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Stratigraphic description of the Tr-4 unconformity in west-central New Mexico and eastern Arizona

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Abstract

The Late Triassic Tr-4 unconformity, which approximates the Carnian-Norian stage boundary, occurs in west-central New Mexico and eastern Arizona as an erosional surface developed at the base of the Sonsela Member of the Petrified Forest Formation (Chinle Group). Correlating measured stratigraphic sections eastward from the Petrified Forest National Park (Apache County, Arizona) through the Zuni Mountains (McKinley County, New Mexico) to the Lucero uplift in Cibola and Socorro Counties, New Mexico, indicates that as much as 100 m of erosional relief characterizes this unconformity. In eastern Arizona, the Sonsela rests disconformably on a thick (81+ m) section of the Blue Mesa Member of the Petrified Forest Formation. Farther east, measured sections in the Zuni Mountains show that the Sonsela rests on Blue Mesa Member sections that average approximately 35 m thick. In the northern Lucero uplift, the Blue Mesa has been entirely removed by pre-Sonsela erosion, and the Sonsela rests directly on red beds of the underlying Bluewater Creek Formation. Throughout this traverse the thickness of the Bluewater Creek Formation remains constant at approximately 50–60 m, demonstrating that the disappearance of the Blue Mesa Member is not due to intertonguing of the floodplain, overbank, and paleosol deposits that typify that unit with the red-bed facies of the Bluewater Creek Formation. Farther south, in the southeast part of the Lucero uplift, the San Pedro Arroyo Formation laterally replaces the Bluewater Creek Formation and is in turn overlain by the Sonsela. The Tr-4 unconformity developed as a response to a drop in base level at or near the end of the late Carnian.

Introduction

The Tr-4 unconformity, as described by Lucas (1991a, 1993), is particularly important in correlating regional Triassic stratigraphy for several reasons. First, tetrapod fossils (Lucas, 1993, in press; Lucas and Hunt, 1993) and palynology (Litwin et al., 1991) indicate that this unconformity approximates the Carnian-Norian boundary, so it is of chronological significance. Second, proper identification of the Tr-4 erosional surface greatly facilitates recognition of lithostratigraphic units in west-central New Mexico, particularly in the structurally complex Lucero uplift. Third, this erosional surface marks the boundary between two depositional systems tracts in the Upper Triassic section and thus allows us to make inferences about base-level changes in the Chinle depositional basin during the Late Triassic.

Stratigraphy

The lower part of the Chinle Group in eastern Arizona and western New Mexico (Fig. 1) consists of the following units (ascending): Shinarump Formation/"mottled strata," Bluewater Creek Formation, and Blue Mesa Member of the Petrified Forest Formation. In the Lucero uplift, the San Pedro Arroyo Formation laterally replaces the Bluewater Creek Formation south of the Rio Salado (Lucas and Heckert, 1994). West of St. Johns, Arizona, the basal Chinle unit is the Mesa Redondo Formation, which essentially overlies, yet exhibits a complex intertonguing relationship with, the Shinarump Formation (Cooley, 1957, 1958). Throughout the study area (Fig. 1) this sequence is trun-

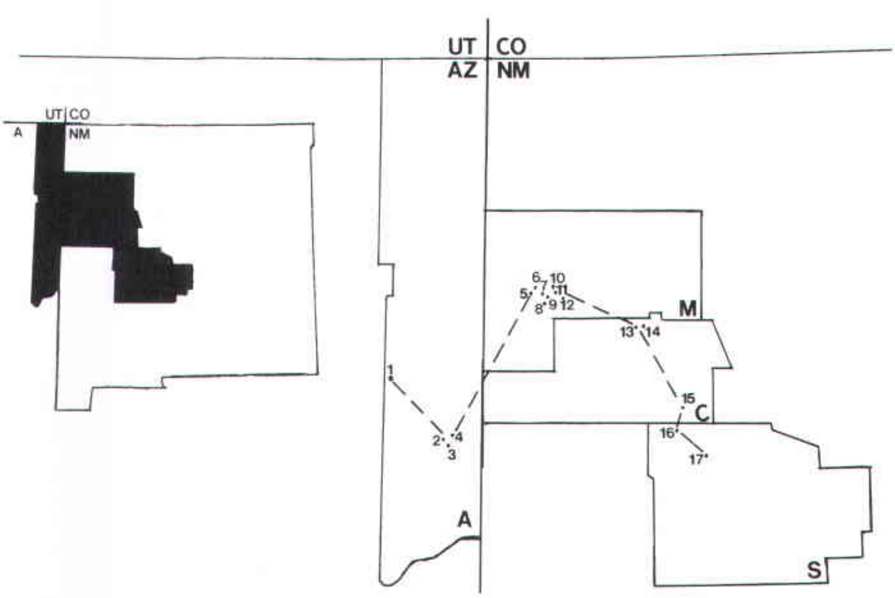

FIGURE 1—Map of New Mexico and eastern Arizona. Counties outlined are **A**, Apache County, Arizona; **M**, McKinley County, New Mexico; **C**, Cibola County, New Mexico; **S**, Socorro County, New Mexico. Numbers correspond to locations of measured sections in Fig. 2. Dashed line indicates transect line of restored cross section in Fig. 5.

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cated by an erosional surface associated with the Tr-4 unconformity, which is in turn overlain by the Sonsela Member of the Petrified Forest Formation.

Shinarump Formation/"mottled strata"

Throughout the study area the base of the Chinle Group is either the conglomerates and conglomeratic sandstones of the Shinarump Formation or the pedogenically modified siliciclastics of the "mottled strata" (Stewart et al., 1972). Shinarump strata are typically trough- to planar-crossbedded extrabasinal conglomerates that fine upward into conglomeratic and/or quartzose sandstones and are as thick as 20 m in this region (Cooley, 1957; Stewart et al., 1972). Clasts are dominantly extraformational pebbles and cobbles of Paleozoic limestones, chert, and quartzite. These strata are channel-fill deposits on the underlying Holbrook or Anton Chico Members of the Moenkopi Formation.

"Mottled strata" are pedogenically modified conglomerates, sandstones, siltstones, and mudstones that represent a weathering profile developed prior to Chinle deposition. Locally, they may underlie the Shinarump Formation (Lucas and Hayden, 1989; Fig. 2 section 8, Fort Wingate 1). These strata can be quite thick, as much as 20.3 m in the vicinity of Fort Wingate (Lucas and Hayden, 1989), and they can also occur as barely observable horizons such as in the measured section at Rio Salado (Lucas and Heckert, 1994; Fig. 2 section 17).

The interrelationships of the Shinarump Formation and the mottled strata demonstrate how a complex incised topography developed during the interval between Moenkopi and Chinle deposition, an interval corresponding to the Tr-3 unconformity (Lucas, 1993; Lucas and Marzolf, 1993; Lucas and Huber, 1994). We will later show how a similar, but not as complex, stratigraphic sequence developed during the latest Carnian and early Norian after the Tr-4 unconformity.

Bluewater Creek Formation

Typical Bluewater Creek Formation sediments are red beds that crop out as interbedded sandstones, siltstones, and mudstones throughout the study area. At its type section (Lucas and Hayden, 1989; Fig. 2 section 13 and Fig. 4E), the Bluewater Creek Formation consists of, in ascending order, a basal sandstone, interbedded mudstones and siltstones, a thin, medial sandstone (the McGaffey Member of Anderson and Lucas, 1993), and additional mudstones and siltstones. This section is 53 m thick. The Bluewater Creek Formation is present throughout most of the study area and is almost uniformly 50-60 m thick. In the Bluewater Creek Formation the McGaffey Member (Anderson and Lucas, 1993) occurs as a thin, 4–20-m-thick, intermittent unit that crops out as a prominent ledge of thinly bedded, ripple-laminated, micaceous sandstone with minor intraformational limestone conglomerates in the upper half of the Bluewater Creek Formation.

Lithofacies are suites or packages of specific lithology that occur together and suggest similar depositional environments. Identification of unique or specific lithofacies facilitates recognition of stratigraphic units in the field. To this effect we recognize three principal lithofacies in the Bluewater Creek Formation: (1) thinly bedded, laminated to ripple-laminated sandstones; (2) red beds of bentonitic mudstone, ripple-laminated siltstone, and discontinuous, lenticular sandstones; and (3) light-greenish-gray and light-gray bentonitic mudstones and localized dark, carbonaceous shales. The sandstone lithofacies is present at the base of the Bluewater Creek Formation in its eastern outcrops, such as the type section, the section at Maldonado Ranch, and in the Lucero uplift at Chicken Mountain Tank. This lithofacies also occurs higher in the section wherever the McGaffey Member is present (Fig. 2). Most of the Bluewater Creek Formation is accounted for by the second lithofacies. Mudstones are typically blue, red, or reddish purple, slightly silty, and bentonitic. Occasional calcrete nodule horizons indicate limited soil horizon development. Siltstones occur as thin, ripple-laminated ledges that are predominantly red with light-green flecks and mottles. In the western portion of the study area the third, muddy-to-shaly lithofacies crops out in low badlands at the base of the unit. We interpret these deposits as representing a poorly drained lowland area developed on the paleotopography generated during the Tr-3 unconformity. These lowlands were only partially filled by mottled strata development and Shinarump deposition. Later, as base level continued to rise, aggradation of floodplain deposits covered these dark shales with oxidized overbank deposits of the second red-beds lithofacies.

Mesa Redondo Formation

Cooley (1957) originally recognized the Bluewater Creek Formation as his "Red Member" of the Chinle Formation, and with it introduced the term Mesa Redondo Member for a correlative unit cropping out in the vicinity of St. Johns, Arizona (Cooley, 1958). In elevating the Chinle to group status, Lucas (1993) concomitantly elevated the Mesa Redondo to a formation rank unit. The Mesa Redondo superficially resembles the Moenkopi Formation, consisting primarily of reddish-brown siltstones and mudstones interrupted by a conglomeratic and sandy unit that may or may not correlate with the McGaffey Member of the Bluewater Creek Formation. The Mesa Redondo Formation has not been explored with any great rigor since the work of Cooley, so its interrelationships with the overlying Petrified Forest Formation are not clear. Although the Blue Mesa Member does overlie this unit, we have not found a locality where a complete section of both units can be measured together.

Petrified Forest Formation

The Petrified Forest Formation consists of three members, the Blue Mesa, Sonsela, and Painted Desert Members, in ascending order. Although all three crop out to some extent in the study area, we are only concerned with the lower two units, the Blue Mesa and Sonsela Members.

Blue Mesa Member—At its type section the Blue Mesa Member is more than 81 m of blue-gray, purple, and white bentonitic mudstones, siltstones, and thin

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sandstones (Lucas, 1993). Calcrete-nodule-rich soil horizons are common in the mudstone intervals. Generally, the contact between the Blue Mesa and underlying Bluewater Creek Formation is fairly abrupt, with very thin (< 1 m) sheet sandstones of the Blue Mesa Member overlying red-bed deposits of the Bluewater Creek Formation. We interpret the Blue Mesa Member to represent more distal fluvial deposits than the Bluewater Creek Formation—the stacked mudstones and calcrete horizons typifying floodplain deposits and soil development, respectively. The unit thins progressively, but somewhat irregularly, to the east, averaging approximately 35 m throughout the Zuni Mountains before disappearing altogether in the Lucero uplift.

Sonsela Member—We recognize the Sonsela Member of the Petrified Forest Formation as a tripartite package consisting of a lower conglomeratic and sandy channel-fill surface, a middle, muddy interval, and an upper conglomeratic and sandy package. The conglomerates and conglomeratic sandstones of the Sonsela Member are coarse-grained, high-energy fluvial deposits that locally scoured as much as 7 m into the underlying Blue Mesa Member (Deacon, 1990). Sonsela clasts typically consist of intraformational mudstone rip-ups and calcrete nodules. Petrified logs are very common, with lenses of chert pebbles and other extrabasinal debris less common. Some outcrops include a 0.5-m-thick coquina of unionid bivalves. Mudstone rip-ups and calcrete nodules were probably derived by cannibalization of Blue Mesa sediments and their equivalents by avulsive processes during Sonsela channel-cutting and deposition. Trough- and planar-crossbedded conglomerates and conglomeratic sandstones, grading upward into ripple-laminar and laminar sandstones, are the dominant bedforms and lithology, commonly with lateral accretion sets and minor syndepositional slumping (Cooley, 1957; Stewart et al., 1972; Deacon, 1990). Paleocurrents indicate a northerly to northeasterly pattern of drainage in Sonsela river channels (Deacon, 1990). The contact between the Sonsela and the overlying Painted Desert Member is gradational but not well exposed and is often ambiguous because the Sonsela usually crops out as either a mesa top (Petrified Forest National Park) or as the dipslope on a hogback (Zuni Mountains and Lucero uplift).

The Tr-4 unconformity

Lucas (1991a, 1993) proposed that two regional unconformities are present in the Chinle Group, in addition to the Tr-3 and J-0 unconformities that bound the unit below and above (Pipiringos and O'Sullivan, 1978). The lowest intragroup unconformity, the Tr-4, is marked by a variety of both lithologic and nonlithologic indicators. Lithologic indicators include trough scours, rip-up clasts, and stratigraphic relief, whereas regionally apparent chronological indicators constraining the timing of this unconformity include tetrapod biochronology, megafossil plant, and palynofloral evidence (Lucas, 1993, in press; Fig. 3). The Tr-5 unconformity is found below the Rock Point Formation and its equivalents, often at the top of the Owl Rock Formation, and is not pertinent to discussion here.

Lithologic evidence for the Tr-4 unconformity

A variety of lithologic and lithostratigraphic indicators demonstrate that channel-fill deposits of the Sonsela Member rest disconformably on underlying units. These include the presence of intraformational clasts in the Sonsela, channel scours at the Blue Mesa–Sonsela contact, and changing stratigraphic thickness of units underlying the Sonsela, indicating the development of as much as 100 m of stratigraphic relief.

Even in structurally complex areas such as the Lucero uplift, the Sonsela Member is readily distinguished from grossly similar units such as the Shinarump Formation by the abundance of intraformational clasts relative to extraformational clasts. Chert and quartzite pebbles, while sometimes present, are a very minor component of Sonsela sandstones and conglomerates in this study area. "Limestone" clasts in the Sonsela are almost uniformly calcrete nodules, whereas those of the Shinarump are Paleozoic extrabasinal clasts, some of which contain fossils (Stewart et al., 1972). Sonsela Member conglomerate clasts are typically mudstone rip-ups and calcrete nodules that we interpret to represent deposits of material scoured and eroded from underlying Chinle Group units.

The stratigraphic relief introduced above and extensively documented below cannot be explained by basinal tectonics because of its variability. The fact that the Blue Mesa Member is irregularly beveled off indicates that the unit was cannibalized by channel incision associated with deposition of the Sonsela rather than systematically thinned by changing basin parameters. Paleocurrent measurements in the Sonsela (Deacon, 1990) indicate a paleoslope descending from south-southwest to north-northeast in the study area. Therefore, the stratigraphic thinning of the Blue Mesa Member from west to east across the study area cannot be accounted for by depositional thinning coincident with the depositional dipslope. Instead, as documented in Fig. 2, the Blue Mesa Member thins irregularly from west to east more or less perpendicular to the depositional slope. These observed relationships are not consistent with the concept of a depositional pinchout of the Blue Mesa Member, and instead represent scouring and beveling of paleotopography associated with the Tr-4 unconformity and onset of Sonsela deposition.

Biochronology

Lucas and Hunt (1993) recently recognized four land-vertebrate faunachrons (lvf) that they used to subdivide the Chinle. Two of these, the Adamanian and the Revueltian, are pertinent to discussion here. The Adamanian lvf is defined as late Carnian in age on the basis of the aetosaur *Stagonolepis* and the phytosaur *Rutiodon*, palynomorphs (Litwin et al., 1991), and magnetostratigraphy (Molina–Garza et al., 1993; Fig. 3). Similar lines of evidence, including the phytosaur *Pseudopalatus* and the aetosaur *Typothorax*, indicate that the Revueltian is Norian in age.

Strata of the Bluewater Creek Formation contain fossils of the Adamanian lvf, including the aetosaur *Stagonolepis* and the phytosaur *Rutiodon* (Fig. 2). Originally based on fragmentary fossils in the study area (Hunt et al., 1989; Lucas and Hayden, 1989), this age assignment has been immeasurably strengthened by the realization that the *Placerias* quarry near St. Johns, Arizona is in the lower Bluewater Creek Formation (Lucas et al., 1995; our observations, Fig. 2). The overlying Blue Mesa Member also produces abundant Adamanian fossils, especially in the Petrified Forest National Park (Long and Murry, 1995). Thus these units are well constrained to the late Carnian by vertebrate fossils.

The Sonsela Member contains a limited fauna typical of the Revueltian lvf. Throughout the Petrified Forest National Park the Sonsela and overlying Painted Desert Members have numerous fossil occurrences of *Typothorax* and *Pseudopalatus* (Long and Murry, 1995), in addition to many other vertebrates, indicating that these strata are, at the oldest, early Norian in age (Fig. 2).

Study area transect

The outcrop pattern and internal variation of the stratigraphy detailed above is well exposed in four distinct areas. From west to east these are eastern Arizona, Fort Wingate, the eastern Zuni Mountains, and the Lucero uplift.

Eastern Arizona

In the south part of the Petrified Forest National Park the Blue Mesa Member is the dominant lithologic unit. Although its base is not exposed at its type section, the exposed portion of the unit measures 81+ m (Fig. 2). Most of the unit is dominated

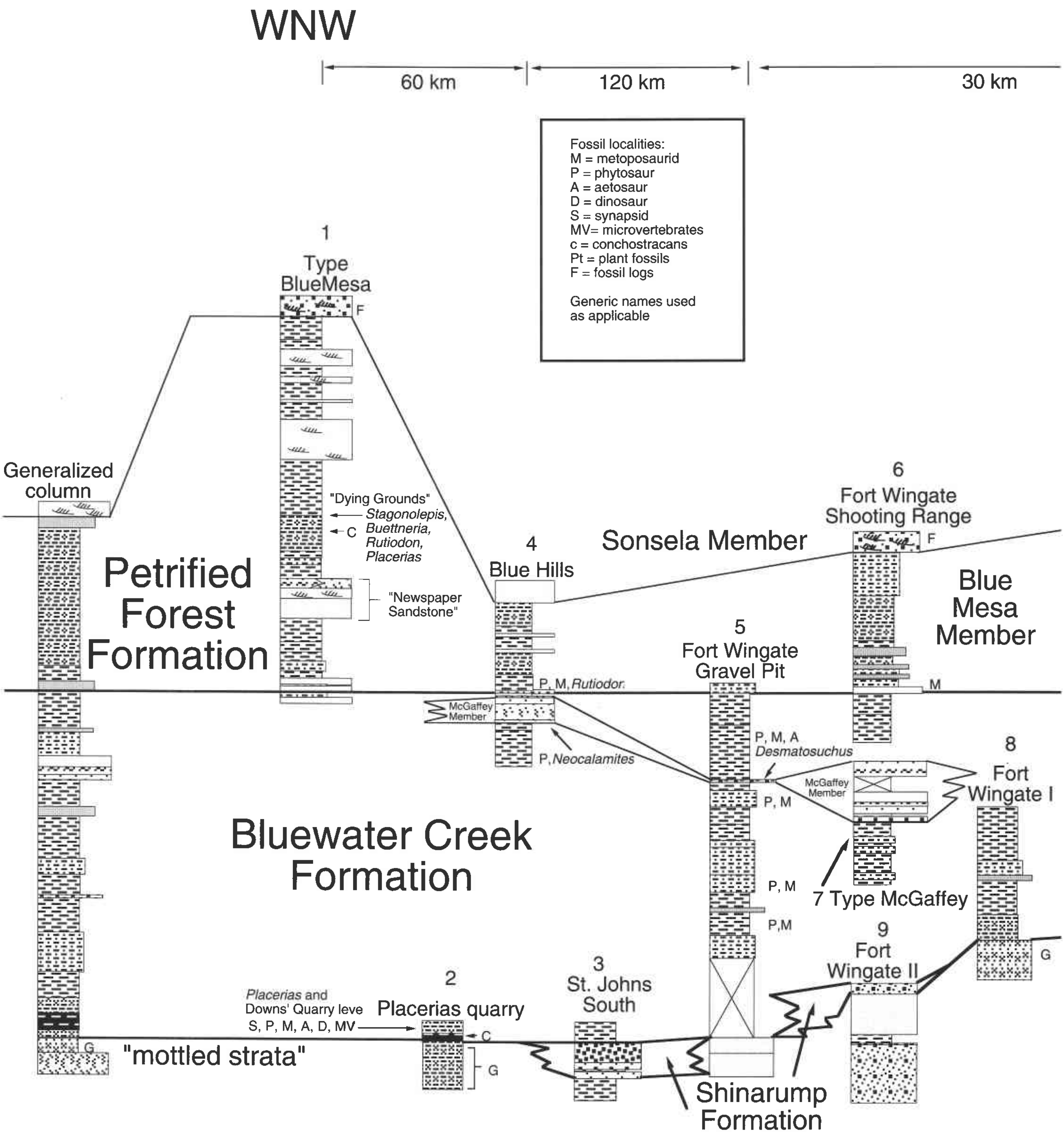
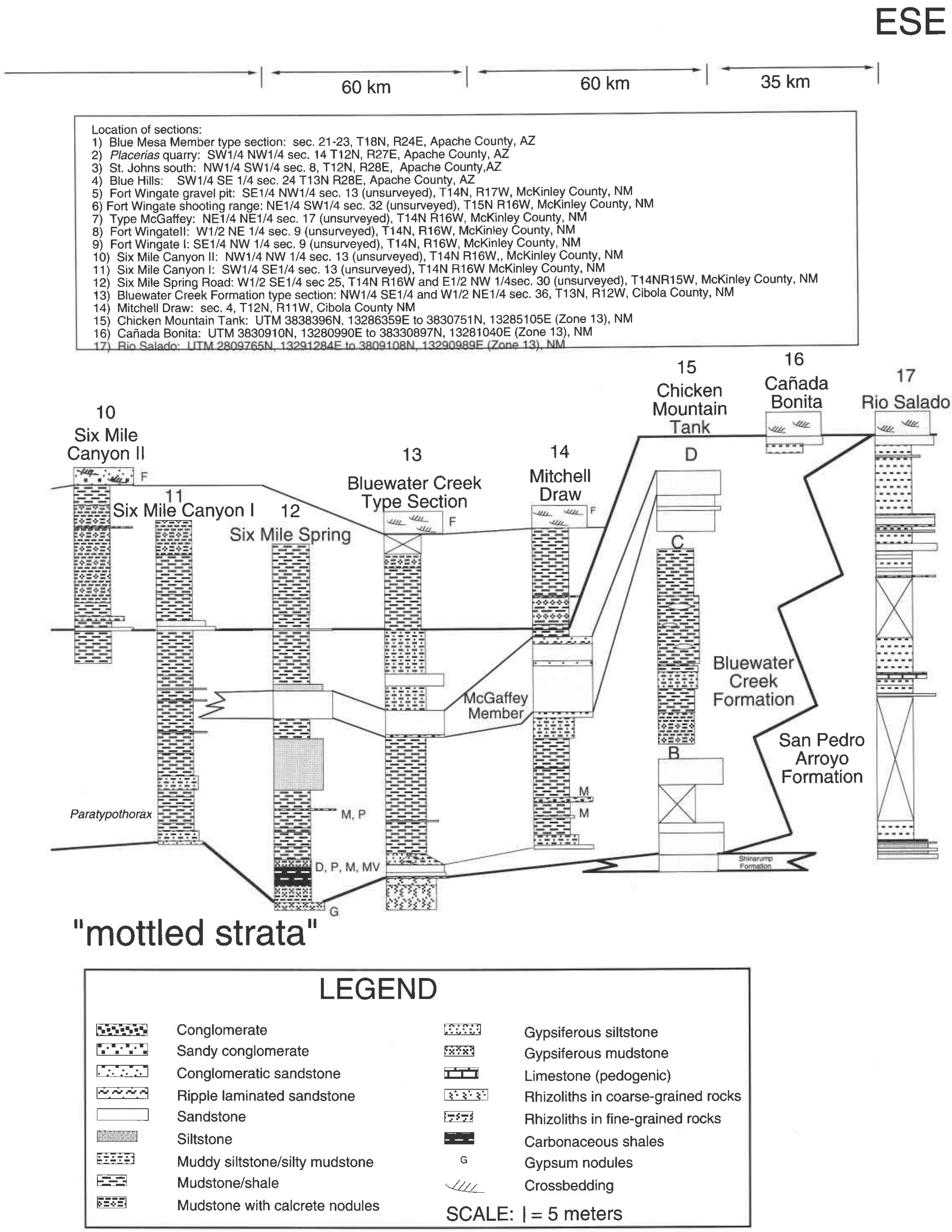


FIGURE 2—Correlated measured sections of lower Chinle Group rocks in eastern Arizona and west-central New Mexico.



ESE
60 km
60 km
35 km
Location of sections:
1) Blue Mesa Member type section: sec. 21-23, T18N, R24E, Apache County, AZ
2) *Placerias* quarry: SW1/4 NW1/4 sec. 14 T12N, R27E, Apache County, AZ
3) St. Johns south: NW1/4 SW1/4 sec. 8, T12N, R28E, Apache County,AZ
4) Blue Hills: SW1/4 SE 1/4 sec. 24 T13N R28E, Apache County, AZ
5) Fort Wingate gravel pit: SE1/4 NW1/4 sec. 13 (unsurveyed), T14N, R17W, McKinley County, NM
6) Fort Wingate shooting range: NE1/4 SW1/4 sec. 32 (unsurveyed), T15N R16W, McKinley County, NM
7) Type McGaffey: NE1/4 NE1/4 sec. 17 (unsurveyed), T14N R16W, McKinley County, NM
8) Fort WingateII: W1/2 NE 1/4 sec. 9 (unsurveyed), T14N, R16W, McKinley County, NM
9) Fort Wingate I: SE1/4 NW 1/4 sec. 9 (unsurveyed), T14N, R16W, McKinley County, NM
10) Six Mile Canyon II: NW1/4 NW 1/4 sec. 13 (unsurveyed), T14N R16W,, McKinley County, NM
11) Six Mile Canyon I: SW1/4 SE1/4 sec. 13 (unsurveyed), T14N R16W McKinley County, NM
12) Six Mile Spring Road: W1/2 SE1/4 sec 25, T14N R16W and E1/2 NW 1/4sec. 30 (unsurveyed), T14NR15W, McKinley County, NM
13) Bluewater Creek Formation type section: NW1/4 SE1/4 and W1/2 NE1/4 sec. 36, T13N, R12W, Cibola County, NM
14) Mitchell Draw: sec. 4, T12N, R11W, Cibola County NM
15) Chicken Mountain Tank: UTM 3838396N, 13286359E to 3830751N, 13285105E (Zone 13), NM
16) Cañada Bonita: UTM 3830910N, 13280990E to 38330897N, 13281040E (Zone 13), NM
17) Rio Salado: UTM 2809765N, 13291284E to 3809108N, 13290989E (Zone 13), NM
10
Six Mile
Canyon II
F
11
Six Mile Canyon I
12
Six Mile Spring
13
Bluewater Creek
Type Section
F
14
Mitchell
Draw
F
15
Chicken
Mountain
Tank
D
C
B
16
Cañada
Bonita
17
Rio Salado
McGaffey
Member
Bluewater
Creek
Formation
San Pedro
Arroyo
Formation
Paratypothorax
M, P
D, P, M, MV
G
M
M
Shinarump
Formation
"mottled strata"
LEGEND
Conglomerate
Sandy conglomerate
Conglomeratic sandstone
Ripple laminated sandstone
Sandstone
Siltstone
Muddy siltstone/silty mudstone
Mudstone/shale
Mudstone with calcrete nodules
Gypsiferous siltstone
Gypsiferous mudstone
Limestone (pedogenic)
Rhizoliths in coarse-grained rocks
Rhizoliths in fine-grained rocks
Carbonaceous shales
G Gypsum nodules
Crossbedding
SCALE: | = 5 meters

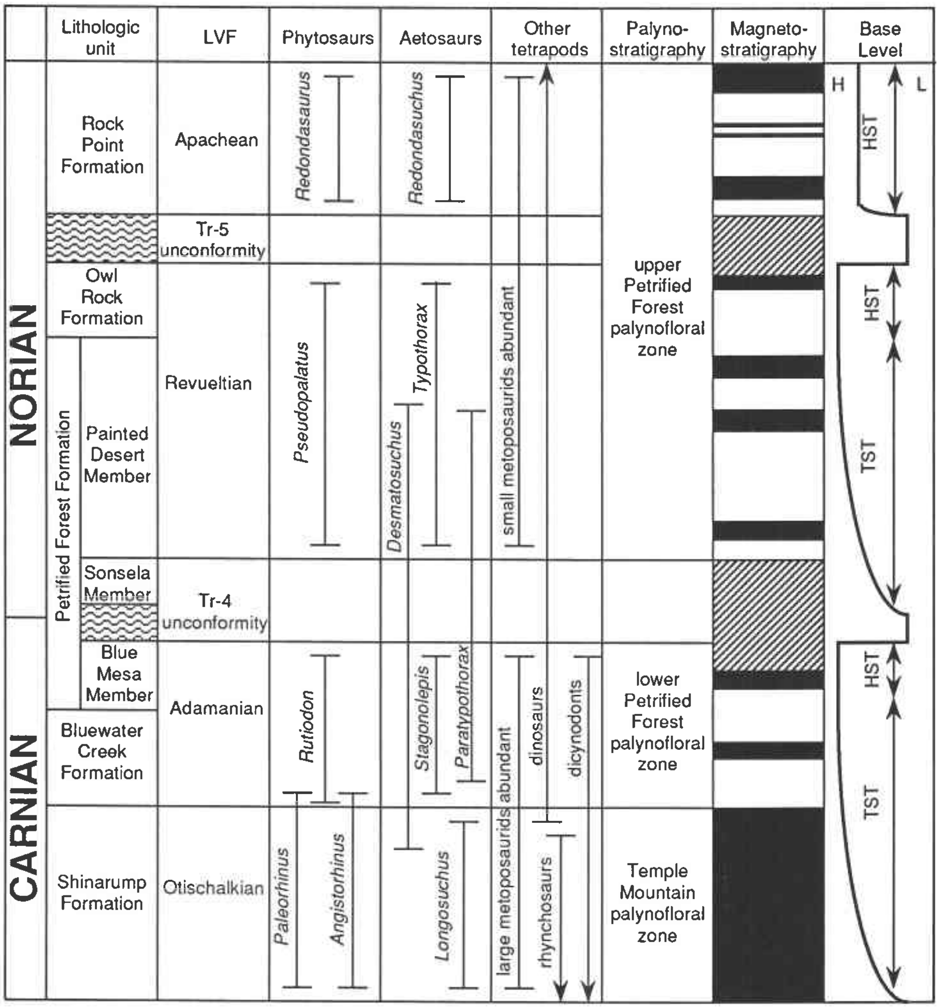


FIGURE 3—Biochronological and magnetostratigraphic controls on the timing of the Tr-4 unconformity and inferred base-level changes. Palynology is after Litwin et al. (1991), tetrapod biochronology follows Lucas and Hunt (1993), and magnetostratigraphy is after Molina–Garza et al. (1993).

by mudstones and calcrete-nodule-bearing mudstones (63%), although there are significant sandstone units such as the Newspaper Sandstone (Billingsley, 1985) totalling 37% of the section (Figs. 2, 4A).

With no base exposed, it is important to demonstrate that this relatively sandy Blue Mesa Member section is in fact the Blue Mesa and does not overlap either the Mesa Redondo or the Bluewater Creek Formations. Several lines of reasoning involving lithologic differences demonstrate that the Blue Mesa Member is the only unit present in the southern Petrified Forest National Park. Nowhere does the Blue Mesa Member resemble the Moenkopi-like Mesa Redondo Formation, therefore the latter unit is clearly not included in the type Blue Mesa section. Blue Mesa Member mudstones appear more bentonitic ("waxy") in hand specimen than their Bluewater Creek Formation counterparts and produce a more "popcorn"-like weathering surface typical of very bentonitic strata. Sandstones of the Blue Mesa Member are lightly colored, dominantly white and pale yellow with darker sandstones being shades of moderately yellowish brown, whereas those of the Bluewater Creek Formation are darker and often grayish red. Blue Mesa Member sandstones are typically "ashy" and much more poorly sorted with a significant component of powdery bentonitic mud, whereas Bluewater Creek Formation sandstones are generally better sorted and cemented quartz- and litharenites.

On the basis of these lines of evidence, the Blue Mesa Member is clearly the only unit cropping out in the southern Petrified Forest National Park beneath the Sonsela, and it is here that the unit is its thickest. To the south and east the first outcrops of units lower than the Blue Mesa Member are found along the Little Colorado River where Cooley measured up to 51 m of the Mesa Redondo Formation (Cooley, 1957). The Mesa Redondo Formation appears to grade into the Bluewater Creek Formation in the vicinity of St. Johns, as the latter unit rests on either the Shinarump Formation or "mottled strata" south of St. Johns at the *Placerias* quarry and along US–180 (Fig. 2).

In the St. Johns area, "mottled strata" underlie either the Shinarump Formation or, if the latter is absent, the Bluewater Creek Formation. Cover and structural complexities have thus far prevented us, or any other worker, from measuring either a complete Bluewater Creek Formation section or an intact Blue Mesa section resting on the Mesa Redondo Formation in this area, but we can draw numerous stratigraphic conclusions regarding these units here.

The basal Bluewater Creek Formation is best exposed south of St. Johns in the vicinity of the *Placerias* quarry. Here, basal Bluewater Creek Formation strata consist of dark shales and gypsum-bearing bentonitic mudstones that overlie color-mottled, gypsum-nodule-bearing mudstones and siltstone of the mottled strata. These strata are identical lithologically and stratigraphically to Bluewater Creek Formation strata of the "Lake Ciniza" locality of Ash (1978) near Fort Wingate, New Mexico (Fig. 2) and represent deposits of our third lithofacies of the Bluewater Creek Formation. Farther south, the Bluewater Creek Formation is poorly exposed on a stripped surface developed in the top of the Shinarump Formation (Fig. 2 section 4, Blue Hills, and Fig. 4B). Here, the base of the Bluewater Creek Formation consists of typical red beds of the second lithofacies.

North of St. Johns, extensive badlands exposures of the Bluewater Creek Formation crop out east of AZ–61 in the Blue Hills. Here, the base of the Bluewater Creek Formation is nowhere exposed, but the upper half of that unit and its contact with the Blue Mesa Member are preserved where a thin but complete section of the Blue Mesa Member rests conformably on red beds of the Bluewater Creek Formation (Fig. 2 section 4, Blue Hills). This section also marks the westernmost known extension of the McGaffey Member, which crops out as 5.3 m of red ripple-laminated sandstones that are identical in lithology and bedform to the type McGaffey Member near Fort Wingate (Anderson and Lucas, 1993).

Fort Wingate

The village of Fort Wingate, New Mexico, and the nearby, now-defunct army depot from which it gets its name are in the midst of excellent outcrops of the lower Chinle Group. We have measured composite complete sections on the grounds of the Fort Wingate Army Depot and east of Fort Wingate in Six Mile Canyon. Additional sections were measured in the immediate vicinity of Fort Wingate by Lucas and Hayden (1989) and Anderson and Lucas (1993), and these are also included in our discussion here (Fig. 2). These exposures represent the westernmost Triassic outcrops in the Zuni Mountains.

The Fort Wingate area exhibits some of

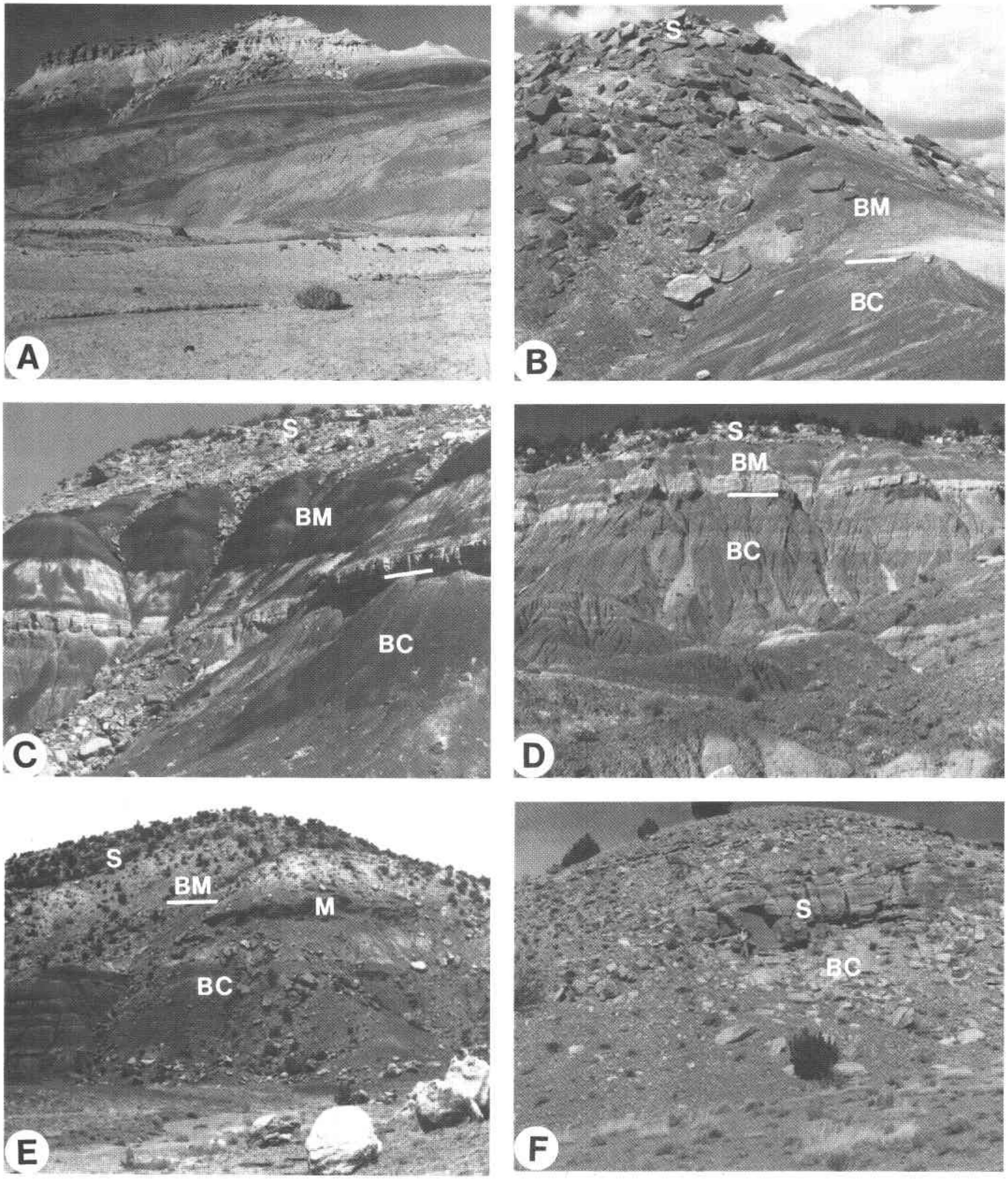


FIGURE 4—Photographs of selected outcrops of lower Chinle Group strata in east-central Arizona and west-central New Mexico. **A**, Camp Mesa, sec. 23 T18N R24E, Petrified Forest National Park, Apache County, Arizona. **B**, Measured section in Blue Hills, SW¼SE¼ sec. 24 T13N R28E, Apache County, Arizona. **C**, Fort Wingate Shooting Range, NE¼SW¼ sec. 13 (unsurveyed) T15N R16W, McKinley County, New Mexico. **D**, Six Mile Canyon I section, SW¼ SE¼ sec. 13 (unsurveyed) T14N R16W. **E**, Type Bluewater Creek Formation, NW¼SE¼ and W½NE¼ sec. 36 T13N R12W, Cibola County, New Mexico. **F**, Cañada Bonita, UTM 3830910N, 13280990E, Socorro County, New Mexico. **BC**, Bluewater Creek Formation; **BM**, Blue Mesa Member, Petrified Forest Formation; **S**, Sonsela Member, Petrified Forest Formation. Line segments indicate the Bluewater Creek Formation–Blue Mesa Member contact.

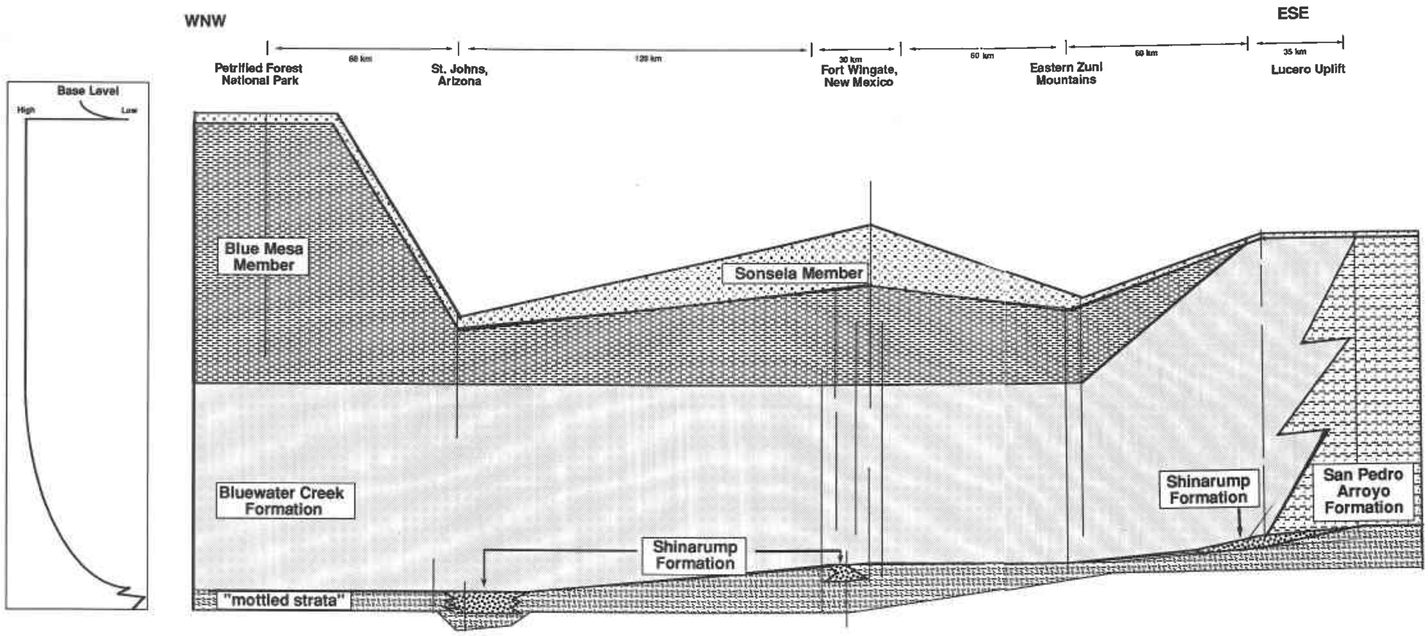


FIGURE 5—Restored cross section from Blue Mesa, Petrified Forest National Park in Apache County, Arizona, to Rio Salado, Socorro County, New Mexico, with inferred base-level changes on left. The cross section is based on the measured sections in Fig. 2.

the thickest-known sections of mottled strata, with 20.3 m measured by Lucas and Hayden (1989) southeast of Fort Wingate (Fig. 2). Here is also one of the few places where Shinarump Formation deposits unambiguously overlie mottled strata, as in the Fort Wingate 1 section. Elsewhere, the Shinarump rests directly on the Moenkopi or is absent. Mottled strata in this area are typified by two primary facies, a blue and white, heavily silicified, resistant "porcellanite" and very muddy, grayish- to bluish-green-mottled, crumbly siliciclastics with large orange mottles and nodules and veins of gypsum.

The basal Bluewater Creek Formation around Fort Wingate is typified by bluish-gray and green mudstones and occasional black shales of our third Bluewater Creek Formation lithofacies. This package is at most 10–15 m thick, probably present in our covered interval near the Fort Wingate gravel pit, and includes Ash's (1978) "Lake Ciniza" locality and a fossiliferous horizon near Six Mile Spring Road (4 Mile Canyon of Hunt and Lucas, 1993) that has produced bones of at least one theropod and numerous other microvertebrates (Heckert et al., 1994). A thin sandstone in this unit has produced footprints of an ornithischian? dinosaur (Hasiotis et al., 1994). These prints represent the oldest dinosaur remains from New Mexico and are among the oldest known dinosaurs from North America.

Above these strata, classic red beds of interbedded red and blue mudstones and red siltstones persist up to the base of the McGaffey Member. The McGaffey Member, defined by Anderson and Lucas (1993) as 6–12 m of ripple-laminated sandstone that form a prominent bench in the upper half of the Bluewater Creek Formation, pinches and swells considerably in this region. Outcrops in the vicinity of Fort Wingate demonstrate the variability of the McGaffey Member in the Bluewater Creek Formation. At its type section and elsewhere in the immediate vicinity of Fort Wingate the unit is approximately 10 m thick and holds up numerous small hogbacks and ridges (see map by O. J. Anderson in Anderson and Lucas, 1993, p. G23). To the west, the unit thins to a single, lenticular calcrete-nodule conglomerate 1.5 m thick at our Fort Wingate Gravel Pit section (Fig. 2). Eastward, the McGaffey Member is strikingly persistent through the head of Six Mile Canyon and along the road connecting that canyon to Four Mile Canyon. In the northern reaches of Six Mile Canyon, however, the McGaffey pinches out about 100–200 m south of our Six Mile Canyon section (Fig. 3, and note the absence of the McGaffey in Fig. 4D). Whether or not the McGaffey Member is present, the upper Bluewater Creek Formation consists of additional red beds siimilar to the lower units (Fig. 4D). The Bluewater Creek in this area is consistently a total of 60 m thick.

We have measured numerous stratigraphic sections in the vicinity of Fort Wingate. Two of these sections, the Fort Wingate Shooting Range and the Six Mile Canyon II sections, are particularly informative regarding the Tr-4 unconformity (Fig. 2). At the Fort Wingate Shooting Range section, measured approximately 150 m WSW of a small-arms firing range, 34.5 m of Blue Mesa Member sediments rest on top of the Bluewater Creek Formation, which is only locally exposed (Fig. 4C). Above the Blue Mesa the 12.3-m-thick tripartite Sonsela described earlier has channeled an irregular surface with as much as 1.5 m of relief visible locally. Twenty kilometers to the south and east, in Six Mile Canyon, a similar situation exists, with approximately 44 m of Blue Mesa resting on red beds of the Bluewater Creek Formation and overlain by at least 18 m of Sonsela.

Several features of these and other nearby measured sections are worth discussing here. At or near both locations both the Bluewater Creek Formation and the Blue Mesa–Sonsela contacts are traceable at the surface for many kilometers (see map by O. J. Anderson in Anderson and Lucas, 1993, p. G23). We have taken advantage of this to (1) correlate both of these sections with complete sections of the Bluewater Creek Formation and (2) demonstrate that the changing thickness of the Blue Mesa Member cannot be accounted for by interfingering of the Blue Mesa Member with either the Bluewater Creek Formation or the Sonsela Member.

On the grounds of the Fort Wingate Army Depot the Blue Mesa–Bluewater Creek contact is laterally traceable for 12 kilometers to the southwest, where it ties into the complete Bluewater Creek Formation section near the Fort Wingate gravel pit. Here, the Blue Mesa Member overlies approximately 60 m of the Bluewater Creek Formation. The "missing" base of the Bluewater Creek Formation here is a covered interval that almost certainly represents the basal fine-grained lithology of the third Bluewater Creek Formation lithofacies.

In any case, the mottled strata are well exposed here in a roadbed stream cut and constrain the maximum thickness of the Bluewater Creek Formation. A complete Blue Mesa section 44 m thick rests on the Bluewater Creek here, although it is not included in Figs. 2 and 5. This thickness is greater than, but consistent with that observed at the Fort Wingate firing range.

A similar situation exists in Six Mile Canyon where the best Blue Mesa Member section is located well down the canyon in an area of relatively modest relief. Here, as well, 44 m of the Blue Mesa rest on only a few meters of exposed Bluewater Creek Formation sediments, but the contact is laterally traceable for several kilometers up canyon (south) to another measured section of the Bluewater Creek Formation (Fig. 2 section 11, Six Mile Canyon I, and Fig. 4D), where a minimum of 52 m of Bluewater Creek Formation sediments are exposed.

Eastern Zuni Mountains

Lucas and Hayden (1989) named the Bluewater Creek Formation for basal Chinle outcrops along that drainage south of Prewitt, New Mexico (Fig. 4E). Since then most regional stratigraphic work on the Chinle has been focused on more western outcrops (Lucas, 1993; Anderson and Lucas, 1993) or in the Lucero uplift (Lucas and Heckert, 1994). Here we briefly synthesize this new information and an additional measured section with the stratigraphic data published by Lucas and Hayden (1989).

Nowhere in the eastern Zuni Mountains is the contact between the Bluewater Creek Formation and the Blue Mesa Member quite as distinct as it is farther west. Here the two units are not divided by a thin tuffaceous sandstone as they are near Fort Wingate, but the Blue Mesa is still readily differentiated lithologically from the Bluewater Creek Formation. Factors used here to distinguish the Blue Mesa from the Bluewater Creek include the presence in the Blue Mesa Member of a high degree of bentonitic alteration in the mudstones, often expressed as slopes exhibiting "popcorn" weathering surfaces, and the presence of multiple, laterally persistent calcrete nodule horizons. Blue Mesa sediments are dominantly very light green or shades of purple, with the red hues typical of the Bluewater Creek Formation much less common.

Lucas and Hayden measured 21.0 m of Blue Mesa Member (their "lower part of Petrified Forest Formation") sediments above the type Bluewater Creek Formation. Farther east, near Mitchell Draw, we measured another section at the eastern terminus of Chinle outcrops in the Zuni Mountains, where we found 22 m of Blue Mesa Member (Fig. 2 section 14).

Although the base of the Mitchell Draw section is not the Bluewater Creek Formation–Shinarump Formation/mottled strata contact, the lowest sandstone, exposed in a valley floor on the south point of the measured section, is lithologically identical to the basal sandstones at the type Bluewater Creek Formation. As Fig. 2 shows, this section is slightly thinner than the type Bluewater Creek Formation, although if one allows 5 m at the base of the Mitchell Draw section to account for the sandstone that is not exposed, then this accommodation amounts to only an extra 1–3 m at the type Bluewater Creek Formation.

Central New Mexico

The easternmost outcrop belt that encompasses these units is the structurally complex Lucero uplift in Cibola, Valencia, and Socorro Counties, New Mexico. As we reported earlier (Lucas and Heckert, 1994), the Blue Mesa Member is entirely absent in the Lucero uplift. Instead, throughout most of the uplift, the Sonsela rests directly on red beds of the Bluewater Creek Formation as in our Cañada Bonita section (Fig. 2 section 16 and Fig. 4F) and in numerous other locations, such as Cerro Pelon, Paint Tank, and Cañon del Alamito (Lucas and Heckert, 1994). As a result of extensive faulting, we have been unable to locate a complete Bluewater Creek Formation section in the Lucero uplift. Fragmentary sections in the vicinity of Chicken Mountain Tank indicate that the Bluewater Creek Formation may exceed 70 m in the Lucero uplift (Fig. 2), but this may include some fault repetition, particularly in the red beds.

South of the Rio Salado, in the southernmost portion of the Triassic outcrop belt in the Lucero uplift, the Bluewater Creek Formation grades into the San Pedro Arroyo Formation, another red-bed-dominated unit that is characterized by extensive fluvial mudstones with numerous very thin (0.5–2.0 m), laterally persistent, ripple-laminated to laminar-sheet sandstones. We reported a complete measured section of this unit previously (Lucas and Heckert, 1994), noting that it is capped by the Sonsela. Accordingly, this modifies the description of the San Pedro Arroyo Formation given by Lucas (1991b), restricting the San Pedro Arroyo Formation to his units 2-9 (Lucas and Heckert, 1994). The San Pedro Arroyo Formation rests directly on the mottled strata in the southern Lucero uplift, where it is as much as 90 m thick. Very few fossils are known from the unit, so it is not certain that the base of this unit correlates with the base of the Bluewater Creek Formation and it may in fact be older. It is clear, however, that the base of the Sonsela here is also an unconformity.

Here we note that it is difficult to ascertain properly the relationships of the Sonsela Member with the San Pedro Arroyo Formation. In our single complete section of the San Pedro Arroyo Formation that unit is approximately 90 m thick (Fig. 2), a thickness comparable to the combined Bluewater Creek Formation and Blue Mesa Member in the eastern Zuni Mountains. The possibility exists that the Blue Mesa Member has graded laterally into an expanded Bluewater Creek Formation section, which in turn has graded into the 90-m-thick San Pedro Arroyo Formation. We choose not to accept this hypothesis on the grounds that it requires more rapid lateral variation of the lithostratigraphy in the vicinity of the Lucero uplift than occurs throughout the rest of the study area. This hypothesis therefore requires more assumptions regarding the lack of continuity of facies than our hypothesis that the Blue Mesa is beveled away by erosive action associated with the Tr-4 unconformity and the Sonsela rests directly upon the Bluewater Creek or San Pedro Arroyo Formation. The latter is unusually thick, perhaps as a reflection of paleotopography associated with the underlying Tr-3 unconformity.

The Sonsela in the Lucero uplift is typified by a significantly higher percentage of mudstone rip-up clasts. This increase comes at the expense not only of extrabasinal clasts, but also of calcrete nodules. More detailed, quantified petrographic work is necessary, but we hypothesize that this change in clast composition may reflect the entrenchment of Sonsela channels in lower Chinle Group floodplains after generating enough relief (up to 100 m) to completely remove the Blue Mesa Member. Therefore the Tr-4 unconformity is readily apparent in the Lucero uplift, where the Sonsela exhibits dramatically different conglomerate clast lithology than the stratigraphically earlier and lower Shinarump Formation.

Conclusions

The Tr-4 unconformity is readily correlated across numerous lithostratigraphic units in eastern Arizona and west-central New Mexico. Differential erosion on this surface has resulted in the removal of up to 100 m of sedimentary section, principally from the Blue Mesa Member of the Petrified Forest Formation, with the greatest erosion occurring in the eastern (landward) portion of the study area. This is clearly demonstrated by examination of our simplified restored cross section (Fig. 5).

In Figs. 2 and 5 we use the Bluewater Creek Formation–Petrified Forest Formation contact to hang our measured sections on because it is the only contact between lithostratigraphic units in this interval for which there is no evidence of an unconformity. Therefore, it is most informative to consider changes of Blue Mesa Member thickness independent of changes in Bluewater Creek Formation thickness. It is possible that there may be a minor depositional hiatus or paraconformity at the end of Bluewater Creek Formation deposition, as evidenced by soil formation at the top of the Bluewater Creek Formation in, for example, the Six Mile Canyon I section. However, the primary variable influencing Blue Mesa Member thickness throughout our transect is erosion and channeling associated with the Tr-4 unconformity and initial deposition of the Sonsela Member (Fig. 5).

The same cannot be said for the Bluewater Creek Formation. Bluewater Creek Formation thickness is instead constrained by multiple variables related not to the Tr-4 unconformity, but rather to the Tr-3 unconformity. Principal among these are the extent of paleotopography generated by, and filled during, the Tr-3 unconformity. Although the contact of the Bluewater Creek Formation with the Blue Mesa Member does not demonstrate any topographic irregularity, even where the latter consists of basal, low-angle cross-bedded sandstones, the basal Bluewater Creek Formation is everywhere either lithologically or topographically gradational. Where the Shinarump Formation is present, the Bluewater Creek Formation contact is interpreted as the first flaggy to sheety, ripple-laminated sandstone. Elsewhere the contact is picked simply at the top of the mottled strata. This results in a highly irregular base to the Bluewater Creek Formation as mottled strata differentially infilled incised paleotopography and do not represent a uniform planar surface. This is best illustrated by the noticeable change in thickness between the Bluewater Creek Formation sections at Six Mile Canyon I and Six Mile Spring Road, where the latter is approximately 10 m thicker just 2 km south-southeast of the Six Mile Canyon I section. A detailed look at the lithostratigraphy of these units shows that this is in large part due to infilling of paleotopographic lows in the vicinity of the latter section, represented by a substantially thicker package of basal mudstones and shales. Indeed, the mottled strata exposed at Six Mile Canyon I are themselves undulose in nature and thus only locally exposed in a valley floor that is otherwise composed entirely of Bluewater Creek Formation sediments.

We believe that the Tr-4 unconformity, as documented here, represents erosive activity associated with a regional fall in base level marking the end of a depositional sequence as argued by Marzolf (1993; Fig. 5). This sequence consists of a transgression systems tract (TST) deposited on and in a paleotopography that was represented in places by mottled strata that developed during regional lowstand. This TST includes the channel-fill deposits of the Shinarump Formation and the fluvially dominated Bluewater Creek Formation and its equivalents. These units fine upward into the high-stand systems tract (HST) of stacked floodplain and paleosol deposits of the Blue Mesa Member (Fig. 3). At some point after deposition of the Blue Mesa Member, base level dropped precipitously and erosion was initiated. The Sonsela therefore represents the onset of the next TST, when base level rose again and re-initiated deposition on the paleotopography we have documented here.

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