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Triassic stratigraphy and chronology in New Mexico

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Abstract

Triassic rocks in New Mexico are nonmarine strata of Middle and Late Triassic age. Middle Triassic (Anisian) strata belong to the Anton Chico Member of the Moenkopi Formation, an unconformity-bounded tectonosequence of fluvial red beds as thick as 41 m. Moenkopi strata are present across most of north and central New Mexico, and in southeast New Mexico they crop out in Lincoln County.

Upper Triassic (late Carnian–Rhaetian) strata in New Mexico belong to the Chinle Group, an unconformity-bounded tectonosequence of fluvial, lacustrine, and rare eolian red beds as thick as 650 m. Chinle strata crop out across north, central, and southeast New Mexico. Lithostratigraphy, and biostratigraphy based primarily on tetrapod vertebrates, allow precise correlation of Chinle Group strata that comprise three depositional sequences separated by basinwide unconformities. These depositional sequences resulted from base-level changes driven by eustasy.

Introduction

Triassic rocks in New Mexico (Fig. 1) are nonmarine strata of Middle and Late Triassic age. They belong to two tectonosequences with bounding unconformities that correspond to significant tectonic reorganizations of the depositional system. Since their first recognition by Marcou (1858), Triassic strata in New Mexico have received extensive study by stratigraphers, sedimentologists, paleontologists, geological field mappers, and economic geologists. Most of these studies focused on particular regions of the state and thus did not produce a unified synthesis of the Triassic stratigraphy and chronology in New Mexico. During the past 12 years, I have studied the Triassic strata in New Mexico and their correlatives throughout the western United States. This work, done in collaboration with several workers, notably O. Anderson, S. Hayden, A. Heckert, P. Huber, A. Hunt, and K. Kietzke, has produced a stratigraphic and chronological framework for the Triassic strata in New Mexico, which is reviewed here.

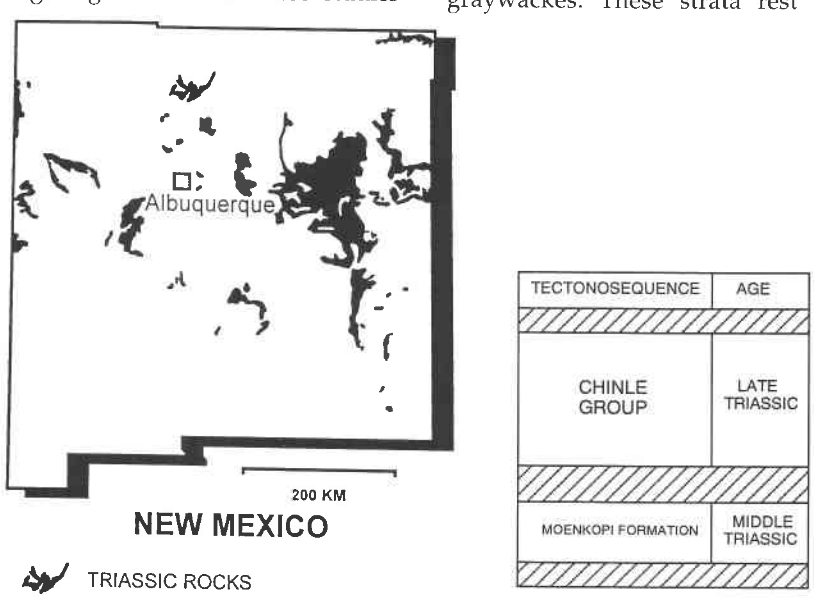

FIGURE 1—Outcrop distribution of Triassic strata in New Mexico (after Dane and Bachman, 1965) and inset showing the two tectonosequences of Triassic strata present in the state.

Moenkopi tectonosequence

The oldest Triassic strata in New Mexico belong to the Moenkopi Formation and are of Middle Triassic (early Anisian) age. Recognition of the Moenkopi Formation in New Mexico was long hindered by McKee (1954), who concluded that no Moenkopi strata are present in the state, and by a variety of geologists who included Moenkopi strata in the Permian "Bernal" (=Artesia) Formation (Lucas and Hayden, 1991). Some previous workers (e.g., Cooley, 1957; Stewart et al., 1972b), however, did recognize "Moenkopi(?) Formation" strata along the south edge of the Colorado Plateau and as far east as the Sevilleta Grant in Socorro County.

Moenkopi strata in New Mexico belong to the Anton Chico Member of Lucas and Hunt (1987). They are fluvial red beds as thick as 41 m dominated by trough-cross-bedded micaceous litharenites and lithic graywackes. These strata rest disconformably on Middle Permian (Guadalupian) strata of the Artesia Group, Glorieta Sandstone, and San Andres Formation. They are disconformably overlain by Upper Triassic Chinle Group strata or younger rocks. Moenkopi strata are present at the base of the Triassic across most of north and south-central New Mexico (Lucas and Hunt, 1987, 1989b; Lucas and Hayden, 1989a, b, 1991; Lucas et al., 1990), and in southeast New Mexico they extend to Bull Gap south of Carrizozo in Lincoln County (Lucas, 1991c).

Moenkopi strata in New Mexico are readily differentiated from underlying Permian red beds (Guadalupian Artesia Group) with which they were long confused by lithologic characteristics of texture, mineralogy, bedform, and color as well as by fossil content (Fig. 2):

1. Texture—Artesia Group sandstones are very fine to fine grained, relatively well sorted, and rounded. Most of the resistant Artesia Group beds are either siltstones or silty sandstones. In contrast, Moenkopi sandstones are fine to coarse grained, poorly to moderately sorted, and subangular to subrounded. Intraformational conglomerates of mudstone and siltstone pebbles are common in the Moenkopi but virtually absent in the Artesia.
2. Mineralogy—Artesia sandstones are quartzarenites or slightly micaceous quartzarenites and are frequently gypsiferous. Moenkopi sandstones are micaceous litharenites and lithic graywackes devoid of gypsum.
3. Bedforms—Artesia Group sandstones typically are laminated, ripple laminated, or massive and form laterally persistent, repetitive (cyclic) beds. Moenkopi sandstones are typically trough crossbedded and have lenticular beds.
4. Color—Artesia Group red beds are characteristically moderate reddish brown (10 R 4/6), commonly called "brick red" or "orange red," with some grayish-green/yellowish-gray reduction mottles or thin bands. Moenkopi strata, in contrast, are characteristically grayish red (5 R 4/2 or 10 R 4/2).
5. Fossil content—Artesia Group strata lack body fossils, whereas Moenkopi strata (especially conglomerates) have bones and bone fragments, ostracods, charophytes, and tetrapod footprints.

These Moenkopi fossils from New Mexico (Lucas and Morales, 1985; Kietzke,1989a, b; Lucas and Hayden, 1989a; Hunt and Lucas, 1993c) indicate correlation of the Anton Chico Member with the Holbrook Member of the Moenkopi Formation in north Arizona and assignment of an early Anisian age to the Anton Chico Member (Morales, 1987). Magnetostratigraphy supports this correlation (Steiner and Lucas, 1992; Steiner et al., 1993).

Chinle tectonosequence

Lucas (1993) assigned all Upper Triassic nonmarine strata in the west-central United States to the Chinle Group. These rocks are mostly red beds of fluvial, lacustrine, and rare eolian origin deposited in a single vast basin that extended at least from Wyoming to Texas and from east Nevada to west Oklahoma (Lucas, 1993; Lucas and Marzolf, 1993; Marzolf, 1993). All Upper Triassic strata in New Mexico belong to the Chinle Group. The base of the Chinle Group is everywhere an unconformity above older rocks (Tr-3 unconformity of Pipiringos and O'Sullivan, 1978), and the top of the Chinle Group also is an unconformity of basinwide scope (J-0 unconformity of Pipiringos and O'Sullivan, 1978).

Chinle Group chronology

Chinle Group biostratigraphy and biochronology is based on palynomorphs, megafossil plants, ostracods, nonmarine molluscs (unionid bivalves and gastropods), vertebrate coprolites, and tetrapod vertebrates (Fig. 3). Articles in Lucas and Hunt (1989a) and Lucas and Morales (1993) present much of this biostratigraphy and biochronology, and Lucas (1995) provides an extensive review. Hunt and Lucas (1993a) summarized tetrapod biostratigraphy and biochronology of the Upper Triassic strata of New Mexico. No syndepositional radiometric ages are available for Chinle Group strata in the state, but magnetostratigraphy has been published for several New Mexico sections (reviewed by Molina–Garza et al., 1993).

A few salient points are:

1. The base of the Chinle Group is everywhere of late Carnian (Tuvalian) age (Hunt and Lucas, 1991a). Chinle strata below the medial sandstone-conglomerate complex termed Sonsela, Poleo, or Trujillo are also of late Carnian age; the Carnian–Norian boundary is approximated by the base of the medial sandstone-conglomerate complex. Strata of this complex and the overlying mudrock-dominated units (Painted Desert Member of Petrified Forest Formation and Owl Rock Formation and their correlatives) are of early-middle Norian age. The youngest Chinle Group strata (Rock Point Formation and correlatives) are here regarded as of Rhaetian age, though they could be slightly older, of late Norian age. No Chinle Group strata are of Jurassic age.
2. Using the Harland et al. (1990) numerical timescale, the base of the Chinle Group is about 225 Ma, and the top is 208 Ma or slightly older (Fig. 3). Chinle Group deposition thus took place during about 17 million years.
3. Tetrapod biochronology of the Chinle Group provides the most precise correlations because tetrapod fossils allow four intervals of time to be characterized biostratigraphically. Palynomorphs and megafossil plants allow only three time intervals to be discriminated, whereas other fossil groups allow recognition of only two intervals (Fig. 3). Nevertheless, correlations based on different kinds of Chinle Group fossils are consistent with each other (Fig. 3).
4. Correlation of the Chinle Group to the SGCS (standard global chronostratigraphic scale) for the Late Triassic (Carnian, Norian, and Rhaetian stages and their subdivisions: Tozer, 1984, 1994; Visscher, 1992) is based on palynomorphs and

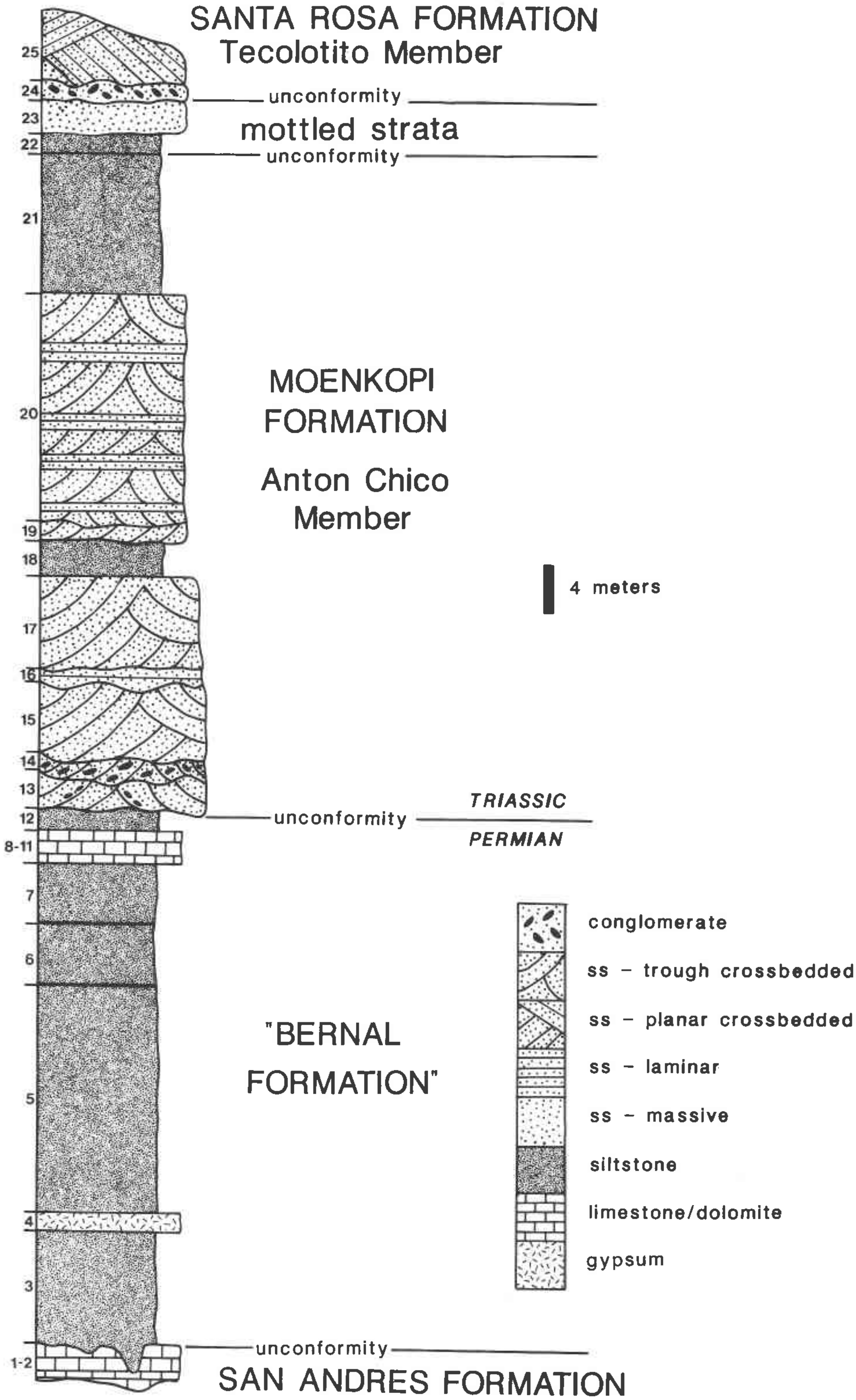

FIGURE 2—Measured stratigraphic section at Bernal Butte (from Lucas and Hayden, 1991) to show contrast between "Bernal" (=Artesia) Formation and Moenkopi Formation.

tetrapods. Palynomorphs allow cross-correlation to marine Alpine strata that contain ammonoids (Dunay and Fisher, 1979; Litwin et al., 1991). Tetrapods from most Chinle Group horizons can be correlated directly to the classic Keuper of the Germanic basin (Lucas and Hunt, 1993).

West-central New Mexico

Lucas and Hayden (1989a), Lucas (1993), Anderson and Lucas (1993), and Lucas and Heckert (1994) provide the current basis for the stratigraphy and chronology of Chinle Group rocks in McKinley and Cibola Counties (Fig. 4). This is the thickest Chinle Group section with a total of 650 m.

The basal unit of the Chinle Group here is the Shinarump Formation and mottled strata with a maximum thickness of 24 m, the thickest sections of mottled strata in New Mexico. Mottled strata are color-mottled, extensively bioturbated sandstone, siltstone, and conglomerate that represent a weathering profile developed on pre-Chinle (commonly Moenkopi) strata (Stewart et al., 1972a). For mapping purposes, the informal unit mottled strata is included in the Chinle Group. The Shinarump strata are mostly trough-crossbedded siliceous conglomerates and quartzose sandstones.

The overlying Bluewater Creek Formation is as thick as 60 m and is dominated by red-bed mudstones and ripple-laminated sandstones. A distinctive 6–12-m-thick ripple-laminated sandstone near the top of the formation is the McGaffey Member of Anderson and Lucas (1993). The Petrified Forest Formation overlies the Bluewater Creek Formation throughout west-central New Mexico and consists of three members (ascending order): Blue Mesa, Sonsela, and Painted Desert. The Blue Mesa Member is mostly bluish and purple smectitic mudstones as thick as 46 m. The Sonsela Member disconformably overlies the Blue Mesa Member, has a maximum thickness of 61 m, and is dominantly trough-crossbedded quartzose sandstones and conglomerates of extra- and intraformational origin with numerous fossil logs. Overlying Painted Desert Member strata are mostly red-bed mudstones with a maximum thickness of 335 m.

The Owl Rock Formation overlies the Painted Desert Member in much of west-central New Mexico (O'Sullivan, 1974; Lucas and Hunt, 1990). It is as thick as 35 m and consists of pedogenically modified siltstones, sandstones, and carbonates. It is disconformably overlain by the Rock Point Formation, as thick as 69 m of mostly reddish-brown sandstones and siltstones. In McKinley–Cibola Counties from Thoreau to Mesa Gigante, the Owl Rock and Rock Point Formations are absent, and the Middle Jurassic Entrada Sandstone rests directly on the Painted Desert Member.

In west-central New Mexico, the Bluewater Creek Formation has an extensive

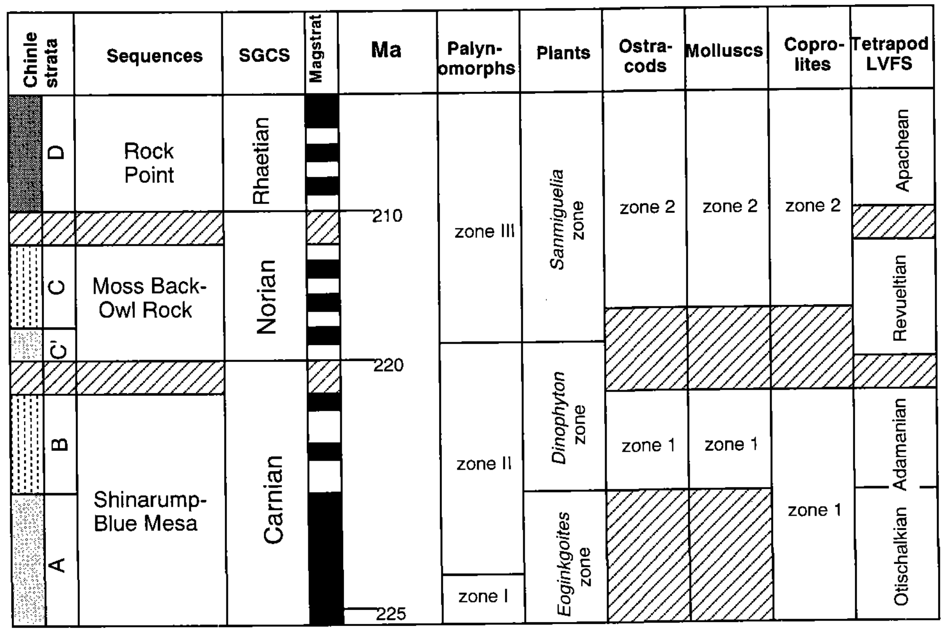

FIGURE 3—Summary of Chinle Group chronology (from Lucas, in press). **LVFS**, land-vertebrate faunachrons; **SGCS**, standard global chronostratigraphic scale.

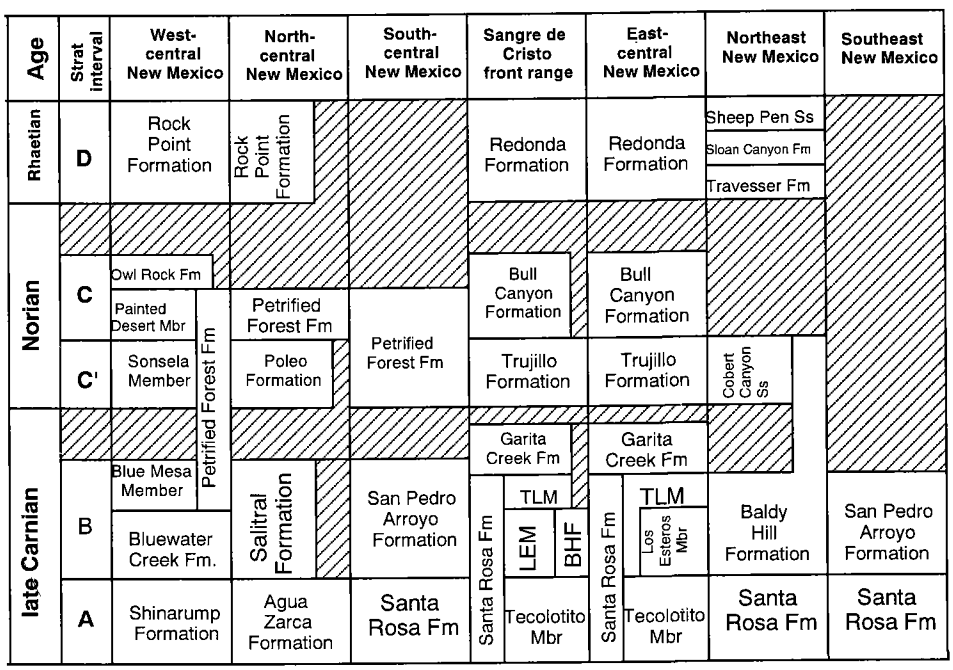

FIGURE 4—Correlation of the Chinle Group in New Mexico. **BHF**, Baldy Hill Formation; **LEM**, Los Esteros Member; **TLM**, Tres Lagunas Member.

paleoflora as well as some tetrapod and invertebrate fossils that establish its age (Ash, 1978; Lucas and Hayden, 1989a). Correlation of other Chinle Group units in west-central New Mexico is based on lithostratigraphic correlation to more fossiliferous sections in north Arizona (Lucas, 1993).

North-central New Mexico

Chinle Group stratigraphy in Rio Arriba and Sandoval Counties (Chama Basin and flanks of the Nacimiento and Jemez Mountains) follows Lucas and Hunt (1992) and Hunt and Lucas (1993b). Huene (1911) and Wood and Northrop (1946) introduced most of the local nomenclature that is used here. This nomenclature is used as far east as the Hagan Basin of Sandoval County and the Placitas–Cedar Crest area of Bernalillo County (Lucas, 1991a).

Above very limited outcrops of mottled strata developed in Lower Permian strata, the base of the Chinle Group is the Agua Zarca Formation, mostly trough-crossbedded quartzose sandstone and silica-pebble conglomerate as thick as 61 m.

The overlying Salitral Formation is dominated by purple smectitic mudstones and has a maximum thickness of 102 m. The Poleo Formation disconformably overlies the Salitral and is grayish-yellow trough-crossbedded litharenite and conglomerate of both intra- and extraformational (silica pebbles) origin as thick as 41 m. Red-bed mudstones above the Poleo are as thick as 200 m and belong to the Petrified Forest Formation. Middle Jurassic (San Rafael Group) strata overlie the Petrified Forest Formation throughout north-central New Mexico except in the Ghost Ranch area of the Chama Basin where the Rock Point Formation is present. Rock Point strata here are reddish-brown and grayish-red siltstones and ripple-laminated sandstones as thick as 70 m.

In north-central New Mexico, the Salitral, Petrified Forest, and Rock Point Formations produce age-diagnostic vertebrate fossils. Palynomorphs place the Carnian–Norian boundary at about the base of the Poleo Formation (Litwin et al., 1991). The Rock Point Formation has yielded all known fossils of the dinosaur *Rioarribasaurus*, formerly known as *Coelophysis* (though the name change is still disputed), New Mexico's state fossil (Hunt and Lucas, 1991b).

South-central New Mexico

Lucas (1991c) and Lucas and Heckert (1994) reviewed Chinle Group stratigraphy in Valencia, Socorro, and Lincoln Counties. Here, the basal Chinle is the Shinarump Formation (Valencia–Socorro Counties) and Santa Rosa Formation (Lincoln County) above a 5-m-thick interval of color-mottled siltstone, sandstone, and conglomerate referred to as the mottled strata. Maximum thickness of the Shinarump–Santa Rosa is 26 m, and lithologies are mostly trough-crossbedded silica-pebble conglomerate and micaceous subarkosic sandstone.

Overlying blue and purple mudstone-dominated strata belong to the San Pedro Arroyo Formation, which is as thick as 55 m. A distinctive limestone in the San Pedro Arroyo Formation, the Ojo Huelos Member, contains Adamanian vertebrates and late Carnian ostracods. The Petrified Forest Formation overlies the San Pedro Arroyo and consists of Sonsela (up to 10-m thickness of sandstone and intraformational conglomerate) and Painted Desert (red-bed mudstones and sandstones up to 58 m thick) members. The Lower–Upper Cretaceous Dakota Group overlies Chinle Group strata in south-central New Mexico except locally where thin outliers of the Jurassic Morrison Formation are present (Hunt and Lucas, 1987; Hayden et al., 1990; Lucas, 1991b).

Sangre de Cristo front range

Lucas et al. (1990) reviewed Chinle Group stratigraphy and correlation along the front range of the Sangre de Cristo Mountains in San Miguel, Mora, and Colfax Counties. Here, the Chinle Group section begins with the Santa Rosa Formation, mostly gray and yellow trough-crosbedded litharenite with a maximum thickness of 38.5 m. South of La Cueva (Mora County), the three Santa Rosa Formation members present in east-central New Mexico (Tecolotito, Los Esteros, and Tres Lagunas) can be recognized, but to the north only the Tecolotito Member is present.

A similar, north-south distinction can be made in immediately overlying Upper Triassic strata. At Ricardo Creek in Colfax County, a 13-m-thick section of mottled siltstone belongs to the Baldy Hill Formation, whereas to the south strata immediately above the Santa Rosa Formation are as much as 26 m thick and are dominantly red-bed mudstones assigned to the Garita Creek Formation.

The overlying Trujillo Formation is the most pervasive Chinle Group unit along the Sangre de Cristo front range. It is olive, yellow, and gray trough-crossbedded and laminated quartzose sandstone with interbeds of limestone- and siltstone-pebble conglomerate. From Naranjos (Mora County) south, red-bed mudstones of the Bull Canyon Formation overlie the Trujillo and are as thick as 140 m. North of Naranjos, the Redonda Formation (=Naranjos Formation of Bachman, 1953; =Johnson Gap Formation of Johnson and Baltz, 1960) overlies the Trujillo Formation. South of Naranjos the Redonda overlies the Bull Canyon Formation. The Redonda is mostly reddish-brown laminated and ripple-laminated siltstones and sandstones with a maximum thickness of 65 m.

No fossils are known from Chinle Group strata along the Sangre de Cristo front range. Therefore, correlation of these strata is based solely on lithology and stratigraphic position.

East-central New Mexico

Chinle Group stratigraphy and chronology in San Miguel, Guadalupe, Torrance, DeBaca, Quay, and Harding Counties was reviewed by Lucas et al. (1985) and Lucas and Hunt (1987, 1989b). The same stratigraphic nomenclature is used as far west as Lamy in Santa Fe County (Lucas, 1991a). Continuity of the Triassic facies from the Santa Rosa area to Lamy disproves earlier ideas of a Late Triassic Pedernal uplift in east-central New Mexico.

Lehman (1994) recently suggested an alternative stratigraphic nomenclature that brings the Texas Dockum units in their entirety into east-central New Mexico, but Lucas et al. (1994) presented a detailed refutation of this proposal. The Chinle Group section in east-central New Mexico is very thick (up to 593 m), and its paleontology has been intensively studied.

The Chinle Group section in east-central New Mexico begins with the Santa Rosa Formation, which consists of three members (in ascending order): Tecolotito, as thick as 34 m and mostly trough-crossbedded quartzarenites and extraformational conglomerate; Los Esteros, as thick as 44 m and dominantly variegated green and blue smectitic mudstones; and Tres Lagunas, mostly trough-crossbedded quartzarenites as thick as 45 m.

The Garita Creek Formation overlies the Santa Rosa and is dominated by red-bed mudstones; its maximum thickness is 152 m. Overlying strata of the Trujillo Formation are mostly trough-crossbedded micaceous litharenites and intraformational conglomerates with thin interbeds of red-bed mudstone. The Trujillo is as thick as 68 m and is overlain by as much as 110 m of Bull Canyon Formation, a dominantly red-bed mudstone unit. The Chinle Group section in east-central New Mexico is capped by the Redonda Formation (maximum thickness of 140 m), cyclic beds of reddish-brown siltstone and sandstone.

Age control for the Chinle Group section in east-central New Mexico is based on tetrapods (Los Esteros, Garita Creek, Trujillo, Bull Canyon, and Redonda) and megafossil plants (Los Esteros, Bull Canyon, Redonda) (Lucas and Hunt, 1989b). These fossils establish the Chinle Group section in east-central New Mexico as one of the most biostratigraphically significant sections of the Chinle Group.

Northeast New Mexico

Lucas et al. (1987) reviewed Chinle Group stratigraphy and chronology in the Dry Cimarron Valley of east Colfax and Union Counties. These strata extend into northwest Oklahoma (Cimarron County) and southeast Colorado (Baca County) where an identical local stratigraphic nomenclature introduced by Baldwin and Muehlberger (1959) is applied (Lucas, 1993).

The oldest Chinle Group strata that crop out in northeast New Mexico belong to the Baldy Hill Formation, color-mottled sandstone and siltstone at least 37 m thick. The base of the Baldy Hill Formation is not exposed, but subsurface data indicate it is underlain by the Santa Rosa Formation (Foster, 1957). The uppermost 3 m of the Baldy Hill Formation, the Cobert Canyon Sandstone Member, disconformably overlies underlying strata and is lithic and limestone-cobble conglomerate. The overlying Travesser Formation is as thick as 168 m and consists of reddish-brown laminated and ripple-laminated quartzose sandstone, siltstone, and rare lithic conglomerate. It disconformably overlies the Baldy Hill Formation and is conformably overlain by yellowish-green and greenish-gray siltstone, sandstone, and limestone of the Sloan Canyon Formation (maximum thickness of 41 m). The youngest Chinle Group strata here are the Sheep Pen Sandstone, yellowish-orange laminated quartzose sandstone as thick as 33 m.

The Cobert Canyon Sandstone Member and Sloan Canyon Formation produce age-diagnostic tetrapod fossils (Lucas et al., 1987). The Sloan Canyon and Sheep Pen Formations have extensive tetrapod ichnofaunas as well (e.g., Lockley and Hunt, 1993). These fossils establish the correlation of the Chinle Group in northeast New Mexico presented here (Fig. 4).

Southeast New Mexico

Lucas and Anderson (1992, 1993a, b) reviewed Chinle Group stratigraphy in Chaves, Eddy, and Lea Counties. Here, the base of the Chinle Group overlies middle Permian (Guadalupian) Artesia Group strata or Upper Permian ("Ochoan") strata of the Quartermaster Formation. The basal unit of the Chinle Group is the Santa Rosa Formation (equivalent to the Tecolotito Member to the north), which is as thick as 25 m and consists of trough-crossbedded extraformational conglomerate and sandstone with rare beds of mudstone and siltstone. Above the Santa Rosa Formation are smectitic mudstone and rare sandstones and conglomerates assigned to the San Pedro Arroyo Formation. A lack of age-diagnostic fossils requires that correlation of Chinle Group strata in southeast New Mexico be wholly dependent on lithology and stratigraphic position.

Chinle Group sequence stratigraphy

The stratigraphic correlation and biochronology of the Chinle Group advocated here (Fig. 4) and elsewhere (Lucas, 1993) identify two intra-Chinle Group unconformities and thus delineate three depositional sequences (Fig. 5). I have labelled these two unconformities Tr-4 and Tr-5, following the scheme of Pipiringos and O'Sullivan (1978). The Chinle Group sequences take their names from included stratigraphic units of the Four Corners area (Fig. 5). Evidence for the widespread intra-Chinle Group unconformities is fourfold:

1. Correlative rocks immediately above each unconformity overlie rocks of different ages in different areas. This probably reflects differential erosion associated with each unconformity.
2. There is a major lithologic change associated with each unconformity. Rocks of the upper part of the Shinarump–Blue Mesa sequence are smectitic mudstones, siltstones, and pedogenic silcretes/calcretes overlain by sandstones and conglomerates at the base of the Moss Back–Owl Rock sequence. Smectitic mudstones and pisolitic calcretes of the upper part of the Moss Back–Owl Rock sequence are directly overlain by nonsmectitic siltstones and mudstones and fine-grained, laterally persistent sandstones of the Rock Point sequence.
3. At the Tr-4 unconformity, channeling into and reworking of underlying sediment is evident in many areas. At the Tr-5 unconformity there is evidence of extensive subaerial weathering (pedogenesis) of sediments immediately beneath the unconformity.
4. Each unconformity corresponds to a significant reorganization of the biota. Few genera of tetrapods cross an unconformity, so that many tetrapod taxa are unique to each of the three depositional sequences. This is also generally true of palynomorphs, megafossil plants, ostracods, and fishes. A temporal hiatus associated with each unconformity best explains this pattern.

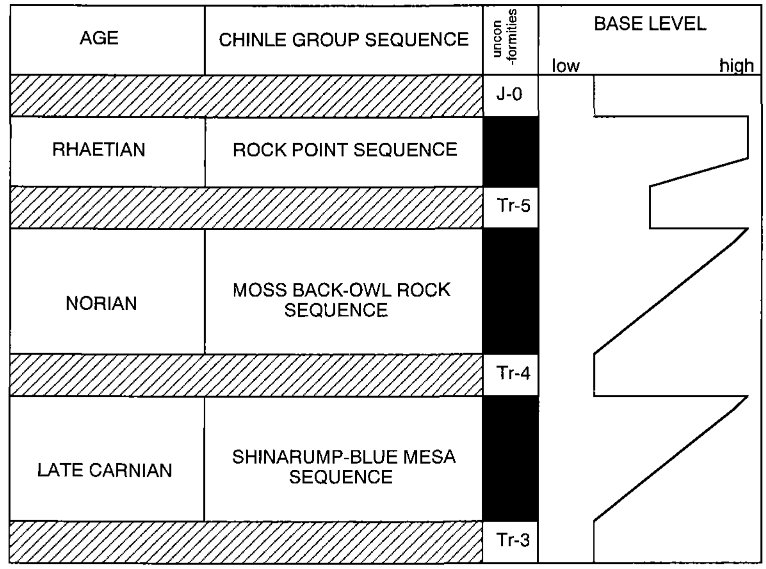

FIGURE 5—Sequence stratigraphy of the Chinle Group and postulated base-level changes.

Base-level-driven sedimentation explains well the unconformities associated with and the fluvial architecture of the Chinle Group (Fig. 5). Deposition of the Chinle Group began during the late Carnian with the regional onset of rising base level. Between the early Anisian (age of the youngest sediments beneath the Chinle) and the late Carnian (about 15 Ma on the Harland et al., 1990 timescale), low base level throughout what was to become the Chinle depositional basin produced an incised topography caused by differential erosion and sediment bypassing. Rising base level that produced the Shinarump–Blue Mesa sequence halted this incision and bypassing so that coarse-grained basal Chinle sediments (Fig. 4, stratigraphic interval A) filled in and buried the pre-Chinle topography. Continued rise in base level produced aggradation of extensive floodplains around channel meanderbelts (Fig. 4, lower part of interval B). This culminated in a stable landscape of fine-grained floodplain deposits undergoing extensive pedogenesis (Fig. 4, upper part of interval B) at peak base level.

Identical base-level changes produced the overlying Moss Back–Owl Rock sequence (Fig. 5). The main difference between the two sequences is the clast composition of their basal conglomerate facies. Basal conglomerates of the Shinarump–Blue Mesa sequence (Fig. 4, interval A) mostly contain extraformational clasts of silica (quartzite, chert, jasper) and Paleozoic limestones, reflecting primary source areas in low-grade-metamorphic- and sedimentary-rock-clad uplifts outside of the Chinle depositional basin. In contrast, basal conglomerates of the Moss Back–Owl Rock sequence (Fig. 4, interval C') mostly contain intraformational clasts of calcrete and siltstone that are rip-ups from underlying Chinle floodplain deposits.

The youngest Chinle sequence (Rock Point sequence) has a different facies architecture than the underlying sequences. No basal sandsheet/conglomerate is present, and the entire sequence is dominated by cyclically bedded siltstones, mudstones, and fine sandstones deposited in lakes, by sheetfloods, or in small dune fields. After a relatively minor base-level fall that produced negligible incision, a rapid rise to peak base level could have produced this sequence (Fig. 5).

Lucas (1993), Lucas and Marzolf (1993), and Marzolf (1993) advocated eustatic sea-level changes as the mechanism that drove Chinle Group base-level changes. A wealth of paleocurrent data indicates that the paleoslope of the Chinle basin was down to the northwest. Large, Mississippi-scale rivers that flowed across the Four Corners to the northwest captured smaller Chinle rivers to the south and southeast. These large rivers flowed to the Late Triassic Pangean shoreline that has been palinspastically restored to approximate the current Nevada–Utah border (Marzolf, 1993). Marine shelfal Late Triassic strata deposited near this shoreline in Nevada (upper Star Peak and Auld Lang Syne groups) have correlative sequence boundaries and similar sequence geometry to the lower two Chinle Group sequences (shelfal marine correlatives of the Rock Point sequence are not preserved) (Lucas and Huber, 1994). This strongly supports eustasy as the mechanism that drove Chinle base-level changes.

Alternative mechanisms are changes in tectonism or climate. Tectonic control of Chinle base-level changes necessitates uplifts rising and the basin subsiding synchronously over a large area (the Chinle basin is at least 2.3 million km^2 in extent), an unlikely possibility. No known Late Triassic climate cycles match Chinle depositional cycles, so climate change driving the base-level changes also seems improbable. Base-level change due to eustasy was the most likely driving mechanism of Chinle Group sedimentation.

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References

Anderson, O. J., and Lucas, S. G., 1993, McGaffey Member of Upper Triassic Bluewater Creek Formation, west-central New Mexico: New Mexico Museum of Natural History and Science, Bulletin 3, p. G30.

Ash, S. R., editor, 1978, Geology, paleontology, and paleoecology of a Late Triassic lake, western New Mexico: Brigham Young University, Geology Studies, v. 25, no. 2, 95 pp.

Bachman, G. O., 1953, Geology of a part of northwestern Mora County, New Mexico: U.S. Geological Survey, Oil and Gas Investigations Map OM-137.

Baldwin, B., and Muehlberger, W. R., 1959, Geologic studies of Union County, New Mexico: New Mexico Bureau of Mines and Mineral Resources, Bulletin 63, 171 pp.

Cooley, M. E., 1957, Geology of the Chinle Formation in the upper Little Colorado River drainage area, Arizona and New Mexico: Unpublished MS thesis, University of Arizona, Tucson, 317 pp.

Dane, C. H., and Bachman, G. O., 1965, Geologic map of New Mexico: U. S. Geological Survey, scale 1:500,000.

Dunay, R. E., and Fisher, M. J., 1979, Palynology of the Upper Triassic Dockum Group (Upper Triassic), Texas, U.S.A.: Review of Palaeobotany and Palynology, v. 28, pp. 61–92.

Foster, R. W., 1957, Subsurface stratigraphy of northern Union County: Oklahoma City Geological Society, 35th Guidebook, pp. 136–141.

Harland, W. B., Armstrong, R. L., Cox, A. V., Craig, L. E., Smith, A. G., and Smith, D. G., 1990, A geologic time scale 1989: Cambridge University Press, Cambridge, 263 pp.

Hayden, S. N., Lucas, S. G., Hunt, A. P., and Beck, W. C., 1990, Triassic–Jurassic stratigraphy, Palo Duro Canyon, Sevilleta Grant, Socorro County, New Mexico: New Mexico Geology, v. 12, pp. 65, 75.

Huene, F. von, 1911, Kurze Mitteilung über Perm, Trias und Jura in New Mexico: Neues Jahrbuch für Geologie, Paläontologie und Mineralogie, v. 32, pp. 730–739.

Hunt, A. P., and Lucas, S. G., 1987, Southernmost outcrops of the Morrison Formation in the Carthage area, Socorro County, New Mexico: New Mexico Geology, v. 9, pp. 58–62.

Hunt, A. P., and Lucas, S. G., 1991a, The *Paleorhinus* biochron and the correlation of the nonmarine Upper Triassic of Pangaea: Palaeontology, v. 34, pp. 467–501.

Hunt, A. P., and Lucas, S. G., 1991b, *Rioarribasaurus*, a new name for a Late Triassic dinosaur from New Mexico: Paläontologische Zeitschrift, v. 65, pp. 191–198.

Hunt, A. P., and Lucas, S. G., 1993a, Triassic vertebrate paleontology and biochronology of New Mexico: New Mexico Museum of Natural History and Science, Bulletin 2, pp. 49–60.

Hunt, A. P., and Lucas, S. G., 1993b, Stratigraphy and vertebrate paleontology of the Chinle Group (Upper Triassic), Chama basin, north-central New Mexico: New Mexico Museum of Natural History and Science, Bulletin 2, pp. 61–69.

Hunt, A. P., and Lucas, S. G., 1993c, Tetrapod footprints from the Middle Triassic Moenkopi Formation, west-central New Mexico: New Mexico Museum of Natural History and Science, Bulletin 3, p. G20.

Johnson, R. B., and Baltz, E. H., Jr., 1960, Probable Triassic rocks along eastern front of Sangre de Cristo Mountains, south-central Colorado: American Association of Petroleum Geologists, Bulletin, v. 44, pp. 1895–1902.

Kietzke, K. K., 1989a, Calcareous microfossils from the Moenkopi Formation (Triassic, Scythian or Anisian) of central New Mexico; *in* Anderson, O. J., Lucas, S. G., Love, D. W., and Cather, S. M. (eds.), Southeastern Colorado Plateau: New Mexico Geological Society, Guidebook 40, pp. 181–190.

Kietzke, K. K., 1989b, Calcareous microfossils from the Triassic of the southwestern United States; *in* Lucas, S. G., and Hunt, A. P. (eds.), Dawn of the age of dinosaurs in the American Southwest: New Mexico Museum of Natural History, Albuquerque, pp. 223–232.

Lehman, T. M., 1994, The saga of the Dockum Group and the case of the Texas/New Mexico boundary fault: New Mexico Bureau of Mines and Mineral Resources, Bulletin 150, pp. 37–51.

Litwin, R. J., Traverse, A., and Ash, S. R., 1991, Preliminary palynological zonation of the Chinle Formation, southwestern U.S.A., and its correlation to the Newark Supergroup (eastern U.S.A.): Review of Palaeobotany and Palynology, v. 68, pp. 269–287.

Lockley, M. G., and Hunt, A. P., 1993, A new Late Triassic tracksite from the Sloan Canyon Formation, type section, Cimarron Valley, New Mexico: New Mexico Museum of Natural History and Science, Bulletin 3, pp. 279–283.

Lucas, S. G., 1991a, Correlation of Triassic strata of the Colorado Plateau and southern High Plains, New Mexico: New Mexico Bureau of Mines and Mineral Resources, Bulletin 137, pp. 47–56.

Lucas, S. G., 1991b, Southeasternmost outcrops of the Morrison Formation, Capitan, Lincoln County, New Mexico; *in* Barker, J. M., Kues, B. S., Austin, G. S., and Lucas, S. G. (eds.), Geology of the Sierra Blanca, Sacramento and Capitan Ranges, New Mexico: New Mexico Geological Society, Guidebook 42, p. 41.

Lucas, S. G., 1991c, Triassic stratigraphy, paleontology and correlation, south-central New Mexico; *in* Barker, J. M., Kues, B. S., Austin, G. S., and Lucas, S. G. (eds.), Geology of the Sierra Blanca, Sacramento and Capitan Ranges, New Mexico: New Mexico Geological Society, Guidebook 42, pp. 243–259.

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

Lucas, S. G., in press, The Chinle Group, western United States: a nonmarine standard for Late Triassic time; *in* Dickins, J. M., Yin, H., and Lucas, S. G. (eds.), Permo–Triassic of the Circum-Pacific: Cambridge University Press, Cambridge.

Lucas, S. G., and Anderson, O. J., 1992, Triassic stratigraphy and correlation, west Texas and eastern New Mexico; *in* Cromwell, D. W., Moussa, M. T., and Mazzullo, L. J. (eds.), Transactions Southwest Section AAPG, Midland, Texas, 1992: West Texas Geological Society, Midland, pp. 201–207.

Lucas, S. G., and Anderson, O. J., 1993a, Stratigraphy of the Permian–Triassic boundary in southeastern New Mexico and west Texas; *in* Love, D. W., Hawley, J. W., Kues, B. S., Adams, J. W., Austin, G. S., and Barker, J. M. (eds.), Carlsbad region, New Mexico and west Texas: New Mexico Geological Society, Guidebook 44, pp. 219–230.

Lucas, S. G., and Anderson, O. J., 1993b, Triassic stratigraphy in southeastern New Mexico and southwestern Texas; *in* Love, D. W., Hawley, J. W., Kues, B. S., Adams, J. W., Austin, G. S., and Barker, J. M. (eds.), Carlsbad region, New Mexico and west Texas: New Mexico Geological Society, Guidebook 44, pp. 231–235.

Lucas, S. G., and Hayden, S. N., 1989a, Triassic stratigraphy of west-central New Mexico; *in* Anderson, O. J., Lucas, S. G., Love, D. W., and Cather, S. M. (eds.), Southeastern Colorado Plateau: New Mexico Geological Society, Guidebook 40, pp. 191–211.

Lucas, S. G., and Hayden, S. N., 1989b, Middle Triassic Moenkopi Formation, Nacimiento Mountains, north-central New Mexico; *in* Lorenz, J. C., and Lucas, S. G. (eds.), Energy frontiers in the Rockies: Albuquerque Geological Society, pp. 16–17.

Lucas, S. G., and Hayden, S. N., 1991, Type section of the Permian Bernal Formation and the Permian–Triassic boundary in north-central New Mexico: New Mexico Geology, v. 13, pp. 9–15.

Lucas, S. G., and Heckert, A. P., 1994, Triassic stratigraphy in the Lucero uplift, Cibola, Valencia and Socorro Counties, New Mexico; *in* Chamberlin, R. M., Kues, B. S., Cather, S. M., Barker, J. M., and McIntosh, W. C. (eds.), Mogollon slope, west-central New Mexico and east-central Arizona: New Mexico Geological Society, Guidebook 45, pp. 241–254.

Lucas, S. G., and Huber, P., 1994, Sequence stratigraphic correlation of Upper Triassic marine and nonmarine strata, western United States and Europe: Canadian Society of Petroleum Geologists, Memoir 17, pp. 241–254.

Lucas, S. G., and Hunt, A. P., 1987, Stratigraphy of the Anton Chico and Santa Rosa Formations, Triassic of east-central New Mexico: Journal of the Arizona–Nevada Academy of Science, v. 22, pp. 21–33.

Lucas, S. G., and Hunt, A. P., editors, 1989a, Dawn of the age of dinosaurs in the American Southwest: New Mexico Museum of Natural History, Albuquerque, 414 pp.

Lucas, S. G., and Hunt, A. P., 1989b, Revised Triassic stratigraphy in the Tucumcari basin, east-central New Mexico; *in* Lucas, S. G., and Hunt, A. P. (eds.), Dawn of the age of dinosaurs in the American Southwest: New Mexico Museum of Natural History, Albuquerque, pp. 150–170.

Lucas, S. G., and Hunt, A. P., 1990, Upper Triassic Owl Rock and Rock Point Members, Chinle Formation, Petaca Pinta, Cibola County, New Mexico: New Mexico Geology, v. 12, p. 92.

Lucas, S. G., and Hunt, A. P., 1992, Triassic stratigraphy and paleontology, Chama Basin and adjacent areas, north-central New Mexico; *in* Lucas, S. G., Kues, B. S., Williamson, T. E., and Hunt, A. P. (eds.), San Juan Basin IV: New Mexico Geological Society, Guidebook 43, pp. 151–172.

Lucas, S. G., and Hunt, A. P., 1993, Tetrapod biochronology of the Chinle Group (Upper Triassic), western United States: New Mexico Museum of Natural History and Science, Bulletin 3, pp. 327–329.

Lucas, S. G., and Marzolf, J. E., 1993, Stratigraphy and sequence stratigraphic interpretation of Upper Triassic strata in Nevada; *in* Dunn, G., and McDougall, K. (eds.), Mesozoic paleogeography of the western United States—II: Pacific Section SEPM, Book 71, pp. 375–388.

Lucas, S. G., and Morales, M., 1985, Middle Triassic amphibian from the basal Santa Rosa Formation, east-central New Mexico; *in* Lucas, S. G., and Zidek, J. (eds.), Santa Rosa–Tucumcari region: New Mexico Geological Society, Guidebook 36, pp. 56–58.

Lucas, S. G., and Morales, M., editors, 1993, The nonmarine Triassic: New Mexico Museum of Natural History and Science, Bulletin 3, 517 pp.

Lucas, S. G., Anderson, O. J., and Hunt, A. P., 1994, Triassic stratigraphy and correlations, southern High Plains of New Mexico–Texas: New Mexico Bureau of Mines and Mineral Resources, Bulletin 150, pp. 105–126.

Lucas, S. G., Hunt, A. P., and Hayden, S. N., 1987, The Triassic System in the Dry Cimarron Valley, New Mexico, Colorado and Oklahoma; *in* Lucas, S. G., and Hunt, A. P. (eds.), Northeastern New Mexico: New Mexico Geological Society, Guidebook 38, pp. 97–117.

Lucas, S. G., Hunt, A. P., and Huber, P., 1990, Triassic stratigraphy in the Sangre de Cristo Mountains, New Mexico; *in* Bauer, P. W., Lucas, S. G., Mawer, C. K., and McIntosh, W. C. (eds.), Tectonic development of the southern Sangre de Cristo Mountains, New Mexico: New Mexico Geological Society, Guidebook 41, pp. 305–318.

(Continued on p. 17)

biochronology thus indicates a short hiatus in the U-Bar Formation at the Aptian–Albian boundary. This hiatus is equivalent to one ammonite zone, the earliest Albian *Hypacanthoplites cragini* zone. A marked lithologic change from *Exogyra* packstones of the uppermost oyster-limestone member to calcareous shales and ledgy, nodular limestones of the overlying limestone-shale member is physical evidence of the disconformity equivalent to this hiatus. In southeastern Arizona, the Aptian–Albian boundary is approximately at the lower Mural–upper Mural contact, and in central Texas it is at the contact of the Hensel Formation with the overlying Glen Rose Limestone, but at these sections earliest Albian strata are present. This suggests that tectonism local to southwestern New Mexico affected marine deposition during the Aptian–Albian transition. □

New Mexico Museum of Natural History and Science exhibit

On June 3, 1995 the New Mexico Museum of Natural History and Science (Albuquerque) will open its new exhibit featuring Early Permian footprints found in the Robledo Mountains near Las Cruces. The exhibit, "Ancient Evidence: Life Before the Dinosaurs," focuses on the phenomenal fossil record of invertebrate and vertebrate tracks preserved in Lower Permian strata of the Abo–Hueco transitional zone in Doña Ana County. In quantity, quality of preservation, and diversity of trackmakers, the Doña Ana County tracks are the best record on earth, one that provides a unique glimpse of terrestrial life and locomotion some 280 million years ago. The exhibit, which occupies about 2,000 square feet, reconstructs the environment in which the tracks were formed; Hueco Formation invertebrates and fossil driftwood are displayed with numerous tracks. The visitor is also taught how fossil tracks are studied and identified.

The New Mexico Museum of Natural History and Science is open 9am–5pm seven days a week; for more information, call (505) 841-8837. □

Barroll and Reiter
(Continued from p. 7)

and potential: Transactions of the Geothermal Resource Council, v. 4, pp. 61–64.

Keller, C. R., and Cordell, L., 1983, Bouguer gravity anomaly map of New Mexico: New Mexico Energy Institute, Las Cruces.

Reiter, M., Eggleston, R. E., Broadwell, B. R., and Minier, J., 1986, Estimates of terrestrial heat flow from deep petroleum tests along the Rio Grande rift in central and southern New Mexico: Journal of Geophysical Research, v. B91, pp. 6225–6245.

Weir, J. E., 1965. Geology and availability of ground water in the northern part of the White Sands Missile Range and vicinity, New Mexico: U.S. Geological Survey, Water-supply Paper 1801, 78 pp.

Appendix A
Present status of "B" series wells in the study area

We attempted to locate the "B" series of wells drilled by the USGS on the Bosque del Apache and described by Cooper (1968). It was found that none of these wells are accessible to a depth sufficient to allow temperature logging. (Subsurface temperature data shallower than about 90 ft is likely to be influenced by temperature fluctuations at the surface, and so such data is of little usefulness.)

B1—Apparently converted into a windmill well, named Army well. We located the well; it's an old broken-down windmill, no longer operational. Now open to about 40 ft (12.2 m), it still has the windmill 'sucker rods' in it, making access to the wellbore difficult.

B2—Cooper (1968) states this well was plugged and abandoned.

B3—Cooper (1968) states this well was plugged and abandoned.

B4—Cooper (1968) states this well was plugged and abandoned.

B5—This well is described as being drilled "on a topographical high in the old channel of the Rio Grande". We located the well in 1990 in the present channel of the Rio Grande, about 50 ft (15 m) from the east shore in shallow water. There is a concrete platform, which presumably was installed at about land surface, now about 3 ft (~1 m) above the surface of the water, attached to the well casing. The casing had a cover with a rusted-out hinge. When we opened the cover, the hinge broke. Inside the casing we found a 1" pipe that led to a serrated metal collar, below which the pipe seemed to widen, but which is blocked by a packer. Everything was rusted and couldn't be budged.

B6—Cooper (1968) reports this well was plugged and abandoned.

B7—We located this well just west of the road along a low-flow channel. The well was blocked just below the water level (no more than 10 ft [3.05 m] deep). □

Lucas
(Continued from p. 13)

Lucas, S. G., Hunt, A. P., and Morales, M., 1985, Stratigraphic nomenclature and correlation of Triassic rocks of east-central New Mexico: a preliminary report; *in* Lucas, S. G., and Zidek, J. (eds.), Santa Rosa–Tucumcari region: New Mexico Geological Society, Guidebook 36, pp. 171–184.

Marcou, J., 1858, Geology of North America, with two reports on the prairies of Arkansas and Texas, the Rocky Mountains of New Mexico and the Sierra Nevada of California: Zurich, 144 pp.

Marzolf, J. E., 1993, Palinspastic reconstruction of early Mesozoic sedimentary basins near the latitude of Las Vegas: implications for the early Mesozoic Cordilleran cratonal margin; *in* Dunn, G., and McDougall, K. (eds.), Mesozoic paleogeography of the western United States—II: Pacific Section SEPM, Book 71, pp. 433–462.

McKee, E. D., 1954, Stratigraphy and history of the Moenkopi Formation of Triassic age: Geological Society of America, Memoir 61, 133 pp.

Molina-Garza, R., Geissman, J. W., and Lucas, S. G., 1993, Late Carnian–early Norian magnetostratigraphy from nonmarine strata, Chinle Group, New Mexico: Contributions to the Triassic magnetic polarity time scale and the correlation of nonmarine and marine Triassic faunas: New Mexico Museum of Natural History and Science, Bulletin 3, pp. 345–352.

Morales, M., 1987, Terrestrial fauna and flora from the Triassic Moenkopi Formation of the southwestern United States: Journal of the Arizona–Nevada Academy of Science, v. 22, pp. 1–19.

O'Sullivan, R. B., 1974, The Upper Triassic Chinle Formation in north-central New Mexico; *in* Siemers, C. T., Woodward, L. A., and Callender, J. F. (eds.), Ghost Ranch: New Mexico Geological Society, Guidebook 25, pp. 171–174.

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

Steiner, M. B., and Lucas, S. G., 1992, A Middle Triassic paleomagnetic pole for North America: Geological Society of America, Bulletin, v. 104, pp. 993–998.

Steiner, M. B., Morales, M., and Shoemaker, E. M., 1993, Magnetostratigraphic, biostratigraphic, and lithologic correlations in Triassic strata of the western U.S.: SEPM, Special Publication 49, pp. 107–119.

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

Stewart, J. H., Poole, F. G., and Wilson, R. F., 1972b, Stratigraphy and origin of the Triassic Moenkopi Formation and related strata in the Colorado Plateau region: U. S. Geological Survey, Professional Paper 691, 195 pp.

Tozer, E. T., 1984, The Trias and its ammonoids: the evolution of a time scale: Geological Survey of Canada, Miscellaneous Report 35, 169 pp.

Tozer, E. T., 1994, Canadian Triassic ammonoid faunas: Geological Survey of Canada, Bulletin 467, 663 pp.

Visscher, H., 1992, The new STS stage nomenclature: Albertiana, no. 10, p. 1.

Wood, G. H., and Northrop, S. A., 1946, Geology of the Nacimiento Mountains, San Pedro Mountain, and adjacent plateaus in parts of Sandoval and Rio Arriba counties, New Mexico: U.S. Geological Survey, Oil and Gas Investigations Map OM-57. □