



## *Pedogenic features of the Chinle Group, Four Corners region: Evidence of Late Triassic aridification*

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# PEDOGENIC FEATURES OF THE CHINLE GROUP, FOUR CORNERS REGION: EVIDENCE OF LATE TRIASSIC ARIDIFICATION

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**ABSTRACT.**—Paleosols and pedogenic features in formations of the Upper Triassic Chinle Group preserve a record of changing paleoclimate in the Four Corners region. The Carnian mottled strata and Shinarump formations contain strongly gleyed and bioturbated paleosols with a prismatic fabric that formed under the influence of a subhumid but (likely) strongly seasonal climate. Thick argillic horizons with epipedons in the overlying Cameron Formation and the Blue Mesa Member of the Petrified Forest Formation, and the prominence of vertic features and calcrete horizons in the Blue Mesa and Painted Desert members suggest that the climate became less humid, but remained strongly seasonal, from late Carnian through early Norian time. Mature calcrete profiles in the middle Norian Owl Rock Formation document continued aridification leading to semiarid conditions. Strata of the Rhaetian Rock Point Formation contain few paleosols other than immature calcretes, but the abundance of eolian and playa facies in this formation suggest increasing aridity through the end of the Triassic. Interformational variations in the carbon-isotope composition of pedogenic carbonate are consistent with this trend of aridification at a time of elevated atmospheric CO<sub>2</sub>. Although not world-wide, aridification was widespread across Pangea, and possibly resulted from the increasing strength of monsoonal flow and the weakening of zonal circulation, particularly at lower latitudes, as the continent drifted northward.

## INTRODUCTION

The spatial and temporal resolution of paleoclimate models has improved dramatically since the interpretations of Robinson (1973), in part through the increasing use of paleosols and pedogenic features as paleoclimate archives. Indeed, the morphology and composition of paleosols have long been used to ascertain past climate conditions (see Kraus, 1999 for a review). Although compaction, erosion, and diagenetic alteration of paleosols may render precise interpretation of the conditions of paleosol formation problematic, many climate-dependent pedogenic features, such as calcrete horizons, gleying, and translocation of clay and sesquioxides, have high preservation potential, rendering paleosols a valuable record of paleoclimate. The geochemistry of paleosols, in particular, the stable isotope composition of calcareous nodules in calcretes, has been shown to be useful for the analysis of paleoclimate and atmospheric composition (Cerling, 1991, 1999; Driese et al., 1992; Driese and Mora, 1993; Caudill et al., 1996; Liu et al., 1996). The estimation of atmospheric paleo-p(CO<sub>2</sub>) using δ<sup>13</sup>C of pedogenic carbonate and the diffusion-reaction model developed by Cerling (1991) is now widely considered reliable because values of δ<sup>13</sup>C do not appear susceptible to diagenetic modification (Cerling, 1991; Driese and Mora, 1993; Mora et al., 1996), and calculated paleo-p(CO<sub>2</sub>) levels compare favorably with values from geochemical modeling (Berner, 1993).

### Geologic Setting and Stratigraphy

The Four Corners region was located at near-equatorial latitudes (less than 10° N) during Late Triassic time (Scotese, 1994; Molina-Garza et al., 1995; Kent and Olsen, 1997). Late Carnian to Rhaetian strata of the Chinle Group, now exposed across much of the Colorado Plateau (Fig. 1), were deposited in a continental back-arc basin that extended from southwestern Texas to northern Wyoming (Lucas, 1993; Lucas et al., 1997; Lucas, 1999). Deposition within the Chinle basin was controlled primarily by streams flowing northwest across a broad alluvial plain. The

source areas for these sediments included the Mogollon highlands, located approximately 500 km to the south and southwest, the Uncompahgre highlands located 200 to 300 km to the east and northeast (Blakey and Gubitosa, 1983; Marzolf, 1994), and more distant upland areas in Texas (McGowan et al., 1983; Riggs et al., 1996). Across most of the Colorado Plateau, lowermost Chinle strata were deposited unconformably on Moenkopi Group and older strata (the Tr-3 unconformity) following an interval of lowered base-level and incision. The Shinarump and Cameron formations, and Blue Mesa Member of the Petrified Forest Formation, and lateral equivalents, were deposited during late Carnian on this incised surface (Lucas, 1993; Lucas et al., 1997). The Tr-4 unconformity separates the Sonsela Member of the Petrified Forest Formation and the laterally equivalent Moss Back Formation from the underlying Blue Mesa strata (Heckert and Lucas, 1996, 2002; Lucas et al., 1997). The Owl Rock Formation was deposited conformably to locally unconformably on the Painted Desert Member of the Petrified Forest Formation during the middle Norian time. The Rhaetian Rock Point Formation unconformably overlies the Owl Rock Formation (Tr-5 unconformity) and grades vertically to the mainly Hettangian Wingate Formation. Previous studies have established the details of the stratigraphy and architectural elements of these formations (Stewart et al., 1972; Blakey and Gubitosa, 1983; Kraus and Middleton, 1987; Dubiel, 1987; Lucas, 1993; Lucas et al., 1997; Tanner, 2000).

### PEDOGENIC FEATURES OF CHINLE GROUP STRATA

Paleosols have long been recognized as prominent components of the Chinle Group formations, and general features of these paleosols have been cited in previous interpretations of Triassic paleoclimate (Dubiel, 1987; Dubiel et al., 1991; Parrish, 1993). Yet few studies have examined the pedogenic features and associated climatic implications in substantial detail. Most existing descriptions have focused on individual formations (Blodgett, 1988; Lucas and Anderson, 1993; Tanner, 2000; Therrien and Fastovsky, 2000), or are cursory summaries of the features of the

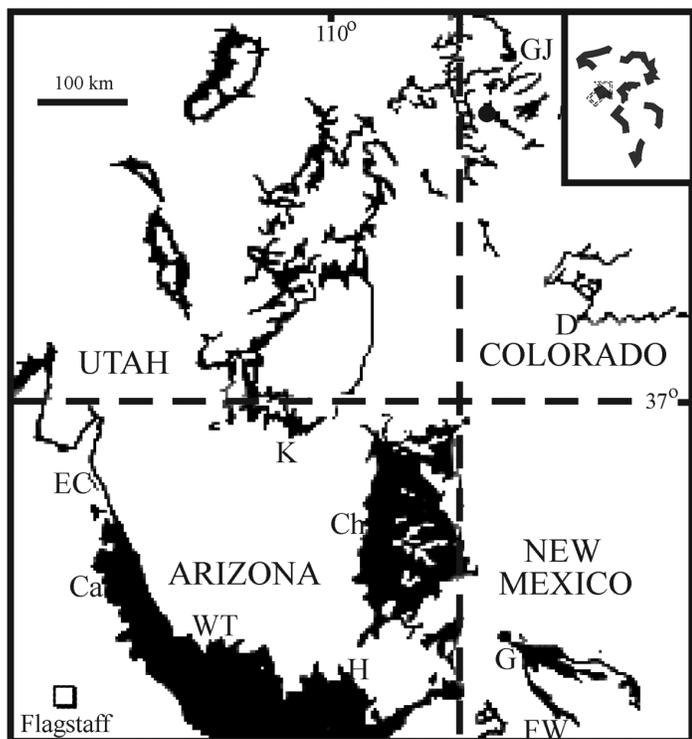


FIGURE 1. Distribution of outcrops of Chinle Group strata (shaded) in the Four Corners region (after Lucas et al., 1997). Paleosols locations mentioned in the text are indicated: Ca = Cameron, Ch = Chinle, D = Durango, EC = Echo Cliffs, FW = Fort Worth, G = Gallup, GJ = Grand Junction, H = Holbrook, K = Kayenta, WT = Ward Terrace.

entire Chinle Group (Dubiel and Hasiotis, 1994a,b; Hasiotis et al., 1998). Thus, little literature is directed toward complete description of these pedogenic features and application of this information to long-term trends of Late Triassic climate change. This paper contributes new data on several of these formations and considers the implications of these data, in combination with that of previous studies, toward a synthesis of Late Triassic climate.

### Mottled Strata /Shinarump Formation

The informally termed “mottled strata” were first described by Stewart et al. (1972) in reference to alluvial sediments (mudstones, sandstones, and conglomerates) at the base of the Chinle Group that exhibit strong pedogenic mottling (gleying). These strata, for which the formal name Zuni Mountains Formation is proposed (Heckert and Lucas, 2003), underlie or are laterally equivalent to the basal conglomerates and sandstones of the Shinarump Formation (Lucas et al., 1997). The mottled strata were deposited as interfluvial paleovalleys incised into the underlying Moenkopi Group and older strata during late Carnian time (Stewart et al., 1972; Blakey and Gubitosa, 1983; Lucas et al., 1997; Demko et al., 1998). The conglomerates and quart-arenite sandstones of the Shinarump Formation were deposited by low-sinuosity streams in these paleovalleys (Stewart et al., 1972; Blakey and Gubitosa, 1983; Lucas et al., 1997; Demko et al., 1998).

### Field Example: Mottled Strata

Near Fort Wingate, New Mexico, over 20 m of strongly mottled mudstone and sandstone beds rest unconformably on strata of the Moenkopi Group (see Stop 1, Day 2 in Roadlogs, this volume; also Lucas and Hayden, 1989). The stratigraphic position of these strata below the coarse sandstones and conglomerates of the Shinarump Formation indicates that they belong to the mottled strata.

Pedogenic modification, consisting of some combination of gleying (color mottling), desiccation, or root traces or casts, is evident in all of the strata in the sequence. Mudstone beds are up to 1.5 m thick and typically display a crudely prismatic fabric and medium bluish gray (5B 5/1) to light yellowish gray (5Y 8/1) gley mottling in a host that varies from dark reddish brown (10R 3/4) to dark yellow orange (10YR 6/6) (Fig. 2A). Locally, the gley mottling follows a coarse reticulate pattern. Through most of the sequence, the beds are penetrated by near-vertical sandstone cylinders, some up to 1.5 m long. These have a nearly straight to slightly twisted and branched shape and an almost smooth to knobby surface texture (see Fig. 2A). Some of these casts display a crude concentric structure in cross section. Other features common to the mudstone beds are relict horizontal lamination, meniscate burrows, fine, drab-colored (light bluish gray) root traces, and desiccation cracks that extend up to 20 cm downward. The interbedded sandstone beds are up to 1.8 m thick, massive to ripple-laminated, and variously display mottling similar to the mudstones or are a uniform dusky purple (5P 2/2) to dark reddish brown (10R 3/4) color.

### Field Example: Shinarump Formation

Strongly gleyed paleosol profiles that typify the mottled strata clearly are not limited to pre-Shinarump sediments. Similar features are seen in thin (< 2 m) profiles that are well developed and laterally persistent in finer-grained strata between the coarse fluvial sandstones of the Shinarump Formation near the town of Chinle, Arizona. The type profile for this location consists of the following layers in descending order (Fig. 2B): 1) The sequence is capped by muddy sandstone with mottled coloring and vertical jointing that approximates a prismatic fabric. This unit has an abrupt contact with the unit below and cylindrical casts filled with sandstone extend downward from the base of the unit into the underlying unit. These casts are up to 1 meter in length, average 10 cm in diameters, have a nearly vertical orientation, and taper downward (Fig. 2C). 2) The underlying unit is sandy mudstone with a blocky/prismatic fabric and prominent desiccation cracks. The color of this unit is mottled gray orange (10YR 7/4) to gray purple (5P 4/2) to medium light gray (N6). X-ray diffraction analysis of the clay fraction from this horizon indicates that it consists mainly of kaolinite. 3) The base of this profile is coarse mudstone with a weakly prismatic fabric (Fig. 2D). A yellow-mottled to reddish orange (10R 6/6) band occurs at the top of this unit, but most of this layer is strongly mottled reddish brown (10R 4/6) to dark purple (5RP 4/2) to brown (5R 4/2) to yellow (10YR 6/6). Relict ripple lamination is visible in the lowermost portion of the unit. The mottling displays a pronounced lack of organization, with irregular patches displaying sharp boundaries, locally bordered by pale haloes. Bedding-plane exposures of this unit exhibit some

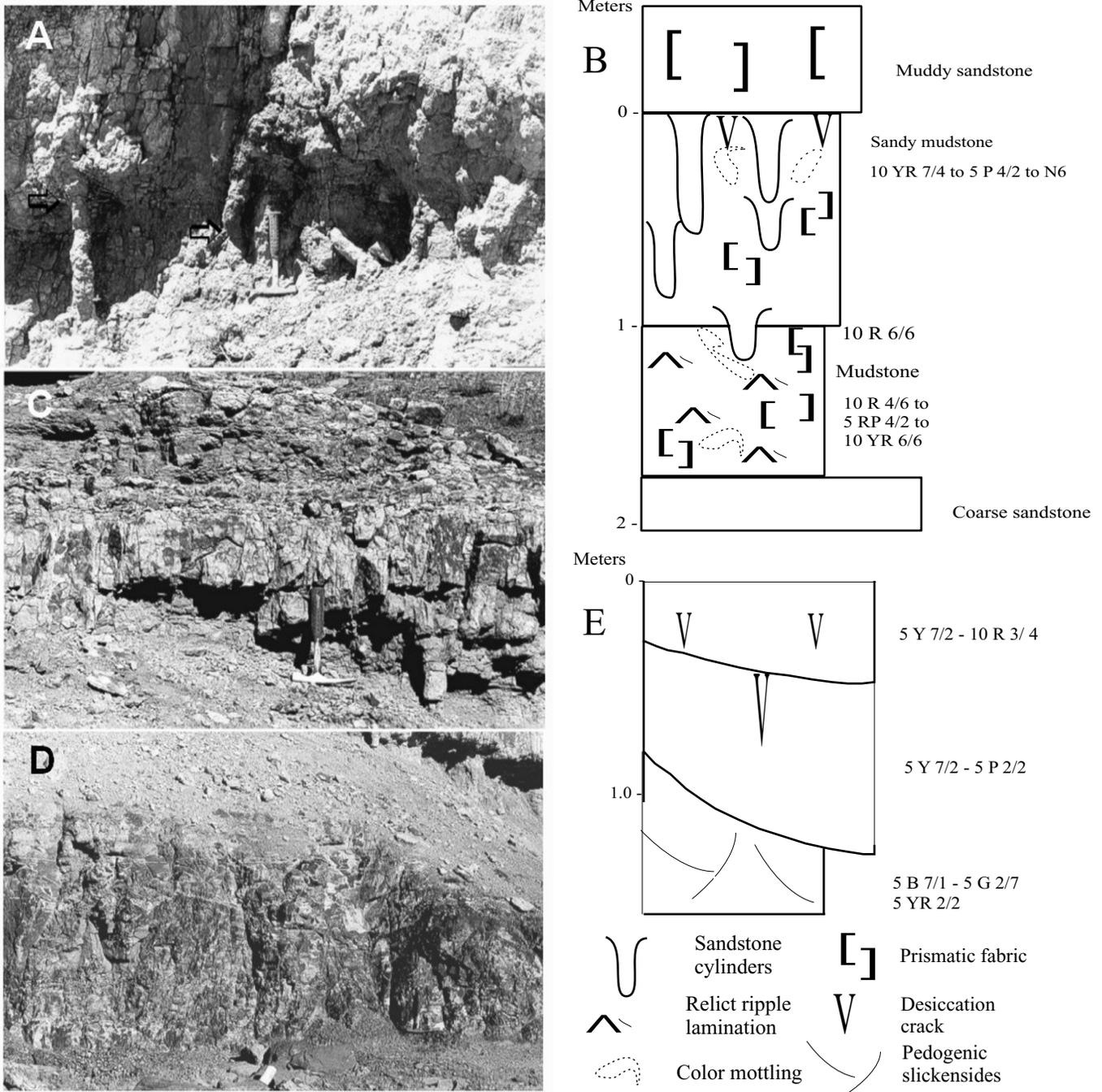


FIGURE 2. Photographs and measured sections of paleosols in the lower Chinle. A. Mottled mudstone in section near Fort Wingate containing elongated vertical casts with twisting shape, knobby appearance. The mudstone has a crudely prismatic fabric. B. Measured section of strongly gleyed paleosol between coarse sandstone ledges in the Shinarump Formation, exposed near the town of Chinle. C. Sandstone-filled casts project downward from the base of the jointed and mottled sandstone unit at the top of the measured paleosol section in B. D. Lower mudstone interval in the paleosol section near Chinle displaying a crude prismatic fabric and distinct light mottling in dark reddish brown host. Mottling approximately follows pattern of jointing and burrowing. E. Paleosol section measured in the basal Cameron Formation, north of Cameron, Arizona.

concentric patterns of alternating purple and yellow coloring. This unit is slightly more resistant to erosion than the unit above. The base of the profile grades into coarse sandstones below. X-ray diffraction indicates that the strong mottling results from local concentrations and zones of depletion of Fe-oxides, mainly hematite.

**Interpretation**

Gleying is the prominence in a soil horizon of low-chroma colors of gray or green that results from a persistently high water table (Mack et al., 1993). Hence, the association of gley features with hydromorphic, or “waterlogged” soils. High but strongly

fluctuating water tables cause alternating oxidizing and reducing conditions, resulting in strong mottling, forming irregularly shaped patches of red, brown, or yellow in a drab matrix. This mottling, resulting from local abundances of Fe- and Mn-oxides, is often accompanied by nodules of these oxides (Mack et al., 1993). Due to the high preservation potential of gleyed horizons, and their applicability to the conditions of soil formation (i.e., high water table), Mack et al. (1993) proposed the paleosol order Gleysol to include paleosols in which gleying is the primary characteristic.

The most striking characteristics of the mottled strata and Shinarump paleosols are the prominent gleyed horizons and penetration of these horizons by the vertical sandstone-filled casts. Various origins have been proposed for these cylindrical structures in these and other Chinle Group units, including lungfish aestivation burrows (Dubiel et al., 1987), crayfish burrows (Hasiotis and Dubiel, 1993), and the casts of deeply penetrating taproots of monopodial vegetation (Tanner, 2000). Although the lungfish hypothesis is now widely rejected, the varying morphology of these structures suggests multiple origins. Indeed, deep tap roots and crayfish burrowing would both be possible, perhaps even likely, in regions where meter-scale, water table fluctuations occur regularly. These hydrologic conditions would have been conducive to water-logged soils for humid intervals, but periodic, perhaps seasonal, drawdown of the water table was sufficient to allow translocation and oxidation of iron and manganese and shrinkage of expandable clays. These profiles represent composite paleosols in the sense that soil layers buried by subsequent increments of sediment remained in an extensively thick soil-forming environment (Wright and Marriott, 1996).

Lower Chinle (undifferentiated) paleosols have been described previously as Gleysols formed in a humid but seasonal environment (Dubiel and Hasiotis, 1994b; Hasiotis et al., 1998). Retallack (2001) notes, however, that true gleyed soils rarely display extensive bioturbation or evidence of desiccation, as do these paleosols, and so their classification as Gleysols is subject to interpretation. Moreover, the assumption of high humidity is questionable given the evidence for episodes of drying and desiccation alternating with hydromorphism. The duration of these episodes may have been seasonal or multi-year. Consequently, an overall subhumid paleoclimate is suggested here for the interval of mottled strata/Shinarump deposition.

#### **Cameron Formation/Bluewater Creek/Monitor Butte Formations**

Lucas (1993) and Lucas et al. (1997) demonstrated the equivalence of upper Carnian strata immediately above the Shinarump Formation. In the Four Corners area, these strata, regionally named the Cameron, Bluewater Creek, and Monitor Butte formations, consist mainly of gray bentonitic to red mudstones, and laminated to cross-bedded fine-grained sandstones (Lucas et al., 1997).

#### **Field Example**

The lowermost Cameron Formation displays pedogenic features quite similar to those of the underlying Shinarump and mottled strata. Where exposed north of Cameron, Arizona, the base

of the formation displays a sequence consisting of the following units, in descending order (Fig. 2E): 1) The top of the sequence consists of fine-grained sandstone that is mottled yellowish gray (5Y 7/2) and dark reddish brown (10R 3/4), and contains dm-scale desiccation cracks. 2) Underlying is mottled pale yellowish gray (5Y 7/2) to very dusky purple (5P 2/2) very fine-grained sandstone. This unit has an erosional base and scours into 3) mudstone that is mottled light bluish gray (5B 7/1) to greenish black (5G 2/1) and dusky brown (5YR 2/2), and contains sandstone-filled desiccation cracks and arcuate pedogenic slickensides. X-ray diffraction analysis indicates that the mudstone is mostly kaolinitic and that the strongly colored mottled areas of both sandstone and mudstone contain Fe-oxide, mainly hematite, and some Mn-oxide.

#### **Interpretation**

The profile in the basal strata of this formation displays multiple gleyed and vertic horizons, suggesting that this is a composite paleosol formed under changing hydrologic conditions. Gleying and desiccation are both consistent with soil development under conditions of strongly fluctuating water tables, suggesting a greatly variable (possibly seasonal) distribution of precipitation under subhumid climate conditions, as for the paleosols in the underlying mottled strata/Shinarump Formation. Dubiel and Hasiotis (1994a,b) interpret profiles such as this in (undifferentiated) lower Chinle strata as Gleysols.

Where exposed in the Little Painted Desert, northwest of Holbrook, the Bluewater Creek paleosols contain thin (cm-scale) dark, carbonaceous shale layers in the epipedon. These may represent histic epipedons, typical of Histosols, which form in marshy, water-logged soil conditions (Retallack, 2001). Fiorillo et al. (2000), in contrast, note an absence of histic epipedons, but an abundance of calcareous nodules in Bluewater Creek paleosols near St. Johns, Arizona. These authors interpret the nodules as having a palustrine origin and suggest that ponding occurred locally on the depositional surface. As described by Dubiel and Hasiotis (1994b) and Hasiotis et al. (1998), paleosols that are stratigraphically higher in the Cameron/Monitor Butte/Bluewater Creek formations typically comprise simple profiles with dm-scale light-colored epipedons overlying thick (up to 8 m) reddened argillic (Bt) horizons. They label the argillic paleosols higher in the formation as Alfisols, implying that they formed in woodlands and forests in subhumid to semiarid climates (Retallack, 2001). Given the abundance of plant life evident in much of the Chinle Group (Demko et al., 1998), this appears a reasonable interpretation.

In sum, the combination of pedogenic features in the Cameron/Monitor Butte/Bluewater Creek formations is consistent with a persistently subhumid climate that allowed soils to form on an alluvial plain that was generally well-drained, but locally subject to ponding or marshy conditions. This is exclusive of the basal strata of these formations, in which episodically high water tables were persistent.

#### **Blue Mesa Member (Petrified Forest Formation)**

The lowermost strata of the Petrified Forest Formation in the Four Corners region are designated the Blue Mesa Member

(Lucas et al., 1997). These strata, of late Carnian age, overlie the Cameron/Bluewater Creek/Monitor Butte formations and consist of pedogenically modified bentonitic mudstones with variegated hues of blue, gray, purple, and red, and thin interbedded sandstones (Kraus and Middleton, 1987).

### Field Example

Thick, well-developed paleosol profiles of the Blue Mesa Member are exposed across a broad area of northeastern Arizona. In Petrified Forest National Park, near Holbrook, for example, paleosol profiles comprise repeated sequences of light-colored sandstones and mudstones alternating with red and purple mudstones (Fig. 3A; Kraus and Middleton, 1987). Sandstones are light to dark gray, 0.4-1.0 m thick, and locally display planar crossbeds in sets up to 0.3 m thick, horizontal lamination, ripple lamination, and climbing ripple lamination. Mudstone occurs in beds of greenish gray (5GY 5/1) to dark reddish-brown (10R 3/4) and mottled gray purple red (5P 4/2) up to 8 m thick. Many beds display arcuate, intersecting slickensides, downward-tapering sandstone-filled fissures, drab root traces up to 0.1 m long, and cm-scale drab reduction spheroids (Fig. 3B). The grayish red mudstones commonly host subspherical calcareous nodules that are 2-8 cm in diameter, irregularly shaped, and commonly display septarian cracking. These nodules are generally scattered widely but locally are concentrated in discrete horizons; they are particularly prominent at the top of the Blue Mesa Member, immediately below the overlying Sonsela Member.

### Interpretation

A wide variety of paleosol characteristics are notable in the Blue Mesa Member, including strongly developed pedogenic slickensides, horizons containing illuviated Fe- and Mn-oxides, gleyed horizons, and weakly developed calcic horizons (Stage I to II of Gile et al., 1966). The alternating gray and red-purple mudstone sequences in the Blue Mesa Member appear to represent stacked profiles in which the A and B horizons are both preserved. The pale mudstone and sandy mudstone beds are interpreted as A-horizons based on the lack of illuviated clay or Fe- or Mn-oxides. Dubiel and Hasiotis (1994b) and Hasiotis et al. (1998) noted many of these features and labeled paleosols of the Blue Mesa Member as Vertisols, where vertic features predominate, and Alfisols, where pale A-horizons overlie reddened argillic horizons. Therrien and Fastovsky (2000) reported that paleosols with gleyed horizons are common locally in the Blue Mesa Member of the Petrified Forest Formation, reflecting poor or impeded drainage of these soils. Purple and red mottles resulted from the concentration of illuviated iron and manganese under oxidizing conditions. Kraus and Middleton (1987) noted a systematic variation in pedogenic development correlating with alluvial facies in the lower Petrified Forest Formation. Paleosols in overbank mudstones are characterized by thicker, more deeply reddened argillic horizons containing translocated iron, manganese, and aluminum oxides. These paleosols reflect soil development under well drained conditions and a subhumid to semi-arid climate. In contrast, laterally equivalent channel-scour mudstones contain paleosols that display thinner profiles with gley mottling and pale coloring, suggesting

localized hydromorphism. Therefore, local hydrologic conditions exercise considerable control over pedogenesis.

### Painted Desert Member (Petrified Forest Formation)

Overlying the sandstone-dominated Sonsela/Moss Back members of the Petrified Forest Formation is the Painted Desert Member of early Norian age (Lucas et al., 1997). These strata consist of grayish red and reddish brown mudstones and thin interbedded sandstones (Lucas et al., 1997).

### Field Examples

In the Painted Desert Wilderness Area (northern Petrified Forest National Park) moderate red mudstones (5R 5/6) in beds up to 20 m thick contain calcareous nodule horizons that weather out of the slope. Small (mm-diameter) tubules, up to 1 cm long, are abundant in the nodules and adjacent mudstone host. Thick mudstone beds locally contain intersecting sets of subvertical, arcuate slickensides, up 0.6 m long. Locally, the mudstone is very sandy and displays a brecciated fabric. In the southern Echo Cliffs and on the Ward Terrace, profiles displaying vertically stacked cm-scale nodules of micritic calcite occur in reddish brown (10R 4/4) mudstone beds (Fig. 3C). The nodules are subspherical to botryoidal to vertically elongate, and downward tapering. Internally, the nodules display septarian cracking. The concentration and size of nodules decreases downward. Typically, these profiles lie immediately below sandstone or intraformational conglomerate beds with significant erosional relief (Fig. 3D). The intraformational conglomerates, in beds up to 3 m thick, comprise clasts mainly of micritic calcite and calcareous mudstone. Locally, coalescing masses of nodules are hosted in thick beds (up to 4 m) of moderate red (5R 4/6) mudstone containing arcuate slickensides.

### Interpretation

As noted by Therrien and Fastovsky (2000), gleying is much less common in the Painted Desert Member of the Petrified Forest Formation than in the older Blue Mesa Member, and Bk horizons are much more prominent. Although the presence of illuviated clay is evident locally on ped surfaces in the red mudstones, pedogenic slickensides and calcrete horizons predominate; Dubiel and Hasiotis (1994b) and Hasiotis et al. (1998) describe these paleosols as Vertisols largely on this basis. Alternatively, some profiles where pedogenic nodules form laterally extensive Bk horizons (Stage II to III) could be described as Calcisols (*sensu* Mack et al., 1993). Both Calcisols and Vertisols are likely to form under subhumid to semiarid conditions with highly seasonal precipitation (Mack et al., 1993; Retallack, 2001). Zuber and Parnell (1989) noted that the clay mineral assemblage in the Painted Desert Member is dominated by mixed-layer illite-smectite, in contrast to the predominantly smectitic mudstones of the Blue Mesa Member. They interpreted this composition as the result of pedogenic illitization of smectitic clays in an alkalinic environment in which precipitation was highly seasonal. The abundance of vertic and calcrete features in Painted Desert strata indicate deposition during drier climatic conditions than existed during Blue Mesa deposition.

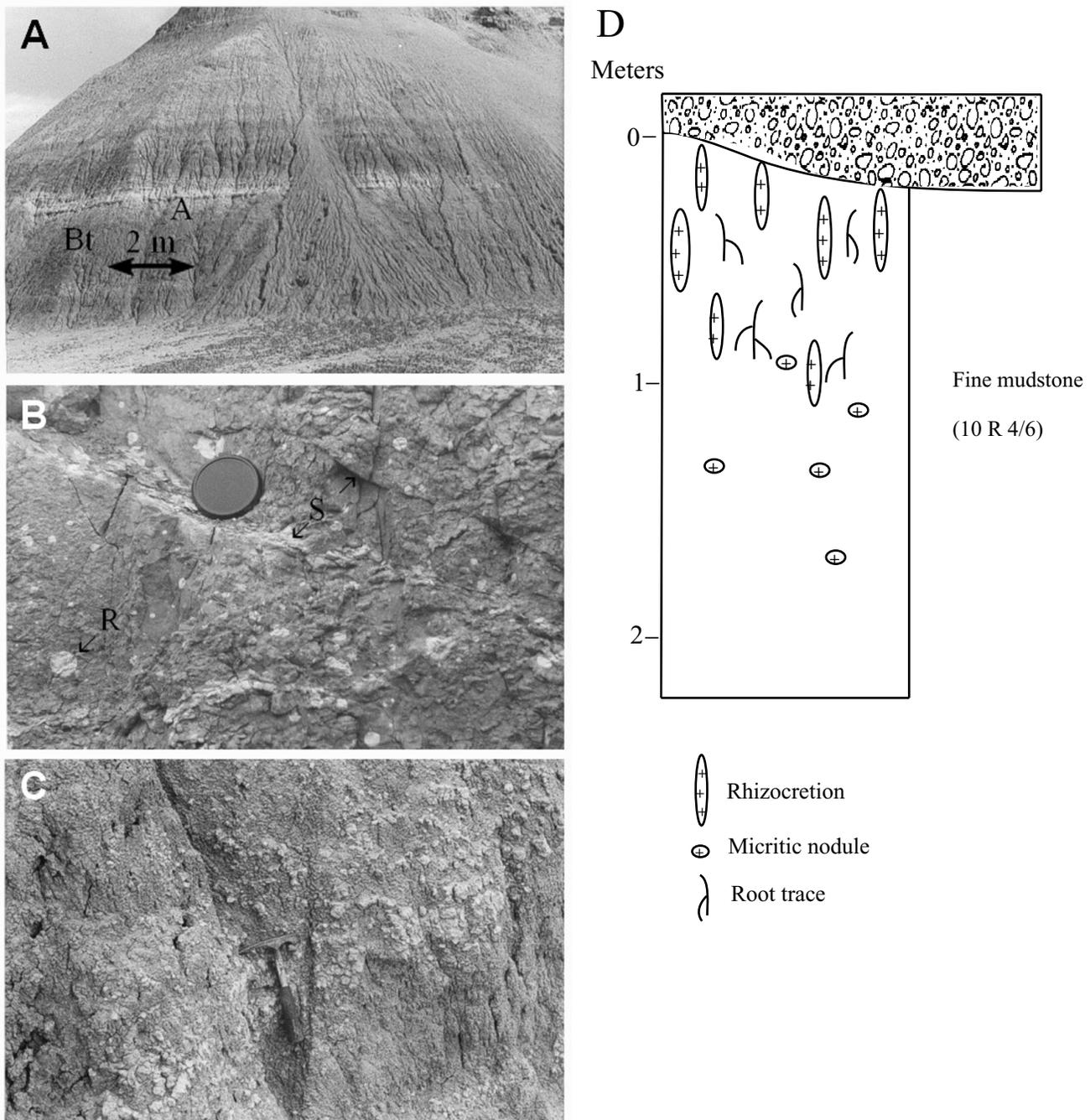


FIGURE 3. Pedogenic features of the Petrified Forest Formation. A. Paleosols in the Blue Mesa Member (Petrified Forest Formation) are well exposed in the southern end of Petrified Forest National Park (at the Tepees). Paleosol sequences consist of repeated stacked profiles of pale A horizons overlying thick, reddened Bt (argillic) horizons. B. Pedogenic features of the Blue Mesa Member at the Tepees include prominent pedogenic slickensides (S) and reduction spheroids (R). C. Stage III calcrete horizon hosted in red mudstone of the Painted Desert Member (Petrified Forest Formation) in the northern Petrified Forest National Park (Lithodendron Wash). Calcrete nodule density increases downward in this profile. D. Section measured below intraformational conglomerate in the upper most Painted Desert Member (Petrified Forest Formation) at the southern end of Echo Cliffs.

### Owl Rock Formation

The Owl Rock Formation comprises interbedded mudstones, sandstones, and limestones of approximately middle Norian age. These strata crop out in northern Arizona, northwestern New Mexico, and southern Utah (Stewart et al. 1972; Lucas and Anderson, 1993; Lucas and Huber 1994; Lucas et al., 1997; Tanner, 2000).

### Field Examples

Paleosols and pedogenic features of the Owl Rock Formation in the Four Corners region were described in detail by Tanner (2000), and only the general characteristics will be summarized here. In the Echo Cliffs of northeastern Arizona, as well as at the type section near Kayenta, red mudstone beds in the Owl Rock Formation host calcareous nodule horizons that are 0.3

to 1.8 m thick (Tanner, 2000). The nodules vary in shape from subspherical or botryoidal to tuberose, downward tapering forms up to 20 cm long. Nodular horizons in the lower 40 m of the type section comprise laterally extensive concentrations of discrete (noncoalescing) nodules (Stage II). Horizons of coalescing nodules higher in the section commonly exhibit vertical stacking of nodules and prismatic fabric grading vertically to platy-laminar fabric (Fig. 4A; Stage III to IV; Tanner, 2000). Palustrine limestones in the uppermost Owl Rock Formation display intense pedogenic brecciation, root-penetration, mottling, pisolitization, and chertification (Tanner, 2000).

**Interpretation**

The mudstone-hosted calcareous nodule horizons represent simple Stage II to IV calcrete profiles (Gile et al., 1966; Machette, 1985), or Calcisols (Mack et al., 1993). Stage II profiles occur lower in the formation than the more mature Stage III and IV

profiles, indicating more mature paleosol development higher in the formation, due either to a decreasing sedimentation rate or to more strongly arid climate conditions (Tanner, 2000). Base level fluctuations operating over tens of thousands of years, probably controlled regionally by climate, caused episodic deposition of lacustrine-palustrine carbonates that were subsequently reworked pedogenically under semiarid conditions (Tanner, 2000).

**Rock Point Formation**

Across the Four Corners area, the late Norian to Rhaetian Rock Point Formation is recognized as the youngest member of the Chinle Group (Lucas, 1993; Lucas et al., 1997). Strata of this formation, consisting mainly of interbedded brown to red, nonben-tonitic mudstones and laminated to rippled sandstones, rest unconformably (the Tr-5 unconformity) on the Owl Rock Formation.

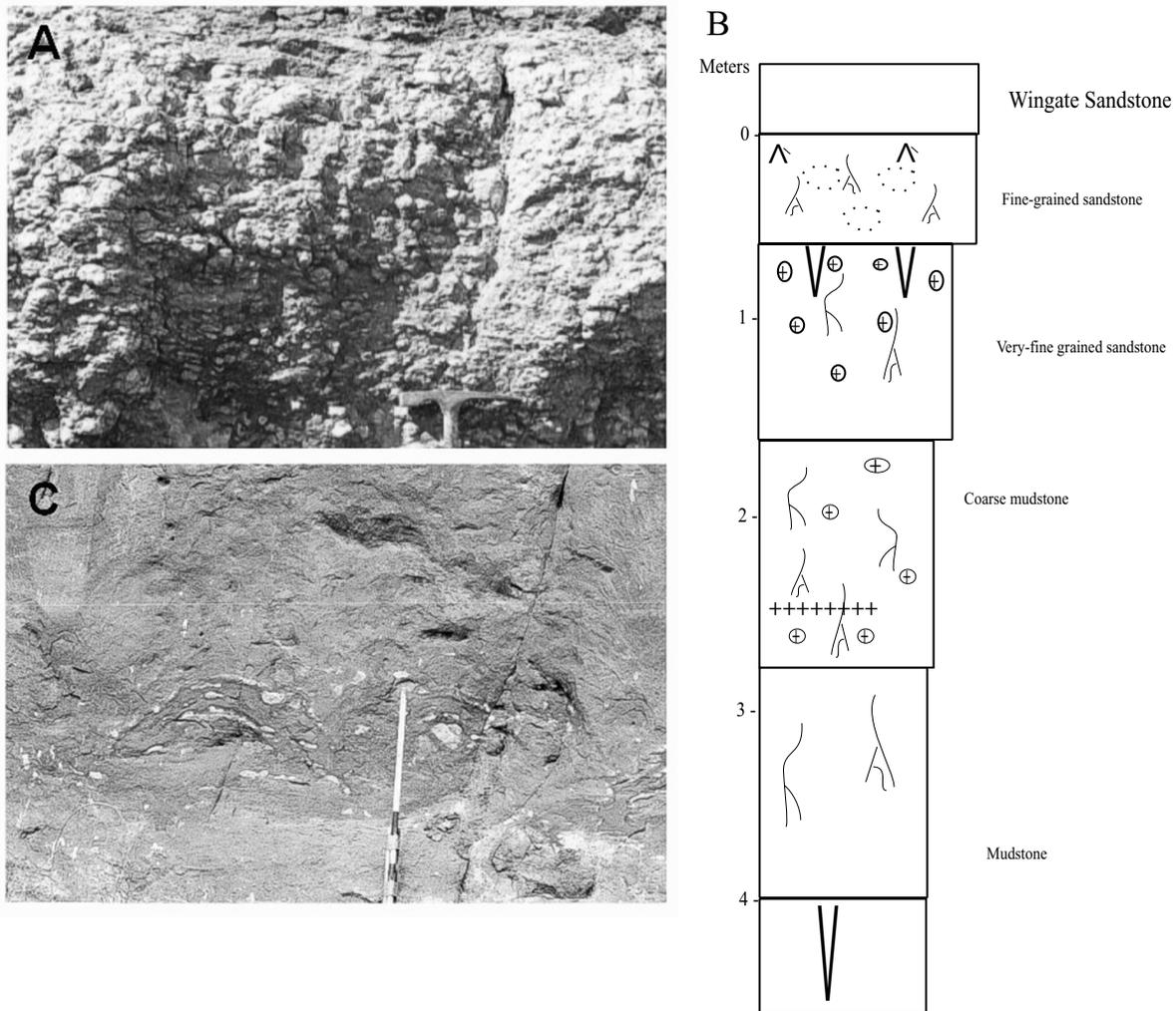


FIGURE 4. Pedogenic features of the Owl Rock and Rock Point formations. A. Mature (Stage IV) calcrete profile in the lower Owl Rock Formation, southern Echo Cliffs. A platy-laminar fabric caps the sequence and nodule density decreases downward. The middle of the section displays a crude prismatic fabric. B. Section measured below the Rock Point – Wingate contact at Colorado National Monument. The section comprises multiple paleosol horizons characterized by roots, desiccation cracking and calcrete nodule formation. C. Uppermost Rock Point strata near Gallup (Red Rocks State Park) display pseudoanticlines formed by interstitial evaporate precipitation. Light areas are drab reduction blotches. Uppermost division on the staff is 0.5 m.

### Field Examples

The Rock Point Formation across much of northeastern Arizona lacks the well-developed pedogenic features of the other formations of the Chinle Group. The red sheet sandstones and coarse mudstones facies that characterize the formation in this area display bedding-parallel burrows and shallow desiccation cracks in some beds, but lack extensive nodular horizons or vertic features. In other areas of the Colorado Plateau, however, much more extensive pedogenesis is evident. For example, at Colorado National Monument (near Grand Junction), coarse mudstones and very fine-grained sandstones that are age-equivalent to the Rock Point Formation (Lucas et al., 1997) rest unconformably on granitic basement and are overlain by sandstones of the Wingate Formation. The strata near the top of this section host multiple pedogenic horizons that display drab root traces up to 70 cm long, desiccation cracks penetrating up to 60 cm, and calcareous nodules that are scattered to coalescing (Stage II to III; Fig. 4B). Pedogenic features in correlative strata north of Durango, in southwestern Colorado, include desiccation cracks that extend up to 50 cm deep, root traces up to 70 cm long, crumb and blocky mudstone fabrics, rhizcretions up to 30 cm long, and calcareous nodules up to 10 cm in diameter that are scattered to locally concentrated in near coalescing horizons (Stage II to III). Details of many of these features were described by Blodgett (1988). Rock Point strata exposed at Red Rock State Park, near Gallup, New Mexico, comprise orange-red sandy mudstones that display sandpatch fabrics (*sensu* Smoot and Olsen, 1988), small (0.5 cm) calcite-filled vugs, and pseudoanticlines with up to 40 cm of relief (Fig. 4C). The latter feature is highlighted by patchy drab reduction zones in the orange-red host.

### Interpretation

Blodgett (1988) interpreted the nodule-bearing horizons in the sheet sandstones of the Dolores Formation, which is equivalent to the Rock Point Formation (Lucas et al., 1997), as calcareous paleosols of the order Aridisol or Inceptisol. These profiles, which lack epipedons and argillic horizons, also could be classified as Calcisols, an interpretation that can be applied to the paleosols at Colorado National Monument as well. Root traces and rhizcretions are evidence that these soils were vegetated by plants with long monopodial root systems, typical of semiarid, seasonal climates (Retallack, 1988). The Rock Point strata near Gallup, in contrast, exhibit features common to many playa mudflats, including sandpatch fabric, calcite vugs, which probably represent pseudomorphs after gypsum, and pseudoanticlines (puffy grounds) formed by interstitial precipitation of evaporites, such as gypsum (Smoot and Olsen, 1988). Most of these features are not considered pedogenic, however, because they form primarily through evaporative draw of groundwater, rather than downward translocation of cations, oxides, or clays. Nevertheless, they reflect conditions of aridity that existed at least seasonally.

### Isotope Stratigraphy

Sampling of pedogenic carbonate for this study followed protocols established by Mora et al. (1993). Paleosol profiles

were described in the field to establish the pedogenic origin of the carbonate layers. All sampled profiles display features, such as gradational lower boundaries, rhizoliths, drab root traces, and circumgranular cracking, that indicate a pedogenic, rather than groundwater origin. The samples were slabbed and thin sections prepared to differentiate micritic and sparry calcite. To ensure selective sampling of displacive micrite, thin section billets and lapped slabs were drilled with the ultrafine point of an engraving tool while viewed with a binocular microscope. Powdered micrite samples were analyzed by Coastal Science Laboratories, Inc. of Houston, Texas, by reacting the carbonate with 100%  $H_3PO_4$  at 25°C. Results are reported in ppt relative to PDB (Table 1).

These early Mesozoic paleosols all formed at low paleolatitudes (10° or less) and are assumed to have formed strictly under the influence of  $C_3$  vegetation with  $\delta^{13}C$  of -25 ‰ (Cerling, 1991, 1999). Mature Calcisols (Stage III and IV profiles) in the Owl Rock Formation are inferred to represent well-drained subtropical to tropical soils with  $S(z) = 5,000$  to 10,000 ppm. Samples of pedogenic micrite in the Owl Rock Formation appear to represent carbonate precipitated at depth (>25 cm) in a soil profile at equilibrium conditions with atmospheric  $CO_2$  (Mora et al., 1993). Eight samples of nodular micrite from the Owl Rock Formation were analyzed ( $\delta^{13}C = -7.4$ ; Table 1). The values reported here are consistent with other reported values from Late Triassic pedogenic calcretes (Suchecky et al., 1988; Cerling, 1991; Tanner, 1996; Tanner, 2000; Tanner et al., 2001). Application of the diffusion-reaction model to these results, assuming  $p(CO_2)_{soil} - p(CO_2)_{atmosphere} = 5,000$  to 10,000 (well-drained subtropical to tropical soils) yields paleo- $p(CO_2)$  of about 2300 to 3750 ppmV.

The isotopically lighter pedogenic carbonate in the Petrified Forest Formation accumulated in paleosols that exhibit evidence

TABLE 1. Isotopic analysis of pedogenic calcite from Chinle Group Formations

Formation	Age	$\delta^{13}C$	$\delta^{18}O$
Petrified Forest Formation			
Blue Mesa Member	Carnian	-9.5	-4.2
		-8.6	-3.9
		-9.1	-4.7
		-9.1	-4.7
Painted Desert Member	Norian	-9.8	-4.9
		-9.5	-5.4
Owl Rock Formation	Norian	-7.8	-4.0
		-7.6	-5.1
		-6.8	-7.3
		-7.4	-5.4
		-6.8	-5.3
		-7.3	-4.6
		-7.6	-5.8
		-7.9	-6.1
Rock Point Formation and equivalents	Rhaetian		
Durango, CO		-5.0	-3.2
		-4.9	-2.6
Colorado National Monument		-6.0	-3.1

of greater humidity than the Owl Rock Formation, such as the dominance of gley and vertic features over calcrete. Therefore,  $S(z)$  for these soils is assumed at 10,000 to 25,000 ppm. The higher  $\text{CO}_2$  productivity in more humid soils decreases the contribution of atmospheric carbon to precipitated calcite (Cerling, 1991). The analyses included six samples of nodular micrite from the Petrified Forest Formation, four from the Blue Mesa Member and two from the Painted Desert Member ( $\delta^{13}\text{C} = -9.3$ ; Table 1). Application of the diffusion-reaction model to the mean  $\delta^{13}\text{C}$  of  $-9.3$  for this formation, assuming  $p(\text{CO}_2)_{\text{soil}} - p(\text{CO}_2)_{\text{atmosphere}} = 10,000$  to  $25,000$  (humid tropical soils), yields a paleo- $p(\text{CO}_2)$  that ranges from 2150 to 3300 ppmV. Slate et al. (1996) recommended caution when analyzing the isotopic composition of hydromorphic paleosols because of the potential influence of groundwater carbonate. Nevertheless, when corrected for greater humidity during formation of these paleosols, these data yield estimates of paleo- $p(\text{CO}_2)$  similar to the Owl Rock paleosols.

The Rock Point Formation and correlative strata are represented by two samples from the Dolores Formation near Durango and one from the outcrop at Colorado National Monument ( $\delta^{13}\text{C} = -5.5$ ). The heavy pedogenic carbonate from the Rock Point and correlative formations appears to have accumulated at shallow depths within soil profiles that were subject to extreme soil cracking and burrowing (Mora et al., 1993). Thus, carbonate in these soils precipitated under the influence of heavier atmospheric carbon, rather than at equilibrium with soil  $\text{CO}_2$ , and so the diffusion-reaction model of Cerling (1991) cannot be applied.

### LATE TRIASSIC PALEOCLIMATE

Gradual aridification and associated changes in floral patterns were initially proposed by Colbert (1958) to explain tetrapod turnover across the Late Triassic. Evaporite and carbonate deposition, combined with the restriction of coal formation to high latitudes, seem to provide abundant evidence of overall warm and dry conditions during the Late Triassic (Frakes et al., 1992; Lucas, 1999). Robinson (1973) recognized that the configuration of the Pangean continent during the Late Triassic had a significant effect in controlling this climate. Significantly, the arrangement of land areas was likely to result in a dry climate belt covering a broad region of western and central Pangea at low to mid-paleolatitudes, and the strengthening of monsoonal flow. Both of these were a consequence of the shrinkage of the humid intertropical convergence zone (ITCZ) and the weakening of zonal circulation. This interpretation received considerable support from early computer modeling exercises by Parrish et al. (1982). Later workers, however, reinterpreted the paleoclimate record for the Late Triassic on the basis of fluvial and lacustrine facies in the Chinle Group strata as indicating significant moisture until near the end of the period (Dubiel et al., 1991; Parrish, 1993).

#### Colorado Plateau

Abundant sedimentary evidence now exists to suggest widespread and gradual aridification of the Pangean continent during the Triassic Period, although some areas may have instead become

more humid from Middle to Late Triassic time (Dickens, 1993; Parrish, 1993). In the Colorado Plateau region, a humid but seasonal climate during the Late Carnian has been suggested by gleyed and illuviated paleosols in the mottled strata and Shinarump Formation (Dubiel and Hasiotis, 1994a,b; Hasiotis et al., 1998). Demko et al. (1998), however, cautioned that the paleoclimate record of the basal Chinle is biased by deposition within paleovalleys underlain by aquicludes, which could have resulted in perched water tables. Indeed, although the prominence of gleying and the kaolinitic composition of these paleosols suggest high humidity, this interpretation is compromised by the presence of a prismatic fabric in paleosols in these formations, and of pedogenic slickensides in the basal Cameron Formation, both of which indicate that these soils were allowed to dry completely at times, possibly seasonally. Deep tap roots and/or crayfish burrows also indicate that the water table dropped severely on a regular basis. Thus, an overall subhumid climate is likely, with high water tables enforced by the position of the lower Chinle strata in paleovalleys and the locally impermeable nature of the underlying Moenkopi strata.

Paleosols in the Monitor Butte/Bluewater Creek formations and overlying upper Carnian Blue Mesa Member of the Petrified Forest Formation are mainly Alfisols and Vertisols (Dubiel and Hasiotis, 1994b; Hasiotis et al., 1998), although gleying is prominent locally (Therrien and Fastovsky, 2000). These differences from the underlying paleosols may indicate that climate at the end of the Carnian was less humid, but still strongly seasonal. Alternatively, these same differences may be attributable to better soil drainage in the younger strata because they were separated stratigraphically from the aquicludes in the Moenkopi Group sediments. By early Norian time, however, a seasonal subhumid to semiarid paleoclimate prevailed during deposition of the Painted Desert Member. Drier conditions allowed increased accumulation of soluble cations in the soils and formation of well-developed calcrete horizons in the Vertisols. The mature calcrete profiles that characterize the Calcisols in the middle Norian Owl Rock Formation suggest a continuation of these strongly seasonal semiarid conditions coeval with a decreasing rate of sedimentation. Or alternatively, increased paleosol maturity may reflect greater aridity while sedimentation rates remained mostly constant. Continued aridification during the late Norian-Rhaetian is clearly indicated by the dominance of eolian and playa sedimentation during deposition of the Rock Point Formation. This trend continued into the Hettangian as the Wingate erg formed over the Four Corners area.

### Global Trends

Facies changes, evaporite occurrences, and paleosols in the Upper Triassic to Lower Jurassic formations of the Newark Supergroup, which span  $15^\circ$  paleolatitude, indicate a similar trend of aridification (Olsen, 1997; Kent and Olsen, 2000). An increasing maturity of calcrete paleosols with decreasing age is noted in the southern basins, for example, the Deep River and Taylorsville basins (Coffey and Textoris, 1996; LeTourneau, 2000). To the north, in the Newark basin, the Carnian to Hettangian Lockatong and Passaic formations consist primarily of cyclically bedded lacustrine strata that lack paleosols, but are evaporite-bearing

and interbedded with minor eolian sandstones near the top of the sequence (see Olsen, 1997 for review). In the Fundy basin, which was located at about 5°N in the early Carnian and drifted to about 15°N by the Hettangian (Olsen, 1997), calcrete-bearing alluvial deposits of the mostly Carnian Wolfville Formation are succeeded by eolian sandstones and evaporite-bearing sheetwash deposits of the Norian to Hettangian Blomidon Formation (Olsen et al., 1989; Olsen, 1997; Tanner, 2000, 2003).

Facies transitions in the rift basins of northwestern Africa display a similar trend of aridification, as in the succession of the Timezgadiwine and Bigoudine formations in the Argana basin, Morocco (Olsen, 1997; Hofmann et al., 2000). Additionally, Late Triassic aridification has been cited as a control of facies changes in the Upper Triassic Mercia Mudstone Group of England (Talbot et al., 1994; Ruffell and Shelton, 1999), and the Keuper of the Germanic basin (Aigner and Bachmann, 1992). Not all areas of Pangea became drier during the Late Triassic, however. Extensive coal deposits formed in Australia, which became wetter at this time (Fawcett et al., 1994), and the growth of large lakes in the Jameson Land basin of eastern Greenland during the Late Triassic is interpreted as a consequence of increasing humidity (Clemmensen et al., 1998).

### Cause of Aridification

A largely azonal pattern of climate is suggested by models of Pangean climate during the Late Triassic. In general, it appears that equatorial regions were mostly dry due to the disappearance of the ITCZ, while orographic effects and the width of the continent maintained aridity across the broad interior; humid belts were limited to higher latitudes and around the Tethyan margin (Parrish and Peterson, 1988; Crowley et al., 1989; Kutzbach and Gallimore, 1989; Dubiel et al., 1991; Parrish, 1993; Fawcett et al., 1994). A strong monsoonal effect caused precipitation across Pangea to be strongly seasonal (Kutzbach and Gallimore, 1989; Parrish, 1993). This effect was enhanced during the Late Triassic by the location of the Pangean landmass, which was nearly evenly distributed between northern and southern hemispheres (Parrish, 1993). In contrast, Olsen (1997) and Kent and Olsen (2000), envisioned latitudinal control of climatic gradients, suggesting that aridification in the Newark Supergroup was a result of a 5° to 10° northward drift of the rift basin toward more arid climate zones. However, this model fails to explain trends of paleosol development (e.g., calcrete maturity) in the southern Newark Supergroup basins in near-equatorial positions. Thus, aridification during the Late Triassic can be envisioned as a likely consequence of the movement of the Pangean continent, which caused strengthening of the monsoonal effect and the gradual breakdown of the ITCZ and zonal circulation.

### CONCLUSIONS

Paleosols and pedogenic features preserved in the formations of the Chinle Group record a trend of gradual aridification during the Late Triassic. The prominence of gleying in the kaolinitic, bioturbated paleosols of the mottled strata, Shinarump, and basal

Cameron formations suggests that climate during the late Carnian was subhumid to humid, and that water tables fluctuated seasonally. High water tables during deposition of these formations may have resulted from their position within paleovalleys incised into the underlying Moenkopi Group strata. Improved soil drainage during Cameron and Blue Mesa deposition is interpreted from the presence of thick argillic profiles interpreted as Alfisols. This condition may have resulted either from climatic drying or from the position of these soils stratigraphically higher above aquicludes in the Moenkopi Group. Increasing aridity during early to middle Norian deposition of the Painted Desert Member is clearly suggested by the prominence of vertic features and immature (Stage II) calcretes. This trend of aridification continued during middle to late Norian Owl Rock deposition, as indicated by mature (Stage III to IV) calcretes. The Rhaetian Rock Point strata lack mature paleosol profiles, but the predominance of eolian and playa facies in this formation suggests that the trend of increasing aridity continued through onset of the Wingate erg. This trend may have been controlled by the position of the Pangean continent, which led to the onset of strong monsoonal flow and the weakening of zonal circulation.

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