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# *Triassic stratigraphy and biostratigraphy in Socorro County, New Mexico*

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# TRIASSIC STRATIGRAPHY AND BIOSTRATIGRAPHY IN SOCORRO COUNTY, NEW MEXICO

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**Abstract**—The Triassic outcrops in Socorro County, New Mexico have received relatively little study compared to correlative strata in the north-central and east-central parts of the state. Triassic sections to the north of Carthage, Socorro County (T5S, R2E), encompass the Middle Triassic Moenkopi Formation and Upper Triassic Chinle Group (Shinarump and San Pedro Arroyo formations). The Moenkopi Formation (Anton Chico Member) disconformably overlies the siltstone-dominated Middle Permian Artesia Formation and is mostly cross-bedded sandstones and less common beds of mudstone, siltstone and intraformational conglomerate. Fragmentary capitosauroid amphibian material near the top of the unit near Carthage are the only identifiable fossils collected from the Moenkopi Formation in Socorro County and are consistent with assigning it a Perovkan (Anisian) age. The Shinarump and San Pedro Arroyo formations of the Chinle Group disconformably overlie the Moenkopi Formation in Socorro County; this is the Tr-3 unconformity, a hiatus of approximately 10 million years. The San Pedro Arroyo Formation is interbedded mudstone and sandstone except for the Ojo Huelos Member, which is a prominent limestone interval that can be used regionally as a marker bed. The San Pedro Arroyo Formation can be subdivided into three member-rank units (in ascending order): the Araya Well, Ojo Huelos and Cañon Agua Buena members; two of which are named here (the Araya Well and Cañon Agua Buena). The Araya Well Member is mudstone dominated with a few siltstones, thinly laminar sandstones and pebble conglomerates. Lithology within the Ojo Huelos Member ranges from lime mudstone to brecciated and pisolitic limestone; the member is a calcrete complex. The Cañon Agua Buena Member consists of thick (>10 m) mudstone slopes with numerous micaceous sandstone ledges. Fossils from the San Pedro Arroyo Formation are characteristic of Late Triassic tetrapod faunas in being metoposaur- and phytosaur-dominated. Abundant fossils of large metoposaurid amphibians have been recovered from the Araya Well and the Ojo Huelos members, and this corresponds to the previously established "metoposaurid acme zone" within the Chinle, which, in addition to a record of *Desmatosuchus* in the Cañon Agua Buena Member, suggests an Adamanian age for much of the San Pedro Arroyo Formation, including the Ojo Huelos Member. The Cretaceous Dakota Formation and/or a thin section of Upper Jurassic Morrison Formation unconformably overlies the San Pedro Arroyo Formation near Carthage.

## INTRODUCTION

The Triassic outcrops of Socorro County, New Mexico (Fig. 1) have received relatively little study, compared to correlative strata in the north-central (Chama Basin: Lucas et al., 2003; 2005a), east-central (Tucumcari area: Lucas et al., 2001) and west-central (Lucas and Heckert, 1994; Heckert and Lucas, 2003) parts of the state. In addition, only a limited Triassic vertebrate fauna has been documented from Socorro County, compared to extensive fossil collections made elsewhere in the state (e.g., Hunt, 2001; Zeigler et al., 2003; Heckert et al., 2005a), and neighboring Arizona (Heckert et al., 2005b) and West Texas (Lucas et al., 1993). Here, we revise previous stratigraphic nomenclature used for the Triassic strata in Socorro County (Fig. 1), summarize the Triassic vertebrate fauna and discuss the age of the principal stratigraphic units. **Institutional abbreviations:** NMMNH, New Mexico Museum of Natural History and Science, Albuquerque; UMMP, University of Michigan Museum of Paleontology, Ann Arbor.

## PREVIOUS STUDIES

Minimal mapping and fossil collecting has focused on the Triassic rocks of Socorro County. Case (1916, p. 708), in a brief note, first reported on Permian and Triassic vertebrates from Socorro County, including indeterminate reptile, phytosaur and amphibian fossils from "two or three miles north of Carthage, New Mexico." Darton (1928), based on field observations, produced a stratigraphic nomenclature for the Triassic rocks of Lincoln County; this nomenclature was applied to neighboring Valencia and Socorro counties. It simply subdivided the Triassic strata into a sandstone-dominated lower unit, identified as the Santa Rosa Sandstone, and an upper mudstone-dominated unit, referred to as the Chinle Formation (or Chinle Shale), both within the Dockum Group (Fig. 2). This nomenclature was used extensively from the 1950s through the 1970s (e.g., Allen and Jones, 1951; Rawson, 1957; Budding, 1964; Smith, 1964; Weber, 1964; Haines, 1968; Ryberg, 1968; Kelley, 1971, 1972a,b).

The most recent study of the Triassic stratigraphy in Socorro County was by Lucas (1991). He recognized that what had previously been termed the Santa Rosa Sandstone actually included Moenkopi Formation (Anton Chico Member) strata of Middle Triassic age and Upper Triassic Santa Rosa Formation or Shinarump Formation (Chinle Group) rocks. Further, he named the San Pedro Arroyo Formation for "the mudstone-dominated Chinle Group strata above the Shinarump and Santa Rosa formations in south-central New Mexico" (Lucas, 1991, p. 246). One of the unique features of the San Pedro Arroyo Formation is the Ojo Huelos Member, also named by Lucas (1991), a persistent limestone bed(s) stratigraphically low in the formation in Valencia and Socorro counties.

## STRATIGRAPHY

Triassic strata in Socorro County pertain to the Middle Triassic Moenkopi Formation (Anton Chico Member) and the Upper Triassic Shinarump and San Pedro Arroyo formations (Fig. 3). Previously, only a single member, the Ojo Huelos, of the San Pedro

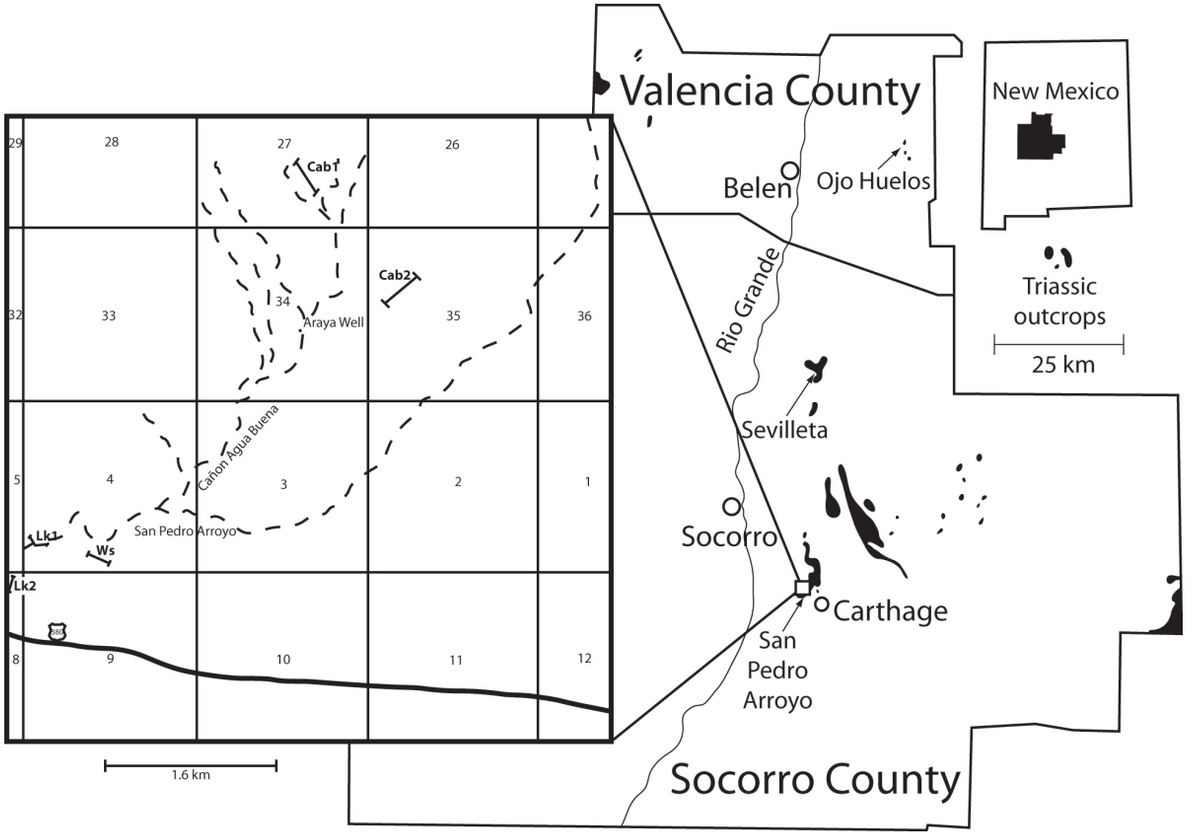



FIGURE 1. Regional map of Valencia and Socorro counties with Triassic outcrops highlighted and locations of measured sections labeled (modified from Lucas [1991]). Inset map of Carthage/San Pedro Arroyo area (T5S, R2E). **Abbreviations: Cab** = Cañon Agua Buena; **Lk** = Lime kilns; **Ws** = Weber's site.

Arroyo Formation was recognized; here, we name two new members of the San Pedro Arroyo Formation, the Araya Well Member and the Cañon Agua Buena Member (Fig. 2).

Field observations in Socorro County, specifically near Carthage, have added significantly to our understanding of the Triassic section (Fig. 3). We have used our recent, additional measured sections (see Fig. 3 and the Appendix for details) to augment the work of Lucas (1991); in addition, we have placed all vertebrate fossil localities from this area into stratigraphic context.

## Moenkopi Formation

The Anton Chico Member of the Moenkopi Formation is up to 61.2 m thick in Socorro County, but farther east in Lincoln County it is nearly twice as thick (102 m: Lucas, 1991). It disconformably overlies the Permian Artesia Formation (Tr-1 unconformity of Pipiringos and O'Sullivan, 1978), and is disconformably overlain by the Upper Triassic Shinarump Formation; this is the Tr-3 unconformity of Pipiringos and O'Sullivan (1978). In Socorro County, the Moenkopi Formation thins southward, which corresponds to an increase in thickness of the overlying Shinarump Formation.

The base of the Moenkopi Formation is generally a moderately thick (1-4 m) laminar or trough crossbedded sandstone, with, in

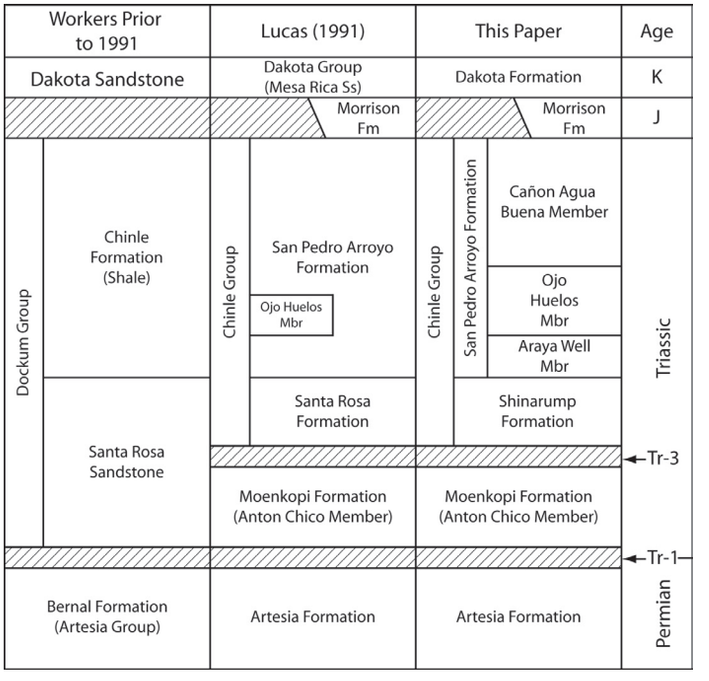



FIGURE 2. Comparison of stratigraphic nomenclature of Triassic strata in Socorro County used by previous workers with that advocated here. Modified from Lucas (1991).

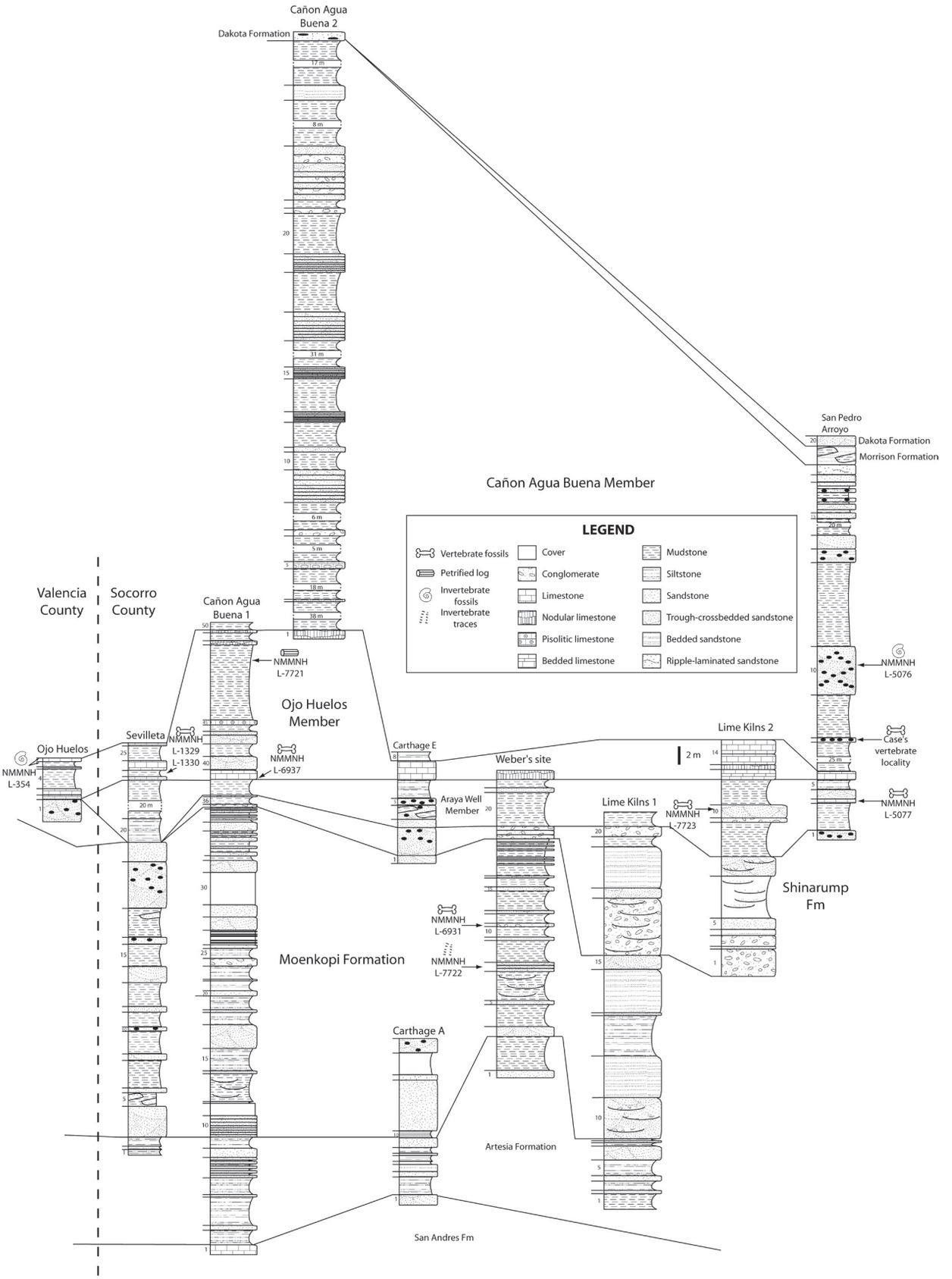



FIGURE 3. Measured sections of Triassic strata in Valencia and Socorro counties. See Fig. 1 for locations of sections. Ojo Huelos, Sevilleta, Carthage A and E and San Pedro Arroyo from Lucas (1991). L = NMMNH fossil locality. See Appendix for lithologic descriptions of numbered units of previously unpublished sections.

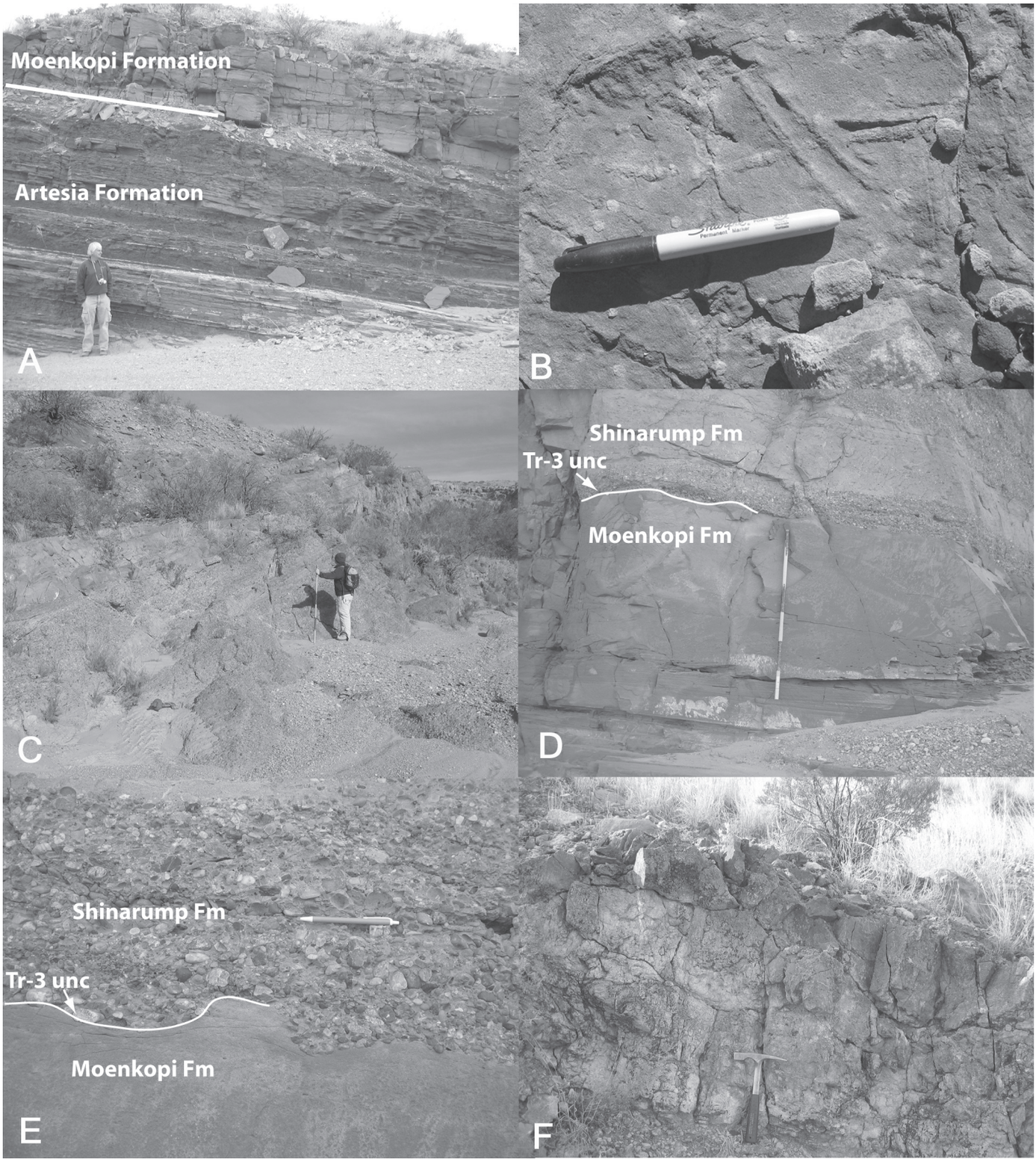



FIGURE 4. Photographs of key beds in the Permian, Middle and Upper Triassic sections of Socorro County. **A**, Artesia Formation/Moenkopi Formation contact at Lime Kilns 1 section. **B**, Invertebrate feeding trace, *Scoyenia*, at NMMNH L-7722, in the Moenkopi Formation. **C**, Shinarump Formation conglomerate at Lime Kilns 1 section (bed 16). **D**, Shinarump Formation conglomerate overlying Moenkopi Formation sandstone at Lime Kilns 1 section. **E**, Detail of the contact in **D**, the Tr-3 unconformity, Shinarump Formation unconformably overlying the Moenkopi Formation. **F**, Overview of the Ojo Huelos Member at the Lime Kilns 2 section.

at least one section, mud chip conglomeratic lenses (Lime Kilns 1, Fig. 3; Appendix). This differs considerably from the underlying Artesia Formation, which is composed of siltstone slopes and ripple-laminated or massive, gypsiferous sandstones. The Moenkopi Formation can also be distinguished from underlying Artesia Formation strata (Fig. 4A) by color (Moenkopi – grayish red, Artesia – reddish brown), bedforms (Moenkopi – trough crossbedded, Artesia – laminar), grain size (Moenkopi – coarser grained with intraformational conglomerate lenses) and sandstone lithology (Moenkopi – litharenite, Artesia – quartzarenite, some beds gypsiferous). The contact of the Moenkopi Formation with the overlying Shinarump Formation is placed beneath the lowest extrabasinal conglomerate or conglomeratic sandstone (Figs. 3, 4D-E).

In Socorro County, the Moenkopi Formation is sandstone dominated (~60% of the measured section), with red to gray, litharenitic or sub-arkosic, trough crossbedded sandstones being most common (Figs. 3, 4A). Invertebrate feeding traces, *Scoyenia*, were observed in one of the multistoried sandstones of the formation (bed 7, Weber's site section, Fig. 4B). However, in one section the unit is mudstone-dominated (Weber's site, Fig. 3; Appendix). The slope-forming units of the Moenkopi are red or gray mudstones/siltstones, with rare sandstone lenses. Intraformational conglomerates with rip-ups of red mud and clay are rare (bed 24, Cañon Agua Buena 1 section).

## Chinle Group

### Shinarump Formation

Our new data indicate that in Socorro County the Shinarump Formation is up to 21.2 m thick, considerably thicker than the 5.5 m observed by Lucas (1991), with a minimum thickness of 1.3 m (Figs. 3, 4C). Lucas (1991) identified a mottled strata unit (laterally equivalent to the Shinarump), consisting of silty sandstone and conglomerates that we include in our Shinarump Formation, given the predominance of conglomerates. The lack of paleosols precludes assignment of the mottled strata unit to the Zuni Mountains Formation (Heckert and Lucas, 2003). In Socorro County, the Shinarump disconformably overlies the Middle Triassic Moenkopi Formation and is conformably overlain by the lower member (Araya Well Member) of the San Pedro Arroyo Formation.

The base of the Shinarump Formation is the lowest extrabasinal conglomerate or conglomeratic sandstone (Fig. 3). Conglomerates dominate the unit (~75%) and have varied compositions: extrabasinal coarse conglomerates with cherts, quartzite, limestone nodules and fossil bones as clasts (bed 39, Cañon Agua Buena 1 section); multistoried, trough crossbedded extraformational conglomerates (bed 19, Weber's site section); and siliceous conglomerate with black and white chert (up to 10 cm in diameter)(bed 3, Lime Kilns 2 section). Rare lithologies within the Shinarump include thins beds of red mudstone (bed 17, Lime Kilns 1 section), trough crossbedded sandstone (bed 7, Lime Kilns 2 section) and laminar sandstone (bed 4, Lime Kilns 2 section).

### San Pedro Arroyo Formation

The San Pedro Arroyo Formation conformably overlies the Shinarump Formation and represents the rest of the Upper Triassic section in Socorro County. The only complete section of the San Pedro Arroyo Formation is the type section, where all three members are exposed. In ascending order, the members of the San Pedro Arroyo Formation are the Araya Well, Ojo Huelos and the Cañon Agua Buena members. The Ojo Huelos Member was named by Lucas (1991); the Araya Well and Cañon Agua Buena members are named and described below for two distinctive, laterally extensive lithosomes that are recognized throughout our study area.

### Araya Well Member

We name the lower, mudstone-dominated unit of the San Pedro Arroyo Formation the Araya Well Member. The name is for the Araya Well in the NE ¼, SE ¼, sec. 34, T4S, R2E (Fig. 1). The base of the Araya Well Member is the first prominent mudstone/siltstone slope (or in one section sandstone) above the highest conglomerate or conglomeratic sandstone of the Shinarump Formation. At the type section, Lime Kilns 2 (Fig. 3; Appendix), the Araya Well Member is 8.2 m thick, though the unit ranges in thickness from 30.6 m (Sevilleta section) to 1.7 m (Cañon Agua Buena 1 section).

The Araya Well Member is dominated by red and yellow mudstones (~70%); rarer lithologies include: grayish red and pale green, non-calcareous siltstone (bed 6, Carthage E section), grayish red trough-crossbedded, thinly laminar sandstone (bed 4, Carthage E section) and calcareous siltstone or clay pebble conglomerate (bed 9, Lime Kilns 2 and bed 5, Carthage E section). The Araya Well Member is a slope-forming unit conformably overlain by the ledge-forming, limestone-dominated Ojo Huelos Member. The base of the Ojo Huelos Member is the first ledge-forming limestone bed above slope-forming strata of the Araya Well Member.

### Ojo Huelos Member

Lucas (1991) reported 7.4 m as the maximum thickness of the Ojo Huelos Member, based on the type section at Ojo Huelos near Belen. Our recent field observations have recognized significantly thicker sections of this unit, with 16.5 m as the maximum thickness at the Cañon Agua Buena 1 section. The base of the Ojo Huelos Member is the lowest limestone bed above the Araya Well Member. Limestones dominate the unit but show variation in their composition, from nodular to brecciated to pisolitic limestone (Fig. 5A-C). Also, we noted in at least one section (Cañon Agua Buena 1) the pisolites near the base of the Ojo Huelos (bed 39) are considerably larger in diameter than pisolites higher in the member (bed 45). Minor lithologies within the unit include: sandy mudstone (bed 2, Cañon Agua Buena 2 section), variegated mudstone (bed 21, Sevilleta Grant section), purple/gray bentonitic mudstone (bed 48, Cañon Agua Buena 1 section), yellow

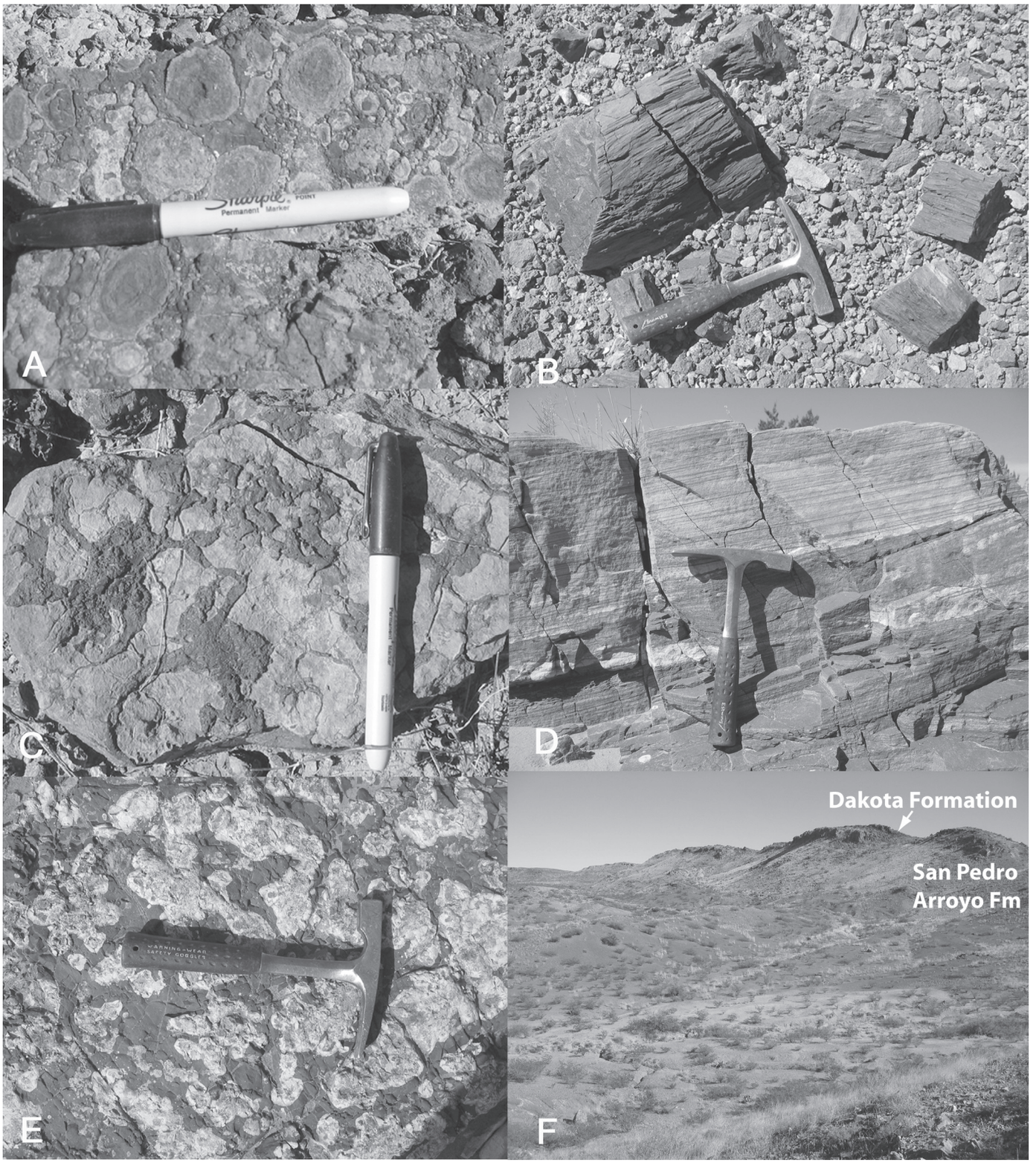



FIGURE 5. Photographs of key beds in the Upper Triassic section of Socorro County. **A**, Close-up of lower Ojo Huelos Member pisolitic limestone, with large pisolites in the Cañon Agua Buena 1 section. **B**, Petrified log in the upper part of the Ojo Huelos Member (NMMNH L-7721). **C**, Brecciated limestone at the top of the Ojo Huelos Member in the Cañon Agua Buena 1 section. **D**, Typical thin-bedded sandstone of the Cañon Agua Buena Member in Cañon Agua Buena 2 section. **E**, Calcrete bed in the Cañon Agua Buena Member of the San Pedro Arroyo Formation in the Cañon Agua Buena 2 section. **F**, Overview of type section of the San Pedro Arroyo Formation with Cretaceous Dakota Formation forming the ridges of the cuesta.

shale (bed 44, Cañon Agua Buena 1 section) and trough crossbedded, litharenitic sandstone (bed 43, Cañon Agua Buena 1 section). One of the basal pisolitic limestone beds (bed 39, Cañon Agua Buena 1) includes conglomeratic lenses with fossil bone (NMMNH L-6937).

The Ojo Huelos Member is a persistent, distinctive marker unit throughout the Upper Triassic section in both Valencia and Socorro counties, from Hubbell Springs near Belen and Carrizo Arroyo in the Lucero uplift to its southernmost outcrop near Carthage (Lucas, 1991; Lucas et al., 2004; Cather and Osburn, 2007). We interpret most (or all) of the limestone beds in the Ojo Huelos Member as calcrete beds; indeed, the pisolites from the unit are likely pedogenic in origin (L. Tanner, written commun., 2009). This suggests the Ojo Huelos Member represents a stable, well-drained landscape at a point early in Chinle deposition.

### Cañon Agua Buena Member

The upper mudstone-dominated unit of the San Pedro Arroyo Formation, with prominent sandstone beds, is named the Cañon Agua Buena Member. This unit is named for Cañon Agua Buena, a prominent drainage that runs roughly north-south through sections 11-14, 23-24 of T4S, R2E. At its type section (Cañon Agua Buena 2, Fig. 3; Appendix), the unit is 183.3 m thick. Brown/purple, red and reddish-brown mudstones dominate the unit (~60%), and numerous micaceous sandstone ledges are conspicuous within the unit (Fig. 5E) and vary in lithology from crossbedded, multistoried and conglomeratic (beds 13, 17, Cañon Agua Buena 2 section) to thinly laminar (bed 19, Cañon Agua Buena 2 section) to ripple laminated (bed 18, San Pedro Arroyo section). Minor lithologies include nodular calcrete (beds 3 and 5, Cañon Agua Buena 2 section), conglomeratic limestone with calcrete nodules (bed 7, Cañon Agua Buena 2 section), multistoried conglomerate with sandstones (bed 23, Cañon Agua Buena 2 section) and limestone- and mudstone-pebble conglomerate (bed 8, San Pedro Arroyo section). The base of the Cañon Agua Buena Member is the first mudstone above the highest limestone bed of the Ojo Huelos Member. However, it should be noted that farther east, in Lincoln County, the Cañon Agua Buena Member directly overlies the Santa Rosa Formation in at least one section (Round Tank) reported by Lucas (1991), suggesting that the lower members of the San Pedro Arroyo Formation are not present east of Socorro County. The Cañon Agua Buena Member is distinguished from the lower, Araya Well Member by its multistoried, micaceous sandstone ledges. The Cañon Agua Buena Member is disconformably overlain by the Upper Jurassic Morrison Formation and/or the Cretaceous Dakota Formation (Figs. 3, 5F).

## PALEONTOLOGY

A limited fossil record is known from the Triassic outcrops of Socorro County, when compared to the rich and diverse assemblages found in the Chama Basin and Tucumcari areas of New Mexico. The Middle Triassic strata yield sparse fossils, mostly bone fragments as clasts in the intraformational conglomerates of the Moenkopi Formation (Anton Chico Member).

Middle Triassic fossils from Socorro County include: an isolated intercentrum and associated skull fragments of a capitosauroid amphibian (Fig 6A-B). Lucas (1991) originally reported a capitosauroid intercentrum from the Carthage E section (bed 14). Additional capitosauroid fossils were discovered by the late Robert Weber in May 2006 in the middle of the Moenkopi Formation (NMMNH locality 6931), and were subsequently donated and cataloged into the NMMNH fossil collection. This material consists of numerous dermal bones and natural casts that we identify as the incomplete skull of a capitosauroid amphibian. The elongate, pustulose patterning of the grooves and pits in the dermal bone is distinct from other contemporaneous labyrinthodont amphibians, which general have a series of closely space pits giving their dermal bone a honeycomb-like texture (Schoch and Milner, 2000).

The invertebrate feeding trace *Scoyenia* occurs in the middle of the Moenkopi Formation (Fig. 4B), at the top of a multistoried, trough-crossbedded, litharenitic sandstone (bed 7, Weber's site section). *Scoyenia* is indicative of an unstable, fluvial substrate (e.g., Buatois and Mángano, 2004).

An archosaur centrum and various bone fragments from an intraformational conglomerate (NMMNH L-7723, bed 9, Lime Kilns section; NMMNH L-5077, bed 3, San Pedro Arroyo section) are the only fossils known from the Araya Well Member of the San Pedro Arroyo Formation (Fig. 3).

Lucas (1991) first reported a fish and invertebrate fauna from the Ojo Huelos Member at its type section in Valencia County (NMMNH locality 354). This fauna included isolated teeth and scales of actinopterygians, neoselachians and a hybodont shark, *Lissodus* cf. *L. humblei*, as well as ostracodes, two species of *Darwinula* and ?*Gerdalia triassica*. Heckert and Lucas (2002; Heckert, 2004) added to this fauna a "spirorbid polychaete" gastropod, *Lissodus humblei*, numerous indeterminate fish (chondrichthyan, redfieldiid, semionotid, actinopterygian), amphibian (temnospondyl), reptile and vertebrate (coprolites) microfossils.

In Socorro County, the Ojo Huelos Member has yielded two fossil collecting areas, one near the Sevilleta section (NMMNH localities 1329 and 1330; unit 23) and one near the Cañon Agua Buena 1 section (NMMNH L-6937 and L-7721; units 39 and 46, respectively). The Sevilleta localities yielded a metoposaurid interclavicle fragment, originally reported by Lucas (1991) as *Metoposaurus* sp. The lack of skull material precludes a genus- or species-level identification. The lower Cañon Agua Buena locality (NMMNH L-6937) is the most diverse assemblage within the Ojo Huelos Member; it includes abundant metoposaur skull, clavicular and vertebral material (Fig. 6C-F), indeterminate archosaur pelvic and limb fossils and isolated phytosaur centra (Fig. 6G-I) and dorsal osteoderms (Fig. 6J). The upper Cañon Agua Buena locality yielded fragments of petrified wood, up to 10 cm in diameter (Fig. 5B).

Case (1916) reported invertebrates (unionid bivalves), amphibians ("stegocephalian," probably metoposaurid), parasuchid (phytosaur) reptiles and indeterminate reptile fossils from the Cañon Agua Buena Member north of Carthage. However, he did not provide precise stratigraphic data, so the location of these occurrences can only be inferred. He noted abundant bivalves in

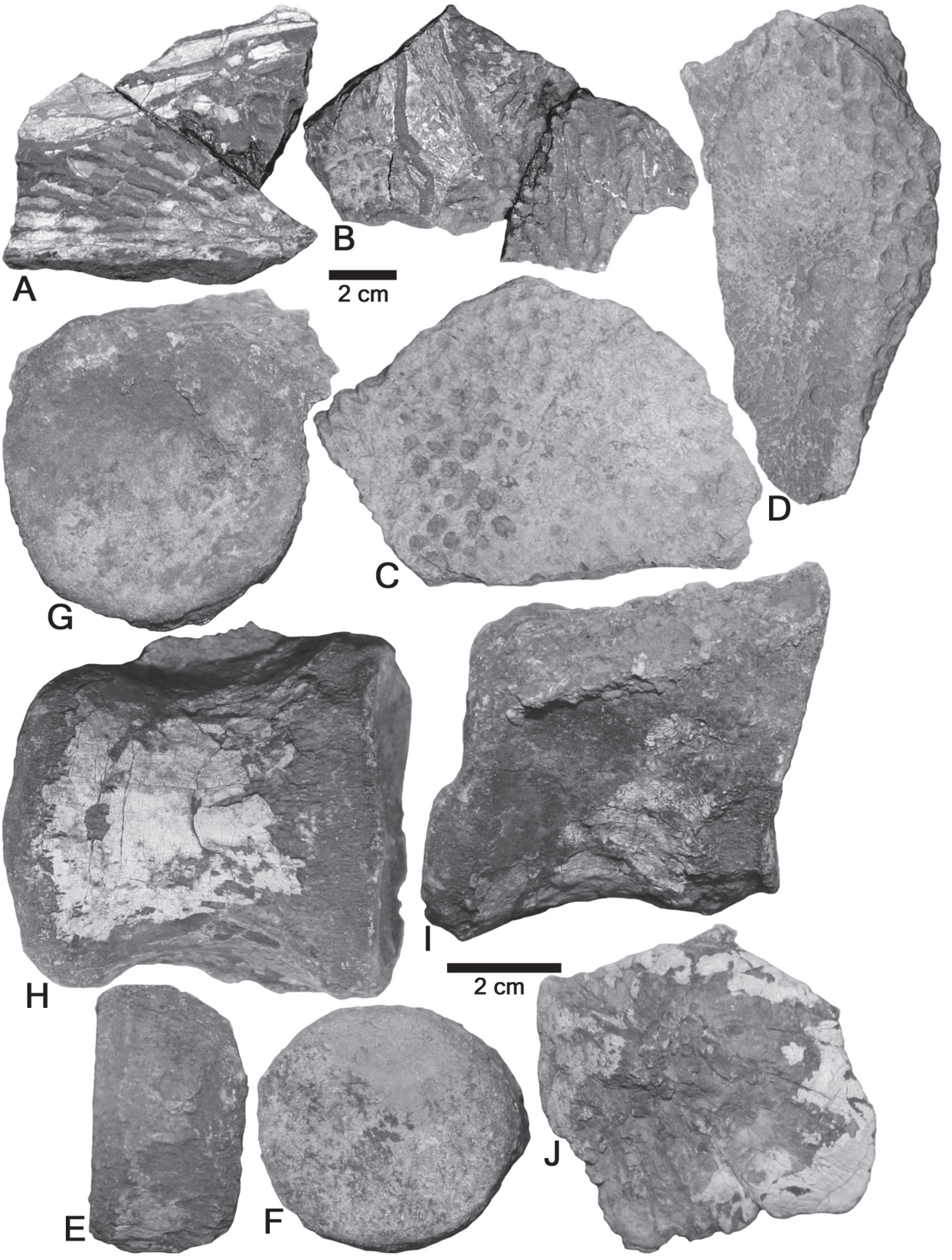



FIGURE 6. Triassic vertebrates from Socorro County. **A-B**, Capitosauroid amphibian, NMMNH P-58077 from locality 6931, skull bone fragments and natural casts of dermal bone. **C-F**, Metoposaurid amphibians from locality 6937. **C**, NMMNH P-58080, interclavicle fragment in ventral view. **D**, NMMNH P-58081, clavicle fragment in ventral view. **E-F**, centrum in **E**, lateral and **F**, anterior view. **G-J**, Phytosaur (Parasuchidae) from locality 6937. **G-I**, NMMNH P-58078, caudal centrum in **G**, posterior, **H**, ventral and **I**, right lateral views **J**, NMMNH P-58079, dorsal osteoderm.

very small patches "close to the lime kiln and about half way up to the base of the Cretaceous…[in] a small bed of conglomerate" (Case, 1916, p. 708). The level of Case's conglomerate likely corresponds to bed 10 (NMMNH L-5076) of the San Pedro Arroyo section of Lucas (1991). Case (1916) described a small fragment of phytosaur jaw (UMMP 9656), which he originally assigned to *Angistorhinus* or *Mystriosuchus*. However, given that phytosaur taxonomy is based primarily on the morphology of the posterior half of the skull roof (Long and Murry, 1995), this jaw fragment is likely not diagnostic below the family level. In addition, Case (1916) listed the following phytosaur material: three vertebrae (UMMP 9651), the proximal and distal ends of a limb bone, probably a humerus (UMMP 9653) and two small dorsal osteoderms. Indeterminate reptile material consisted of various ends of large limb bones, two of which he identified as the ends of tibia and radius. The amphibian material collected by Case include two fragments of a clavicle with radial pitting and a large vertebral centrum (UMMP 9652). The radial pitting on the clavicle identifies the material as metoposaurid. The vertebrate material was all collected from a single locality, possibly within bed 8 of Lucas' (1991) San Pedro Arroyo section. Thus, both the invertebrate and vertebrate localities of Case (1916) occur stratigraphically low in the Cañon Agua Buena Member (San Pedro Arroyo Formation).

Lucas and Heckert (1994, fig. 9) reported and illustrated a fragment of a dorsal paramedian osteoderm of an aetosaur from their Rio Salado section in the Lucero uplift of Socorro County. They identified this specimen as *Desmatosuchus* based on the deep, random pitting that is arranged along the preserved margin of the osteoderm. Given the incomplete nature of this material we tentatively agree with their identification of the specimen. This specimen was recovered from the middle of the Cañon Agua Buena Member, and is stratigraphically the highest fossil occurrence in the San Pedro Arroyo Formation.

## BIOSTRATIGRAPHY

The fossil record of the Triassic strata in Socorro County is limited, but provides taxa that indicate the age of most of the Triassic section.

The Anton Chico Member of the Moenkopi Formation has long been considered Middle Triassic (Anisian) in age based on its vertebrate fauna and magnetostratigraphy (Lucas and Schoch, 2002). Notable Anisian age faunas from the correlative Holbrook Member of the Moenkopi in Arizona, including the Geronimo, Holbrook area, Joseph City and Radar Mesa, all contain abundant capitosauroids (e.g., Heckert et al., 2005b, table 2). These faunas are of Perovkan age, following the land-vertebrate faunachron scheme of Lucas (1998; Lucas et al., 2007). The presence of a capitosauroid amphibian in the Moenkopi in Socorro County supports a Perovkan age assignment.

Only very limited fossil remains, none of them age diagnostic, have been collected from the Shinarump Formation of Socorro County. Based on plant biostratigraphy (Ash, 1980) and palynology (Litwin et al., 1991) the Shinarump has regionally been interpreted as late Carnian (Tuvalian) in age, specifically within the *Eogingkoites* florachron of Ash (1980).

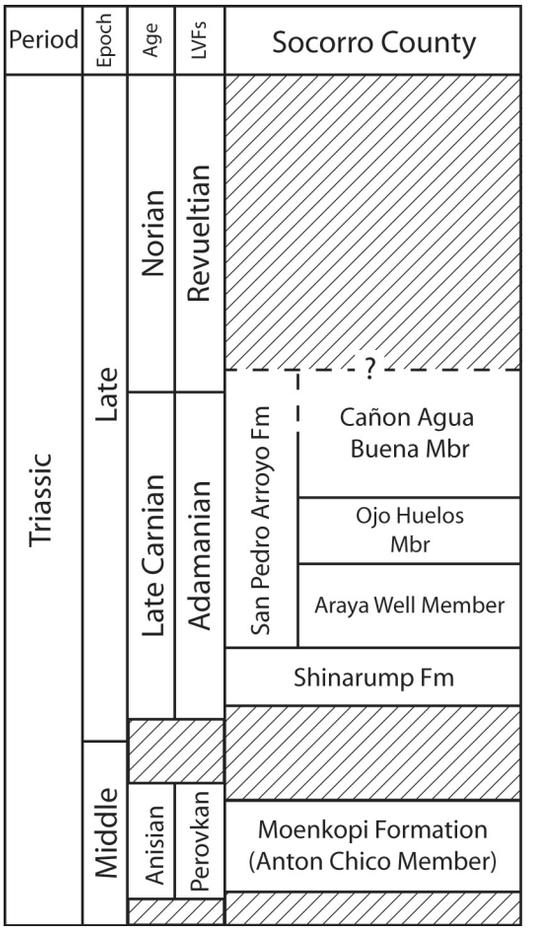



FIGURE 7. Correlation of Triassic units in Socorro County. LVFs based on Lucas (1998) and Lucas et al. (2007).

The single archosaur centrum and associated bone fragments from the Araya Well Member of the San Pedro Arroyo Formation cannot be used to determine the precise age of the unit.

The predominance of large metoposaurid fossils in the lower part of the Ojo Huelos Member suggests a late Carnian (Tuvalian) age, corresponding to the "*Buettneria perfecta* acme zone" of Hunt and Lucas (1993). The fossils of the other vertebrate taxa from the Ojo Huelos, indeterminate reptiles and phytosaurs, are too fragmentary for precise identification. Phytosaurs range throughout the Late Triassic (Carnian-Rhaetian), and thus are of little help in determining the precise age of the unit.

The presence of phytosaur remains, in addition to the fragmentary record of *Desmatosuchus*, from the Cañon Agua Buena Member indicate that this unit, at least in part, is Adamanian (late Carnian) in age, as *Desmatosuchus* is an index taxon of the Adamanian (Lucas, 1998; Lucas et al., 2007). While the record of *Desmatosuchus* is the highest occurrence of fossils in the section, it does not rule out the possibility that the upper half of the Cañon Agua Buena Member may be, in part, Revueltian (early Norian).

Thus, even with a fragmentary fossil record collected from the Triassic section in Socorro County, we concur with previous assessments that the Moenkopi Formation is Middle Triassic (Anisian) in age and the Shinarump Formation is late Carnian

(Adamanian). The fauna of the San Pedro Arroyo Formation indicates that nearly all of the unit (Araya Well, Ojo Huelos and the lower half of the Cañon Agua Buena members) is demonstrably late Carnian (Adamanian) in age, while the upper half of the Cañon Agua Buena Member may include strata of early Norian (Revueltian) age (Fig. 7).

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## APPENDIX

Lithologic descriptions of numbered units of previously unpublished sections in Fig. 3. All UTM data uses NAD 27.

### Cañon Agua Buena 1

Start at 13S 340979E 3755684N, top at 13S 341091E 3755324N. Sec. 27, T04S, R02E. Dip 11° to N80°E

**Chinle Group: San Pedro Arroyo Formation: Cañon Agua Buena Member**

50. Red mudstone. **Not measured**

**Chinle Group: San Pedro Arroyo Formation: Ojo Huelos Member**

49. Brown, nodular limestone calcrete with silica. **0.3**
48. Purple/gray, bentonitic mudstone. **0.8**
47. Same as bed 49, without silica. **0.5**
46. Same as bed 48. **8.4**
45. Pisolitic limestone, smaller pisolites than below. **0.6**
44. Yellow shale. **0.7**
43. Trough crossbedded, litharenite sandstone. **0.4**
42. Same as bed 43, more massively bedded. **1.0**
41. Red mudtone, with trough crossbedded sandstone lenses. **1.3**
40. Yellow, trough crossbedded sandstone, with quartz like the Santa Rosa Formation. **1.5**
39. Pisolitic limestone with conglomeratic lenses with fossil bone. NMMNH L-6937 with phytosaur and metoposaur fossils. **1.0**

**Chinle Group: San Pedro Arroyo Formation: Araya Well Member**

38. Yellow mudstone slope. **1.7**

**Chinle Group: Shinarump Formation**

37. Extrabasinal conglomerate with amphibian? bone, quartzite and chert. Conglomerate is finer than bed 35. **0.2**
36. Mudstone slope. **0.8**
35. Extrabasinal coarse conglomerate with cherts, quartzite and limetone nodules. Base of the Chinle Group. **0.3**

**Moenkopi Formation: Anton Chico Member**

34. Red mudstone slope with lenses of a litharenite sandstone. **1.6**
33. Crossbedded, red-brown, litharenite sandstone. **0.9**
32. Mudstone slope with lenses of trough crossbedded sandstone. **3.2**
31. Crossbedded, red, litharenite sandstone. **1.3**
30. Covered slope. **3.5**
29. Thin platy, subarkosic sandstone. **1.3**
28. Shallow crossbedded, platy, litharenite sandstone. **1.4**
27. Covered slope with 0.1 m thick subarkosic sandstone lenses. **1.6**
26. Coarse, red, litharenite sandstone. **0.4**
25. Red siltstone slope. **1.1**
24. Intraformational conglomerate with rip-ups of red mud and clay. **0.8**
23. Same as bed 25. **1.4**
22. Lenticular, discontinuous, red-gray, litharenite sandstone. **0.2**
21. Same as bed 25. **1.1**
20. Coarse, gray, subarkosic sandstone. **0.6**
19. Same as bed 25. **1.5**
18. Ledge forming, red, subarkosic sandstone. **0.3**
17. Same as bed 25. **1.2**
16. Crossbedded, platy, coarse, litharenite sandstone. **2.6**
15. Fine, red siltstone. **2.4**
14. Intermediate bedded, subarkosic sandstone. **0.3**
13. Red clay with lenses of gray siltstone. **3.0**
12. Gray siltstone. **0.2**
11. Covered slope. **1.3**
10. Crossbedded, flaggy, subarkosic sandstone. Coarser grained than lower beds. Base of the Moenkopi Group. **2.3**

**Artesia Formation**

09. Olive to yellow gray, laminated siltstone slope. **1.2**
08. Massively bedded sandstone with gypsum. **1.0**
07. Flaggy, gypsiferous sandstone with ripple marks and siltstone interbeds. **2.2**
06. Same as bed 09. **1.8**
05. Ledge-forming, gypsiferous sandstone with ripples on top of the bed. Thicker bedded than bed 03. **0.3**
04. Same as bed 09. **3.1**
03. Ledge-forming, gypsiferous, fine-grained sandstone. **0.5**
02. Same as bed 09. **1.6**

**San Andres Formation**

01. Limestone bed. Top of San Andreas Formation. **Not measured**

### Cañon Agua Buena 2

Type section of Cañon Agua Buena Member of the San Pedro Arroyo Formation. Start at 13S 342107E 3754621N, top at 13S, 341616E 3754368N. Sec. 26, 35, T04S, R02E. Dip 20° to S60°W.

**Dakota Formation**

27. Very pale orange (10 YR 8/2), fine-grained, conglomeratic quartz sandstone with siliceous pebbles up to 1.5 cm in diameter, not calcareous. **0.5+**

**Chinle Group: San Pedro Arroyo Formation: Cañon Agua Buena Member (Type section)**

26. Grayish red (5R 4/2) sandy mudstone, calcareous. **21.2**
25. Pale red (5R 6/2), thinly laminated, fine grained, trough crossbedded, litharenite sandstone, with sparse biotites and hematites, not calcareous, forms cuesta. **1.7**
24. Red mudstone with green color mottling and some calcrete nodules. **12.3**
23. Conglomerate with some sandstone, multistoried. **6.1**

22. Same as bed 24. **0.9**
21. Limestone pebble conglomerate with a pale red matrix (5R 6/2), clast supported with clasts up to 1.5 cm in diameter, sparse matrix of quartz sand and minor light gray (N7) mudstone pebbles. **0.6**
20. Same as bed 24. **4.6**
19. Thinly laminar sandstone, multistoried. **2.1**
18. Same as bed 24. **4.4**
17. Crossbedded conglomeratic sandstone, multistoried, forms cuesta. **3.2**
16. Grayish red (5R 4/2) silty mudstone with green color mottling and some calcrete nodules, calcareous, forms slope in strike valley. **33.1**
15. Medium gray (N4), thinly laminar, fine-grained, subrounded, litharenitic sandstone, full of biotites, calcareous, multistoried beds. **1.3**
14. Red mudstone. **3.7**
13. Crossbedded conglomeratic sandstone, multistoried. **1.2**
12. Red mudstone. **2.8**
11. Same as bed 13. **0.6**
10. Red mudstone. **2.0**
09. Crossbedded, medium to coarse grain, subangular, moderately sorted, conglomeratic litharenitic sandstone, intraformational conglomerate has clasts of silt/mudstone pebbles up to 2 cm in diameter, not calcareous, sandstone is medium gray (N4) and the conglomerate is grayish red (5R 4/2), beds are multistoried, forms large cuesta. **3.7**
08. Red to pale reddish-brown sandy mudstone, some dispersed calcrete nodules and some cover. **8.2**
07. Moderate red (5R 5/4) and light olive gray (5Y 5/2) conglomeratic limestone with calcrete pebbles, forms ledge. **0.7**
06. Same as bed 08. **7.0**
05. Moderate red (5R 5/4) and light olive gray (5Y 5/2), nodular, muddy calcrete, forms ledge. **0.8**
04. Same as bed 08, forms slope. **20.7**
03. Moderate red (5R 5/4) and light olive gray (5Y 5/2) limestone mixed with mudstone. **0.2**
02. Red to pale reddish-brown sandy mudstone, some dispersed calcrete nodules and some cover, calcareous. **40.2**

**Chinle Group: San Pedro Arroyo Formation: Ojo Huelos Member**

01. Brown nodular lime mudstone, calcareous, forming cuesta. **Not measured**

### Weber's Site

Start at 13S, 338899E, 3751957N, top at 13S, 339123E, 3751857N. Sec. 24, T05S, R02E. Dip 10° to S40°E.

**Chinle Group: San Pedro Arroyo Formation: Ojo Huelos Member**

23. Bluish gray, nodular limestone. **1.0**

**Chinle Group: San Pedro Arroyo Formation: Araya Well Member**

22. Red mudstone. **0.8**
21. Thin bedded, trough crossbedded sandstone. **0.5**
20. Red mudstone. **3.6**

**Chinle Group: Shinarump Formation**

19. Multistoried, trough crossbedded, intraformational conglomerate and sandstone. **1.3**

**Moenkopi Formation**

18. Red mudstone, with some thin (~0.1 m) sandstone lenses. **3.9**
17. Same as bed 21. **0.2**
16. Red mudstone. **0.9**
15. Thin bedded, trough crossbedded sandstone, with intraformational conglomeratic troughs. **0.4**
14. Red mudstone. **2.1**
13. Same as bed 21. **0.3**
12. Red mudstone. **1.0**
11. Sandstone/intraformational conglomerate. NMMNH locality 6931 with capitosauroid amphibian dermal fragments. **0.3**
10. Red mudstone. **1.1**
09. Thin bedded, laminar sandstone. **0.4**
08. Red mudstone. **2.3**
07. Multistoried, trough crossbedded, litharenite sandstone. Top of bed NMMNH L-7722 with invertebrate feeding traces (*Scoyenia*). **1.0**
06. Red mudstone with some lenticular sandstone bodies, similar to bed 05. **3.1**
05. Trough crossbedded, litharenite sandstone, forms cuesta. **0.4**
04. Grayish red mudstone. **2.3**
03. Same as bed 05. 1.1

**Artesia Formation**

02. Orange, thin-bedded siltstone with some green color mottling, forms slope. **3.6**
01. Massive, gypsiferous sandstone. **Not measured**

### Lime Kilns 1

Base at 13S, 338373E, 3752031N, top at 13S, 338301E, 3752049N. Sec. 4, T05S, R02E. Dip 21° to S57°W.

**Chinle Group: San Pedro Arroyo Formation: Araya Well Member**

19. Red mudstone. **Not measured**

**Chinle Group: Shinarump Formation**

18. Trough crossbedded, intraformational conglomerate and red sandstone. **0.5**
17. Red mudstone. **1.1**
16. Thin, flaggy sandstone, slope forming. **4.4**
15. Trough crossbedded sandstone. **1.1**
14. Extrabasinal conglomerate with a few thin sandstone lenses, some grading. **6.2**

**Moenkopi Formation**

13. Intraformational, trough crossbedded, conglomeratic

sandstone. **1.5**
12. Hackly, red siltstone slope. **4.3**
11. Thin bedded, ripply sandstone. **4.5**
10. Trough crossbedded sandstone with mud chip conglomerate lenses, a few clay partings. Offset on top of bed 10, change dip to 44° to S65°W. **4.4**

**Artesia Formation**

09. Laminar siltstone. **0.2**
08. Sandstone with ripples. **0.2**
07. Same as bed 09. **0.3**
06. Crossbedded sandstone with climbing ripples, forms ledge. **1.5**
05. Same as bed 09. **1.7**
04. Sandstone with climbing ripples, forms ledge. **0.6**
03. Same as bed 09. **1.0**
02. Planar bedded sandstone, forms ledge. **0.3**
01. Flaggy, orange and green mottled sandstone with ripples. **1.7**

### Lime Kilns 2

Type section of the Araya Well Member of the San Pedro Arroyo Formation. Start at 13S, 338052E, 3751751N, top at 12S, 338023E, 3751720N. Sec. 8, T05S, R02E. Dip 20° to S30°W.

**Chinle Group: San Pedro Arroyo Formation: Ojo Huelos Member**

14. Light gray (N7) brecciated, sandy lime mudstone with medium dark gray (N4) siliceous veins along brecciation boundaries. **1.2**
13. Color mottled pale greenish yellow (10Y 8/2) and grayish red (5R 4/2), laminar, nodular sandy lime mudstone. **0.5**
12. Pale greenish yellow (10Y 8/2), bedded sandy lime mudstone with some red/green mudstone/clay drapes. **1.1**

**Chinle Group: San Pedro Arroyo Formation: Araya Well Member (Type section)**

11. Pale olive (10Y 6/2) and grayish red (5R 4/2) mottled siltstone, calcareous, forms slope. **2.7**
10. Moderate red (5R 5/4) thin bedded, fine grained, micaceous, subrounded, trough crossbedded litharenitic sandstone, somewhat calcareous, with bed 09 forms ledge. **1.4**
09. Litharenitic, medium grained angular, micaceous, clay pebble conglomerate, medium dark gray (N4) matrix supported with moderate red (5R 5/4) clasts. **0.4**
08. Mudstone slope with thinly laminar, grayish red (5R 4/2), fine grained, subangular, very calcareous litharenitic sandstone. **3.7**

**Chinle Group: Shinarump Formation**

07. Pale brown (5YR 5/2), medium grained, subangular, not calcareous, trough crossbedded sandstone, with clay pebble conglomerate lenses up to 0.3 m thick. **2.1**
06. Cover, with some red sandstone lenses. **4.5**
05. Pale brown (5YR 5/2), fine grained, subangular, litharenitic sandstone, not calcareous. **1.2**
04. Grayish yellow green (5GY 7/2), medium grained, subangular, micaceous, laminar, litharenitic sandstone, not calcareous, with mud rip-ups and green micas. **0.7**
03. Pale yellowish brown (10YR 6/2), fine to coarse grained quartz sandstone with siliceous conglomerate, with clasts of black and white chert and quartzite up to 10 cm in diameter, low angle crossbeds, fine to coarse grading. **1.2**
02. Sandstone with floating clasts. **0.3**
01. Same as bed 03. **3.0**