of the Blue Mesa Member, as the latter thins dramatically across the Zuni Mountains while the thickness of the Sonsela Member remains relatively constant. Within our broader understanding of the Chinle depositional system, Sonsela strata represent the deposits of fluvial systems draining highlands to the south (e.g., Stewart et al., 1972a; Lucas, 1993; Heckert and Lucas, 1996, 2002a). These systems were themselves tributaries to a trunk drainage running southeast to northwest across the Four Corners area, where intraformational conglomerate is more common in the Sonsela interval, and correlative strata are termed the Moss Back Formation (Stewart et al.,1972a; Lucas, 1993; Lucas et al., 1997b).

Diverse lines of evidence, including palynology (Litwin et al., 1991) and tetrapod biostratigraphy (e.g., Lucas and Hunt, 1993; Lucas, 1997, 1998) indicate that the Sonsela is Revueltian (early-mid Norian) in age. Underlying Blue Mesa Member strata are Adamanian (latest Carnian). The Sonsela-Blue Mesa contact is sharp and, 1-2 m of erosional relief is evident at the outcrop scale. Heckert and Lucas (1996, 2002a) and Heckert (1997a) documented as much as 23 m of erosion by comparing a 44-m-thick Blue Mesa section on the Fort Wingate Military Depot in the west to a 21-m-thick section of equivalent strata near Bluewater in the eastern Zuni Mountains. Farther to the east, in the Lucero uplift, the Blue Mesa Member was apparently removed during the development of the Tr-4 unconformity (Lucas and Heckert, 1994; Heckert and Lucas, 1996, 2002a; Heckert, 1997a). This transect is one of the few well-constrained indications of the degree of erosion associated with the development of the Tr-4 unconformity.

The Painted Desert Member is the most uniform of the three members of the Petrified Forest Formation, both in the Zuni Mountains and throughout its outcrop belt across the southern Colorado Plateau. These strata are easily correlated based on the persistence of characteristic reddish-brown mudstone-dominated intervals above the Sonsela Member. Painted Desert Member strata in the Zuni Mountains therefore correlate to similar strata to the west in the Petrified Forest National Park (Heckert and Lucas, 2002b), northward across the Four Corners (Lucas et al., 1997b) and to the northwest in the Chama basin of north-central New Mexico (Lucas et al., 2003a). The Painted Desert Member is also an obvious correlative of the Bull Canyon Formation of east-central New Mexico and West Texas (Lucas et al., 2001a).

There are many locally persistent sandstones in the Painted Desert Member, both within the Zuni Mountains and regionally across the southern Colorado Plateau. Cooley (1957) recognized several in the Petrified Forest National Park itself, named two in New Mexico (Perea and Taaiylone sandstones) and two more in Arizona outside the Petrified Forest (Chambers and Zuni River sandstones), each in a distinct outcrop belt. Laterally persistent planar-crossbedded sandstones crop out at multiple stratigraphic levels within the Petrified Forest National Park and have been referred to as "Flattops" and "Painted Desert" sandstones (Billingsley, 1985a,b; Ash, 1987) and are now formalized as Flattops and Lithodendron Wash beds (Heckert and Lucas, 2002b). These sandstone typically occur in the lower half of the Painted Desert Member and are much less common at higher stratigraphic levels. Presently, our biostratigraphic database is unable to support more detailed correlations in this interval. However, the lithologic similarity of some of these beds and their apparent homotaxial position in the lower 100 m of the Painted Desert Member suggest that at least some of these beds may be correlative. Specifically, the Perea Bed likely correlates to the Taaiylone bed in the south near Zuni Pueblo and to the Flattops Bed 2 and Lithodendron Wash beds in the Petrified Forest National Park (Heckert and Lucas, 2002b). The Perea may also be equivalent to Cooley's (1957) Chambers and Zuni River sandstones, but we have not reexamined those strata to the same level of detail. On an even broader scale, a similar sandstone (Saladito Point Bed) crops out low in the homotaxial Bull Canyon Formation in east-central New Mexico (Lucas et al., 2001a). These strata are all stratigraphically lower than the lithologically similar Correo Bed, a persistent sandstone high in the Painted Desert Member that crops out throughout central New Mexico (e.g., Lucas and Hayden, 1989; Lucas and Heckert, 1994; Lucas et al., 1999).

The Owl Rock Formation is one of the most distinctive units of the Chinle Group, and is readily correlated to the numerous outcrops in the west (e.g., Stewart et al., 1972a; Tanner, 2000). Lucas and Heckert (1994) documented Owl Rock Formation outcrops as far east as Petaca Pinta on the western flank of the Lucero uplift (Lucas and Heckert, 1994). We follow Tanner (2000) and consider the Owl Rock Formation to represent an

interval of increasing aridity during Chinle deposition, with most Owl Rock limestones recording extensive pedogenesis on a low-gradient flood plain.

We use the term Wingate Sandstone to replace the name Iyanbito Member of the Entrada Formation. The supposed "Iyanbito Member" of the Entrada is unconformity bounded, and there are no strata elsewhere in the Entrada lithosome, which spans at least five states, that are similar to or homotaxial with the Iyanbito and still conformable with the medial silty member (Lucas and Anderson, 1998; Lucas et al., 2001b; Lucas and Heckert, 2003). Instead, we note that the Wingate Sandstone thins southward from the Four Corners into the Gallup area, while also resting on progressively older strata, as Harshbarger et al. (1957) and Cooley et al. (1969) demonstrated both in text and extensive mapping. Therefore, we interpret the type "Iyanbito" as a thin but otherwise typical exposure of the Wingate Sandstone, of Late Triassic-Early Jurassic age, and abandon the term Iyanbito Member of the Entrada Sandstone, *contra* Robertson and O'Sullivan (2001) and O'Sullivan (2003). This 38-m-thick tongue is now the only interval identified as the Wingate Sandstone in the type area described by Dutton (1885).

PALEONTOLOGY

Heckert (1997a,b) and Heckert and Lucas (2002a) have recently summarized the paleontology of the Triassic System in the Zuni Mountains, which was also updated by Heckert (2001). Consequently, we provide only a general overview of paleontological studies in the Triassic System of the Zuni Mountains.

Mehl et al. (1916) were the first to report significant tetrapod fossils from the Chinle in the Zuni Mountains, although Darton (1910, p. 46) earlier mentioned indeterminate bone fragments from this region. The material described by Mehl et al. (1916) was derived entirely from the Bluewater Creek Formation. Charles Camp visited the area briefly in the 1920s, was disappointed in the apparent barrenness of the area, and struck west for more prosperous locales, although he (Camp, 1930) briefly mentioned indeterminate postcrania of metoposaurids and phytosaurs from the Fort Wingate area. Camp's fossils were almost surely collected from the Bluewater Creek Formation as well.

Ash (1967, 1970a,b, 1978, 1989) reported numerous megafossil plants and some fragmentary vertebrates, including coprolites, from the Bluewater Creek Formation in the Fort Wingate area. Plant fossils identified by Ash (1978, p. 21) include "leaves, leafy shoots, stems, spores, [and] pollen." He (Ash, 1978) distinguished 27 plant taxa, the most common of which are the gymnosperm *Dinophyton*, pith casts assigned to *Neocalamites*, and the palynomorphs *Pityosporites* and *Klausipollenites*. By 1989, Ash recognized at least 40 taxa of plants, including representatives of the horsetails, ferns, cycads, gingkoes, and conifers from the megaflora and ferns, seed ferns, cycads or ginkgoes, and conifers from palynological specimens (Ash, 1989, p. 226). Almost all plant fossils recovered from the Chinle Group on the Fort Win-gate quadrangle are from Ash's "Ciniza Lake Beds" low in the third lithofacies assemblage of the Bluewater Creek Formation. Ash assigned this paleoflora to his "*Dinophyton* floral zone" of late Carnian age (Ash, 1980, 1989). All non-woody Upper Triassic plant fossils in the Zuni Mountains are from low in the Bluewater Creek Formation and occur in strata assigned to the third lithofacies assemblage. The only other Triassic plant fossils known from the Zuni Mountains are the abundant petrified logs, probably of the genus *Araucarioxylon*, that weather out of the Sonsela Member throughout the region. Tasch (1978) named the concostrachan arthropod *Cyzicus* (*Lioestheria*) *wingatella* based on specimens from the "Ciniza Lake Beds" locality. Ash (1989) also published a summary article of the Chinle flora in the Zuni Mountains.

Lucas and Hayden (1989) first reported Moenkopi Formation fossils, principally footprints, in the Zuni Mountains. These footprints appear to represent both capitosaurid amphibians and dicynodont reptiles (Lucas et al., 2003b). Except for the abundant coprolites described by Ash (1978), the only Upper Triassic tetrapod trace fossils thus far reported from the Zuni Mountains area are the footprints of a small dinosaur, probably a theropod, from the vicinity of Fort Wingate (Hasiotis et al., 1994; Lucas and Heckert, 2002). This specimen was recovered from sandstones of the second lithofacies assemblage very low in the Bluewater Creek Formation, geographically and stratigraphically close to Ash's plant localities.

Hunt and Lucas (1989, 1993) reviewed the vertebrate paleontology of the Fort Wingate area. Heckert (1997b) recently summarized the tetrapod fauna of the lower Chinle Group in the Zuni Mountains, reporting numerous new records, as did Heckert (2001) (Table 1). All of the fossils they documented came from the Bluewater Creek Formation. Indeed, almost all fossils from the Triassic System in the Zuni Mountains come from the lower Chinle Group. To date, we have not recovered any fossils from the Painted Desert Member, although Stewart et al. (1972a) reported some unidentifiable bone fragments from the Perea Bed at the type section. Similarly, there is no fossil record from either the Owl Rock Formation or the Wingate Sandstone in the Zuni Mountains at this time.

BIOCHRONOLOGY

No biochronologically significant fossils are known from the Zuni Mountains Formation, either in the Zuni Mountains or elsewhere in the region. For this reason, the age of the Zuni Mountains Formation continues to be based entirely on its stratigraphic position between better constrained units. Unfortunately, the Shinarump Formation in the Zuni Mountains is not one of these well-constrained units, as it too lacks age-diagnostic fossils. Palynological and tetrapod evidence from Arizona implies that the Shinarump Formation is of Otischalkian (late Carnian) age (Litwin et al., 1991; Lucas, 1997).

Fossil plants from the lower part of the Bluewater Creek Formation on the Fort Wingate quadrangle belong to Ash's (1980) *Dinophyton* floral zone of late Carnian age. Fossil tetrapods from the Bluewater Creek Formation, especially the aetosaur *Stagonolepis*, indicate an Adamanian age, which is latest Carnian (Lucas and Hunt, 1993; Heckert, 1997a,b). Although the Blue Mesa Member is essentially barren in the Zuni Mountains, the type Adamanian fauna was collected from the Blue Mesa Member in the Petrified Forest National Park in western Arizona, and there

TABLE 1. Vertebrate faunal list of the lower Chinle Group in the Zuni Mountains (after Heckert, 1997a, 2001).

Chondrichthyes:
"*Xenacanthus*" sp.
Hybodontoidea indet.
Osteichthyes:
Chinlea sp.
Redfieldiidae indet.
Palaeoniscidae indet. aff. *Turseodus*
Coelacanthidae indet.
Actinopterygii indet.
Amphibia:
Buettneria perfecta
Apachesaurus cf. *A. gregorii*
microvertebrate taxa
Primitive Reptiles:
several microvertebrate taxa
Procolophonidae:
aff. *Chinleogomphius*
Synapsida:
Indeterminate ?dicynodont
Phytosauria:
aff. *Angistorhinus* sp.
aff. *Rutiodon* sp.
Aetosauria:
Desmatosuchus haplocerus
Stagonolepis wellesi
Paratypothorax andressorum
Dinosauria:
aff. *Tecovasaurus murryi*
Ornithischian n. sp.
two theropods of unknown affinities
Trace fossils (vertebrate):
cf. *Grallator*
abundant coprolites

is no reason to think that the Blue Mesa Member in the Zuni Mountains is of different age. West of the Zuni Mountains the Bluewater Creek Formation yields an Adamanian fauna from the *Placerias* quarry in Arizona (Lucas et al., 1997c). Similarly, the occurrence of *Stagonolepis* in the Lucero uplift indicates an Adamanian age for that unit to the east (Lucas and Heckert, 1994; Heckert, 1997a,b, 1999), so the Bluewater Creek Formation appears to be well-constrained to the Adamanian. No age-diagnostic fossils are known from the Sonsela Member in the Zuni Mountains, but palynological (Litwin et al., 1991) evidence from elsewhere indicates a Revueltian (early-mid Norian) age. Similarly, lithostratigraphic correlation of the Painted Desert Member in the Zuni Mountains to strata in the east (Lucas et al., 1999), north (Lucas et al., 2003a) and west (Heckert and Lucas, 2002b) all indicate that the Painted Desert Member is of Revueltian age. The only Owl Rock Formation fossils, from outcrops in Arizona, support a Revueltian age for that unit as well (Lucas, 1997). The Wingate Sandstone is at least in part Triassic in the Four Corners area (Lucas et al., 1997b,d), based in part on lithostratigraphy and the presence of a phytosaur low in the unit (Morales and Ash, 1987; Lucas et al., 1997b,d).

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