STRATIGRAPHY OF THE UPPER TRIASSIC CHINLE GROUP, FOUR CORNERS REGION

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Abstract—Upper Triassic strata exposed in the Four Corners region belong to the Chinle Group of late Carnian–Rhaetian age. Chinle Group strata can be divided into eight lithostratigraphic intervals: (1) mottled strata/Temple Mountain Formation—as much as 31 m of mostly color mottled, deeply pedoturbated siltstone, sandstone and conglomerate; (2) Shinarump Formation—up to 76 m of trough-crossbedded sandstone and siliceous extrabasinal conglomerate; (3) Monitor Butte/Cameron/Bluewater Creek Formations—up to 84 m of varied lithofacies ranging from green bentonitic mudstones (Monitor Butte) to sandstones (Cameron) to red-bed mudstones (Bluewater Creek); (4) Blue Mesa Member of Petrified Forest Formation—up to 100 m of blue, gray, purple and red variegated bentonitic mudstone; (5) Moss Back Formation/Sonsela Member of Petrified Forest Formation—up to 50 m of trough-crossbedded sandstone and intrabasinal conglomerate; (6) Painted Desert Member of Petrified Forest Formation—up to 150 m of mostly red-bed bentonitic mudstone and siltstone; (7) Owl Rock Formation—up to 150 m of pale red and orange siltstone interbedded with ledges of pedogenic calcrete limestone; (8) Rock Point Formation—up to 300 m of reddish brown, cyclically-bedded sandstone and non-bentonitic siltstone. In southwestern Colorado, the base of the Chinle Group is the Moss Back Formation resting on Lower Permian strata. We abandon the term Dolores Formation and correlate its informal members as follows: (1) lower member = Moss Back Formation; (2) middle member = Painted Desert Member of Petrified Forest Formation; and (3) upper member = Rock Point Formation. The informal term "Kane Springs strata," applied to some Chinle Group coarse-grained strata in southeastern Utah, is also abandoned. Church Rock Member (Formation) is a synonym of Rock Point Formation, and the term Church Rock should not be applied to nearly all the Chinle Group section in southeastern Utah. Palynomorphs, megafossil plants and fossil vertebrates support the following age assignments for Chinle Group strata in the Four Corners region: late Carnian = mottled strata/Temple Mountain Formation, Shinarump Formation, Monitor Butte/Cameron/Bluewater Creek Formations and Blue Mesa Member of Petrified Forest Formation; early-middle Norian = Moss Back Formation/Sonsela Member of Petrified Forest Formation, Painted Desert Member of Petrified Forest Formation and Owl Rock Formation; and Rhaetian = Rock Point Formation. The Chinle Group consists of three unconformity-bounded sequences: Shinarump–Blue Mesa sequence of late Carnian age; Moss Back–Owl Rock sequence of early-middle Norian age; and Rock Point sequence of Rhaetian age. Facies architecture and biostratigraphy support a genetic relationship between Chinle Group strata on the Colorado Plateau and shallow marine strata of the Mesozoic marine province of western Nevada. This relationship suggests that eustasy was the primary allochthonous control on Chinle Group sedimentation. At Big Indian Rock in the Lisbon Valley of southeastern Utah, a skull of the phytosaur *Redondasaurus* is in a thin, discontinuous mud-pebble conglomerate near the base of the Wingate Sandstone. *Redondasaurus* is an index fossil of the Late Triassic Apachean (Rhaetian) land-vertebrate faunachron. Unabraded surface texture, large size and preservation of thin, fragile bone suggest that the phytosaur skull is not reworked, so the Triassic-Jurassic boundary is stratigraphically above it. No unconformity surface is present in the lower Wingate Sandstone above the skull. Thus, at Big Indian Rock, the J-0 unconformity is not at the base of the Wingate Sandstone. If the basal Wingate is of Late Triassic age, then the Moenave Formation, with which it intertongues laterally, must also include Triassic strata. This suggests the Triassic-Jurassic boundary on the Colorado Plateau is relatively transitional—not a profound unconformity—within the Wingate–Moenave lithosome.

INTRODUCTION

Upper Triassic strata exposed in the Four Corners region of Arizona, Utah, Colorado and New Mexico (Fig. 1) belong to the Chinle Group of late Carnian–Rhaetian age (Lucas, 1993). Chinle strata are siliciclastic red beds that contain one of the most significant fossil records of the Late Triassic terrestrial biota. Here, we review the stratigraphy, biostratigraphy and sequence stratigraphy of the Chinle Group in the Four Corners region.

STRATIGRAPHY

Stewart et al. (1972a) detailed the evolution of stratigraphic nomenclature applied to Upper Triassic strata in the Four Corners region, obviating the need for a review here. The nomenclature Stewart et al. (1972a, b) advocated for these rocks was unnecessarily complex and redundant (Fig. 2). This was because of a lack of understanding of some correlations within the Upper Triassic strata and an unwillingness to abandon duplicative nomenclature, particularly names peculiar to one of the Four Corners states but not applied outside of that state.

Lucas (1993; also see Lucas, 1991a; Lucas and Hunt, 1992) presented a more unified and streamlined stratigraphic nomenclature of Upper Triassic strata in the Four Corners region. We employ that nomenclature here and further develop and justify its use. According to Lucas (1993), all Upper Triassic strata in the Four Corners region belong to the Chinle Group, divided (in ascending order) into mottled strata/Temple Mountain Formation and Shinarump, Salitral/Cameron/Monitor Butte, Moss Back, Petrified Forest, Owl Rock and Rock Point Formations (Fig. 3).

Chinle Group

About 50 lithostratigraphic terms are presently applied to Upper Triassic nonmarine strata in the western United States. Most of these names were long considered members or beds of the Chinle Formation of Gregory (1916, 1917). However, several other formation names have been used for Upper Triassic strata in this region, including Popo Agie Formation in Wyoming, Jelm Formation in Wyoming–Colorado, Gartra Formation in Utah–Colorado, Ankareh Formation in Idaho–Utah, Dolores Formation in Colorado and several formation names, usually included in the Dockum Group, applied to Upper Triassic strata on the southern High Plains of Colorado, Kansas, Oklahoma, New Mexico and West Texas. Many of these lithostratigraphic names, and their constituent members and beds, refer to lithologically distinct, mappable units and thus denote valid and useful lithostratigraphic units. However, some names are old, parochial constructs (for example, Dolores Formation, discussed below) that duplicate nomenclature in nearby areas.

Recent studies of Upper Triassic stratigraphy, sedimentology and paleontology emphasize the inter-relatedness of Upper Triassic nonmarine

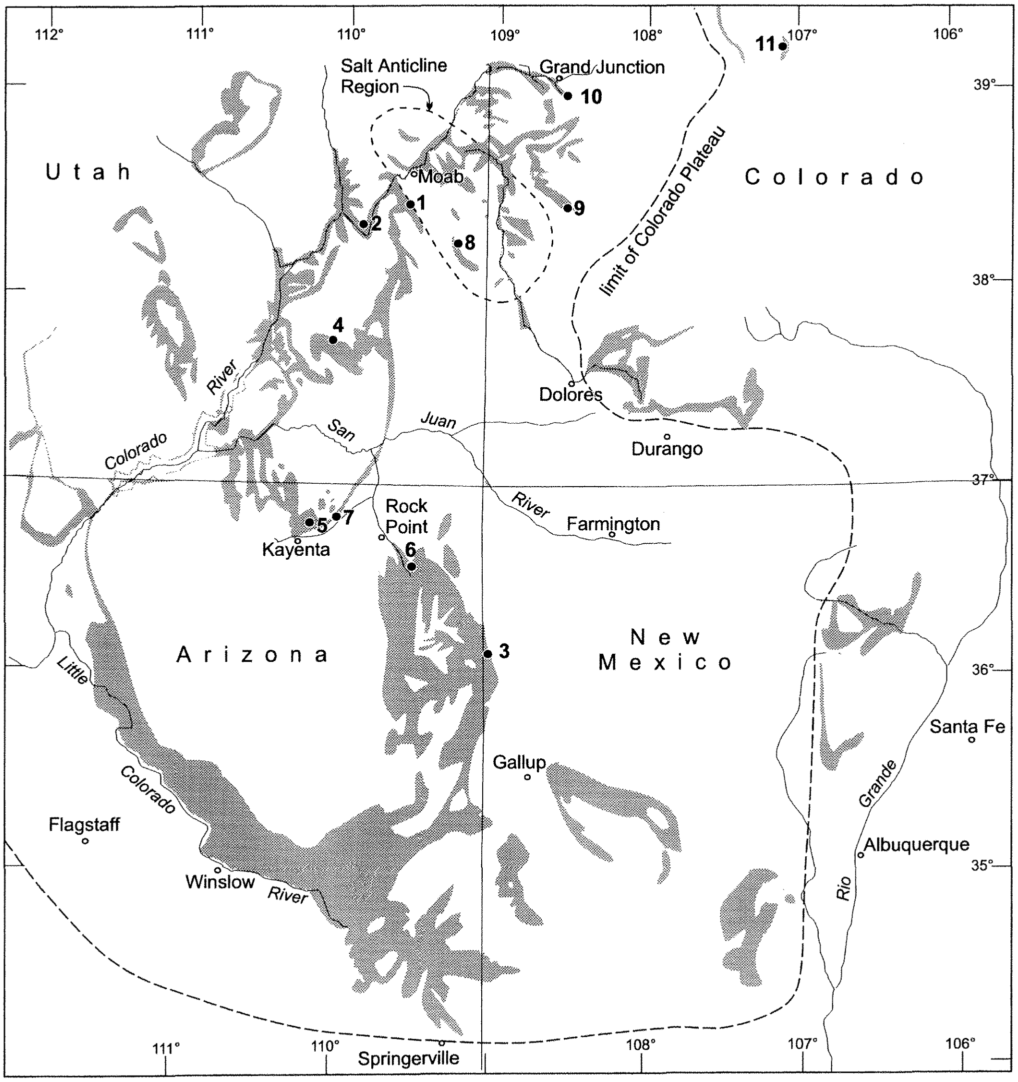

FIGURE 1. Distribution of the Chinle Group in the Four Corners region (after Stewart et al., 1972b), showing locations of measured sections in Figures 5–6.

strata across the western United States. Indeed, the continuity of Upper Triassic sedimentation across the Colorado Plateau and adjacent regions is well documented (e.g., Stewart et al., 1972a; Blakey and Gubitosa, 1983, 1984; Blakey, 1989; Dubiel, 1987a, b, 1989a, 1994; Lucas, 1991a; Lucas and Anderson, 1992, 1993a; Lawton, 1994; Riggs et al., 1996).

McGowen et al. (1979, 1983) attempted to demonstrate the existence of a separate Late Triassic depositional basin in eastern New Mexico–West Texas east of the Late Triassic Uncompaghre and Pedernal uplifts, an old idea (e.g., McKee et al., 1959). However, this conclusion was based only on a small number of paleocurrent measurements from the Santa Rosa Formation in eastern New Mexico (McGowen et al., 1979; Granata, 1981) and on the northwest–southeast orientation of Upper Triassic sandbodies in the subsurface, a bidirectional flow indicator. Indeed, most paleocurrents from Upper Triassic strata in eastern New Mexico and West Texas indicate that paleoflow was directed to the north, northwest and west (e.g., Cazeau, 1960; Kiatta, 1960; Lupe, 1988; May 1988; DeLuca and Eriksson, 1989; May and Lehman, 1989; Lucas and Anderson, 1992, 1993a). Furthermore, Upper Triassic strata on the High Plains can be traced across small (< 30 km) gaps into Upper Triassic strata on the Colorado Plateau in central New Mexico (Lucas, 1991b; Lucas and Heckert, 1994, 1995, 1996). Some facies and thicknesses change, but not enough to indicate separate depositional basins.

We thus conclude that available data indicate that Upper Triassic strata in the western U.S. were deposited in a vast basin, which may have included several sub-basins, that at least extended from northern Wyoming to southwestern Texas and from southeastern Nevada to northwestern Oklahoma, an area of at least 2.3 million km^2 (Lucas and Heckert, 1997). We refer to this Late Triassic depositional basin as the Chinle basin.

This continuity of deposition accounts for the long-known lithologic integrity of Upper Triassic nonmarine rocks in the western U.S. These rocks are mostly red beds, though some portions are variegated blue, purple, olive, yellow and gray. Sandstones are mostly fluvial-channel deposits that range from mature quartzarenites to very immature litharenites and graywackes. Conglomerate clasts are either extrabasinal (silica-pebble and Paleozoic limestone-pebble), intrabasinal (mostly nodular calcrete with some mudstone rip-ups) or a mixture of both. Most mudstones are bentonitic, except in the youngest Triassic strata. Lacustrine deposits encompass analcimolite and pisolitic limestone. Within this variety exists overall sandstone immaturity, red coloration, textures and sedimentary structures of fluvial origin and a general abundance of volcanic detritus that lend the Upper Triassic strata a lithologic character that facilitates their ready identification.

Also, the paleontology of these rocks is remarkably uniform over a broad area. For example, the same phytosaur taxa are found at the base of the Upper Triassic strata in northern Wyoming and in southwestern Texas (Hunt, 1994; Long and Murry, 1995). Paleontology thus supports age correlation of these strata across wide areas and suggests some level of uniformity of biofacies across their extent.

Recognizing that Upper Triassic nonmarine sediments are part of a regionally extensive depositional system in the western U.S. has long been

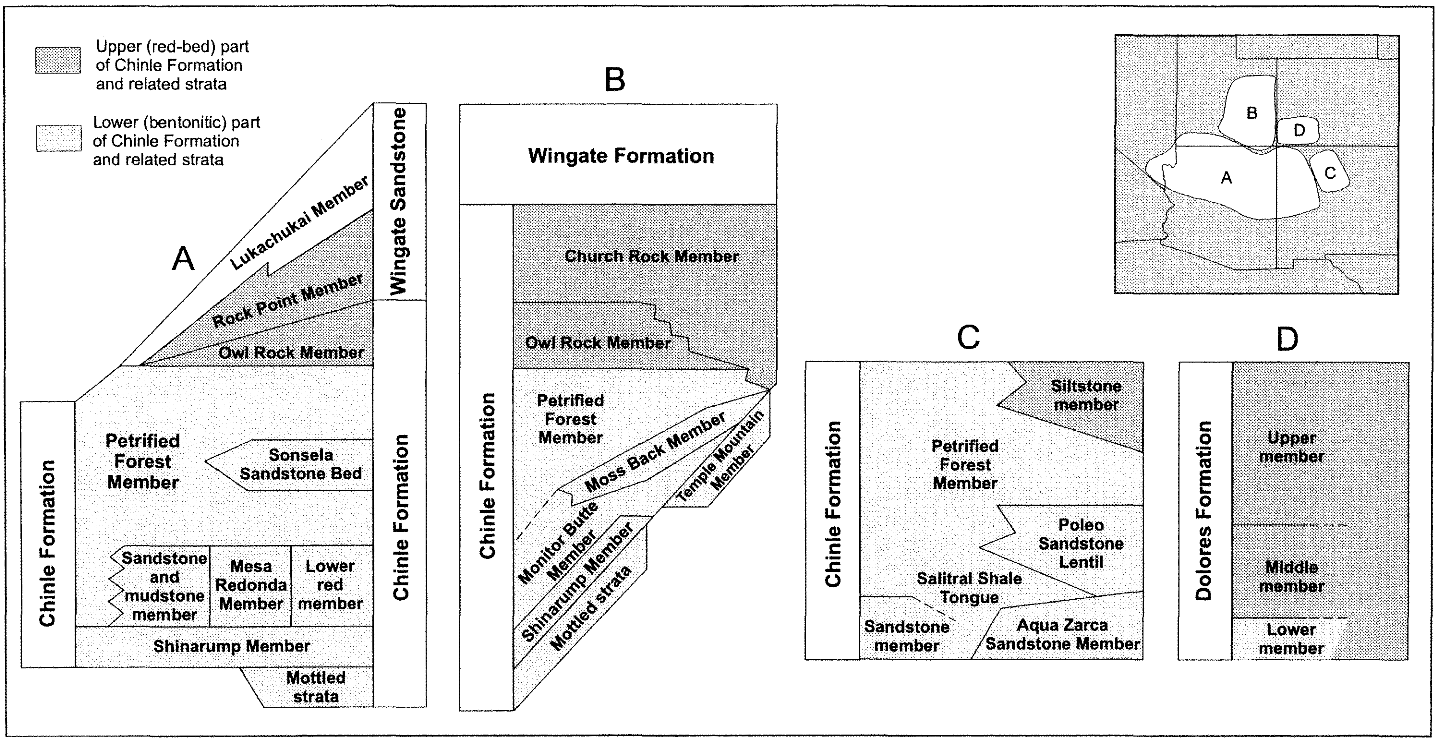

FIGURE 2. Upper Triassic stratigraphic nomenclature in the Four Corners region according to Stewart et al. (1972a).

hindered, however, by the lack of a unified lithostratigraphic nomenclature. This problem is particularly obvious in the Four Corners region, where four sets of regional nomenclature meet each other (Fig. 2), and some strata could easily be assigned multiple names. Some unity of nomenclature has long been needed to express the unity of Upper Triassic nonmarine strata in the western U.S.

For this reason, Lucas (1993) raised Chinle Formation to Group rank to "express the natural relationship of associated formations" (NACSN, 1983, p. 858). In so doing, he advocated Chinle Group as a term to encompass all Upper Triassic nonmarine strata in the Western Interior. He did so because these are associated strata deposited in a single depositional basin or closely

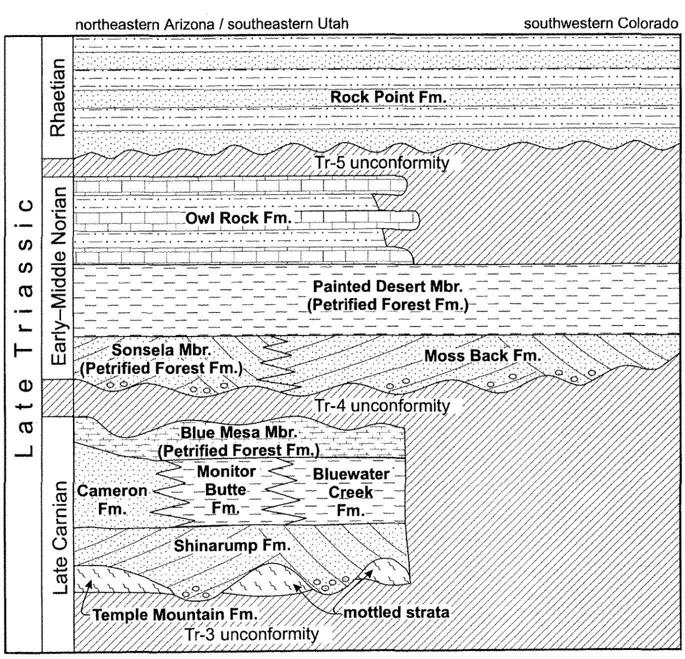

FIGURE 3. Summary of Chinle Group stratigraphy and age relationships in the Four Corners region according to this paper.

interconnected array of sub-basins during the late Carnian–Rhaetian. Chinle Group encompasses 27 formational names applied to Upper Triassic nonmarine rocks in Wyoming, Colorado, Idaho, Utah, Nevada, Arizona, New Mexico, Oklahoma and Texas.

One possible objection to raising Chinle to Group status is that in some parts of its outcrop belt the Upper Triassic section is too thin to merit group status. Fortunately, the flexibility of the code of stratigraphic nomenclature (NACSN, 1983, p. 859) allows for a change in rank from group to formation and for various formations within the Chinle Group to change rank to members in areas where the local section merits such changes.

In raising Chinle to Group rank, Lucas also raised its constituent members and beds one rank in the lithostratigraphic hierarchy. This is particularly useful for the "Petrified Forest Member" on the Colorado Plateau, a complex, thick (at least 350 m; Repenning et al., 1969) unit previously divided into several stratigraphic units (Cooley, 1957; Akers et al., 1958; Repenning et al., 1969; Stewart et al., 1972; Billingsley, 1985; Robertson, 1989). The long-recognized major subdivisions of the Petrified Forest Member—lower part, Sonsela Sandstone Bed, upper part—are mappable units (Akers, et al., 1958) and, in some areas, one or more of these units can be subdivided into mappable units (Billingsley, et al., 1985; Robertson, 1989; Lucas et al., 1997). These major subdivisions of the Petrified Forest Member are more logically recognized as members of a Petrified Forest Formation. Lucas (1993) introduced formal terminology for the two unnamed members of the Petrified Forest Formation. In raising Chinle Formation of Gregory (1916, 1917) to Group rank, Lucas ignored the priority of the older names Dolores Formation (Cross, 1899) and Dockum "Beds" (Cummins, 1890). He did so because neither of these names has achieved such wide use as Chinle Formation nor does the type section (area) of either the Dolores or Dockum encompass strata equivalent to as much of the Chinle Group as does Gregory's original type area of the Chinle Formation. Specifically, the largely unused term Dolores Formation does not encompass the lower Chinle below the Sonsela–Mossback interval (Figs. 3, 4) and the type Dockum does not contain any strata of Rhaetian age (Lucas, 1993). The type Chinle, even as described by Gregory (1916, 1917), includes all of the Upper Triassic strata on the Colorado Plateau.

"Dolores Formation"

The name Dolores Formation has long been applied to Upper Triassic strata in southwestern Colorado, but it has not been used for equivalent

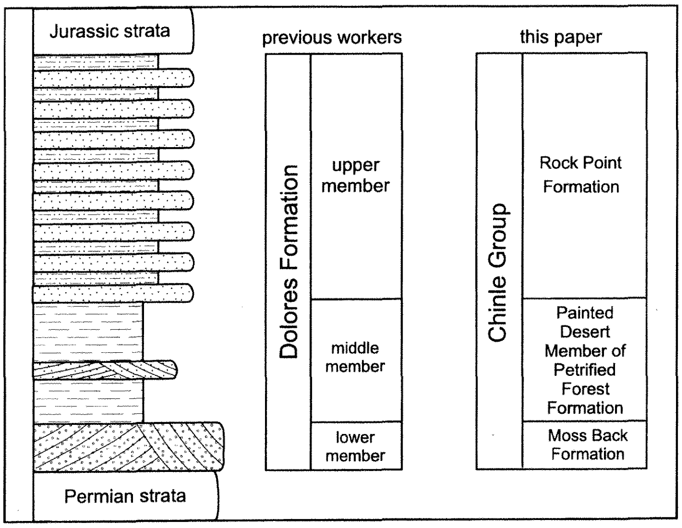

FIGURE 4. Chinle Group stratigraphic nomenclature in southwestern Colorado.

strata in Utah, Arizona and New Mexico that were long included in the Chinle Formation (Fig. 2). Cross (1899) introduced the term Dolores Formation, and Cross and Howe (1905) redefined it to its current status, so it has priority over Chinle Formation of Gregory (1916, 1917). It has long been recognized that Chinle and Dolores strata are equivalent, and indeed can be closely correlated (e.g., Stewart et al., 1972a). Despite this, both names persist, with Dolores being applied only locally in southwestern Colorado.

Like Lucas and Hunt (1989) and Lucas (1993), we abandon the name Dolores and replace it with Chinle. Although Dolores has priority, the Colorado name has been little used outside a small area, and the more widely used term Chinle thus is preferable. Furthermore, Dolores strata are only the middle-upper Chinle Group, not the essentially complete Chinle Group section encompassed by Gregory's type Chinle.

Stewart et al. (1972a) summarized "Dolores Formation" stratigraphy and reviewed and correlated its three informal members (Fig. 4). The "lower member" is the Moss Back Formation of our usage. In southwestern Colorado, it is as much as 27 m of greenish gray to tan, fine-grained quartzose sandstone and limestone-pebble conglomerate, which locally contains siliceous pebbles. It rests unconformably on the Lower Permian Cutler Formation.

The "middle member of the Dolores Formation" in southwestern Colorado is the Painted Desert Member of the Petrified Forest Formation of our usage (Fig. 4). It is as much as 83 m of grayish red mudstone, siltstone and minor beds of trough-crossbedded, fine-grained sandstone and limestone-pebble conglomerate. These conglomerates are the "saurian conglomerates" of Cross and Howe (1905) and produce abundant but fragmentary fossils of phytosaurs and rauisuchians (*Postosuchus*).

The "upper member of the Dolores Formation" is the Rock Point Formation of our usage. It is as much as 360 m thick and mostly cyclically and horizontally bedded, light brown and reddish brown fine-grained sandstone and non-bentonitic siltstone.

"Kane Springs strata"

Gubitosa (1981; Blakey and Gubitosa, 1984) introduced the term "Kane Springs strata" for some Chinle Group strata in the Canyonlands and Lisbon Valley areas of southeastern Utah. According to Blakey and Gubitosa (1984), the "Kane Springs strata" are 30–60 m thick and represent a coarse-grained facies of the Petrified Forest and Rock Point Formations. However, a detailed section of the Chinle Group strata in Kane Springs Canyon near Moab, Utah measured by us (Fig. 5; Appendix) reveals that "Kane Springs strata" actually are equivalent to the Shinarump and Cameron Formations. In effect, Gubitosa (1981) and Blakey and Gubitosa (1984) assumed that "Kane Springs strata" are a coarse-grained facies of the upper Chinle Group derived from the Salt anticline region to the northeast (Fig. 1). No stratigraphic relationship to the upper Chinle Group was actually demonstrated, and "Kane Springs strata" is not a useful stratigraphic construct.

Mottled strata/Temple Mountain Formation

Stewart et al. (1972a) introduced the informal term "mottled strata" to refer to pre-Shinarump pedogenically modified sediments, usually at the top of the Moenkopi Group, but sometimes at the top of the Permian. These strata are as much as 31 m thick and consist of color mottled, generally massive siltstone, sandstone, mudstone and conglomerates. They do not usually preserve original bedding and instead display evidence of deep weathering and pedogenic modification in the form of nodules, rhizoliths, color mottling and brecciation. Typically, the mottled strata are present and/or thickest where the Shinarump Formation is thin or absent.

Robeck (1956) introduced the name Temple Mountain Formation (Member) in the San Rafael Swell of east-central Utah for rocks lithologically similar to and in the same stratigraphic position as the mottled strata. In some areas, Temple Mountain strata retain original bedforms, but otherwise they are very similar to the mottled strata (Lucas, 1991b; Fig. 5.). As Stewart et al. (1972a, p.13) noted, "in the San Rafael Swell these mottled strata form a well-defined unit that has been named the Temple Mountain Member of the Chinle Formation by Robeck (1956)."

Shinarump Formation

The Shinarump Formation is mostly yellowish gray, trough-crossbedded quartzarenites and conglomerates that are almost exclusively extrabasinal, composed of clasts of quartzite, chert, quartz, and Paleozoic limestone. It reaches thicknesses of 76 m in channel fills in the Four Corners region (Young, 1964; Stewart et al., 1972a), but it typically is 10 to 20 m thick. The Shinarump lies at the base of the Chinle Group or just above the mottled strata or Temple Mountain Formation in southeastern Utah and northeastern Arizona (Figs. 3, 5). In north-central New Mexico, its lateral equivalent is the Agua Zarca Formation (Lucas and Hunt, 1992). The Shinarump Formation is not present in southwestern Colorado, where the lower Chinle Group is absent, and the Moss Back Formation rests directly on pre-Chinle, Permian strata (Figs. 3, 6).

Monitor Butte/Bluewater Creek/Cameron Formations

Three mappable lithofacies can be recognized immediately above the Shinarump Formation in the Four Corners region:

1. Strata dominated by greenish gray bentonitic mudstone with minor lenses of clayey, fine-grained sandstone and rare, low-grade coal lenses. This is the Monitor Butte Formation (Kiersch, 1956; Witkind, 1956; Stewart, 1957; Stewart et al., 1972a; Dubiel, 1987a, b, 1989a; Lucas, 1993), and it is only present in southeastern Utah, where its maximum thickness is 78 m; average thickness is 30–50 m (Stewart et al., 1972a, pl. 4).

2. A complexly interbedded succession dominated by trough-crossbedded and laminated sandstone with minor beds of mudstone, shale, siltstone and silcrete. This is the sandstone–mudstone or sandstone–siltstone member of the Chinle Formation in northeastern Arizona (Phoenix, 1963; Repenning et al., 1969; Stewart et al, 1972a), named the Cameron Formation by Lucas (1993). It typically is 40–50 m thick and reaches a maximum thickness of 84 m (Fig. 5).

3. A red bed mudstone-dominated unit with persistent, bench-forming interbeds of ripple-laminated litharenite. This is the Bluewater Creek Formation of west-central New Mexico and northeastern Arizona (Lucas and Hayden, 1989; Heckert and Lucas, 1996; Heckert, 1997), formerly termed the lower red member of the Chinle Formation (Stewart et al, 1972a). In the Four Corners area, the Bluewater Creek Formation crops out only along the western flank of the Defiance uplift in northeastern Arizona, where it has a maximum thickness of about 50 m.

No strata equivalent to the Monitor Butte/Cameron/Bluewater Creek Formations are present in southwestern Colorado, where the Moss Back Formation rests directly on older strata. The pattern of Chinle Group lithofacies distribution preserved by this interval is a varied one in the Four Corners region. In southeastern Utah, Monitor Butte lacustrine and flood plain deposits were fed by fluvial systems of the Cameron and Bluewater Creek Formations flowing from the southwest, south, and southeast. An ancestral Uncompaghre highland occupied much of southwestern Colorado and part of southeastern Utah at that time (Dubiel, 1989a).

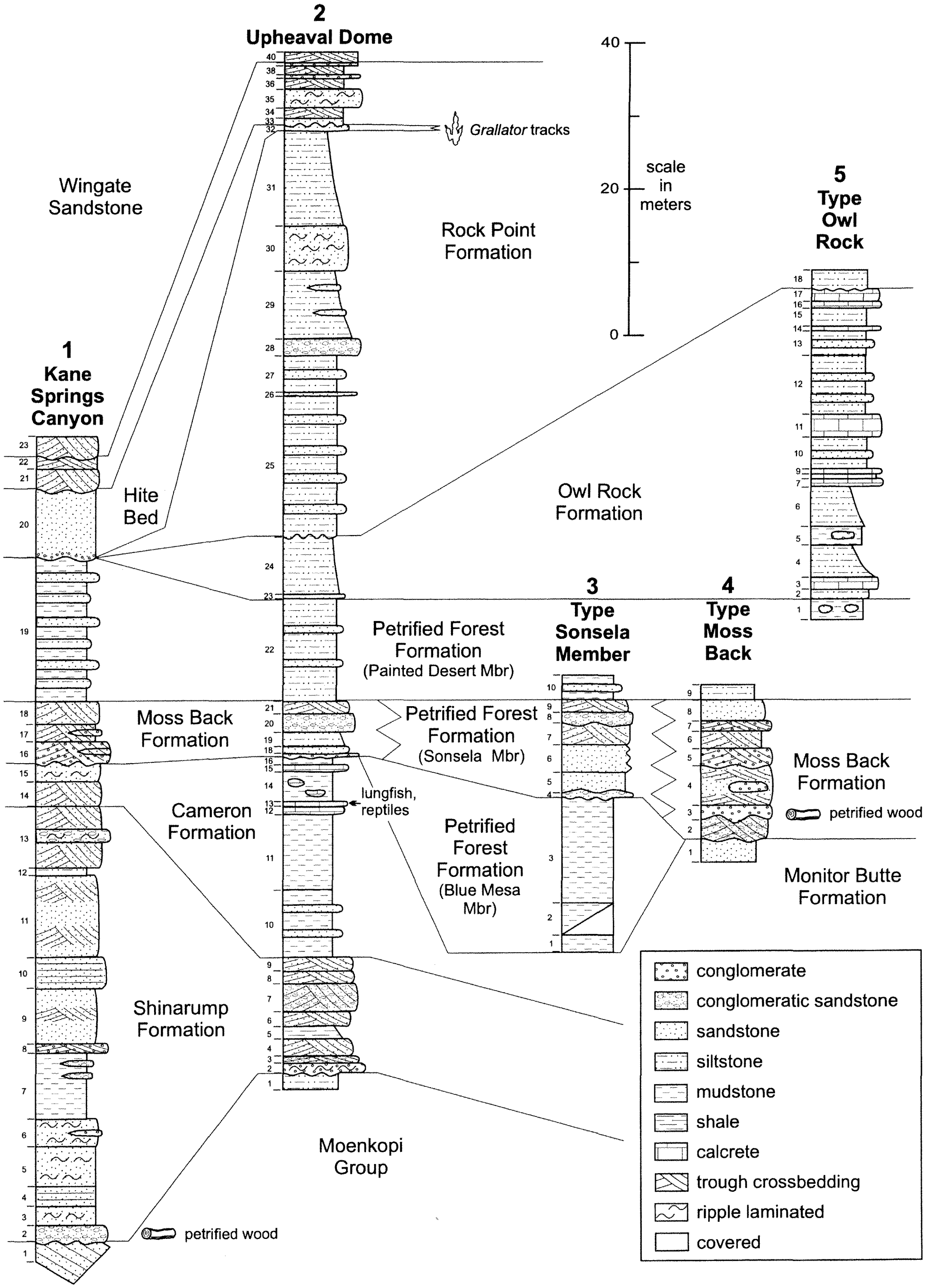

FIGURE 5. Selected measured sections of Chinle Group units in the Four Corners region. See Appendix for descriptions of numbered stratigraphic units.

Blue Mesa Member of Petrified Forest Formation

Strata that crop out in southeastern Utah and northeastern Arizona between the Monitor Butte/Cameron/Bluewater Creek interval and the Moss Back/Sonsela interval pertain to a single lithofacies named the Blue Mesa Member of the Petrified Forest Formation by Lucas (1993). These strata are mostly bentonitic mudstone with variegated hues of purple, blue, gray and red (Fig. 5). They contain lenses of trough-crossbedded, biotite-rich sandstones and numerous calcrete nodules indicative of extensive pedogenesis. The Blue Mesa Member is not present in southwestern Colorado (Fig. 6). In southeastern Utah and northeastern Arizona it is typically 50–100 m thick.

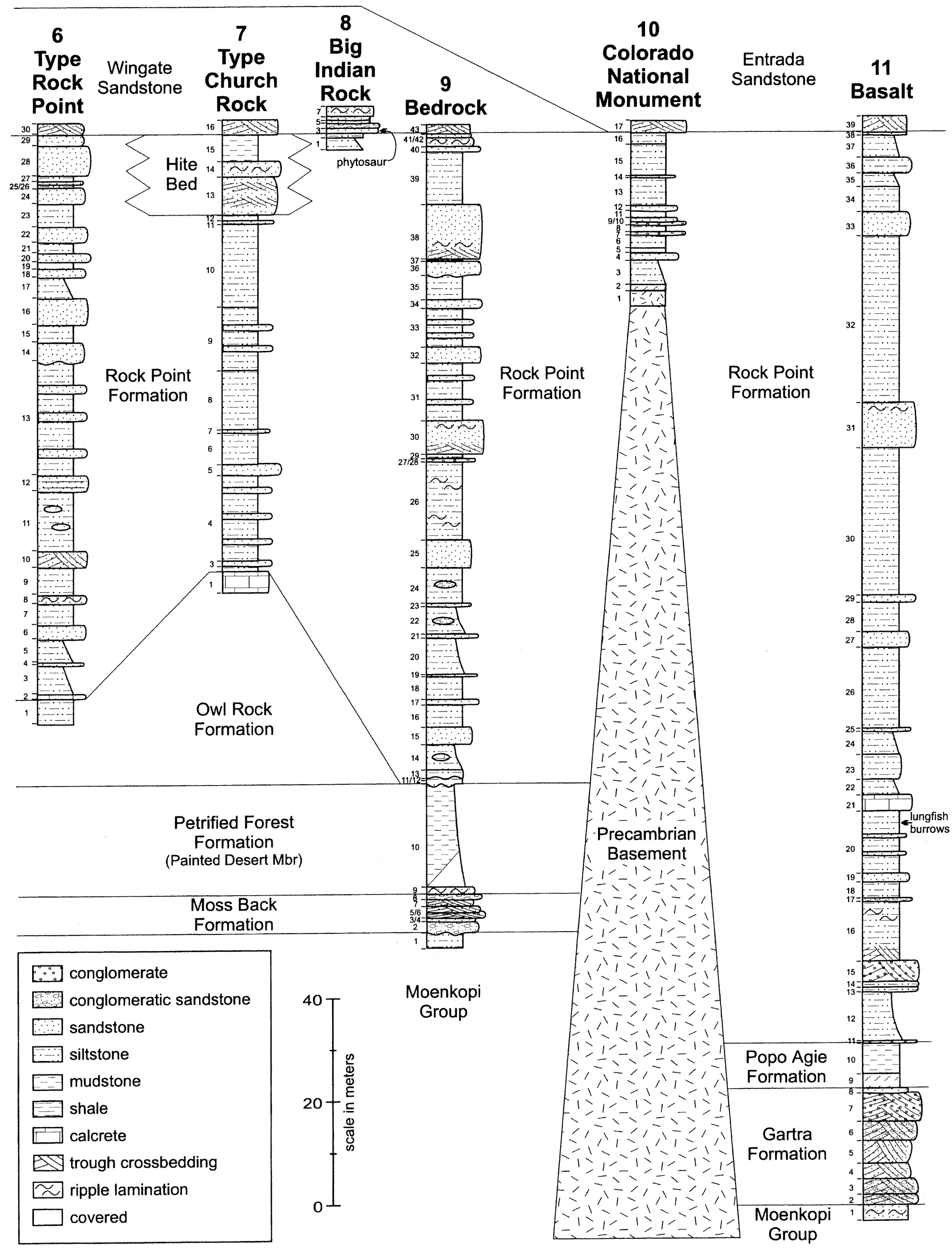

FIGURE 6. Selected measured sections of Chinle Group units in the Four Corners region. See Appendix for descriptions of numbered stratigraphic units.

Moss Back Formation/Sonsela Member

The base of the Chinle Group in southwestern Colorado is the Moss Back Formation. To the west, in southeastern Utah, the Moss Back is a medial unit of the Chinle Group, disconformably overlying the Blue Mesa Member of the Petrified Forest Formation. To the southwest, in northeastern Arizona, the Sonsela Member of the Petrified Forest Formation disconformably overlies the Blue Mesa Member and is the correlative of the Moss Back.

The Moss Back Formation is mostly yellowish gray, medium-grained litharenite and abundant conglomerate, dominantly of intrabasinal calcrete and siltstone rip-ups. Extrabasinal conglomerates—clasts of quartzite, chert and quartz—are present, but much less common than intrabasinal conglomerates. Average thickness is 20 m, but channel fills are as much as 50 m thick. The Moss Back Formation forms a prominent ledge or bench, and its base is a sharp, often scour-and-fill contact (Fig. 5).

The Sonsela Member is white, orange and gray trough-crossbedded sublitharenite and subarkose with numerous beds of extrabasinal conglomerate—clasts of chert, quartz, quartzite and lesser limestone and volcanic rocks (Stewart et al., 1972a; Deacon, 1990). The main difference between it and the Moss Back is clast composition of the conglomerates—dominantly intrabasinal in the Moss Back and extrabasinal in the Sonsela. Sonsela thickness in northeastern Arizona is generally 10–20 m, though it can be as thick as 30 m in channel fills (Fig. 5). Like the Moss Back, the Sonsela forms a ledge or bench and has a sharp, often scour-and-fill base.

Paleocurrent studies (Stewart et al., 1972a; Deacon, 1990) indicate northerly to northeasterly flow in the Sonsela Member, and northwesterly flow in the Moss Back Member. This suggests that the Moss Back was the trunk drainage in the Four Corners portion of the Chinle basin, capturing the northeasterly-flowing Sonsela drainage. Therefore, we suggest that the dominance of extrabasinal clasts in the Sonsela results from its proximity to the edge of the Chinle depositional basin. The Moss Back is considerably more distal to the source of these clasts and thus is dominated by intraformational clasts from the extensive Chinle basin to the southwest, with extrabasinal conglomerate clasts provided by captured Sonsela streams.

Painted Desert Member, Petrified Forest Formation

Above the Moss Back–Sonsela interval lie red bed mudstone-dominated strata of the Painted Desert Member of the Petrified Forest Formation in northeastern Arizona. Long termed the "upper" Petrified Forest Member, these strata were formalized as the Painted Desert Member by Lucas (1993). They are dominantly grayish red and moderate reddish brown, bentonitic mudstones and siltstones with ledgy beds of trough-crossbedded and ripple-laminated litharenite. Thickness is as much as 150 m, but 40–50 m is an average thickness in the Four Corners region (Figs. 5, 6).

Owl Rock Formation

In northeastern Arizona, northwestern New Mexico and southeastern Utah, the Owl Rock Formation rests conformably on the Painted Desert Member of the Petrified Forest Formation. The Owl Rock Formation (Kiersch, 1956; Witkind, 1956; Stewart, 1957; Stewart et al., 1972a; Dubiel, 1989a; Kirby, 1991, 1993) is mostly interbedded sheets of calcrete limestone and pale red and brown siltstone (Fig. 5). Thickness in the Four Corners region is about 70 to 150 m (Stewart et al., 1972a, pl. 5). The Owl Rock Formation is not present in southwestern Colorado, where the Rock Point Formation rests directly on the Painted Desert Member of the Petrified Forest Formation. The calcrete limestones of the Owl Rock Member are typically stage III to stage VI calcretes, according to the scheme of Gile et al. (1966) and Bachman and Machette (1977). Lucas and Anderson (1993b) argued for a paleosol origin for these calcretes *contra* some earlier workers who identified them as lacustrine limestones (e.g., Blakey and Gubitosa, 1983; Dubiel, 1989a, b). We follow Lucas and Anderson (1993b) and consider these calcretes to represent soil horizons developed during an interval of raised base level equivalent to a high-stand systems tract (see later discussion) with little or no lacustrine influence.

Rock Point Formation

The youngest strata of the Chinle Group in the Four Corners region belong to the Rock Point Formation (Figs, 3, 5, 6), which rests unconformably on the underlying Owl Rock Formation or older strata, on an erosional surface recognized as the Tr-5 unconformity of Lucas (1991a, 1993). Throughout most of the Four Corners region, the Rock Point Formation is conformably overlain by the Wingate Sandstone (see later discussion). However, farther north, the Entrada Sandstone rests unconformably on the Rock Point (Fig. 6).

The Rock Point consists mostly of reddish brown and pale red, nonbentonitic siltstone and laminated or ripple-laminated sandstones that are very fine- to fine-grained micaceous quartzarenites. These beds typically are laterally continuous and give the impression of cyclical deposition of the Rock Point Formation. A few beds of limestone-siltstone-quartzite-pebble conglomerate and trough-crossbedded sandstone are locally present in the Rock Point.

Most of the Chinle Group in southwestern Colorado is Rock Point Formation, where its maximum thickness is about 300 m. The Rock Point Formation elsewhere in the Four Corners region is usually 50–100 m thick.

The Church Rock Member of the Chinle Formation (Witkind and Thaden, 1963) is a synonym of the Rock Point Member of the Wingate Sandstone of Harshbarger et al. (1957), and the name Church Rock should be abandoned (Lucas, 1993; Fig. 6). We do not follow O'Sullivan's (1970) suggestion, and the practice of Harshbarger et al (1957), Stewart (1957), Witkind and Thayer (1963), and Stewart et al. (1972a), to use the name Church Rock north of Laguna Creek, Arizona and apply the name Rock Point *to the same stratigraphic interval* to the south.

Consequently, we recognize the Hite Bed of the Church Rock Member (Stewart et al., 1972a) as the Hite Bed of the Rock Point Formation. The Hite Bed is a prominent, 6–20-m-thick ledge-forming sandstone unit near the top of the Rock Point Formation (Fig. 6).

Stewart et al. (1959, 1972a) assigned the entire Chinle Group in some parts of southeastern Utah to the "Church Rock Member." This was largely a result of their inability to correlate precisely the northward and northwestward thinning Chinle units from the Four Corners region across Utah (Lucas, 1991b, 1993), not a correct correlation of Rock Point ("Church Rock") strata. Chinle Group strata in southeastern Utah include the entire Temple Mountain to Rock Point succession (e.g., Fig. 5).

The interbedded, fine-grained sandstones and siltstones of the Rock Point Formation are among the most persistent of all Chinle Group lithologies. Therefore, they are readily correlated across the Four Corners region and northward into Wyoming and Idaho, where they overlie lower Chinle Group strata we identify as the Popo Agie Formation (Fig. 6).

Tracing the Rock Point Formation across the study area also demonstrates the magnitude of the Tr-5 unconformity of Lucas (1991a, 1993) and the nature of the erosional surface associated with the development of that unconformity. As documented in Figure 6, the Rock Point Formation infills scours and channels in the Owl Rock Formation associated with erosion during the Tr-5 unconformity, resulting in differential thickness of the Owl Rock beneath the Rock Point. The presence of a basement-cored highland in the vicinity of the Uncompaghre Plateau that persisted until near the end of Chinle deposition is indicated by the presence of Rock Point Formation sediments on Precambrian granites in the vicinity of Colorado National Monument (Fig. 6).

BIOSTRATIGRAPHY

Chinle Group biostratigraphy is primarily based on palynomorphs, megafossil plants and tetrapods (Fig. 7). Lucas (1997) provides a comprehensive summary, and we briefly review the biostratigraphic correlation of the Chinle Group in the Four Corners region.

Palynology

Litwin et al. (1991) and Cornet (1993) recently reviewed Chinle Group palynostratigraphy in some detail. Palynomorphs are abundant and well preserved throughout the Chinle Group and have been studied for at least 30 years. Litwin et al. (1991) defined three palynomorph zones that nearly parallel the megafossil plant zones of Ash (1980, 1987) discussed below (Fig. 7). The lowest zone, from the Temple Mountain Formation, is characterized by two taeniate bisaccate taxa, *Lunatisporites* aff. *L. noviaulensis* and *Infernopollenites claustratus* (the latter also is found in the Shinarump Formation). The next zone is widely distributed and is characterized by more than 100 taxa. Key among these are *Brodispora striata, Microcachrydites doubingeri, Lagenella martinii, Samaropollenites speciosus, Plicatisaccus badius, Camerosporites secatus* and *Infernopollenites claustratus*, and it includes a large number of FADs (first appearance datums) and LADs (last appearance datums). This zone is of Tuvalian age, based on correlation to European palynomorph zones and cross-correlation to Tuvalian ammonite-bearing strata with palynomorphs (Dunay and Fisher, 1974, 1979). The second zone occurs between the Shinarump and Sonsela–Moss Back intervals.

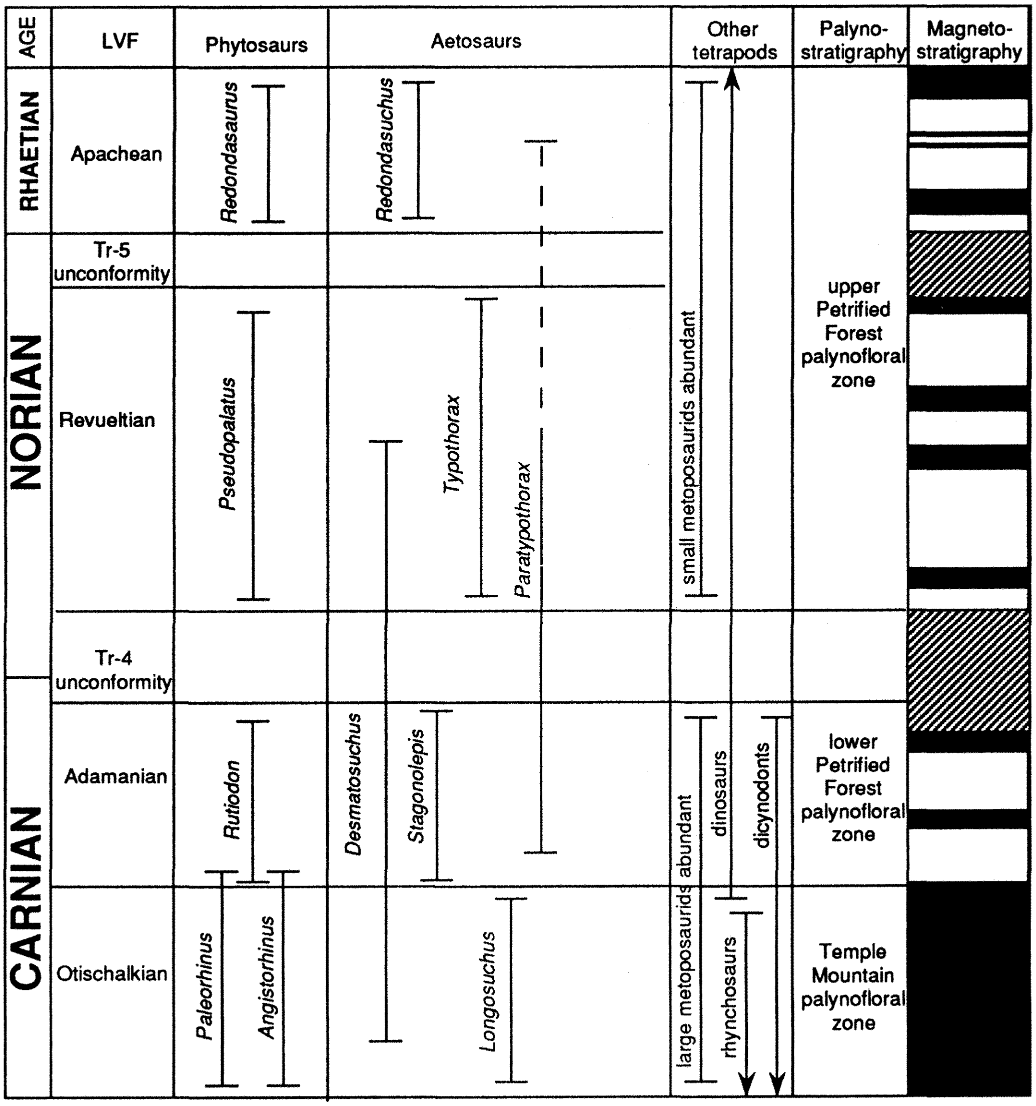

FIGURE 7. Summary of Chinle Group tetrapod biostratigraphy, palynostratigraphy and magnetostratigraphy (modified from Lucas, 1997).

The youngest zone encompasses all of the upper Chinle Group (post-Sonsela/Moss Back strata). This zone lacks many common to cosmopolitan late Carnian palynomorphs, and includes the FADs of several taxa—*Foveolatitriletes potoniei*, *Kyrtomisporis speciosus*, *K. laevigatus* and *Camerosporites verucosus*—which indicate a Norian age (Litwin et al., 1991).

Litwin et al. (1991) claimed that the presence of *Pseudenzonalasporites summus* indicates an early Norian age for all of the youngest zone, citing Visscher and Brugman (1981) as authority for an early Norian age of *P. summus*. However, Visscher and Brugman (1981) stated that *P. summus* extends into the late Norian. Indeed, *P. summus* is known from the youngest Triassic (Rhaetian) strata of the Newark Supergroup in eastern North America (upper Passaic Formation) (Cornet, 1993; Huber et al., 1993a), so it cannot be considered indicative of only an early Norian age.

Litwin et al. (1991, p. 280) also claimed that the absence of *Corallina* (=*Classopollis*), *Triancoraesporites ancorae*, *Rhaetipollis germanicus*, *Ricciisporites tuberculatus* and *Heliosporites reissingeri* in the youngest zone "precludes a younger age assignment for upper members of the Chinle because these palynomorphs occur commonly in late Norian (i.e., "Rhaetian") strata in Europe, the North Atlantic (Greenland) and the Arctic." Nevertheless, *Classopollis*, *Ricciisporites tuberculatus*, *Heliosporites reissingeri* and other supposed Rhaetian index palynomorphs are known from ammonoid-bearing early Norian strata in Svalbard, calling into question their validity as Rhaetian index taxa (Smith, 1982). Furthermore, we do not consider the absence of taxa to be as strong an indicator of age as the presence of taxa, so the absence of a few so-called Rhaetian index palynomorphs from the youngest zone is of doubtful biochronological significance. We thus conclude that Litwin et al.'s (1991) youngest palynomorph zone is post-late Carnian Triassic, but we do not believe it can provide a more precise correlation within the Norian-Rhaetian interval.

Palynomorphs provide an important means by which Chinle Group strata are correlated. Particularly significant is the potential that palynomorphs may provide for direct link to the marine timescale, thus allowing precise assignment of late Carnian, Carnian-Norian boundary and post-late Carnian Triassic to the Chinle Group strata. Clearly, the frontier for Chinle Group palynostratigraphy is in the upper part of the group, the youngest zone of Litwin et al. (1991). This assemblage needs more extensive documentation to subdivide it and/or arrive at a more precise, palynomorph-based correlation of the upper Chinle Group.

Megafossil plants

Study of Chinle Group fossil plants extends back to 1850, but the work of Daugherty (1941) and Ash (1989, and references cited therein) provides most of our knowledge of Chinle Group megafossil plants. Ash (1980, 1987) proposed that three floral zones can be recognized in Chinle Group strata: (1) *Eogingkoites* zone from the Shinarump interval; (2) *Dinophyton* zone from the post-Shinarump to pre-Moss Back/Sonsela interval; and (3) *Sanmiguelia* zone from the post-Moss Back/Sonsela interval.

When the stratigraphic ranges of all Chinle megafossil plant genera are plotted (Lucas, 1997), some clear patterns emerge: (1) the majority of genera (26 of 49, or 53%) are confined to the *Dinophyton* zone; (2) very few genera (8 of 49, or 16%) are found in the *Sanmiguelia* zone; and (3) a minority of genera (18 of 49, or 37%) are found in the *Eogingkoites* zone, of which only five are restricted to that interval. *Eogingkoites* is restricted to the Shinarump, but the other genera in this interval either are rare or known only from one locality.

The *Dinophyton* zone of Ash (1980) is the bulk of the Chinle megafossil flora, probably due to preservational biases. *Nemececkigone* is a possible seed of *Sanmiguelia*, and *Synangispadixis* is its possible pollen-bearing organ (Cornet, 1986), so these two taxa in the *Sanmiguelia* zone are redundant of *Sanmiguelia*. Clearly, the *Sanmiguelia* zone cannot be characterized except by the presence of *Sanmiguelia*, which is known from about a half dozen localities and is endemic to the Chinle Group.

The two older Chinle Group megafossil plant zones do allow internal correlation of Chinle Group strata that reinforce tetrapod-based correlations (i.e., the *Eoginkgoites* zone is of Otischalkian age, and the *Dinophyton* zone is of Adamanian age, see below). Furthermore, these two zones can be correlated to strata in several Newark Supergroup basins, correlations that are consistent with tetrapod-based correlations (Ash, 1980; Axesmith and Kroehler, 1988; Lucas and Huber, 1993; Huber et al., 1993b). We conclude that Chinle Group late Carnian plants provide a strong basis for correlation, but that the Norian–Rhaetian megaflora of the Chinle Group needs further collection and study before it will be of much biostratigraphic and biochronologic utility.

Bivalves and gastropods

Nonmarine molluscs (unionid bivalves and prosobranch mesogastropods) are widespread in the Chinle Group and were among the first Chinle Group fossils described (Good, 1989, 1993a, b). As Lucas (1991a, 1993) and Good (1993a, b) indicated, these fossils are much more abundant in the upper Chinle Group than in the lower, probably due to differences in favorable living habitats and preferential preservation in the more oxidized upper Chinle Group sediments. Kietzke (1987, 1989) reported "spirorbids" from the Chinle Group, but these are more likely to be vermiform gastropods (Kietzke and Lucas, 1991b; Weedon, 1990).

Good (1993a, b) recognized two "molluscan faunas" based on Chinle Group nonmarine molluscs that we will call zones: (1) a lower zone (below the Moss Back/Sonsela) characterized by two unionid taxa, *Uniomerus*? *hanleyi* and *Antediplodon hanleyi*; and (2) an upper zone (post-Moss Back/ Sonsela) of various species of *Antediplodon* and with gastropods of the genera *Lioplacodes* and *Ampullaria*. *Diplodon gregoryi* is known from one problematic specimen from the Shinarump Formation (Reeside, 1927) and is of no biostratigraphic or biochronologic utility. The gastropod-dominated interval without unionids in Rock Point strata probably reflects a particular facies, but may be of biostratigraphic and biochronological utility.

Unionids and gastropods provide a robust internal correlation of Chinle Group strata into two time intervals. They are more abundant than ostracods and thus are more useful in Chinle Group correlations. However, no effort has been made to compare Chinle Group nonmarine molluscs with molluscs from other Late Triassic nonmarine strata, so their utility in broader correlations remains to be tested.

Fishes

Chinle Group fossil fishes range from isolated scales to complete articulated skeletons and are found at many outcrops throughout the stratigraphic range of the Chinle Group (Schaeffer, 1967; Johnson, 1980; Murry, 1982; Huber et al., 1993c). Huber et al. (1993c) provided a comprehensive review of Chinle Group fishes and identified three assemblages: (1) a late Carnian (pre-Moss Back/Sonsela) assemblage with cf. *Turseodus, Tanaocrossus* sp., *Cionychthys greeni*, representatives of the *Synorichthys–Lasalichthys* complex, indeterminate colobodontids, cf. *Hemicalypterus, Chinlea* sp., *Arganodus* sp., *Xenacanthus moorei* and *Lissodus humblei*; (2) an early-middle Norian assemblage (Painted Desert/Moss Back interval) with cf. *Turseodus, Tanaocrossus* sp., indeterminate redfieldiids and colobodontids, *Semionotis* cf. *S. brauni, Chinlea* n. sp. and *Chinlea* sp., *Arganodus* and *Acrodus*; and (3) a Rhaetian assemblage (Rock Point interval) with *Turseodus dolorensis, Tanaocrossus kalliokoski, Cionychthys dunklei, Synorichthys stewarti, Lasalichthys hillsi,* indeterminate colobodontids, *Semionotus* sp., *Hemicalypterus weiri, Chinlea sorenseni, Arganodus* sp. and *Lissodus* n. sp. Most of these taxa are either long ranging or unique to a particular assemblage, so they are of little biostratigraphic or biochronologic utility. We do not expect this to change with further collecting and study, although much work remains to be done on Chinle Group fossil fishes.

Tetrapods

Tetrapod vertebrates (amphibians and reptiles) provide one of the strongest and most refined means for correlating Late Triassic nonmarine strata. The Chinle Group has an extensive tetrapod fossil record that has long played a key role in Late Triassic correlations. Lucas and Hunt (1993) recently organized Chinle Group tetrapod stratigraphic ranges to define four land-vertebrate faunachrons (lvfs) of Late Triassic age (Fig. 7). These lvfs rely heavily on the distribution of four groups of abundant, widespread Late Triassic tetrapods—metoposaurs, phytosaurs, aetosaurs and dicynodonts. Their biostratigraphy and biochronology are reviewed here, as is that of Chinle Group tetrapod footprints. At present, other Chinle Group tetrapods are less useful biostratigraphically and biochronologically because of inadequate sampling and/or a confused taxonomy in dire need of revision. Fraser (1993) well emphasized the need to document better the distribution and taxonomy of small tetrapods of Late Triassic age, especially sphenodontians, as an aid to correlation. This work is well underway by several paleontologists and promises further reinforcement and refinement of Chinle Group tetrapod biochronology.

Metoposauridae

All Chinle Group temnospondyl amphibians are metoposaurids. Hunt (1993) revised the metoposaurids and identified three biochronologically useful Chinle Group taxa: (1) *Metoposaurus bakeri*, known only from Otischalkian-age strata in West Texas; (2) *Buettneria perfecta*, known mostly from Otischalkian–Adamanian-age strata, though it occurs less frequently in Revueltian–Apachean age strata; and (3) *Apachesaurus gregorii*, most common in Revueltian–Apachean age strata, but also present less frequently in Otischalkian–Adamanian age strata. Thus, the Otischalkian–Adamanian is an acme zone for *Buettneria perfecta*, whereas the Revueltian–Apachean is an acme zone for *Apachesaurus gregorii* (Hunt and Lucas, 1993a).

Phytosauria

The use of phytosaurs in Chinle Group biostratigraphy and biochronology has a long tradition (e.g., Camp, 1930; Gregory, 1957; Colbert and Gregory, 1957), and their fossils are abundant. Phytosaurs had a broad distribution across Late Triassic Pangaea. Ballew (1989) most recently revised the phytosaurs, and based on her revision, five biochrons can be defined using Chinle Group phytosaurs (for details see Hunt, 1991, 1994; Hunt and Lucas, 1991a, 1993a):

1. *Paleorhinus* biochron—*Paleorhinus* is the most primitive phytosaur. All Chinle Group occurrences of *Paleorhinus*, except its youngest occurrence in eastern Arizona, are of Otischalkian age. *Paleorhinus* occurs in marine Tuvalian strata in Austria, and its other occurrences are generally considered to be of late Carnian age (Hunt and Lucas, 1991a). It provides important evidence of the Tuvalian age of the base of the Chinle Group and an important cross-correlation between Chinle Group nonmarine biochronology and the marine Late Triassic timescale. *Angistorhinus* co-occurs with *Paleorhinus* in the Chinle Group.
2. Overlap biochron of *Paleorhinus, Angistorhinus* and *Rutiodon*—the oldest Chinle Group localities of Adamanian age in eastern Arizona and northern New Mexico produce rare *Paleorhinus* and *Angistorhinus* and more common *Rutiodon* (Lucas et al., 1997b).
3. The remainder of the Adamanian produces only one phytosaur genus, *Rutiodon* (*sensu* Ballew, 1989).
4. Revueltian-age strata of the Chinle Group produce only one phytosaur genus, *Pseudopalatus* (*sensu* Ballew, 1989). The German Stubensandstein of early-middle Norian age produces phytosaurs that Ballew (1989) identified as *Belodon, Mystriosuchus* and *Nicrosaurus*. Some of these specimens appear to be congeneric with North American specimens she termed *Pseudopalatus*. This supports a Revueltian–Stubensandstein correlation and assignment of an early middle Norian age to the Revueltian.

5. The youngest Chinle Group phytosaur, of Apachean age, is *Redondasaurus* (Hunt and Lucas, 1993b). This endemic taxon is the most evolutionarily advanced phytosaur and thus suggests the Apachean is of late Norian or Rhaetian age.

Hunt (1994) has recently completed but not yet published a revision of the phytosaurs that somewhat alters Ballew's (1989) taxonomy. However, his taxonomy does not change the phytosaur-based biochronology and correlations outlined here. The problems posed by phytosaurs as index fossils reside in the need to have a nearly complete phytosaur skull to arrive at a precise identification, thus rendering the vast majority of phytosaur fossils, which are isolated bones, teeth and skull fragments, useless for correlation. Despite this, enough phytosaur skulls are known from the Chinle Group and elsewhere to continue their longstanding use in Late Triassic tetrapod biochronology.

Aetosauria

Aetosaur fossils are at least as abundant as phytosaur fossils in strata of the Chinle Group. Furthermore, a genus-level identification of an aetosaur can be made from an isolated armor plate or fragment of a plate. For example, the syntype specimens of *Typothorax coccinarum* Cope, a common upper Chinle Group aetosaur, are only fragments of paramedian plates, but they are diagnostic (Lucas and Hunt, 1992). Skulls are not needed, so aetosaurs provide much easier-to-identify index fossils than do phytosaurs. Aetosaurs also had a broad distribution across Late Triassic Pangaea, and some aetosaur genera found in the Chinle Group (e.g., *Longosuchus, Stagonolepis, Desmatosuchus* and *Paratypothorax*) are also known from the Newark Supergroup and/or western Europe. Aetosaurs thus provide an important basis for correlating Chinle Group and other nonmarine Late Triassic strata (Lucas and Heckert, 1996; Heckert et al., 1996).

Six aetosaur biochrons can be identified in the Chinle Group:

1. *Longosuchus* biochron—*Longosuchus* is of Otischalkian age and co-occurs in the lowermost Chinle Group with *Desmatosuchus*; this co-occurrence is also documented in the late Carnian Pekin Formation of the Newark Supergroup (Hunt and Lucas, 1990).
2. *Stagonolepis* (=*Calyptosuchus*) biochron—*Stagonolepis* is confined to strata of Adamanian age in the Chinle Group. It is also known from the late Carnian Lossiemouth Sandstone of Scotland (Walker, 1961; Hunt and Lucas, 1991b).
3. *Paratypothorax* biochron—*Paratypothorax* in the Chinle Group ranges in age from Adamanian to Revueltian (Hunt and Lucas, 1992a). In Germany, it is known only from the early Norian lower Stubensandstein (Long and Ballew, 1985).
4. *Desmatosuchus* biochron—*Desmatosuchus* ranges in age from Otischalkian to early Revueltian in the Chinle Group.
5. *Typothorax* biochron—this endemic Chinle Group aetosaur is of Revueltian age.
6. *Redondasuchus* biochron—this endemic Chinle Group taxon (Hunt and Lucas, 1991c; Heckert et al., 1996) is of Apachean age.

Dicynodontia

Non-archosauromorph reptiles and mammals are rare in the Chinle Group, with the exception of the dicynodont *Placerias*. The Chinle Group dicynodonts are *Placerias hesternus* (=*P. gigas*) and cf. *Ischigualastia* sp. *Placerias* is known from Otischalkian–Adamanian strata in Arizona and Wyoming, whereas the possible *Ischigualastia* is known from earliest Adamanian strata in New Mexico (Lucas and Hunt, 1993b). *Placerias* (=*Mohgrebeeria*) is also known from the Pekin Formation of North Carolina and the Argana Formation of Morocco. Its occurrences in Wyoming, Arizona, North Carolina and Morocco define a *Placerias* biochron of late Carnian age. The possible *Ischigualastia* in the Chinle Group provides a possible direct correlation to Argentinian and Brazilian strata of late Carnian age that contain this large dicynodont (Cox, 1965; Araújo and Gonzaga, 1980; Rogers et al., 1993).

Tetrapod footprints

Tetrapod footprints are abundant in the uppermost strata of the Chinle Group, the Rock Point Formation and correlatives (Hunt and Lucas, 1992b). Only a handful of tetrapod footprints are known from older Chinle Group strata (Hunt et al., 1993a), so they are of no biostratigraphic or biochronologic significance.

The tetrapod ichnofauna of the Rock Point interval is dominated by the ichnotaxa *Brachychirotherium, Grallator, Pseudotetrasauropus, Tetrasauropus* and *Gwyneddichnium* (e.g., Lockley et al., 1992; Hunt et al., 1989, 1993a, b). These footprints provide a basis for intra-Chinle correlation of strata of the Rock Point interval in Wyoming, Utah, Colorado, New Mexico and Oklahoma. They also indicate a Late Triassic age, by comparison with tetrapod footprint assemblages in eastern North America, Europe and South Africa. Most significant is the prosauropod footprint *Tetrasauropus*. Prosauropod footprints are also known from the lower Elliott Formation (lower Stormberg Group) of South Africa (Ellenberger, 1970; Olsen and Galton, 1984) and marginal marine strata of Rhaetian age in Switzerland (Furrer, 1993). Their distribution may define a *Tetrasauropus* biochron of Rhaetian age recognizable across much of Pangaea.

SEQUENCE STRATIGRAPHY

Lithostratigraphic and biostratigraphic correlation of Chinle Group strata identifies two intra-Chinle unconformities that delimit three depositional sequences (Lucas, 1991a, c, 1993, 1997; Lucas and Huber, 1994; Fig. 8). The oldest of these is the upper Carnian Shinarump–Blue Mesa sequence. It begins with sandstones and silica-pebble conglomerates that rest unconformably on older Triassic or Paleozoic strata. Overlying units are variegated mudrock, sandstone and minor carbonate. These strata are overlain by mudrock-dominated lithofacies that show extensive pedogenic modification (Lucas, 1993).

The second sequence of the Chinle Group is the lower to middle Norian Moss Back–Owl Rock sequence. It begins with pervasive, primarily intrabasinal conglomeratic sandsheets that rest disconformably on older Chinle Group strata. Above the Moss Back–Sonsela interval are fluvial- and flood plain-deposited red beds. These red beds are gradationally overlain by carbonate-siltstone strata of the Owl Rock Formation, which is restricted to the Colorado Plateau region of the Chinle outcrop area (Dubiel, 1989a, b; Lucas, 1993).

The upper Chinle Group sequence is the Rhaetian Rock Point sequence. The base of the Rock Point sequence is everywhere defined by an unconformity that truncates various formations of the underlying sequences. The Rock Point lithofacies are varied, but consist mostly of repetitive, laterally persistent beds of siltstone, litharenite and minor carbonate. The Rock Point sequence is conformably (see below) or unconformably overlain by formations of the Lower Jurassic Glen Canyon Group or other younger strata.

On the Colorado Plateau, the basal Chinle Group locally consists of the late? Carnian Spring Mountains (southeastern Nevada) and Temple Mountain (southeastern Utah) Formations and a paleo-weathering zone informally termed "mottled strata," which is variably present in other parts of the Chinle basin (Stewart et al., 1972a, b; Lucas, 1991a, 1993; Lucas and Marzolf, 1993). These strata are as much as 31 m thick and may represent a depositional sequence older than and disconformably overlain by the Shinarump–Blue Mesa sequence (Marzolf, 1993). However, the detailed stratigraphic relationships of these oldest Chinle strata and weathering horizons have not been well studied. We presently consider them to represent early, incised valley fills of the Shinarump–Blue Mesa sequence.

In the Mesozoic marine province of northwestern Nevada, shelf and basinal rocks are juxtaposed along the trace of the late Mesozoic Fencemaker thrust fault (Speed, 1978a, b; Oldow, 1984; Oldow et al., 1990). Lucas and Marzolf (1993; also see Lupe and Silberling, 1985) considered the Cane Spring Formation of the Star Peak Group and overlying strata of the Auld Lang Syne Group to be correlative and genetically related to Chinle Group strata (Fig. 8).

In the northeastern part of the Star Peak outcrop area, the base of the Cane Spring Formation is chert-pebble to cobble conglomerate and planar-crossbedded conglomeratic sandstone up to 100 m thick (Nichols and Silberling, 1977) containing lenses of deeply weathered clastic rocks (Nichols, 1972). These basal clastics closely resemble the Shinarump Formation of the Chinle Group and were deposited on a subaerially eroded, channelized and karsted surface developed on the underlying Middle Triassic Smelser Pass Member of the Augusta Mountain Formation.

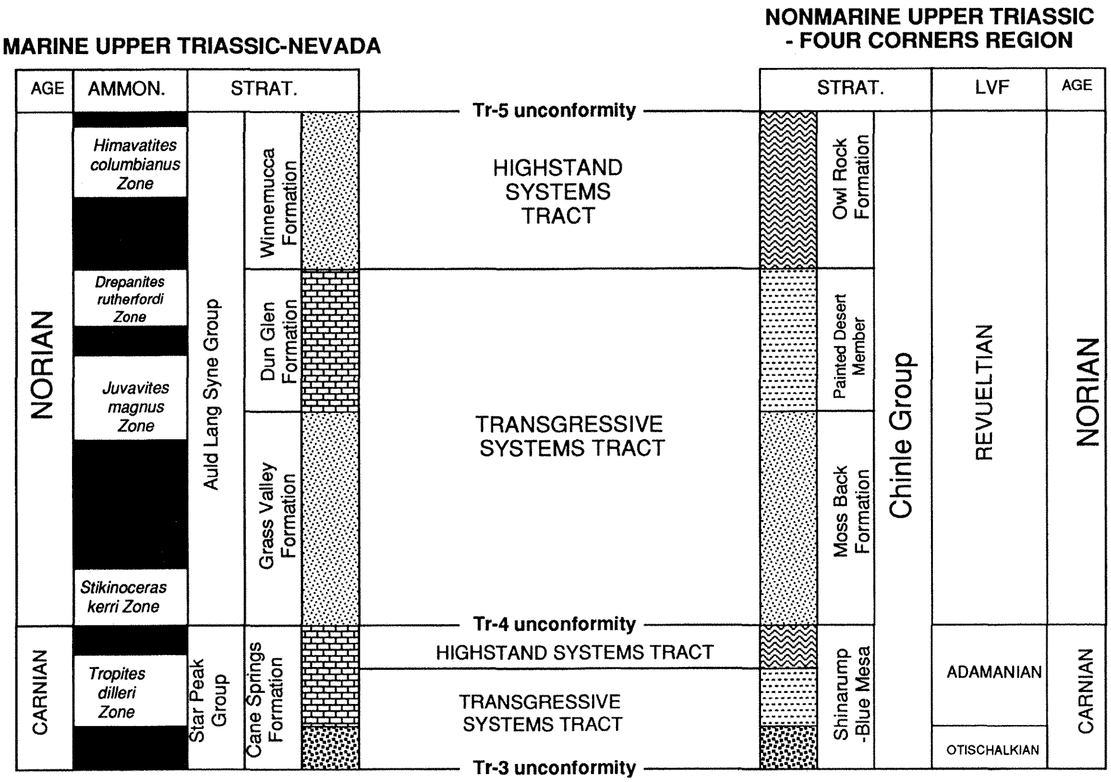

FIGURE 8. Correlation of Chinle Group sequence stratigraphy in the Four Corners region with shallow marine sequences in the Mesozoic marine province of Nevada.

The basal coarse clastics are overlain by bioclastic wackestone up to 300–400 m thick (Nichols and Silberling, 1977). In the western part of the Star Peak outcrop area, these carbonates have been informally divided into a lower, brownish weathering, evenly bedded silty and argillaceous limestone, and an upper, more massive and thickly bedded gray limestone.

The latter is overlain by the Grass Valley Formation or equivalent Osobb Formation. These two formations represent a voluminous influx of siliciclastic sediment interpreted by Silberling and Wallace (1969) as a deltaic system. Paleocurrent indicators and a westward increase in mud-to-sand ratios indicate that distributaries transported sand from delta plains in the east to delta fronts and prodeltas in the west. Wood fragments and logs are locally abundant in fine-to-coarse sandstones of eastern sections.

The deltaic sediments of the Grass Valley–Osobb Formations are conformably overlain by massive, thick-bedded dolostone and limestone of the Dun Glen Formation. The Dun Glen is uniform in composition and thickness across its outcrop area. Its fossils suggest a shallow water depositional environment. The Dun Glen is gradationally overlain by mixed siliciclastic and carbonate sediments of the Winnemucca Formation. The Winnemucca contains a much higher proportion of carbonate compared to sandstone and clay than do deltaic sediments of the Grass Valley Formation and is the stratigraphically highest unit of the shelf sequence.

Ammonoids provide a reasonably precise biochronology of the shelfal strata of the Cane Spring Formation and Auld Lang Syne Group (Silberling, 1961; Silberling and Tozer, 1968; Silberling and Wallace, 1969; Nichols, 1972; Burke and Silberling, 1973; Nichols and Silberling, 1977). Lower Cane Spring Formation clastics approximate the upper Carnian *Tropites dilleri* zone, and the lower Norian *Stikinoceras kerri* zone is found in basal calcareous beds of the Osobb Formation. *Juvavites magnus* zone ammonites are present in the uppermost Grass Valley Formation and the Dun Glen Formation, and the Winnemucca Formation probably is as young as the *Himavatites columbianus* zone.

Recent refinement of Chinle Group stratigraphy and biochronology prompted Lucas (1991a; Lucas and Marzolf, 1993) and Marzolf (1993) to reexamine Lupe and Silberling's (1985) proposal of a possible genetic relationship between deposition of Chinle Group and upper Star Peak–Auld Lang Syne Group strata. As noted above, the Chinle Group is composed of three third-order cycles bounded by unconformities. Criteria that define the regional extent of these unconformities are: (1) evidence of extensive, subaerial weathering and channeling at the base of each depositional sequence; (2) major shifts in dominant lithologies (and facies) at the base of each sequence; (3) correlative rocks immediately above each unconformity overlie rocks of different ages in different regions; and (4) each unconformity corresponds to a significant reorganization of the biota (Lucas, 1991a, 1993).

The conglomeratic sand sheets at the bases of the Shinarump–Blue Mesa and Moss Back–Owl Rock sequences were deposited in a broad alluvial basin characterized by extensive paleovalley incision and prolonged subaerial exposure during periods of nondeposition (e.g., Blakey and Gubitosa, 1983; Lucas, 1991a; Lucas and Anderson, 1993a). In each sequence, the basal sand sheets are overlain by fluvial and/or lacustrine facies throughout the Chinle depositional basin. Each sequence is capped by paludal carbonate and siltstone that show evidence of channeling and subaerial weathering prior to deposition of the overlying sequence.

Lucas (1991a, c, 1993; Lucas and Marzolf, 1993) interpreted the basal sand sheets as low stand systems tracts (LSTs) whose deposition occurred in response to initial coastal onlap at the onset of a transgressive-regressive cycle. The overlying fluvial and fluvio-lacustrine siliciclastics represent the transgressive systems tracts (TSTs), and the highstand systems tracts (HSTs) were defined as aggradational deposits of paludal-lacustrine siltstone and carbonate (Fig. 8).

In Nevada, the Shinarump equivalent is the Cane Springs conglomerate (LST) and is overlain by shelfal, dolomitized carbonate that represents the TST (Fig. 8). Overlying basal clastics of the Grass Valley Formation are identified as the HST. The lowstand surface of the next sequence is an unconformity in the Grass Valley Formation. Because the Osobb Formation contains basal Norian ammonoids (*Stikinoceras kerri* zone) and thus straddles the Carnian-Norian boundary, we suggest that it and its correlative, the Grass Valley Formation, contain an unconformity that reflects a basinward strandline shift that accompanied the regression-transgression cycle that defines the Carnian–Norian boundary on the Colorado Plateau.

The Dun Glen Formation is a platform carbonate interpreted to be the TST, where transgressing base level entrapped sediment landward of the deepening shelf, and is correlated to most of the upper Petrified Forest Formation (Fig. 8). The Winnemucca and Owl Rock thus represent homotaxial high-stand deposits. The shelf sequence, however, does not preserve age-correlative strata of the Rock Point sequence (Fig. 8).

The importance of the sequence stratigraphic correlations just outlined lies not only in their suggestion that eustasy was a driving force of Chinle Group sedimentation. These correlations also provide a rationale for correlating selected Late Triassic ammonoid zones to Chinle Group strata (Lucas, 1991c; Lucas and Luo, 1993). These correlations are consistent with the palynological and tetrapod-based correlations of the Chinle Group outlined above. They identify the base of the Chinle Group as approximately equivalent to the late Carnian (Tuvalian) *Tropites dilleri* zone. The Carnian-Norian boundary (base of *Stikinoceras kerri* zone) is about at the base of the Moss Back–Sonsela interval. The Owl Rock Formation is no younger than the middle Norian *Himavatites columbianus* zone. The Rock Point Formation has no equivalent in the Nevada shelfal terrane.

TRIASSIC–JURASSIC BOUNDARY

The Triassic-Jurassic boundary on the Colorado Plateau has either been viewed as transitional or marked by a substantial unconformity. Viewed as transitional, the boundary was generally placed in the Glen Canyon Group, near its base in the Wingate Sandstone–Moenave Formation interval. In contrast, an unconformable Triassic-Jurassic boundary has been placed between the Chinle and Glen Canyon Groups—in other words, at the Rock Point-Wingate contact. Here, we discuss the significance of a phytosaur skull found in the Wingate Sandstone in southeastern Utah (Fig. 9) for placement of the Triassic-Jurassic boundary on the Colorado Plateau.

Big Indian Rock phytosaur locality

Morales and Ash (1993) first reported the phytosaur skull and other fossils found near Big Indian Rock in the Lisbon Valley of southeastern Utah (Fig. 9). The phytosaur locality is at UTM 4224540N, 653900E, zone 12 (SW1/4 SW1/4 sec. 24, T30S, R24E). Here, a nearly complete phytosaur skull, parts of other skulls and phytosaur bones are present on a single bedding plane in an overhanging ledge of sandstone (Fig. 10).

The section at Big Indian Rock encompasses two distinct lithostratigraphic units (Figs. 9, 10A). The Rock Point Formation of the Chinle Group forms the slope below the sandstone that contains the phytosaur fossils (Lucas, 1993). Just below that sandstone, the Rock Point consists of color-mottled reddish brown, grayish red and brownish gray siltstones with numerous limestone (calcrete) nodules.

The phytosaur fossils occur 1.4 m above the base of a 2.1-m-thick interval of trough-crossbedded sandstone and intrabasinal conglomerate

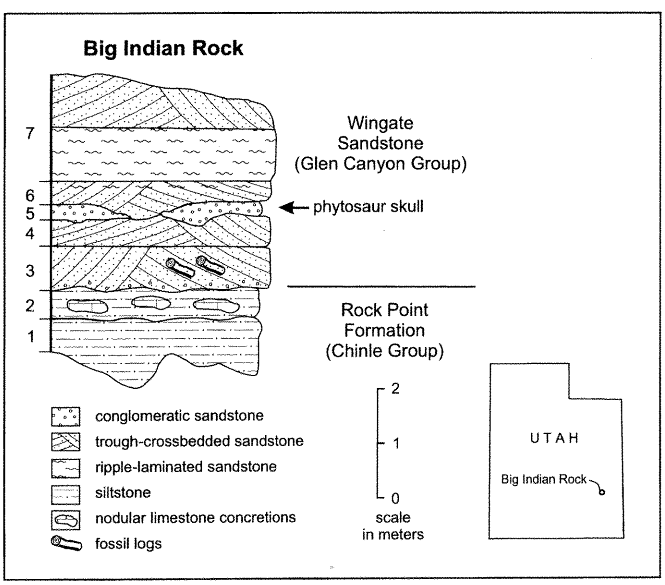

FIGURE 9. Measured stratigraphic section at the Big Indian Rock phytosaur locality. See Appendix for description of numbered stratigraphic units.

that is the basal unit of the Wingate Sandstone. This 2.1-m-thick interval has a sharp, basal, scoured contact where sandstone with rip-ups of siltstone rests on Rock Point siltstone (Figs. 9, 10B–D). The lower 1.4 m of the Wingate contains numerous fossil logs.

A 0.2 to 0.3-m-thick bed of sandstone and conglomerate contains the phytosaur fossils. Clasts in the conglomerate are grayish red muddy siltstone rip-ups and phytosaur bones. The bone-bearing unit pinches out laterally to the northeast over a distance of approximately 50 m (Figs. 10E–F). Above the bone-bearing conglomerate is orange sandstone with small-scale trough crossbeds and ripple laminations. Larger-scale trough crossbeds characterize the cliff of sandstone that caps this unit.

Depositional interpretation

Color-mottled siltstones with calcrete nodules of the upper Rock Point Formation are readily seen as fine-grained, pedogenically modified flood plain deposits (cf. Blodgett, 1988; Dubiel, 1989a). The basal 2.1 m of the Wingate Sandstone appear to be primarily of fluvial origin, based on trough crossbedding, rip-up-clast conglomerates, lateral lenticularity and the presence of petrified wood an vertebrate bones. Overlying sandstones display large-scale trough crossbeds and ripple laminations, and are very fine-grained and well sorted. They are clearly of eolian origin (Nation, 1990).

The Rock Point–Wingate section at Big Indian Rock is remarkably similar to some of the Chinle–Wingate sections described by Clemmensen et al. (1989). It particularly resembles their section Old Paria 1 (Clemmensen et al., 1989, fig. 13) in having basal Wingate stream deposits overlain by sand sheet deposits and capped by dunal beds. Thus, the basal 2.1-m-thick interval of the Wingate that contains the phytosaur fossil at Big Indian Rock probably represents a broad, flat channel full of mudstone rip-ups. It could represent flash flood deposits at the onset of Wingate deposition.

It is possible that the phytosaur skull and other bones in the lowermost Wingate at Big Indian Rock are reworked from the underlying Rock Point Formation. However, like Morales and Ash (1993), we are impressed with the completeness and high quality of preservation, especially the lack of abrasion and preservation of thin, fairly delicate, bony structures of the Big Indian Rock phytosaur skull (Fig. 11). Although reworking cannot be disproved, these features strongly suggest the skull and accompanying bones are not reworked.

Phytosaur skull

The phytosaur skull from Big Indian Rock has mostly weathered away, leaving a clear, natural mold in the rock (Fig. 11). In spite of the fact that almost no original bone material remains, the unique preservation of the mold of the skull enables identification of the specimen. In particular, the unusual preservation of this mold of the dorsal skull surface allows us to reconstruct a dorsal view of the skull from what would normally be a ventral view (Fig. 11). A rubber peel taken from the natural mold is in the collections of the Museum of Northern Arizona, Flagstaff (Morales and Ash, 1993, fig. 1).

Morales and Ash (1993, p. 357) stated the Big Indian Rock phytosaur shows affinities with *Pseudopalatus* or *Redondasaurus*. We identify the skull as *Redondasaurus* because it possesses supratemporal fenestrae that are concealed in dorsal view, which is the defining characteristic of the genus *Redondasaurus* (Hunt and Lucas, 1993). Like the type species of *Redondasaurus*, *R. gregorii*, the Big Indian Rock phytosaur skull lacks a rostral crest, separating it from the crested species *R. bermani* (Hunt and Lucas, 1993). Therefore, we identify the Big Indian Rock phytosaur as *Redondasaurus gregorii*.

Stovall and Savage (1939, p. 758, figs. 1-2) illustrated a phytosaur skull collected from the Travesser Formation in northeastern New Mexico. They noted that this specimen was unique among the phytosaurs in that it possessed supratemporal fenestrae that were completely concealed in dorsal view. Colbert and Gregory (1957) and Gregory (1972) described this skull, and other specimens collected from the Redonda Formation in eastern New Mexico, as a new, unnamed taxon. In her review of the phytosaurs of the American Southwest, Ballew (1989) referred another skull, from the Rock Point Formation at Ghost Ranch, to *Pseudopalatus*. All of these phytosaur skulls have supratemporal fenestrae that are obscured in dorsal view; all but the Rock Point specimen lack rostral crests. Hunt and Lucas

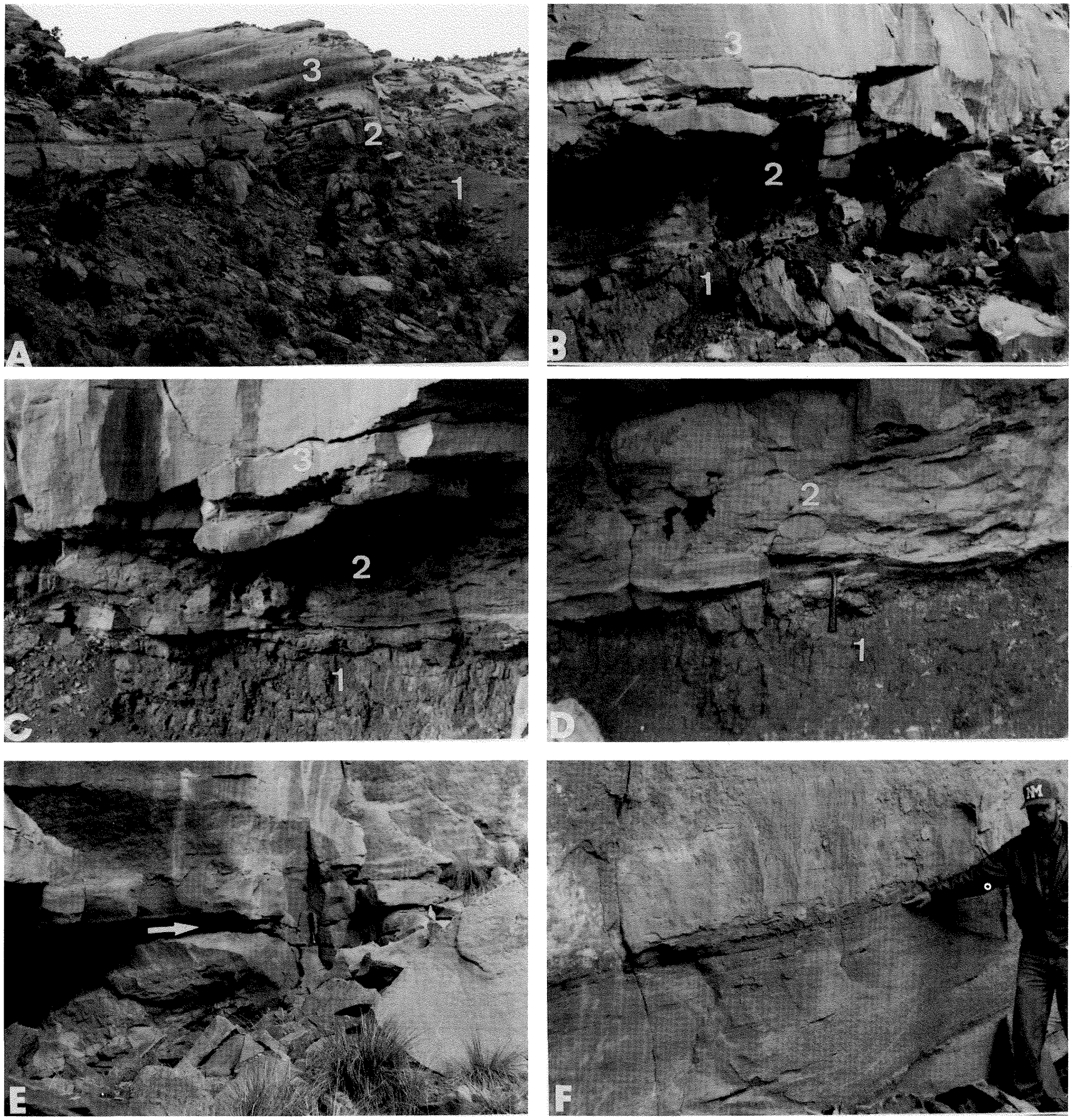

FIGURE 10. Photographs of the Big Indian Rock phytosaur locality and vicinity. A, Overview of section just northeast of the phytosaur locality (NE1/4 SW1/4 sec. 24, T30S, R24E), showing Rock Point Formation (1), overlain by fluvial interval at base of Wingate Sandstone (2), capped by eolian interval of Wingate Sandstone (3). B–D, Close views of phytosaur locality showing Rock Point Formation (1), fluvial interval of Wingate (2), and eolian Wingate (3). In B, John Marzolf points upward to the surface on which the phytosaur skull and other bones are preserved. This surface is just above the number "2" in C. Note the sharp basal Wingate contact on the Rock Point in C and D. E, Arrow indicates lateral pinchout of surface on which phytosaurs are preserved. F, John Marzolf points to this pinchout surface about 50 m northeast of the phytosaur locality.

(1993) named *Redondasaurus* for the genus represented by these skulls, and recognized two species, *R. gregorii*, which lacked a rostral crest, and *R. bermani*, which possesses such a crest. Morales and Ash (1993, p. 358) first illustrated the specimen described in detail here, noting that it closely resembled either *Pseudopalatus* (*sensu* Ballew, 1989) or *Redondasaurus*. Long and Murry (1995) refused to recognize *Redondasaurus*, instead considering the type species, *R. gregorii*, a junior subjective synonym of *Pseudopalatus pristinus* Mehl (1928) and considered the skull pertaining to *R. bermani* conspecific with the type of their new genus *Arribasuchus buceros*.

We concur with Hunt and Lucas (1993) and differ from Long and Murry (1995) in recognizing the validity of *Redondasaurus*, and therefore assign the Big Indian Rock phytosaur to *Redondasaurus*. As shown in Figure 11, the supratemporal fenestrae are concealed in dorsal aspect. Long and Murry

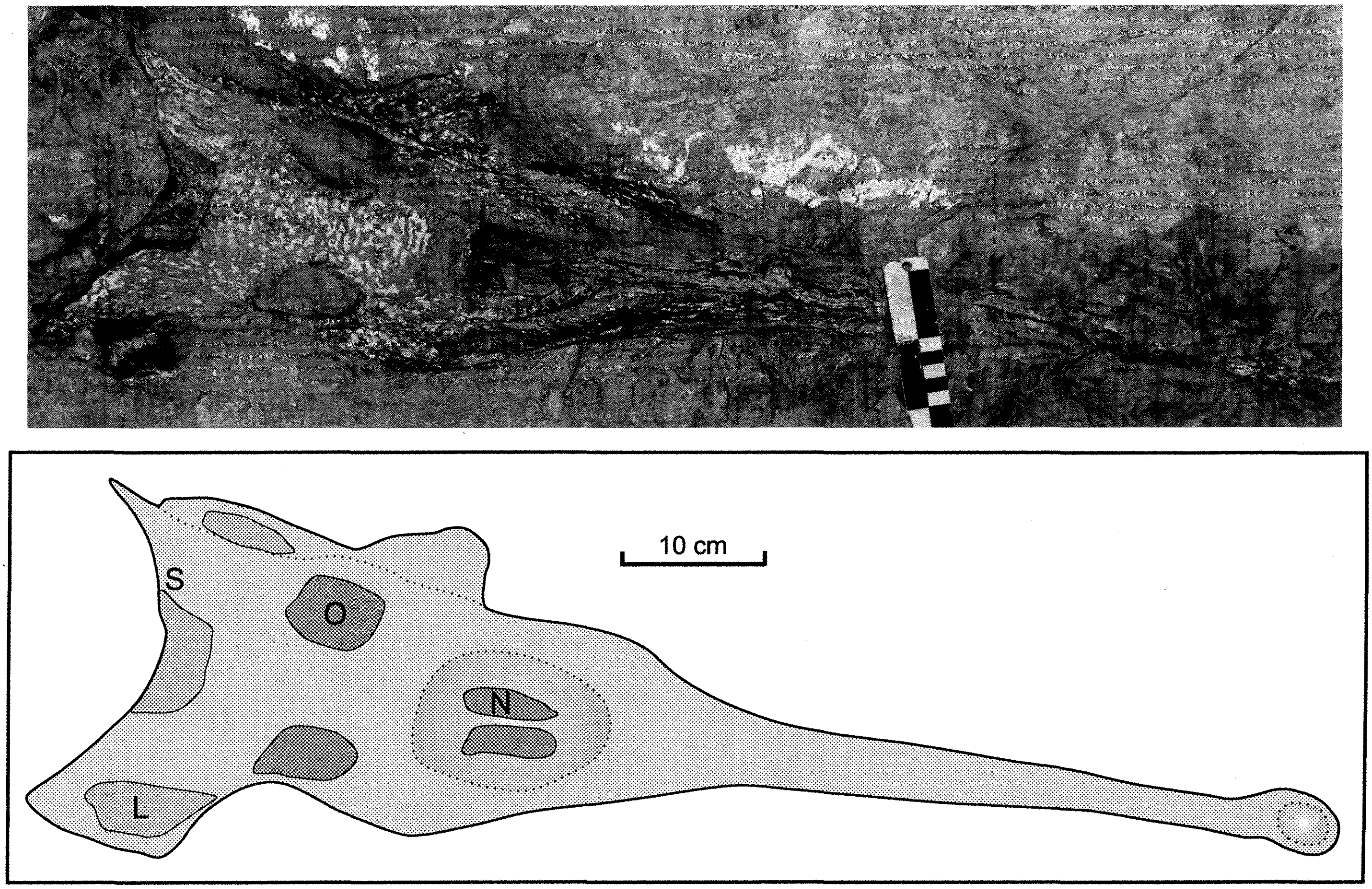

FIGURE 11. Natural mold of *in situ* skull of *Redondasaurus* at Big Indian Rock. Scale is in cm. Abbreviations: L = lateral temporal fenestra; N = nasal aperture; O = orbit; S = squamosal.

(1995, p. 53, 55) considered nearly concealed supratemporal fenestrae "typical of southwestern pseudopalatines" and thus considered specimens referred to *R. gregorii* by Hunt and Lucas (1993) to represent "poorly preserved *Pseudopalatus*." However, the supratemporal fenestra is clearly visible in the holotype of *Pseudopalatus pristinus*, as illustrated by both Mehl (1928, p. 8 and fig. 1B, p. 23, pl. 1A) and by Long and Murry (1995, p. 52, fig. 40B), yet cannot be discerned in dorsal aspect either in specimens of *R. gregorii* or *R. bermani* illustrated by Hunt and Lucas (1993, p. 194–195, figs. 1A, 1C, 2A, 2C) or in the skull illustrated here (Fig. 11). Furthermore, the supratemporal fenestrae of European pseudopalatines, such as *Nicrosaurus*, are even more completely exposed than those of *Pseudopalatus*, so the Big Indian Rock phytosaur cannot be assigned to any of the European taxa (Hunt, 1994). Numerous anatomical differences regarding the size and placement of the supratemporal fenestra, placement of the antorbital fenestra, and posterior skull morphology, particularly the length of the squamosals, preclude assigning the Big Indian Rock phytosaur to any other recognized phytosaur genera, including *Paleorhinus*, *Angistorhinus*, or *Rutiodon*. Consequently, we agree with Stovall and Savage (1939), Colbert and Gregory (1957), Gregory (1972), Hunt and Lucas (1993), and Morales and Ash (1990) and consider *Redondasaurus* a distinct genus, to which we assign the Big Indian Rock phytosaur.

Of the two species of *Redondasaurus* erected by Hunt and Lucas (1993), *R. gregorii* and *R. bermani*, the Big Indian Rock phytosaur most closely resembles *R. gregorii*. Hunt and Lucas (1993) noted that *R. gregorii* lacked a rostral crest, unlike the crested *R. bermani*. Most recent workers, including Ballew (1989), Hunt (1994) and Long and Murry (1995), have accepted the presence or absence of rostral crests as a valid species character. As observed in the field and illustrated by Morales and Ash (1993, p. 358, fig. 1), the Big Indian Rock phytosaur lacks a rostral crest so we assign it to *R. gregorii*.

Lucas and Hunt (1993) recognized *Redondasaurus* and the aetosaur *Redondasuchus* as index taxa of the Apachean lvf (Fig. 7), considered to be latest Triassic (Rhaetian) in age (Lucas and Hunt, 1993; Lucas, 1993, 1997; Lucas and Huber, 1998). Therefore, the occurrence of the phytosaur *Redondasaurus* at Big Indian Rock indicates a latest Triassic age for the fossiliferous strata (see following discussion).

Discussion

Pipiringos and O'Sullivan (1978) identified the J-0 unconformity as a regional break on the Colorado Plateau that separated Upper Triassic strata (Chinle Group) from Lower Jurassic strata (Glen Canyon Group). This gained wide acceptance until relatively recently when new stratigraphic and paleontologic studies suggested there may be a continuous Triassic-Jurassic transition preserved on the Colorado Plateau (Lucas et al., 1996, 1997). However, definitive data to support this suggestion have not yet been collected and analyzed, so we present only a preliminary discussion of the problem.

Near the Four Corners, in the Little Round Rock–Lukachukai area, the Rock Point Formation disconformably overlies the Owl Rock Formation. The Wingate Sandstone overlies the Rock Point; Harshbarger et al. (1957) viewed this contact as conformable, but most later workers (e.g. Stewart et al., 1972a; Pipiringos and O'Sullivan, 1978; Dubiel, 1989a, b; Lucas, 1993) considered it to be an unconformity (the J-0 unconformity). The Owl Rock–Rock Point–Wingate succession is also well established through much of southeastern Utah (Lucas, 1993).

However, west of the Four Corners in both northeastern Arizona and southwestern Utah, the Moenave Formation rests on the Owl Rock, and the Kayenta Formation overlies the Moenave (Harshbarger et al., 1957; Cooley et al., 1969; Blakey, 1994). Significantly, although the Moenave and the Rock Point Formation occupy the same stratigraphic position with

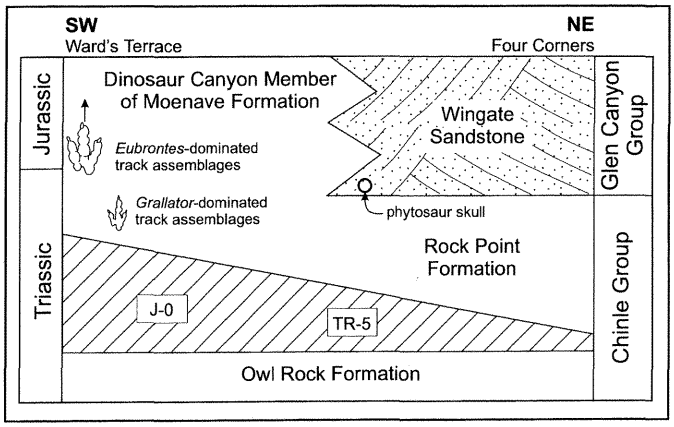

FIGURE 12. Stratigraphic and temporal relationships around the Triassic-Jurassic boundary on the Colorado Plateau.

respect to the Owl Rock, the Moenave has generally been considered younger (Early Jurassic) than the Upper Triassic Rock Point.

The Early Jurassic age of the Moenave rests on three lines of fossil evidence:

1. The primitive crocodylomorph *Protosuchus richardsoni* from the Dinosaur Canyon Member of the Moenave (Colbert and Mook, 1951) is correlated to other Liassic records of *Protosuchus* in the Newark Supergroup of Canada (Sues et al., 1996) and the upper Stormberg Group of South Africa (Kitching and Raath, 1984).

2. Theropod dinosaur footprints assigned to the ichnogenus *Eubrontes* occur in the Dinosaur Canyon Member (Irby, 1993a, b). *Eubrontes* is a characteristic Liassic tetrapod ichnogenus (Haubold, 1984).

3. Samples from the Whitmore Point Member of the Moenave Formation in southwestern Utah yield a *Corallina*-dominated palynoflora (Peterson and Pipiringos, 1979; Litwin, 1986). This type of palynoflora is generally considered to be of Liassic age.

However, it should be noted that these presumed Liassic indicators all are present in the upper part of the Dinosaur Canyon Member or in the Whitmore Point Member, which is younger than the Dinosaur Canyon Member. A *Grallator*-dominated footprint assemblage has been reported from the lower part of the Dinosaur Canyon Member ("Wingate Sandstone") (Morales, 1996) and suggests that this part of the Moenave may be of Triassic age.

The presence of a phytosaur skull in the basal Wingate Sandstone at Big Indian Rock indicates a Late Triassic age. Furthermore, the characteristic Late Triassic tetrapod ichnogenus *Brachychirotherium* occurs in lower Wingate equivalent strata of the Glen Canyon Group at Dinosaur National Monument in northeast Utah (Lockley et al., 1992). This provides further evidence that the lower part of the Wingate Sandstone is of Triassic age.

The Wingate and Moenave are laterally equivalent, at least in part, so the Triassic-Jurassic boundary must be within the intertongued Wingate–Moenave interval (Fig. 12). This means the Triassic-Jurassic boundary is not at the Wingate–Rock Point contact, identified by some previous workers as the J-0 unconformity between Upper Triassic and Lower Jurassic strata, but instead within the relatively continuously deposited Moenave–Wingate lithosome.

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APPENDIX 1: Descriptions of measured sections

1 - Kane Springs Canyon, Utah

Measured in the SE1/4 sec. 28, T26S, R21E, San Juan County, Utah. Strata are flat lying.

unit	lithology	thickness (m)
Glen Canyon Group:		
Wingate Sandstone:		
23	Sandstone; moderate reddish orange (10R6/6) fresh, weathers pale red (10R6/2); very fine-grained, subangular, well-sorted very-clean quartzarenite; not calcareous; trough crossbedded; scour base.	not measured

Unit	Lithology	Thickness (m)
Chinle Group:		
Rock Point Formation:		
22	Sandstone; pale red (10R6/2) to moderate orange pink (10R7/4); very fine- to fine-grained, subrounded, moderately well-sorted quartz-rich sublitharenite; some clay pellet rip-ups, up to 6 mm diameter as floaters; not calcareous; trough crossbedded.	2.0
21	Sandstone; moderate orange pink (10R7/4) fresh, weathers grayish red (10R4/2) to pale brown (5YR5/2); very fine-grained, subangular, well-sorted feldspathic quartzarenite; ripple laminated in trough crossbeds; scour base; slightly calcareous.	2.6
"Hite Bed"		
20	Sandstone; pale reddish brown (10R5/4) to moderate reddish orange (10R6/6); fine-grained, subangular, moderately well-sorted quartzarenite; not calcareous; ripples in very low-angle trough crossbeds; scour at base with up to 1.5 m relief; basal 15 cm is a conglomerate; some pebbly beds of very coarse-grained sandstone and conglomeratic sandstone; clasts are mudstone rip-ups.	9.0
unconformity (Tr-5 unconformity of Lucas, 1991)		
Petrified Forest Formation:		
Painted Desert Member:		
19	Silty mudstone and muddy siltstone interbedded with sandstone; mudstone is grayish red (10R4/2); bentonitic; not calcareous; sandstone is pale reddish brown (10R5/4) to pale red (10R6/2) with some grayish yellow green (5GY7/2) lenses; very fine- to medium-grained, subangular, moderately-sorted sublitharenite; micaceous; not calcareous; ripple laminated; some cover.	20.0
Moss Back Formation:		
18	Sandstone; light brownish gray (5YR6/1) to pale red (5R6/2); medium-grained, subrounded, lithic-rich sublitharenite; slightly micaceous; very calcareous; trough crossbedded and ripple-laminated; some lenses of conglomerate like units 16 and 17.	3.0
17	Sandstone (60–80%) and conglomerate; sandstone is light bluish gray (5B7/1) fresh, weathers medium gray (N5); fine-grained, subrounded, moderately well-sorted sublitharenite; calcareous; conglomerate is light gray (N7) fresh, weathers brownish gray (5YR4/1); locally clast-supported; clasts are largely intraformational limestone pebbles up to 10 mm diameter; matrix is identical to the sandstone in this unit; very calcareous; trough crossbeds.	2.5
16	Conglomerate (60–70%) and sandstone; pale green (5G7/2) fresh, weathers to grayish orange pink (5YR7/4); conglomerate is clast-supported with clasts up to 30 mm diameter; clasts are intraformational debris; very calcareous; sandstone is similar colors; fine- to medium-grained, subangular to subrounded, moderately-sorted muddy sublitharenite; calcareous; both are trough crossbedded.	3.0
unconformity (Tr-4 unconformity of Lucas, 1991)		
Cameron Formation:		
15	Sandstone; pale reddish brown (10R5/4); fine-grained, subrounded, feldspar-rich litharenite; calcareous; ripple laminated.	2.3
14	Sandstone; pale red (10R6/2) fresh, weathers grayish orange pink (5YR7/2); fine-grained, subangular, moderately well-sorted quartzarenite to subarkose; calcareous; trough crossbedded with some ripples.	3.3
Shinarump Formation:		
13	Sandstone and conglomeratic sandstone; greenish gray (5G6/1) fresh, weathers as dark as greenish gray (5G4/1), mostly coarse-grained, subrounded, moderately-sorted quartzarenite to sublitharenite; some fine-grained sandstones; conglomerate is similar with limestone clasts up to 8 mm long; trough crossbedded to ripple laminated; some carbonaceous plant debris; calcareous to very calcareous.	8.8
12	Sandy siltstone; pale green (5G7/2) to pale yellowish green (10GY7/2); calcareous; forms a notch.	1.0
11	Sandstone; very light gray (N8) to greenish gray (5GY6/1); very fine- to fine-grained, subrounded, well-sorted quartz-rich sublitharenite; calcareous; trough and wedge-planar crossbedded.	11.0
10	Sandstone; light greenish gray (5GY8/1 to 5G8/1); fine-grained, subrounded, moderately well-sorted quartzarenite; calcareous; laminar to very low-angle trough crossbeds; some mud pellet rip-ups at base; forms a prominent cliff.	4.5
9	Sandstone; very pale green (10G8/2); very fine-grained, subrounded to subangular, moderately well-sorted sublitharenite; micaceous; weakly calcareous; some trough crossbeds.	7.4
8	Conglomerate with some sandstone; brownish gray (5YR4/1) to greenish gray (5G6/1); clast-supported with limestone and siltstone lithics up to 35 mm diameter; sandstone is fine- to coarse-grained, subrounded, moderately poorly-sorted sublitharenite; very calcareous; some bone and wood fragments; trough crossbedded to ripple laminated; forms a ledge.	1.3
7	Mudstone; pale green (5G7/2); calcareous; some lenses of ripple laminated sandstone and conglomerate in upper half; sandstone and conglomerate are same color; sandstone is very fine-grained, subangular, well-sorted quartzarenite; very calcareous; conglomerate is mud pellet and limestone rip-ups up to 10 mm diameter; clast-supported, very calcareous; coarse-grained units form ledges.	9.0
6	Sandstone; pale green (5G7/2) fresh, weathers to darker shades of green; fine-grained, subangular to angular, well-sorted, slightly micaceous quartzarenite; calcareous; some 0.15–0.30-m-thick lenses of limestone pebble conglomerate that are similar color; clast-supported; clasts up to 8–10 mm diameter; very calcareous; ripple laminated.	3.9
5	Sandstone; pale red (5R6/2); fine-grained, subangular, well-sorted arkosic sublitharenite; calcareous; massive to ripple laminated.	5.3
4	Sandstone; grayish orange pink (10R8/2) fresh, weathers pale red (10R6/2); same lithology as unit 5; planar to planar crossbedded.	3.0
3	Sandstone; pale red (5R6/2) to pale brown (5YR5/2); very fine- to fine-grained, subrounded, well-sorted sublitharenite; slightly calcareous; small trough crossbeds and ripples.	2.7
2	Conglomerate and sandstone; pale green (5G7/2) fresh, weathers light olive gray (5Y5/2) and olive gray (5Y4/1); clast-supported; cobbles of extraformational limestone, quartzite, and chert; very calcareous; some grayish yellow (5Y8/4) to grayish red (10R4/2) petrified wood.	1.8
angular unconformity (Tr-3 unconformity of Pipiringos and O'Sullivan)		
Chinle Group dips 10° to N30°W		
Moenkopi Formation dips 23° to N30°E		
1	Sandstone; pale red (5R6/2) with light greenish gray (5GY8/1 to 5G8/1) bleach out in top 0.3 m; fine- to medium-grained, subrounded, well-sorted lithic-rich sublitharenite; bleach-out is fine- to medium-grained, subrounded, well-sorted quartzarenite; all are calcareous; trough crossbedded.	not measured

2 - Upheaval Dome, Utah

Measured in the N1/2 SW1/4 sec. 21, T27S, R18E, San Juan County, Utah. Strata dip 20° to N60°E

unit	lithology	thickness (m)
Glen Canyon Group:		
Wingate Formation:		
40	Sandstone; moderate reddish orange (10R5/4) to pale reddish brown (10R6/6); very fine- to fine-grained, subangular, well-sorted quartzarenite; not calcareous; trough crossbedded; forms a cliff.	not measured
Chinle Group:		
Rock Point Formation (upper):		
39	Conglomerate; mostly pale reddish brown (10R5/4) with moderate pink (5R7/4) matrix; clasts are mud pellets up to 30 mm long axis, most are less than 10 mm diameter; sandstone matrix is moderately poorly sorted, fine- to medium-grained, subangular, sublitharenite; very slightly calcareous.	0.4
38	Sandstone; pale reddish brown (10R5/4); fine-grained, subangular, moderately well-sorted sublitharenite; significant mud clasts in coarser strands; slightly micaceous; not calcareous; trough crossbedded; much like unit 36.	1.3
37	Conglomerate; same colors and lithologies as unit 39.	0.4
36	Sandstone; moderate reddish brown (10R6/6) with darker mud-rich bands of pale reddish brown (10R5/4); very fine- to fine-grained, subangular, moderately sorted sublitharenite; somewhat muddy; not calcareous; trough crossbedded; some mud balls.	1.5
35	Sandstone; pale reddish brown (10R5/4); very fine-grained, subangular, well-sorted sublitharenite; not calcareous; ripple laminated; forms a sandstone cliff.	2.5
34	Sandstone; same colors and lithology as unit 35; flaggy; trough crossbedded; forms a notch in cliffs.	1.3
33	Sandstone; light greenish gray (5GY8/1 and 5G8/1) fresh, weathers pale reddish brown (10R5/4); medium- to coarse-grained, subrounded, moderately sorted litharenite; many clay clasts; calcareous; scours into unit 32; locally conglomeratic; grades upward into finer-grained lithologies.	1.2
Hite Bed:		
32	Sandstone; bluish white (5B9/1) fresh, weathers to light greenish gray (5G8/1) on bedding planes and stained moderate reddish orange (10R6/6) to pale reddish brown (10R5/4) on face; not calcareous; planar and trough crossbedded; *Grallator* track horizon.	0.6
Rock Point Formation (lower):		
31	Siltstone; same color and lithology as unit 29.	13.5
30	Sandstone; moderate orange pink (5YR8/4) fresh, weathers to pale reddish brown (10R5/4); very fine-grained, subangular to subrounded, moderately well-sorted silty quartzarenite; weakly calcareous; laminated to ripple laminated; forms a cliff.	6.0
29	Siltstone and very fine sandstone; pale reddish brown (10R5/4); some yellowish gray (5Y8/1) spots up to 3 cm diameter; calcareous; some lenses of ripple-laminated sandstone of typical Rock Point Formation lithology; forms a slope.	8.9
28	Sandstone and conglomerate; light greenish gray (5GY8/1) or moderate reddish orange (10R6/6) fresh, weathers pale reddish brown (10R5/4) and moderate red (5R5/4); conglomerate is pebbles of mudstone rip-ups; sandstone is very fine- to fine-grained, subangular to subrounded, moderately well-sorted quartzarenite; calcareous; trough to tabular crossbedded; some bioturbation, siltstone interbedded in middle of unit.	2.3

Unit	Lithology	Thickness (m)
27	Siltstone and sandstone; same colors and lithologies as unit 25.	5.2
26	Sandstone; pale reddish brown (10R5/4); very fine- to fine-grained, subangular to subrounded, moderately well-sorted quartzarenite; calcareous; massive; forms a ledge.	0.6
25	Siltstone and sandstone; pale reddish brown (10R5/4) and moderate reddish orange (10R6/6) with some grayish orange pink (10R8/2); sandstones are very fine- to fine-grained, subrounded, moderately well-sorted quartzarenites; calcareous.	19.2
unconformity (Tr-5 unconformity of Lucas, 1991)		
Owl Rock Formation:		
24	Siltstone; pale red (5R6/2); very calcareous; forms a slope.	8.0
23	Siltstone; light greenish gray (5GY8/1) to pale red (5R6/2); bio- and pedoturbated; forms a ledge.	0.3
Petrified Forest Formation:		
Painted Desert Member:		
22	Siltstone with minor sandstone; moderate reddish brown (10R4/6), light greenish gray (5GY8/1) and grayish red (5R4/2); slightly calcareous; sandstones are very fine-grained, subrounded, moderately sorted sublitharenites; some coarse stringers of mud pebble rip-ups; weakly calcareous.	14.2
Moss Back Formation:		
21	Sandstone; moderate red (5R5/4) to grayish red (10R4/2); fine-grained, subrounded, moderately sorted litharenite; some feldspar; trough crossbedded; some mudstone interbeds.	1.9
20	Sandstone and conglomeratic sandstone; pale olive (10Y6/2) and pale red (5R6/2) fresh, weathers grayish red (5R4/2); fine- to medium-grained, subrounded, moderately sorted sublitharenite; most clasts are intraformational mudstone; lots of muddy lithics; very calcareous.	2.3
19	Siltstone; pale red (5R6/2); weakly calcareous; forms a slope.	1.9
18	Sandstone; greenish gray (5G6/1) with pale red (5R6/2) to dark reddish brown (10R3/4) bands; fine-grained, subrounded, moderately well-sorted sublitharenite; calcareous; ripples and small troughs; some possible analcime.	1.0
17	Conglomerate; greenish gray (5G6/1) and lighter intraformational clasts up to 25 cm diameter; some recrystallized unionid bivalves; sandstone and limestone rip-rips; rounded; clast supported; calcareous; some trough crossbeds.	0.5
unconformity (Tr-4 unconformity of Lucas, 1991)		
Cameron Formation:		
16	Mudstone; bleach-out; pale greenish yellow (10Y8/2); some darker mudstone is pale green (10R6/2); bentonitic; very calcareous.	0.8
15	Pisolitic calcrete; pale yellowish green (10GY7/2); very calcareous; forms a ledge.	1.0
14	Silty mudstone; grayish blue (5PB5/2); bentonitic; calcareous; abundant light greenish gray (5G8/1) to grayish yellow green (5GY7/2) calcrete nodules up to 80 cm long.	4.2
13	Calcrete; very light gray (N8) fresh, weathers greenish gray (5GY6/1); forms a ledge. Lungfish and reptile site.	0.7
12	Calcrete; grayish green (5G5/2), greenish gray (5G6/1) and lighter shades of grays and greens; heavily burrowed.	1.2
11	Mudstone; grayish red purple (5RP4/2) with light greenish gray (5G8/1) reduction spots; slightly silty; weakly calcareous.	10.3

Unit	Lithology	Thickness (m)
10	Mudstone and sandstone; pale red (10R6/7) to pale reddish brown (10R5/4); slightly silty; weakly calcareous; sandstones are very fine-grained, subangular to subrounded, well-sorted sublitharenites and litharenites; micaceous; calcareous.	9.0
Shinarump Formation:		
9	Sandstone; similar colors and lithologies to underlying units; shallow trough crossbeds.	2.3
8	Sandstone; grayish orange pink (5YR7/2) to light brownish gray (5YR6/1); fine- to medium-grained, subrounded, moderately well-sorted quartzarenite; calcareous; some pebbly conglomeratic lenses that are slightly richer in lithics; trough crossbeds.	1.5
7	Sandstone and conglomeratic sandstone; yellowish gray (5Y8/1) fresh, weathers light brownish gray (5YR6/1); very coarse-grained to pebble conglomerate; poorly sorted; clasts are rich in chert d quartzite pebbles with some limestone clasts and minor lithics; very calcareous; trough crossbedded.	3.8
6	Sandstone; yellowish gray (5Y8/1) fresh, weathers pale reddish brown (10R5/4) and brownish gray (5YR4/1); fine- to medium-grained, subrounded, moderately sorted quartzarenite; very calcareous; trough crossbedded.	2.1
5	Shale; pale blue (5B6/2) to light olive gray (5Y6/1); slightly calcareous; forms a green slope.	1.6
4	Sandstone; yellowish gray (5Y8/1) to light greenish gray (5GY8/1) fresh; weathers light brownish gray (5YR6/1) to grayish olive (10Y4/2); medium-grained, subrounded, moderately well-sorted quartzarenite; very calcareous; trough crossbedded to laminated; some black chert floaters.	2.2
3	Sandstone and conglomeratic sandstone; yellowish gray (5Y8/1) with some medium gray (N5) bands fresh; weathers greenish gray (5GY6/1); fine- to medium-grained, subangular to subrounded, moderately well-sorted quartzarenite; very calcareous; pebbles are chert, quartzite and limestone; trough crossbedded.	1.3
2	Conglomerate; yellowish gray (5Y8/1) fresh, weathers as dark as medium gray (N5); clast-supported, with extrabasinal chert, quartzite, and Paleozoic limestone common, some Moenkopi Formation rip-up clasts; calcareous; crude ripples to small trough crossbeds.	1.2
unconformity (Tr-3 unconformity of Pipiringos and O'Sullivan)		
Moenkopi Formation:		
1	Siltstone; yellowish gray (5Y7/2); nodular to laminar; calcareous.	not measured

3 - Type Sonsela Member, Arizona

Section measured in the SW1/4 SE1/4 sec. 15, T5N, R6W, Apache County, Arizona. Strata are flat-lying. This is the type section of the Sonsela Member of Akers et al. (1958)

unit	lithology	thickness (m)
Chinle Group:		
Petrified Forest Formation:		
Painted Desert Member:		
10	Mudstone and sandstone; mudstone is medium light gray (N6) to medium gray (N5); bentonitic; calcareous; sandstone interbeds are grayish pink (5R8/2) fresh, weathering to grayish red (5R4/2); very fine- to medium-grained, subangular, subarkose; some mud pellets up to 1 cm diameter; calcareous.	3.1+
Sonsela Member:		
9	Sandstone; grayish pink (5R8/2) fresh, weathers grayish red (10R4/2); medium- to coarse-grained, subrounded, moderately well-sorted subarkose; planar rossbedded; calcareous.	1.5
8	Conglomeratic sandstone; very pale blue (5B8/2) to white (N9) fresh, weathers medium light gray (N6); medium- to very coarse-grained with some chert pebbles up to 1 cm in diameter; subangular to subrounded, moderately well-sorted subarkose; some clay pellets; fills scours in top of unit 7; calcareous.	1.3
7	Sandstone; pinkish gray (5YR8/1) fresh, weathers light greenish gray (5GY8/1); fine- to medium-grained, moderately well-sorted subarkose; small scale (0.3-m-thick) trough crossbeds, calcareous; forms a cliff.	3.0
6	Sandstone; yellowish gray (5Y8/1) to light greenish gray (5GY8/1) fresh, weathers as dark as medium gray (N5); fine- to coarse-grained, subangular to subrounded, moderately sorted subarkose; no conglomeratic clasts; ledgy; slightly calcareous.	3.8
5	Sandstone; yellowish gray (5Y8/1) fresh, weathers dark medium gray (N4); fine- to medium-grained, subrounded, moderately well-sorted, slightly micaceous sublitharenite; some jasper and quartzite floaters; planar bedded with some very low-angle crossbeds; scours up to 0.7 m; calcareous.	3.1
4	Very coarse sandstone to conglomerate; light greenish gray (5GY6/1) fresh, weathers as dark as medium gray (N5); mudstone rip-ups and calcrete nodules dominate the intraformational conglomerate; sandstone fraction is coarse- to very coarse-grained, subangular, moderately well-sorted litharenite; much scour and fill; some crude trough crossbeds.	0.3
unconformity (Tr-4 unconformity of Lucas, 1991)		
Blue Mesa Member:		
3	Mudstone; grayish blue (5PB5/2); bentonitic; slightly silty; calcareous. In the middle of the unit is a very light gray (N8) silty mudstone; bentonitic; slightly calcareous.	14.5
2	Mudstone; same colors and lithologies as unit 1 except much slump and cover.	4.3
1	Mudstone; grayish blue (5PB5/2); bentonitic; calcareous; crops out at bottom of gully.	2.5

4 - Type Moss Back, Utah

Measured in the SE1/4 SE1/4 sec. 9, T37S, R16E, San Juan County, Utah.

unit	lithology	thickness (m)
Chinle Group:		
Petrified Forest Formation:		
Painted Desert Member:		
9	Siltstone; light greenish gray (5G8/1); ripple laminated; many sand-sized micas; calcareous.	not measured
Moss Back Formation:		
8	Sandstone; light greenish gray (5GY8/1) fresh with a grayish yellow green (5GY7/2) weathered crust; coarse-grained, subangular, moderately well-sorted quartzarenite; calcareous; planar crossbedded to ow-angle trough crossbedded.	2.7
7	Conglomerate and conglomeratic sandstone; light greenish gray (5GY8/1) with "salt and pepper" clasts fresh, weathers grayish yellow green (5GY7/2) to pale yellowish brown (10YR6/2); sandstone is medium- to very coarse-grained, subangular to angular, poorly sorted sublitharenite; conglomerate clasts are primarily light-colored intraformational mudstone rip-up clasts; very calcareous; trough crossbedded.	1.2
6	Sandstone; light greenish gray (5G8/1) fresh, weathers pale yellowish brown (10YR6/2), fine- to medium-grained, subangular, moderately well-sorted	

Unit	Lithology	Thickness (m)
	quartzarenite; some minor conglomerate pebbles; not calcareous; trough crossbedded; friable.	2.7
5	Conglomerate; light olive gray (5Y6/1) and grayish orange pink (5YR7/2); clasts are 2–10 mm in diameter with occasional larger clasts; very calcareous; clast-supported; most clasts are mudstone rip-ups or calcrete nodules, with some quartzite and angular jaspers included; trough crossbedded.	2.1
4	Sandstone; light greenish gray (5GY8/1) fresh, stained pale reddish brown (10R5/4); medium-grained, subrounded, moderately well-sorted quartzarenite; some 0.6–1.2-m-thick lenses of coarser sandstone and conglomerates; slightly calcareous; planar and trough crossbedded; forms a cliff.	5.4
3	Conglomerate; matrix is very light gray (N8) with dark gray (N3), brownish gray (5YR4/1) and dark reddish brown (10R3/4) clasts; matrix-supported; many siliceous pebbles and extrabasinal clasts; matrix is a fine-grained quartzarenite; calcareous; some clasts are fragments of petrified wood; much scour and fill accounts for thickness variations that range from 0.6–3.0 m.	2.1
2	Conglomerate and sandstone; conglomerate is dark greenish gray (5GY4/1); clasts are primarily quartzite pebbles with some intraformational calcrete nodules up to 5 cm in diameter, well-rounded; clast-supported; very calcareous; sandstone is light greenish gray (5GY8/1), coarse grained to conglomeratic, well-indurated, very calcareous; trough-crossbedded, much cut and fill; some soft sediment deformation and carbonized wood.	2.7
Monitor Butte Member:		
1	Clayey sandstone; pale green (10G6/2); very fine-grained, moderately well-sorted litharenite; micaceous; not calcareous; laminated.	not measured

5 - Type Owl Rock, Arizona

Measured at Owl Rock, NW1/4 sec. 1, T39N, R15E, Navajo County, Arizona. Strata dip 15° to S60°E.

unit	lithology	thickness (m)
Chinle Group:		
Rock Point Formation:		
18	Siltstone; moderate reddish orange (10R6/6); calcareous.	not measured
unconformity (Tr-5 unconformity of Lucas, 1991)		
Owl Rock Formation:		
17	Calcrete; light greenish gray (5G8/1) with some grayish red purple (5RP4/2) spots; upper 0.3 m cherty; nodular.	0.9–1.8
16	Calcrete; light greenish gray (5G8/1) with some moderate red (5R5/4) mottles; very calcareous; nodular.	0.9
15	Siltstone; same colors and lithology as unit 10.	2.7
14	Calcrete; very pale green (10G8/2) and pinkish gray (5YR8/1); much aggregation of sand-sized grains; very calcareous.	0.3
13	Interbedded sandstone and siltstone; sandstone is moderate pink (5R7/4) and pale red purple (5RP6/2) with spots and mottles of light greenish gray (5G8/1); very fine-grained, micaceous, silty quartzarenite; ripple laminated to trough crossbedded; calcareous; forms several ledges; siltstone is pale reddish brown (10R5/4) to moderate reddish orange (10R6/6); forms notches between sandstone ledges; very calcareous.	3.7
12	Sandstone and siltstone; sandstone is moderate orange pink (10R7/4); very fine-grained, muddy quartzarenite to quartzwacke; calcareous; siltstone is moderate reddish orange (10R6/6) to pale reddish brown; calcareous.	8.2
11	Pisolitic limestone/calcrete; mottled light greenish gray (5G8/1), pale red purple (5RP4/2) and moderate reddish orange (10R6/6); generally calcareous, although some (?cherty) mottles/nodules not calcareous; four consecutive ledges 0.3–0.9 m thick.	2.7
10	Siltstone with interbeds of sandstone and mudstone; moderate pink (5R7/4); slightly calcareous; poorly indurated; calcareous; sandstone is pale green (5G7/2); very fine-grained, well-sorted quartzarenite; not calcareous; mudstone is moderate red (5R5/4); calcareous.	4.6
9	Calcrete; same colors and lithologies as unit 8; forms a blocky ledge.	0.7
8	Calcrete; mottled light greenish gray (5G8/1), greenish gray (5GY6/1) and moderate red (5R5/4); pisolitic; calcareous.	0.5
7	Calcrete; mottled light greenish gray (5GY8/1), grayish orange pink (10R8/2) and pale red purple (5RP6/2); nodular; calcareous.	0.9
6	Siltstone; same colors and lithologies as unit 4.	5.8
5	Mudstone; pale red (10R6/2) to pale reddish brown (10R5/4); calcareous; some lenses of conglomerate; moderate red (5R5/4) with clast-supported mudstone and calcrete rip-ups; calcretes are light bluish gray (5B7/1) and light greenish gray (5G8/1); mudstone rip-ups are moderate red (5R5/4); calcareous.	2.1
4	Siltstone; moderate orange pink (10R7/4); hematitic; calcareous; forms a slope.	4.6
3	Calcrete; mottled light greenish gray (5GY8/1); pale green (5G7/2 and 10G6/2), medium gray (N5) and pale red (10R6/2); calcareous; pisolitic; cherty.	1.5
2	Siltstone and calcrete nodules in matrix of unit 1 lithologies; grayish orange pink (10R8/2) with some light greenish (5GY8/1) mottles; calcareous; udstone matrix is pale red (10R6/2).	1.4
Petrified Forest Formation:		
Painted Desert Member:		
1	Mudstone with lenses of sandstone; mudstone is moderate red (5R5/4) to pâle reddish brown (10R5/4); bentonitic; calcareous; sandstone is light greenish gray (5GY8/1); very fine-grained, subrounded, moderately well-sorted micaceous quartzarenite; calcareous.	not measured

6 - Type Rock Point, Arizona

Measured on the southeast end of Little Round Rock, NW1/4, SE1/4 sec. 16, T36N, R26E, Apache County, Arizona.

unit	lithology	thickness (m)
Glen Canyon Group:		
Wingate Formation:		
30	Sandstone; moderate orange pink (10R7/4) fresh, weathers moderate reddish orange (10R6/6); fine-grained, subangular, well-sorted quartzarenite; minor white clayey clasts; trough crossbedded; calcareous.	not measured
Rock Point Formation:		
29	Sandstone; moderate reddish orange (10R6/6); very fine-grained, subangular to subrounded, moderately well-sorted, sublitharenite; silty; flaggy; bioturbated; calcareous; siltstone is pale reddish brown (10R5/4); not calcareous.	2.1

Unit	Lithology	Thickness (m)
28	Silty sandstone; moderate orange pink (10R7/4) to moderate reddish orange (10R6/6) when fresh, weathers to moderate reddish orange (10R6/6); very fine-grained, subangular, moderately sorted quartzarenite; forms a massive ledge; bioturbated; not calcareous.	5.8
27	Siltstone; same color and lithology as unit 13.	0.9
26	Sandstone; same color and lithology as unit 18.	0.8
25	Siltstone; same color and lithology as unit 13.	0.6
24	Sandstone; same color and lithology as unit 18.	3.0
23	Siltstone; same color and lithology as unit 13.	4.6
22	Sandstone; same color and lithology as unit 18.	3.0
21	Siltstone; same color and lithology as unit 13.	1.8
20	Sandstone; same color and lithology as unit 18.	1.7
19	Siltstone; same color and lithology as unit 13.	1.5
18	Sandstone; moderate reddish orange (10R6/6) to pale reddish brown (10R5/4); some light greenish gray (5GY8/1) reduction spots; fine-grained, subrounded, moderately well-sorted, slightly silty quartzarenite; calcareous; bioturbated; forms a massive ledge; some flaggy sandstone interbeds.	1.8
17	Siltstone; same color and lithology as unit 13; forms a slope.	4.0
16	Sandstone; same color lithology as unit 14; upper portion heavily bioturbated; forms a ledge.	4.9
15	Siltstone; same color and lithology as unit 13.	3.7
14	Sandstone; moderate reddish orange (10R6/6) fresh, weathers pale reddish brown (10R5/4); very fine-grained, subangular to subrounded, moderately well-sorted sublitharenite; calcareous; massive; scour base 0.3 m into underlying unit.	3.7
13	Siltstone with occasional sandstone interbeds; siltstone is pale reddish brown (10R5/4); calcareous; sandstone ledges every 1.5–3.0 m are thin (0.6 m), similar to unit 10 lithologies, typically moderate reddish orange (10R6/6) with rare light greenish gray (5G8/1) spots; fine-grained, subangular, quartzarenites; calcareous.	21.9
12	Sandstone; moderate reddish orange (10R6/6) to pale reddish brown (10R5/4); fine-grained, subangular, moderately well-sorted sublitharenite; calcareous; aminar; some reduction spots.	3.0
11	Siltstone; same color and lithology as unit 9; some 0.6–1.5 m lenses of unit 10 lithology; a ledge of unit 10 lithology may also be present halfway up.	11.6
10	Sandstone; moderate reddish orange (10R6/6); very fine- to fine-grained, subangular, moderately well-sorted quartzarenite; calcareous; blocky to massive with some crude trough crossbeds; some flat beds at top of unit.	3.0
9	Siltstone; pale reddish brown (10R3/4); some yellowish gray (5Y7/2) "smiles"; calcareous.	5.5
8	Sandstone; moderate reddish orange (10R6/6) to pale reddish brown (10R5/4); very fine- to fine-grained, subangular, moderately sorted quartzarenite; calcareous; ripple laminated to trough crossbedded and massive.	1.5
7	Siltstone; same color and lithology as unit 5; forms a slope.	4.3
6	Sandstone; moderate reddish orange (10R6/6) to pale reddish brown (10R5/4); very fine- to fine-grained, subangular to subrounded, moderately well-sorted sublitharenite to quartzarenite; calcareous; first prominent ledge at base of butte; trough crossbedded; ripples; massive; some desiccation cracks.	2.7
5	Siltstone; moderate reddish orange (10R6/6) to pale reddish brown (10R5/4); some light greenish gray (5GY8/1) reduction spots; bioturbated to nodular; forms a slope; calcareous.	4.6
4	Sandstone; pale reddish brown (10R5/4); some light greenish gray (5GY8/1) spots and mottles; fine-grained, subangular, moderately poorly sorted sublitharenite; many clasts are mud chips; weakly calcareous.	0.3
3	Siltstone; pale reddish brown (10R5/4); bioturbated; calcareous; some pale red (10R6/2) burrow casts that are cylindrical, 1 cm diameter, 3–4 cm long; *Skolithos* ichnofacies.	5.8
unconformity (Tr-5 unconformity of Lucas, 1991)		
Owl Rock Formation:		
2	Calcrete ledge; yellowish gray (5Y8/1) to light olive gray (5Y6/1) with some pale reddish brown (10R5/4) stains; nodular; weakly calcareous.	0.3-0.6
1	Siltstone; moderate reddish brown (10R4/6) with light greenish gray (5GY8/1) to yellowish gray (5Y7/2) reduction spots; not calcareous.	not measured

7 - Type Church Rock, Arizona

Measured on Comb Ridge, SE1/4 sec. 21, T39N, R16E, Navajo County, Arizona. Strata dip 15° to S60°E.

unit	lithology	thickness (m)
Glen Canyon Group:		
Wingate Sandstone:		
16	Sandstone; moderate orange pink (10R7/4); very fine- to fine-grained, rounded, very well-sorted quartzarenite; trough crossbedded; slightly calcareous; forms a cliff.	not measured
Chinle Group:		
Rock Point Formation:		
Hite Bed:		
15	Mudstone; moderate red (5R5/4); very silty to sandy; calcareous.	4.9
14	Sandstone; moderate red (5R5/4) to pale reddish brown (10R5/4); fine- to medium-grained, subangular to subrounded, moderately well-sorted sublitharenite; some small-scale trough crossbeds and ripples; forms a ledge; calcareous.	3.3
13	Sandstone; moderate reddish orange (10R6/6) to moderate red (5R5/4), fine- to coarse-grained, subangular, moderately poorly sorted sublitharenite; trough crossbedded in stacked sets; slightly calcareous.	7.3
12	Siltstone; same colors and lithologies as unit 10.	1.1
Rock Point Formation (lower):		
11	Sandstone; same colors and lithologies as unit 7.	0.5
10	Siltstone; pale reddish brown (10R5/4); calcareous; with gypsum layer that is grayish orange pink (10R8/2).	16.2
9	Sandstone and siltstone; interbeds of unit 6 and 7 lithologies.	12.2
8	Siltstone; same color and lithology as unit 6 but with some grayish yellow green (5GY7/2) streaks in sandier bands.	11.3
7	Sandstone; moderate reddish orange (10R6/6); very fine-grained, subangular to subrounded, moderately well-sorted sublitharenite; ripple-laminated to massive, calcareous.	0.9
6	Siltstone; moderate reddish orange (10R6/6) to pale reddish brown (10R5/4); massive; slightly silty; very calcareous.	5.8
5	Sandstone; pale reddish brown (10R5/4) to moderate reddish orange (10R6/6); some light greenish gray (5GY8/1) reduction spots; very fine- to fine-grained, subangular, well-sorted sublitharenite; massive; alcareous; forms a ledge.	2.1
4	Siltstone interbedded with sandstone ledges; siltstones are moderate orange pink (10R7/4) to pale reddish brown (10R5/4); slightly sandy; very calcareous; sandstones are similar colors with more moderate reddish orange (10R6/6); very fine- to fine-grained, subangular to subrounded, moderately well-sorted sublitharenite; ripple-laminated; calcareous.	16.5

Unit	Lithology	Thickness (m)
3	Sandstone; moderate pink (5R7/4) to pale reddish brown (10R5/4); very fine- to fine-grained, subrounded, well-sorted quartzarenite; laminar with some bioturbation; upper 0.3 m is grayish orange pink (10R8/2) fresh, weathers to pale reddish brown (10R5/4); very fine-grained, subangular to subrounded, well-sorted sublitharenite; ripple-laminated; calcareous.	1.2
unconformity (Tr-5 unconformity of Lucas, 1991)		
Owl Rock Formation:		
2	Siltstone and limestone; moderate orange pink (10R7/4) to pale reddish brown (10R5/4); limestone is nodular and pedogenic; with much light greenish gray (5GY8/1) to white (N9) mottles; calcareous.	0.9
1	Pisolitic limestone; moderate orange pink (10R7/4), moderate reddish orange (10R6/6) and light bluish gray (5B7/1); brecciated; nodular; well-indurated; very calcareous.	not measured

8 - Big Indian Rock, Utah

Measured at the Big Indian Rock phytosaur locality, UTM 4224540N, 653900E, zone 12 (SW1/4 SW1/4 sec. 24, T30S, R24E, San Juan County, Utah). Strata are essentially flat-lying.

unit	lithology	thickness (m)
Glen Canyon Group:		
Wingate Sandstone:		
7	Sandstone; pinkish gray (5YR8/1) with moderate orange pink (10R7/4) hematitic stains; quartzose, very fine grained; subrounded, well sorted; not calcareous; ripple-laminated to laminated; forms a cliff.	not measured
6	Sandstone; very pale orange (10YR8/2) and moderate reddish orange (10R6/6); quartzose; very fine grained, subangular, well sorted; not calcareous; small trough crossbeds and ripple laminates.	0.4
5	Sandstone and conglomerate; sandstone is pale reddish brown (10R5/4) and lithologically identical to unit 6; conglomerate has matrix of this sandstone with bones, teeth and muddy siltstone rip-ups as clasts; bones/teeth are mostly white (N9), whereas siltstone clasts are grayish red (5R4/2); not calcareous; trough crossbedded; unit is lenticular, pinching out laterally between units 4 and 6.	0.2–0.3
4	Sandstone; pale reddish brown (10R5/4); lithic quartzarenite; very fine grained; subangular; well sorted; not calcareous; trough crossbeds and climbing ripple laminations; forms a cliff.	0.6
3	Sandstone; same color and lithology as unit 4; base has rip-ups of siltstone that is mottled pale yellowish green (10GY7/2) and pale reddish brown (10R5/4); not calcareous; trough crossbedded; forms a cliff.	0.8
Chinle Group:		
Rock Point Formation:		
2	Siltstone with limestone nodules; siltstone is moderate red (5R5/4), sandy, and not calcareous; limestone nodules are mottled light brownish gray (5YR6/1) and pale reddish brown (10R5/4).	0.5
1	Siltstone; grayish red (5R4/2); not calcareous; blocky and bioturbated; forms a slope.	not measured

9 - Bedrock, Colorado

Measured in the SE1/4 NW1/4 sec. 2, T47N, R14W, Montrose County, Colorado. Strata dip 3° to due east.

unit	lithology	thickness (m)
Glen Canyon Group:		
Wingate Sandstone:		
43	Sandstone; pale reddish brown (10R5/4) to moderate reddish orange (10R6/6); very fine-grained, subrounded, well-sorted quartzarenite; trough crossbedded; very weakly calcareous.	not measured
Chinle Group:		
Rock Point Formation:		
42	Sandstone; moderate orange pink (10R7/4) fresh, weathers to medium gray (N5) and brownish gray (5YR4/1); very fine-grained, subrounded, well-sorted quartzarenite; not calcareous; laminated to ripple laminated.	0.8
41	Silty sandstone; pale reddish brown (10R5/4); very fine-grained, subrounded, moderately well-sorted quartzarenite; not calcareous; ripple laminated; top 1–3 cm is a grayish red (10R4/2) clayey siltstone; not calcareous.	1.6
40	Sandstone; moderate reddish orange (10R6/6); weathers to pale reddish brown (10R5/4); very fine-grained, subrounded, well-sorted very clean quartzarenite; not calcareous; ripple laminated to assive; forms a ledge.	1.2
39	Siltstone; pale reddish brown (10R5/4) fresh, weathers as light as pinkish gray (5YR8/1); slightly sandy; forms a hackly slope with massive cliffs where well-exposed; not calcareous.	10.0
38	Sandstone; pale reddish brown (10R5/4); very fine-grained, sometimes coarser; subrounded, moderately well-sorted quartzarenite; very slightly micaceous; not calcareous; ripple laminated in trough crossbeds; upper half massive and bioturbated; orms a cliff.	10.5
37	Sandy siltstone; pale reddish brown (10R5/4); not calcareous; forms a notch.	0.3
36	Sandstone; moderate reddish orange (10R6/6) with spots of yellowish gray (5Y8/1); very fine- to fine-grained, subangular, moderately well-sorted, lean quartzarenite; not calcareous; forms a ledge; massive with some scours.	2.9
35	Siltstone; pale reddish brown (10R5/4); not calcareous; forms a hackly slope.	4.6
34	Sandstone; pale reddish brown (10R5/4) to moderate reddish orange (10R6/6); very fine- to fine-grained, subrounded, moderately well-sorted quartzarenite; not calcareous; trough crossbedded; forms a ledge.	1.8
33	Siltstone; same color and lithology as unit 31.	7.5
32	Sandstone; moderate reddish orange (10R6/6) to moderate orange pink (10R7/4); very fine-grained, subrounded, moderately well-sorted quartzarenite; alcareous; massive but ledgy due to trough scours; some bioturbation.	3.0
31	Sandy siltstone; pale reddish brown (10R5/4) to moderate reddish orange (10R6/6); hackly; interbedded with some ledges of trough crossbedded sandstones; calcareous.	11.3
30	Sandstone; moderate orange pink (10R7/4) with lenses of light greenish gray (5G8/1); fine- to medium-grained with lenses of coarser sandstone; subangular, moderately sorted quartzarenite; calcareous; pple and plane bedded; lower 0.2 m contains unionid molds; some trough crossbeds; this is first big ledge below the Wingate.	6.8
29	Siltstone; pale reddish brown (10R5/4); calcareous; ripple laminated; forms a notch.	0.3

Unit	Lithology	Thickness (m)
28	Sandstone; pale reddish brown (10R5/4) to moderate reddish orange (10R6/6); very fine- to fine-grained, subrounded, moderately well-sorted micaceous sublitharenite; weakly calcareous; ripple laminated to small trough crossbeds.	0.2
27	Conglomerate; light greenish gray (5G8/1) fresh, stained pale red (10R6/2); matrix-supported, clasts are intraformational limestone and siltstone pebbles; rounded, moderately poorly sorted in matrix of very ne- to fine-grained, subrounded, moderately poorly orted sublitharenite; calcareous; unit is at base of cliff dominated by unit 30.	0.1
26	Siltstone; grayish red (10R4/2) to pale reddish brown (10R5/40; ripple laminated to laminated; hackly; 8-cm-thick limestone 5 m below top is light greenish gray (5G8/1); calcareous.	15.6
25	Sandstone; pale reddish brown (10R5/4); very fine-grained, subrounded, well-sorted sublitharenite; ledgy; with interbeds of hackly siltstone; all calcareous.	5.2
24	Siltstone; pale reddish brown (10R5/4); calcareous; hackly; some beds of light greenish gray (5G8/1), very coarse-grained sandstone and pebble conglomerates; rounded; matrix-supported; clasts up to 8–10 mm diameter; very calcareous.	7.0
23	Sandstone; pale reddish brown (10R5/4); very fine-grained, subangular, moderately well-sorted quartzarenite; calcareous; trough crossbedded and ripple laminated; calcareous.	0.5
22	Siltstone; grayish red (10R4/2) to pale reddish brown (10R5/4), occasionally light greenish gray (5G8/1); calcareous; forms a hackly slope interrupted by ledges of grayish red (10R4/2) to pale reddish brown (10R5/4); conglomerate clasts are intraformational limestone and siltstone up to 8 mm in diameter supported by a matrix of coarse- to very coarse-grained, rounded sandstone of similar colors and lithology.	5.5
21	Sandy siltstone; pale reddish brown (10R5/4) with mottles and spots of light greenish gray (5G8/1); not calcareous; pedogenically modified; abundant bioturbation and trace fossils, including horizontal tubes; some trough crossbedding; forms a ledge.	0.6
20	Siltstone; mottled grayish red (10R4/2), pale reddish brown (10R5/4), and light greenish gray (5G8/1); hackly and pedogenically modified; forms a slope with few ledgy breaks; calcareous.	7.0
19	Sandstone; grayish red (10R4/2), pale reddish brown (10R5/4), and moderate reddish orange; very fine-grained, subrounded, moderately well-sorted quartzarenite; calcareous; bioturbated with some trough crossbedding; forms a ledge.	0.4
18	Siltstone; dark reddish brown (10R3/4) to pale reddish brown (10R5/4) with mottles of light greenish gray (5G8/1); calcareous; forms a hackly slope.	4.5
17	Sandstone; pale reddish brown (10R5/4); very fine-grained, subangular, well-sorted quartzarenite; calcareous; ripple laminated; forms a prominent ledge.	0.9
16	Siltstone; grayish red (10R4/2) to pale reddish brown (10R5/4); some light greenish gray (5G8/1); very similar to unit 14; calcareous.	4.5
15	Silty sandstone; grayish red (10R4/2) to pale reddish brown (10R5/4); very fine-grained, subrounded, moderately well-sorted quartzarenite; calcareous; massive with some scour surfaces approximately every meter.	3.2
14	Siltstone; pale reddish brown (10R5/4) with spots and mottles of light greenish gray (5G8/1); some nodular pale red (10R4/2) siltstone/calcrete concretions/nodules as well; calcareous; ledgy; pedogenically modified; generally forms a slope.	5.0
13	Siltstone; pale reddish brown (10R5/4); pedogenically odified; calcareous; some crossbeds; some beds with medium gray (N5) to grayish red (10R4/2) pebble conglomerate; clasts are intraformational limestone and siltstone rip-ups up to 12 mm in diameter; rounded; very calcareous; this is a lateral accretion urface that has been pedogenically modified; unit ours into the top of unit 12.	1.5
12	Sandstone; light greenish gray (5GY8/1 to 5G8/1) fresh; weathers to pale reddish brown (10R5/4); very coarse-grained, rounded, moderately-sorted litharenite; composed of sedimentary rip-up clasts; very calcareous; trough crossbedded.	0.6
11	Siltstone; pale reddish brown (10R5/4) with yellowish gray (5Y7/2) spots and mottles; hackly; weathering profile on the top of the Painted Desert Member.	0.6
unconformity (Tr-5 unconformity of Lucas, 1991)		
Petrified Forest Formation:		
Painted Desert Member:		
10	Mudstone; pale reddish brown (10R5/4) with some light greenish gray (5G8/1) spots; silty; bentonitic; forms a slope; lower third is much covered.	20.0
9	Sandstone; grayish red (10R4/2) to pale reddish brown (10R5/4); coarse beds are coarse- to very coarse-grained and conglomeratic; rounded, moderately poorly sorted litharenite; calcareous; finer beds are very fine-grained, well-sorted sublitharenite; alcareous; ripple laminated; ledgy.	1.3
Moss Back Formation:		
8	Conglomeratic sandstone; light greenish gray GY8/1) to grayish orange pink (10R8/2); very coarse-grained to conglomeratic, rounded, moderately poorly sorted litharenite; abundant limestone pebbles, me cobble conglomerate; very calcareous; trough crossbedded; forms a ledge.	1.1
7	Sandstone; pale red (5R6/2) fresh, weathers pale yellowish brown (10YR6/2); medium-grained, subrounded, well-sorted sublitharenite; not calcareous; trough and planar crossbedded.	1.3
6	Sandstone and conglomerate; grayish orange pink (5YR7/2) fresh, weathers to light brownish gray YR6/1); coarse-grained, subrounded, moderately well-sorted litharenite; calcareous; trough and planar rossbeds; forms a ledge.	1.2
5	Conglomerate; grayish red (10R4/2) to pale reddish brown (10R5/4); calcareous; largely clast-supported, obbles up to 25 mm diameter; limestone clasts; very alcareous; trough crossbedded; forms a notch.	1.0
4	Sandstone; pale red purple (5RP6/2) fresh, weathers pale red (10R6/2); medium-grained, subangular to subrounded, moderately well-sorted quartzarenite; ot calcareous; scour base; trough crossbedded.	0.4
3	Sandstone; grayish red purple (5RP6/2); medium- to coarse-grained, subangular, poorly sorted quartzarenite; some clay at top of crossbeds is same color; trough crossbedded; forms a notch; not calcareous.	0.4
2	Conglomeratic sandstone; light gray (N7) fresh, weathers medium light gray (N6); coarse-grained, subangular, poorly sorted quartz-rich sandstone; conglomerate clasts are quartzite up to 100 mm diameter; scour base; calcareous; trough crossbedded.	1.9
unconformity (Tr-3 unconformity of Pipiringos and O'Sullivan, 1978)		
Moenkopi Group:		
1	Siltstone; pale reddish brown (10R5/4); laminar; some sandstone that is also pale reddish brown (10R5/4); very fine-grained, subangular to angular, well-sorted sublitharenite; calcareous.	not measured

10 - Colorado National Monument, Colorado

Section measured at UTM zone 12, 695751E, 4331240N in the SW1/4 NE1/4 sec. 31, T1S R1W, Mesa County, Colorado.

unit	lithology	thickness (m)
San Rafael Group:		
Entrada Sandstone:		
17	Sandstone; grayish orange pink (5YR7/2) fresh, weathers moderate reddish orange (10R6/6); very ne- to fine-grained, subrounded, well-sorted quartzarenite; trough crossbedded; not calcareous; orms a cliff.	not measured
unconformity (J-2 unconformity of Pipiringos and O'Sullivan, 1978)		
Chinle Group:		
Rock Point Formation:		
16	Siltstone; moderate reddish brown (10R4/6) to dark reddish brown (10R3/4); slightly sandy; micaceous; some ball and pillow structures.	2.0
15	Siltstone; same colors and lithology as unit 13.	5.8
14	Sandstone, same colors and lithology as unit 10; mostly bioturbated.	0.7
13	Siltstone; same colors and lithologies as unit 3 with some ledges (10%) of unit 4 lithologies.	5.3
12	Sandstone; same colors and lithology as unit 10.	0.8
11	Siltstone; same colors and lithology as unit 3.	1.7
10	Sandstone; moderate reddish brown (10R4/6); very fine-grained, subrounded, well-sorted litharenite; trough crossbedded and bioturbated; calcareous.	0.4
9	Conglomerate; same colors and lithology as unit 7; forms two ledges.	0.9
8	Siltstone; same colors and lithology as unit 3.	1.3
7	Conglomerate; pale red (10R6/2) fresh; weathers pale reddish brown (10R5/4) to moderate reddish brown (10R4/6); pebble conglomerate and very coarse-grained sandstone; lithic-rich, subangular, well-sorted, clast-supported conglomerate; some crude trough crossbeds; very calcareous.	0.6
6	Sandstone and siltstones; interbeds; lithologies and colors of units 3 and 4.	2.2
5	Siltstone; same colors and lithology as unit 3.	1.0
4	Sandstone and siltstone; moderate red (5R5/4) to moderate reddish brown (10R4/6); sandstone is very fine-grained, subrounded, well-sorted sublitharenite; both are calcareous; heavily bioturbated.	1.3
3	Siltstone; moderate reddish brown (10R4/6) fresh; weathers lighter; very laminar to blocky; calcareous; orms a slope.	5.0
2	Deeply weathered zone; bluish white (5B9/1), grayish black (N2) and pale blue (5PB7/2) mottles; heavily mottled; lots of granite fragments.	0.9
unconformity (Tr-5 unconformity of Lucas, 1991)		
1	Granite; white to black; fine-grained, slightly weathered.	not measured

11 - Basalt, Colorado

Section measured in the NE1/4 sec. 5, T8S, R86W, Eagle County, Colorado. Strata dip 10° to N40°W.

Unit	Lithology	Thickness (m)
San Rafael Group:		
Entrada Formation:		
39	Sandstone; light greenish gray (5G8/1) to light bluish gray (56B7/1) fresh, weathers to greenish gray (5G6/1 and 5GY6/1); coarse-grained, hematitic, subangular, moderately well-sorted sublitharenite; calcareous; trough crossbedded; water laid.	not measured
unconformity (J-2 unconformity)		
Chinle Group:		
Rock Point Formation:		
38	Sandy siltstone/silty sandstone; pale reddish brown (10R5/4) with some bands of yellowish gray (5Y7/2); sandstone is very fine-grained, well-sorted sublitharenite; calcareous; trough crossbedded.	0.2
37	Siltstone; grayish red (5R4/2); massive; weakly calcareous; forms a slope.	4.0
36	Siltstone; grayish red (5R4/2); laminated to ripple laminated; not calcareous; forms a cliff; some bioturbation.	2.9
35	Siltstone; grayish red (10R4/2) to moderate brown (5YR4/4) with some grayish yellow green (5GY7/2) pots; calcareous; laminated; forms a slope.	2.7
34	Siltstone; pale reddish brown (10R5/4) with minor spots of moderate orange pink (10R7/4) less than 4 mm in diameter; weakly calcareous; hackly; some thin sandstones of unit 33 lithology.	4.8
33	Sandstone; moderate orange pink (10R7/4) to pale reddish brown (10R5/4); very fine-grained, subrounded, well-sorted micaceous sublitharenite; massive; upper half forms a cliff; calcareous.	4.8
32	Siltstone; same colors and lithology as unit 26.	32.0
31	Sandstone; pale reddish brown (10R5/4); very fine-grained, subrounded, moderately sorted muddy sublitharenite; massive; upper 1/3 laminated and ripple laminated; forms a prominent ledge.	9.0
30	Siltstone; same colors and lithology as unit 26.	28.3
29	Sandstone; moderate reddish brown (10R4/6); some very dusky red (10R2/2) weathering crusts; very fine- to fine-grained, subrounded, moderately well-sorted sublitharenite; calcareous; massive; forms a ledge.	1.3
28	Siltstone; same colors and lithology as unit 26.	6.0
27	Sandstone; pale reddish brown (10R5/4); very fine-grained, subrounded, moderately well-sorted sublitharenite; calcareous; mostly massive; top is bioturbated, mottled purple and gray-green.	3.0
26	Siltstone; pale reddish brown (10R5/4) to moderate red (5R5/4) fresh, weathers as light as moderate reddish orange (10R6/6); very hackly pedogenically modified; prominent soil profile with purple mottles in rhizoliths; calcareous.	15.5
25	Sandstone; pale reddish brown (10R5/4); very fine- to fine-grained, subrounded, moderately well-sorted sublitharenite; massive; calcareous.	0.6
24	Siltstone; same color and lithology as unit 22.	4.5
23	Siltstone; pale reddish brown (10R5/4) fresh, weathers moderate orange pink (10R7/4); calcareous; ledgy; massive to bioturbated.	4.7
22	Siltstone; pale reddish brown (10R5/4) to pale red (10R6/7); some green mottles; slightly bioturbated; hackly; forms a slope.	3.1
21	Limestone; medium light gray (N6) to very light gray (N8) with recrystallized calcite; some siltstone pebbles; very calcareous; forms a cliff.	3.0
20	Siltstone and sandstone; hackly silt; fine-grained sandstone in thin bioturbated ledges; forms a slope; includes a thin sandstone–pebble conglomerate near top; top 2 m has "lungfish burrows"; also includes a sandstone that is medium gray (N5) with pale reddish rown (10R5/4) stains; very coarse-grained to conglomeratic, rounded, moderately well-sorted litharenite composed of limestone clasts; very calcareous.	12.3
19	Sandstone; pale reddish brown (10R5/4); conglomerate at base is pebbly, clast-supported, clasts up to 5 mm diameter; calcareous; sandstone is very fine-grained, well-sorted, sublitharenite; calcareous.	1.6–1.8

Unit	Lithology	Thickness (m)
18	Siltstone; pale reddish brown (10R5/4); muddy; not bentonitic.	2.8
17	Conglomeratic sandstone; grayish red (10R4/2); very coarse-grained to conglomeratic, well-sorted litharenite composed of mud chips and calcrete rip-ups; very calcareous.	0.8
16	Siltstone and very fine-grained sandstone; pale reddish brown (10R5/4) to moderate red (5R5/4); ripple-laminated to laminated; some small-scale trough crossbeds; calcareous.	11.5
15	Conglomerate; grayish red (10R4/2) to pale reddish brown (10R5/4) fresh, weathers pale red (10R6/2); clast-supported; clasts up to 12 mm diameter; clasts are reworked siltstone and limestone pebbles; extremely calcareous; laminar to trough crossbedded; top of cliff.	3.9
14	Siltstone; pale red (10R6/1) to pale reddish brown (10R5/4); massive; slightly calcareous; forms a cliff.	1.2
13	Siltstone; pale red (10R6/2) to pale reddish brown (10R5/4); pedogenically modified; calcareous; forms the base of a cliff.	1.0
12	Siltstone; pale reddish brown (10R5/4) fresh, weathers to moderate orange pink (10R7/4); calcareous; not bentonitic; ripple laminated and hackly; forms a slope.	10.0
11	Conglomerate; grayish red (10R4/2) fresh, weathers moderate orange pink (10R7/4) and pale red (10R6/2); clast-supported; very calcareous; clasts are limestone pebbles up to 5-7 mm in diameter.	0.1
unconformity (Tr-4 and Tr-5 unconformities of Lucas, 1991)		
Popo Agie Formation:		
10	Mudstone; grayish red purple (5RP4/2) with some light greenish gray (5G8/1) streaks and calcrete nodules; nodules restricted to upper 1/2 of unit; weakly to very calcareous.	6.0
9	Mottled zone; pale red purple (5RP6/2), pale purple (5P6/2) and light greenish gray (5G6/1); heavily silicified, not calcareous; well-indurated sandy siltstone.	2.5
Gartra Formation:		
8	Sandstone; moderate red (5R5/4) to pale reddish brown (10R5/4); fine-grained, subrounded, well-sorted micaceous sublitharenite; some quartzite pebble floaters; some pedogenic structures; calcareous.	1.0
7	Conglomerate; very light gray (N8) to white (N9) fresh, weathers to medium light gray (N6); clast-supported; calcite dike fractures; quartzose; trough crossbedded; coarser than unit 6; not calcareous.	5.3
6	Conglomeratic sandstone; very light gray (N8) fresh, weathers as dark as moderate orange pink (10R7/4); very coarse-grained, angular to subangular, moderately orted quartzarenite and quartz-pebble conglomerate; trough crossbedded; not calcareous.	3.8
5	Sandstone; coarse fraction is very light gray (N8), fine fraction is moderate red (5R5/4) to pale reddish brown (10R5/4); coarse fraction is very coarse-grained to conglomeratic, angular, moderately well-sorted quartzarenite; not calcareous; trough crossbedded; iner faction is fine- to medium-grained, subangular, moderately well-sorted quartzarenite; laminar; lower 3 m is mostly covered.	4.5
4	Sandstone; very light gray (N8) to medium light gray (N6); coarse- to very coarse-grained, some pebble floaters, subangular to subrounded, moderately well-sorted quartzarenite; trough crossbedded; calcareous.	3.0
3	Conglomeratic sandstone and sandstone; pale green 5G7/2) to pale yellowish green (10GY7/2); coarse- to very coarse-grained, subangular, moderately sorted quartzarenite; trough crossbedded, grading upward to ripples; not calcareous.	3.0
2	Conglomeratic and sandstone; dark greenish gray (5G4/1); large clasts of quartzite and novaculitic chert up to 40 mm diameter; trough crossbedded; not calcareous.	2.0
unconformity (Tr-3 unconformity of Pipiringos and O'Sullivan)		
Chugwater Formation:		
1	Sandstone; grayish red (10R4/2); very fine-grained, well-sorted micaceous sublitharenite to litharenite; ripple laminated to laminated; micaceous; not calcareous; colors and lithology similar to that of Chugwater Formation.	not measured

This footprint of a meat-eating dinosaur is one of many preserved in the Lower Jurassic Springdale Sandstone Member of the Kayenta Formation near Tuba City in northeastern Arizona. This type of large track is generally assigned to the ichnogenus *Eubrontes* and is a good index fossil of the Early Jurassic (Liassic).