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STRATIGRAPHY AND CORRELATION OF THE PERMO-CARBONIFEROUS CUTLER GROUP, CHAMA BASIN, NEW MEXICO

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Abstract.—Nonmarine siliciclastic red beds at the base of the Phanerozoic section across most of the Chama Basin of northern New Mexico are assigned to the Pennsylvanian-Permian Cutler Group. These strata are here divided into two mappable lithostratigraphic units, the El Cobre Canyon and overlying Arroyo del Agua formations. The El Cobre Canyon Formation is up to 500 m of brown siltstone, sandstone and extraformational conglomerate of an ephemeral braided stream environment that overlies Proterozoic basement in the subsurface and is conformably overlain by the Arroyo del Agua Formation. Siltstone beds of the El Cobre Canyon Formation contain numerous rhizoliths and comprise relatively thin, slope-forming units between multistoried sandstone beds that are arkosic, micaceous, coarse grained and trough crossbedded. The Arroyo del Agua Formation is up to 120 m of orange siltstone, sandstone and minor intraformational and extraformational conglomerate of a braided to anastomosed stream depositional environment. The siltstones are thick, slope-forming units with abundant calcrete nodules between thin sandstone sheets that are arkosic and trough crossbedded. In the Chama Basin, the De Chelly Sandstone (= Meseta Blanca Member of the Yeso Formation) locally overlies the Arroyo del Agua Formation, but at most outcrops the Upper Triassic Chinle Group rests unconformably (some slight angularity is evident) on the Arroyo del Agua Formation. Megafossil plants, palynomorphs and fossil vertebrates indicate the El Cobre Canyon Formation is of Late Pennsylvanian-Early Permian (early Wolfcampian) age. Sparse fossil vertebrates indicate the Arroyo del Agua Formation is of late Wolfcampian age. Correlation of Cutler Group strata southward to Jemez Springs suggests that the Abo Formation is equivalent to the upper part of the El Cobre Canyon Formation and the entire Arroyo del Agua Formation. The lower part of the El Cobre Canyon Formation in the Chama Basin is correlative to mixed marine-nonmarine strata of the upper "Madera Group" at Jemez Springs.

INTRODUCTION

The oldest bedrock strata exposed in the Chama Basin in northern New Mexico are siliciclastic red beds long assigned to the Cutler Group (Formation). These strata are particularly well exposed in the drainage of the Rio Gallinas, the drainage of the Rio Puerco from Arroyo del Agua to the western edge of Abiquiu Reservoir and in El Cobre Canyon east of Abqiuiu Reservoir (Fig. 1). Since the 1870s, fossils from Cutler Group strata in the Chama Basin have been collected by numerous paleontologists to produce some of North America's most extensive assemblages of Early Permian fossil vertebrates. These rocks have also been the subject of detailed sedimentological studies. However, their lithostratigraphy remains understudied, a fact well reflected by them simply being referred to as Cutler Group or Formation. Here, we present the results of detailed lithostratigraphic studies of Cutler Group strata in the Chama Basin.

PREVIOUS STUDIES

Newberry's (1876) geological report on the 1858 Macomb Expedition identified the bedrock strata of the Chama Basin as Triassic, Cretaceous and Tertiary rocks. In the southern portion of the basin, Newberry climbed Cerro Pedernal (he called it "Abiquiu Peak") and visited the old copper mines in El Cobre Canyon. In the roof of one of the mines, Newberry collected the first Triassic plant fossils with leaves discovered in the American West (Triassic fossil wood had been discovered in the 1840s). Newberry (1876) described and illustrated these plants and recognized their similarity to Triassic plants already known from Sonora, Mexico and from Virginia and North Carolina. He thus concluded (p. 69) that "we have, therefore, in these plants evidence of the Triassic age of *all* the variegated gypsiferous rocks of northern New Mexico; for the Lower Cretaceous sandstones immediately overlie the plant-beds of the *Cobre*." Newberry was correct about the Triassic age of the plants (they are from the Upper Triassic Shinarump Formation of the Chinle Group: Lucas and Hunt, 1992), but he was incorrect that Cretaceous sandstones immediately overlie them at El Cobre Canyon; the sandstones above the plant-bearing horizon are Upper Triassic Poleo Formation of the Chinle Group. Nevertheless, based on the fossils he collected in El Cobre Canyon, Newberry assigned what are now known to be Pennsylvanian-Permian (Cutler Group), Upper Triassic (Chinle Group) and Jurassic (Entrada, Todilto, Summerville and Morrison formations) strata to his "Triassic formation."

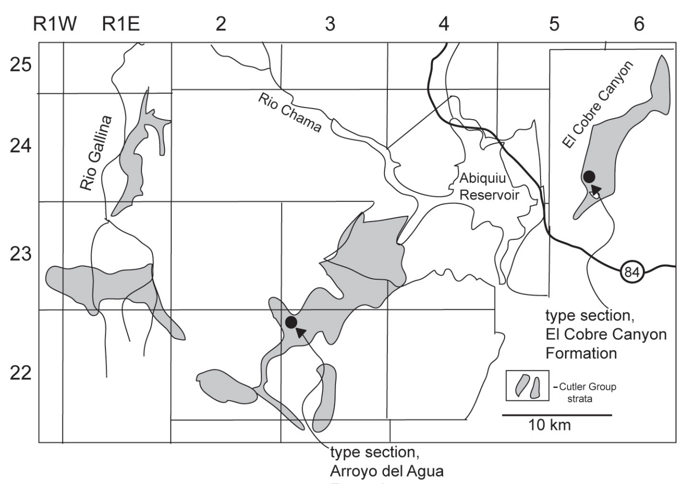

FIGURE 1. Index map showing distribution of Cutler Group outcrops in the Chama Basin and location of type sections of El Cobre Canyon and Arroyo del Agua formations.

In 1874, E. D. Cope traveled through part of the Chama Basin, observing Cutler Group strata along the Rio Gallinas. Like Newberry, he (Cope, 1875) also considered these red beds to be of Triassic age, primarily because Cope found Late Triassic fossils of unionid bivalves and reptiles in the upper part of the red bed succession (Petrified Forest Formation of Chinle Group of current usage: Lucas et al., 2003). Fossils subsequently collected by David Baldwin from the lower part of the red bed succession convinced Cope (1881; also see Marsh, 1878) of their Permian age.

Williston and Case (1912, 1913; also see Huene, 1911) described the Cutler Group red beds in El Cobre Canyon and in the Rio Puerco valley. They applied no lithostratigraphic names to these strata, but did assign them a Pennsylvanian-Permian age. Particularly important was their discovery of a loose brachiopod (*Sprifier rockymontanus*) in the floor of El Cobre Canyon, which they deemed evidence of a Pennsylvanian age. They based an Early Permian age on the vertebrate fossil assemblages, which they correlated to the lower part of the Wichita Group in Texas.

On his geological maps, Darton (1928a, b) assigned the red beds below the "Poleo sandstone," to the Abo Sandstone of Carboniferous age (Fig. 2). However, on his geologic cross sections, Darton (1928a, fig. 69) simply referred to these strata as "red shale and sandstone" between the Carboniferous Magdalena Group and the Poleo sandstone. He also (p. 21) noted that "bones from the red beds now regarded as representing the Abo sandstone near Coyote, in Rio Arriba County, were classified as Permian by Marsh and Cope and later by Williston and Case."

Wood and Northrop (1946) mapped the geology of the southern flank of the Chama Basin, and called the Pennsylvanian-Permian red beds north of latitude 36ºN Cutler Formation, and south of that Abo Formation. Northrop (1950, p. 85) followed up by stating that "the Cutler formation (200'-1100'?)…is the northward equivalent of the Abo and Yeso formations." Romer (1950, 1960) referred to the strata as "Abo (Cutler) Formation" and reviewed their fossil vertebrates, correlating them to the lower or middle portion of the Wichita Group in Texas.

Langston (1953, p. 351) stated that "all Permian red beds in Rio Arriba County are assigned to the Cutler formation." He described in detail the vertebrate fossil localities near Arroyo del Agua, and documented the fossil amphibians from these localities. Langston correlated the Arroyo del Agua vertebrate fossils to the lower and middle Wichita Group of the Texas section (Langston, 1953, fig. 24). He also discounted the idea that the El Cobre Canyon vertebrate fossils are Pennsylvanian, and assigned them an Early Permian age.

Smith et al. (1961) referred to the red bed strata as Cutler Formation and mapped their distribution in the southeastern Chama Basin. They (p. 7) described them as a "seemingly cyclic alternation of cross-bedded, purple, arkosic sandstones which are locally conglomeratic, and of purple and orange mudstones" at least 1500 ft (500 m) thick. Smith et al. (1961, p. 7) also noted that "no lithologic break could be found throughout the section, [so] the entire thickness is mapped as Permian Cutler Formation." In an appendix, they presented a composite section said to be based on the surface section on the western wall of El Cobre Canyon and on the log of a well drilled in the canyon floor (Fig. 3). Particularly significant was Smith et al.'s (1961) identification of a Pennsylvanian plant locality in the northern end of El Cobre Canyon that they assigned to the Hermosa Formation (we, however, assign this site to the Cutler Group).

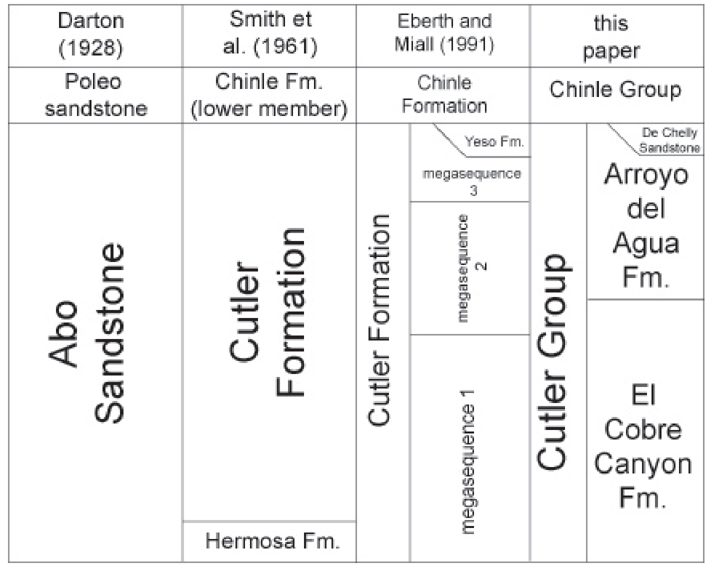

FIGURE 2. Development of lithostratigraphic nomenclature of the Cutler Group in the Chama Basin.

Baars (1962) well reflected the consensus when he referred the older red beds in the Chama Basin to "Cutler Group undifferentiated" and indicated they are generally equivalent to the Abo Formation and thus of Early Permian age. However, Fracasso (1980) presented megafossil plant (also see Hunt and Lucas, 1992) and fossil vertebrate evidence (also see Vaughn, 1963) that the lower part of the Cutler Group in El Cobre Canyon is of Pennsylvanian age.

In the 1980s and 1990s, sedimentological studies of Cutler Group strata in the Chama Basin were published by Eberth and Berman (1983, 1993), Eberth (1987), Fracasso (1987) and Eberth and Miall (1991). Particularly significant was Eberth's division of the Cutler Group into three depositional cycles he referred to as megasequences (Fig. 2). Berman (1993) summarized the vertebrate paleontology of the Cutler Group strata in the Chama Basin. Our studies of Cutler Group stratigraphy in the Chama Basin began in 2000 (Krainer and Lucas, 2001).

LITHOSTRATIGRAPHY

Cutler Group

We assign the oldest siliciclastic red beds in the Chama Basin to the Cutler Group. Our work indicates that Cutler strata can be divided into two, mappable lithostratigraphic units deserving of formation status (Fig. 2). Here, we name these two formations.

El Cobre Canyon Formation

We propose the name El Cobre Canyon Formation for the lower formation of the Cutler Group in the Chama Basin. It is

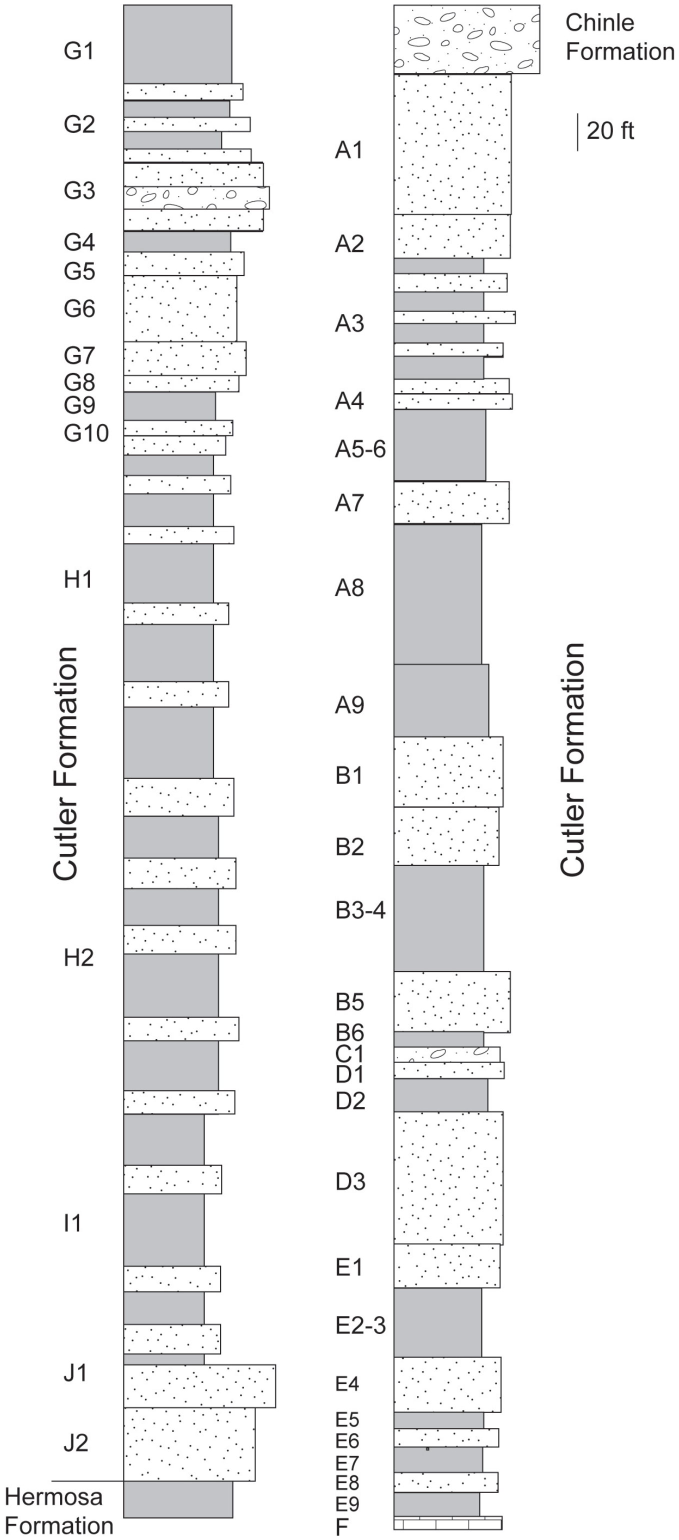

FIGURE 3. Stratigraphic section of Cutler Group strata in El Cobre Canyon given by Smith et al. (1961).

named for El Cobre Canyon (Spanish Cañon del Cobre, literally "copper canyon") located primarily in the western half of T24N, R5E and adjacent eastern edge of T25N, R6E (Fig. 1). The type section of the El Cobre Canyon Formation (Figs. 4, 5A) is in El Cobre Canyon, and was measured in the N1/2 sec. 25, T24N, R5E (see the Appendix).

At the type section, the El Cobre Canyon Formation is ~ 111 m thick and is mostly siltstone (66% of the measured section) and sandstone (21%). Minor rock types are conglomerate/conglomeratic sandstone (9%), sandy shale (2%) and calcrete (1%). These rocks are characteristically "brown" (pale reddish brown) and are readily distinguished from the overlying Arroyo del Agua Formation based on color and lithology (Table 1). Siltstones of the El Cobre Canyon Formation contain numerous rhizoliths (Fig. 6E), and sandstones are typically coarse grained, arkosic, micaceous, trough crossbedded and form multistoried bodies that erode to thick cliffs and benches (Figs. 5, 6A). Conglomerates characteristically have extraformational clasts of quartzite, granite and gneiss (Fig. 6C). The various lithofacies are described in detail by Eberth and Miall (1991).

The El Cobre Canyon Formation is best exposed in the floor of El Cobre Canyon and in the Rio Puerco Valley near Arroyo del Agua. Its lower contact is not exposed, and subsurface data indicate it rests on Proterozoic basement (Smith et al., 1961; Eberth and Miall, 1991). The upper contact of the El Cobre Canyon Formation appears to be conformable at the base of the first "orange" siltstone slope of the Arroyo del Agua Formation.

The El Cobre Canyon Formation approximately corresponds to megasequence 1 of Eberth and Miall (1991). According to Eberth and Miall (1991), the sediments were deposited in a shallow, ephemeral braided stream environment.

The age of the El Cobre Canyon Formation is Late Pennsylvanian-Early Permian. Fossils from the lower part of the formation in the floor of El Cobre Canyon indicate a Pennsylvanian age: palynomorphs (J. Utting, written commun., 2001), megafossil plants (*Alethopteris* flora: Smith et al., 1961; Fracasso, 1980; Hunt and Lucas, 1992) and fossil vertebrates such as *Desmatodon* and *Limnoscelis* (Fracasso, 1980; Lucas, 2002). The plants suggest an age possibly as old as late Desmoinesian, but a Late Pennsylvanian age is most likely.

Fossil vertebrates stratigraphically higher in the El Cobre Canyon Formation, especially in the Arroyo del Agua area, indicate an Early Permian (early Wolfcampian) age (Langston, 1953). These include *Zatrachys*, *Eryops*, *Bolosaurus* and other taxa indicative of faunachron A of Lucas (2002).

TABLE 1. Contrasting features of the El Cobre Canyon and Arroyo del Agua formations.

El Cobre Canyon Formation	Arroyo del Agua Formation
"brown" (pale reddish brown—10 R 5/4)	"orange" (moderate reddish brown—10 R 4/6)
extraformational conglomerates (quartzite, granite, gneiss clasts)	few conglomerates except uppermost beds; most other conglomerates are intraformational (calcrete clasts)
most beds calcareous to very calcareous	most beds not calcareous
multistoried sandstone beds	thin sandstone sheets
thin siltstone slopes	thick siltstone slopes
rhizoliths common	calcrete nodules very abundant

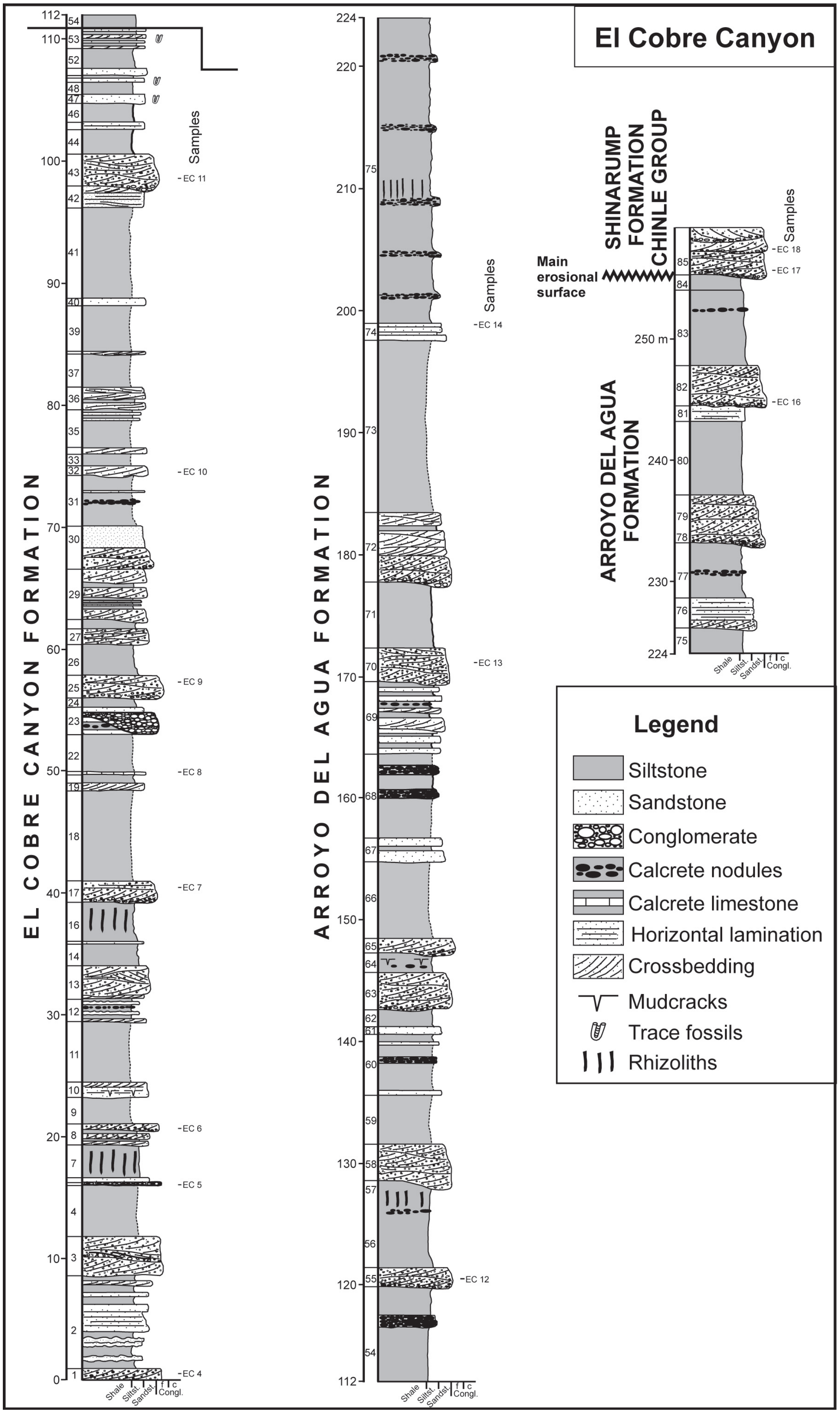

FIGURE 4. Type section of the El Cobre Canyon Formation (see Appendix for description of numbered lithologic units).

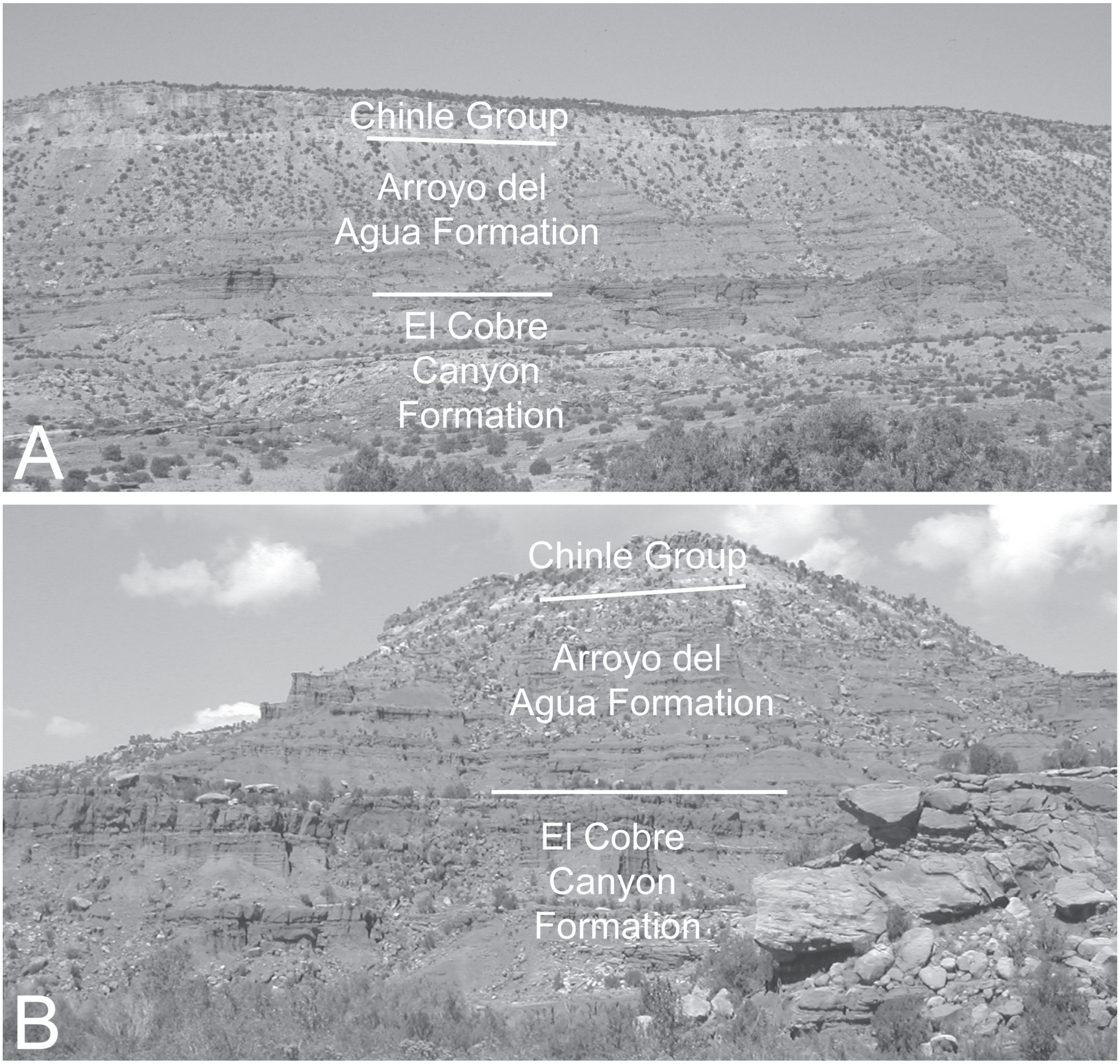

FIGURE 5. Overviews of Cutler Group lithostratigraphy in the Chama Basin. A, Western wall of El Cobre Canyon at and around El Cobre Canyon Formation type section. B, Point of Mesa Montosa at Arroyo del Agua Formation type section.

Arroyo del Agua Formation

We propose the name Arroyo del Agua Formation for the upper formation of the Cutler Group in the Chama Basin. The name is for the village of Arroyo del Agua near the type section. The type section (Figs. 5B, 7) is just north of the village in the SW ¼ sec. 5, T22N, R3E (Appendix).

At the type section, the Arroyo del Agua Formation is ~ 120 m thick and is mostly siltstone (58% of the measured section) and sandstone (34%). Minor rock types are calcrete (Fig. 6D) and conglomerate/conglomeratic sandstone (each about 4% of the measured section). Siltstones of the Arroyo del Agua Formation are characteristically "orange" (moderate reddish brown) and contain abundant calcrete nodules (Fig. 6F). They form relatively thick slopes (Figs. 5, 6B) between thin sheets of sandstone that are coarse grained, arkosic and trough crossbedded. Conglomerates are not as common in the Arroyo del Agua Formation as in the underlying El Cobre Canyon Formation, and most are

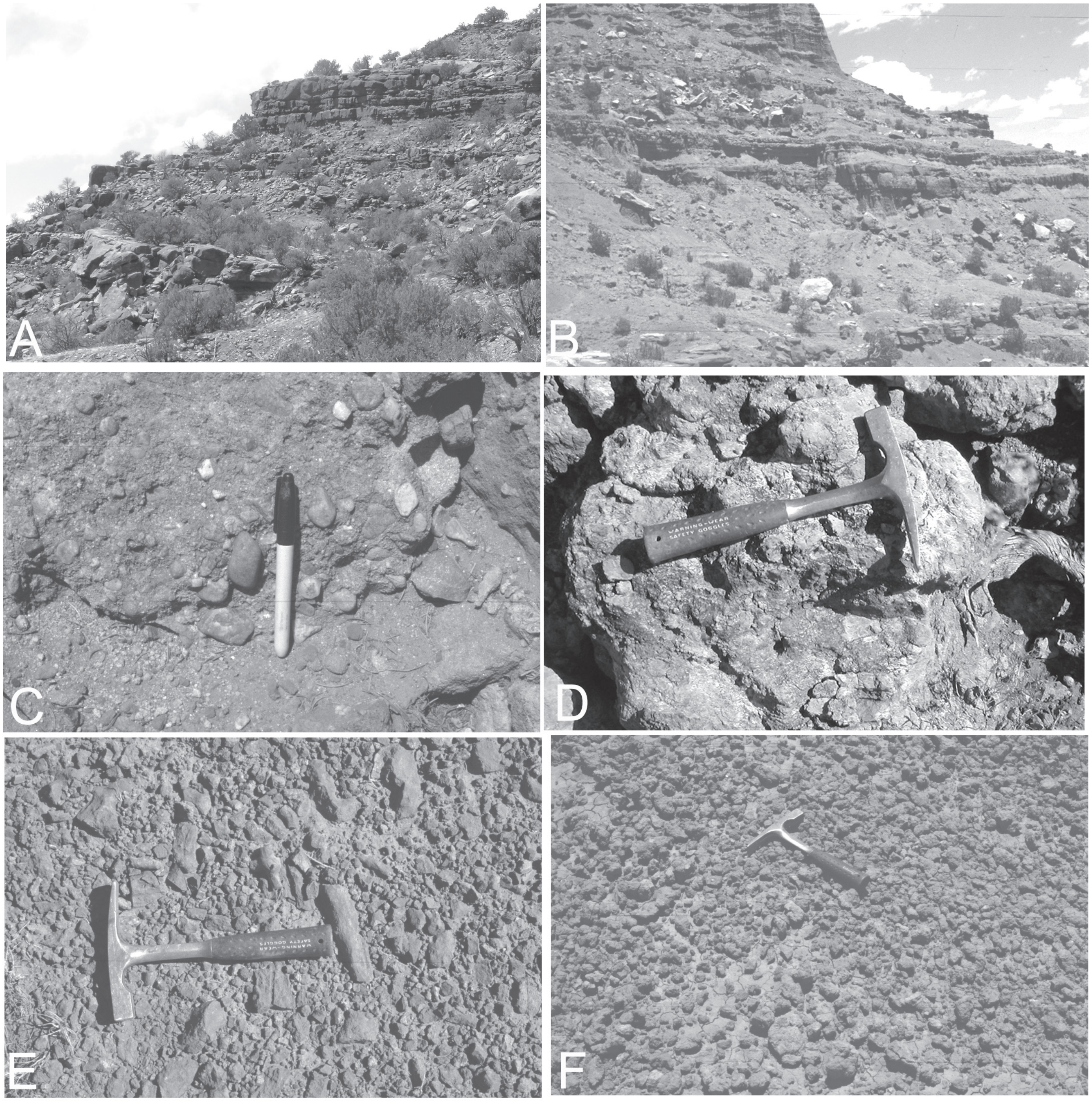

FIGURE 6. Selected outcrops of Cutler Group strata in the Chama Basin. A, Typical multistoried sandstones of the El Cobre Canyon Formation in El Cobre Canyon. B, Typical siltstone slopes of Arroyo del Agua Formation at Arroyo del Agua Formation type section. C, Extraformational conglomerate of El Cobre Canyon Formation. D, Calcrete bed in Arroyo del Agua Formation. E, Rhizoliths in siltstone bed, El Cobre Canyon Formation. F, Calcrete nodules in siltstone bed, Arroyo del Agua Formation.

intraformational (composed of calcrete clasts). However, in the upper part of the Arroyo del Agua Formation, extraformational conglomerates (primarily composed of quartzite clasts) are present (this is megasequence 3 of Eberth and Miall, 1991). Several features distinguish the Arroyo del Agua Formation from the underlying El Cobre Canyon Formation (Table 1).

The Arroyo del Agua Formation is well exposed along the walls of El Cobre Canyon and in the Rio Puerco Valley from Arroyo del Agua east to Abiquiu Reservoir. At all outcrops in the Chama Basin, the Arroyo del Agua Formation conformably overlies the El Cobre Canyon Formation. Gradation and interfingering characterizes this contact, so it is apparently conformable.

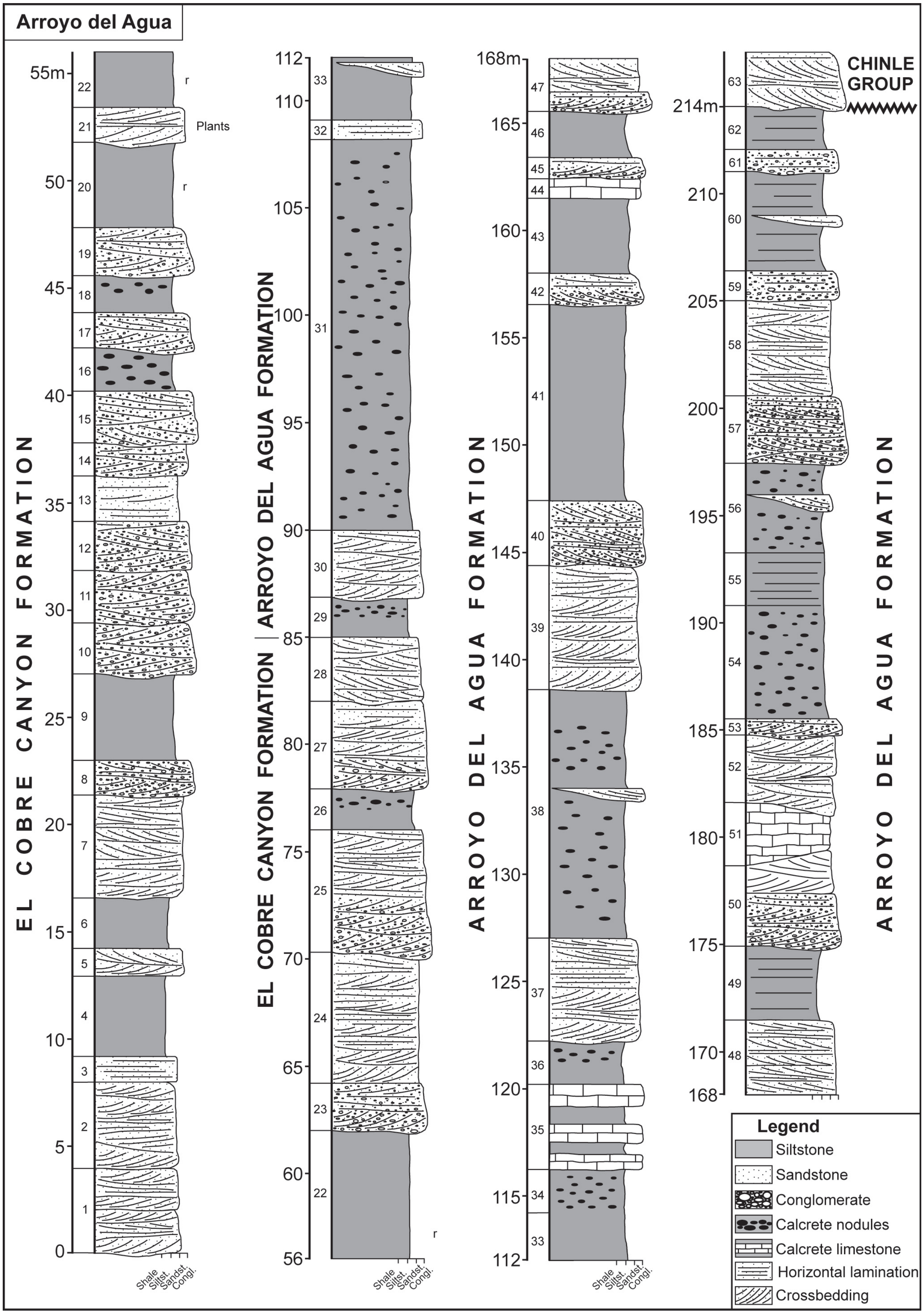

FIGURE 7. Type section of the Arroyo del Agua Formation (see Appendix for description of numbered lithologic units).

Throughout most of the Chama Basin, the Chinle Group rests disconformably on the Arroyo del Agua Formation (Lucas et al., 2003). Shari Kelley (written commun., 2005) has recently found local remnants of the basal Yeso Formation between the Arroyo del Agua Formation and Chinle Group along Coyote Creek near the boundary of the Youngsville and Arroyo del Agua quadrangles. Eberth and Miall (1991) also noted thin Yeso Formation in one of their measured sections along the Rio Puerco in the south-central portion of the Arroyo del Agua quadrangle. These are strata conventionally referred to the Meseta Blanca Member of the Yeso Formation, but we follow Baars (1962) in assigning them to the De Chelly Sandstone.

The Arroyo del Agua Formation approximately encompasses megasequence 2 of Eberth and Miall (1991). The facies shows some significant differences compared to the El Cobre Canyon Formation. Thus, the Arroyo del Agua Formation is characterized by locally abundant major sandstone ribbons and U-shaped channel fills, separated by thick intervals of siltstone containing abundant calcrete nodules. When compared to El Cobre Canyon Formation deposition, the fluvial style had changed to laterally extensive floodplains that developed between relatively stable channels, and locally anastomosed channels formed. The climate was more arid than during deposition of the El Cobre Canyon Formation (Eberth and Miall 1991).

The Arroyo del Agua Formation has only yielded age-diagnostic fossils from two localities. These are a *Sphenacodon* bonebed high on the eastern wall of El Cobre Canyon and a *Seymouria* bonebed along the Rio Puerco north of Youngsville (Eberth and Berman, 1983; Berman et al., 1987; Eberth and Miall, 1991). The co-occurrence of *Sphenacodon* and *Seymouria* indicates a faunachron B age (Lucas, 2002), which is late Wolfcampian. The De Chelly Sandstone (Yeso Formation) above the Arroyo del Agua Formation is conventionally assigned a Leonardian age, although age data to demonstrate that its base in northern New Mexico is Leonardian are lacking (e.g., Mack and Dinterman, 2002; Lucas and Zeigler, 2004). Therefore, the fossil evidence and age of adjacent units suggests a late Wolfcampian age for the Arroyo del Agua Formation.

SEDIMENTARY PETROGRAPHY

We undertook some petrographic analysis of the sandstones of the El Cobre Canyon and Arroyo del Agua formations and contrast their petrography with the very different sandstones at the base of the Upper Triassic Chinle Group (Figs. 8-9). Cutler Group sandstones are medium- to coarse-grained, moderately to poorly sorted, angular arkoses and lithic arenites; they are rarely sublitharenites according to the classification of Pettijohn et al. (1987). Dominant grain types are mono- (up to 29%) and polycrystalline quartz (up to 32%; Fig. 8 B-C) and detrital feldspars (14-37%: mostly alkali feldspars, frequently showing microcline twinning, some perthitic feldspars, and untwinned feldspars; slightly altered to clay minerals; Figs. 8 B,C,F, 9B). Rock fragments are present (9-35%); most are granitic rock fragments composed of large quartz and feldspar (Fig. 8A). Subordinate sedimentary rock fragments composed of fine-grained, brownish carbonate and a few small angular quartz grains are present (Figs. 8C, 9A). Fine-grained metamorphic rock fragments composed of small quartz and micas (phyllites) rarely occur (Fig. 8E). A few micas (muscovite and green biotite) are present. In the lower part of the El Cobre Canyon Formation, micas are quite abundant, comprising up to 9% of the rock (Fig. 8D). Sandstones are cemented by sparry clacite (up to 36%), which locally replaces feldspars and quartz. A few grains of detrital garnet were recognized in thin section. The texture indicates short distance of transport, and composition points to a dominantly granitic source rock, and subordinate metamorphic rocks (phyllites). Sedimentary rock fragments represent reworked calcrete crusts.

In contrast, sandstones of the Shinarump Formation of the Chinle Group are moderately sorted, subangular to subrounded subarkoses, rarely lithic arenites (classification of Pettijohn et al. 1987) composed of dominantly mono- (up to 48%) and polycrystalline quartz (up to 18%). Detrital feldspars (mostly alkalifeldspars) constitute up to 18%, and a few granitic and metamorphic rock fragments are present (mostly < 10%, rarely up to 25%). Muscovite is very rare (Fig. 9C-F). The sandstone is cemented by quartz and calcite (21-28%). Quartz cement occurs as authigenic overgrowths on detrital quartz grains (Fig. 9C). Due to the poorly developed "dust lines" around the detrital quartz grains the overgrowths are not well visible. Locally, the pore space is filled with fine-crystalline quartz (chalcedony). Sparry calcite cement dominates. Calcite replaces detrital feldspars, and subordinately quartz (Fig. 9D-F). Compared to the underlying Cutler Group sandstones, those of the Shinarump Formation are characterized by higher textural maturity (better rounding and sorting), higher compositional maturity (composed mostly of quartz, smaller amounts of feldspar and rock fragments) and presence of abundant authigenic quartz overgrowths. Due to their better sorting and rounding, and higher compositional maturity, these sandstones are probably reworked sandstones from the underlying Cutler Group.

We also studied seven samples from the Cutler Group section at Arroyo del Agua, all derived from medium- to coarse-grained sandstone beds. All samples are grain-supported, carbonate cemented, and the grains are angular to subangular. Most samples are moderately to poorly sorted, rarely moderately to well sorted.

Monocrystalline quartz (14-24%) is more abundant than polycrystalline quartz (6-22%), the latter including rare stretched metamorphic grains. Detrital feldspars constitute 12-25% of the sandstones, almost all being alkali feldspars appearing as untwinned and perthitic grains and microcline. Some of the feldspars, particularly microcline, are quite fresh, and many detrital feldspars are altered to various degrees.

Among the rock fragments, which constitute 12-25%, granitic types composed of quartz and feldspar, or rarely of different feldspars, are common. A few fine-grained, schistose metamorphic rock fragments composed of quartz and phyllosilicates (phyllites) are present. Some of the samples contain sedimentary rock fragments consisting of fine-grained carbonate with a few small angular quartz grains (reworked caliche). Detrital micas (biotite and muscovite) are rare. Accessory minerals determined in thin

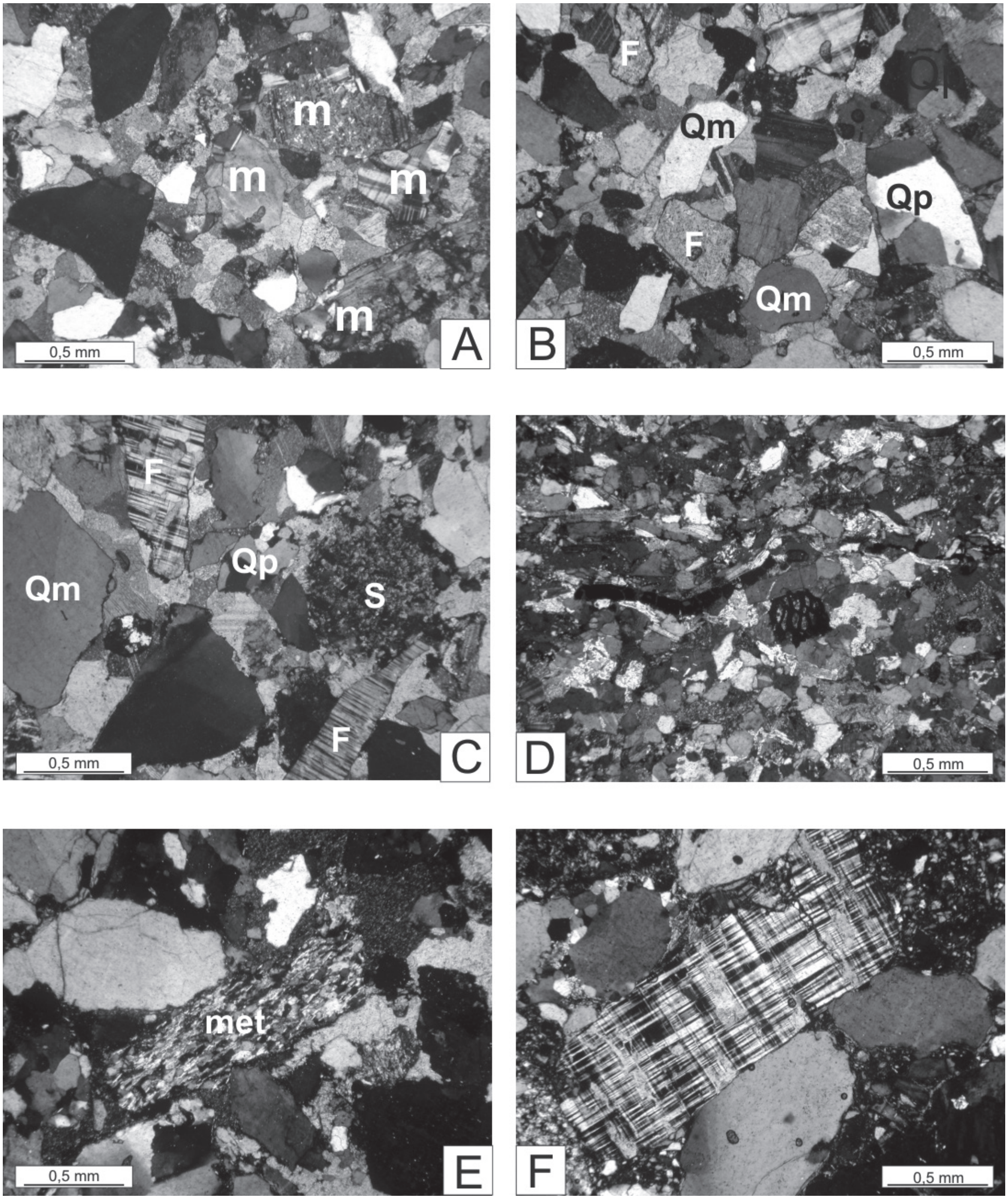

FIGURE 8 Photomicrographs of sandstones of the El Cobre Canyon Formation of the Cutler Group at El Cobre Canyon (Fig. 4). A, Poorly sorted, angular sandstone (arkosic arenite) composed of quartz, granitic rock fragments (m), detrital feldspars and sparry calcite cement. Crossed polars, sample EC 5. B, Moderately sorted, angular sandstone (arkose) consisting of mono- (Qm) and polycrystalline quartz (Qp), feldspar (F), a few granitic rock fragments and sparry calcite cement. Crossed polars, sample EC 5. C, Poorly sorted angular sandstone (arkosic arenite). Quartz grains (Qm, Qp), detrital feldspars (F), a few granitic rock fragments and a sedimentary rock fragment composed of dark brown carbonate (S), are cemented by sparry calcite. Crossed polars, sample EC 5. D, Arkosic arenite from the base of the section containing abundant detrital micas (Mostly biotite) and plant debris (black, centre of photograph). Crossed polars, sample EC 1.E: Lithic arenite containing a large, fine-grained, schistose metamorphic rock fragment (met) composed of quartz and micas. Crossed polars, sample EC 4. F: Arkosic arenite containing a large derital feldspar grain (perthitic microcline). Crossed polars, sample EC 9.

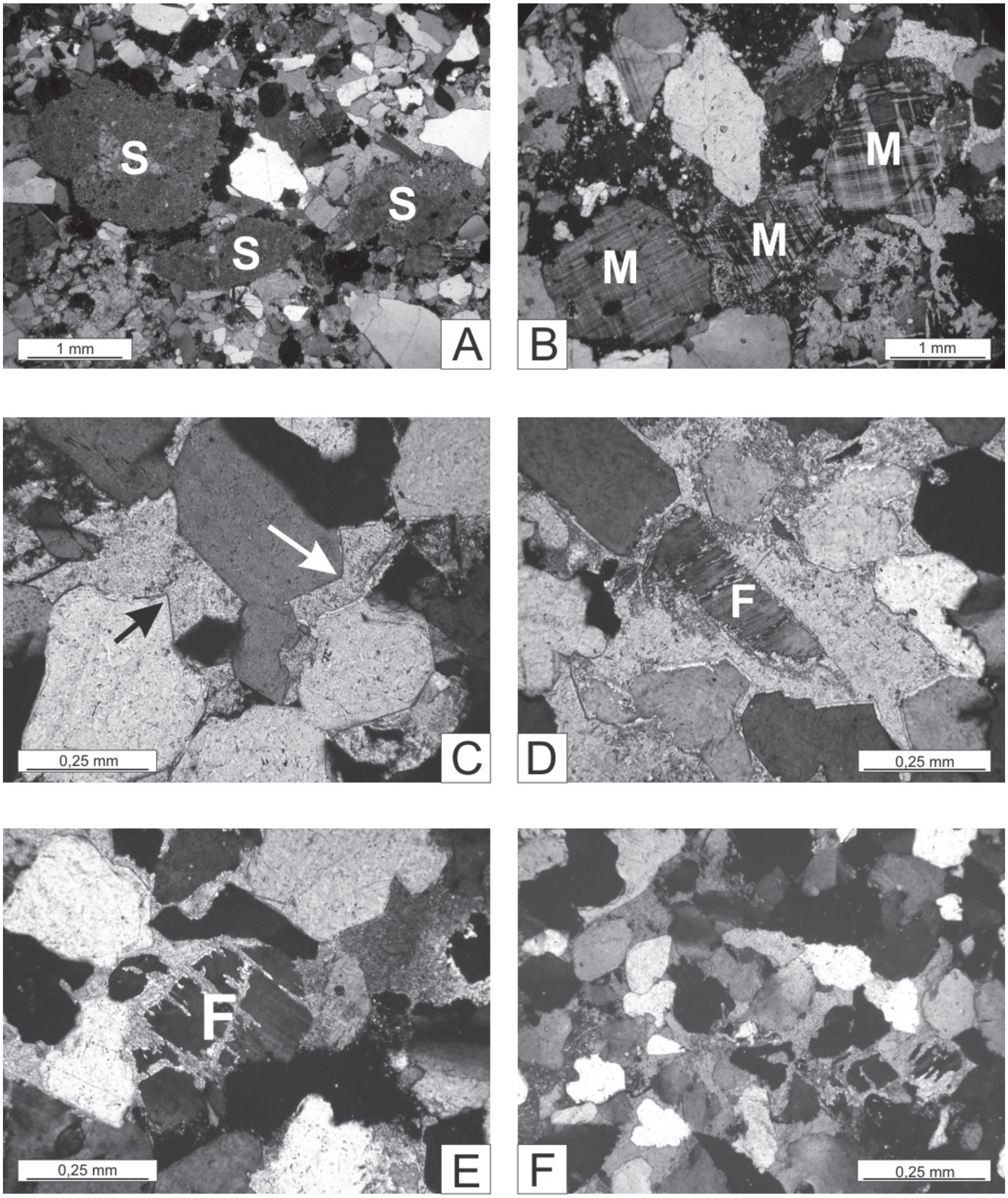

FIGURE 9. Photomicrographs of sandstones of the Arroyo del Agua Formation of the Cutler Group (A,B) and Upper Triassic Shinarump Formation (C-F) at El Cobre Canoyn. A, Poorly sorted sandstone containing abundant mono- and polycrystalline quartz, detrital feldspars, some granitic rock fragments and large sedimentary rock fragments (S) composed of fine-grained carbonate and a few very small angular quartz grains (reworked caliche crusts). The sandstone is cemented by sparry calcite. Crossed polars, sample EC 11. B, Coarse-grained, poorly sorted angular sandstone (arkosic arenite) with large detrital feldspars (mostly microcline; M), quartz and granitic rock fragments cemented by calcite. Crossed polars, sample EC 16. C, Sandstone (subarkose) containing detrital quartz grains with authigenic overgrowths (arrows). Pore space filled with sparry calcite cement. Crossed polars, sample EC 18.D, Sandstone (subarkose) composed of abundant quartz grains (mostly monocrystalline quartz) and rare detrital feldspars (grain F in the center). The sandstone is cemented by sparry calcite, which is replacing the feldspar grain in the center and also some quartz grains. Crossed polars, sample EC 18.E, Sandstone (subarkose) composed of abundant quartz grains, some feldspars (F, center of photo) and sparry calcite cement. Quartz grain in the upper left shows a well developed authigenic overgrowth, the feldspar grain in the center is partly replaced by calcite. Crossed polars, sample EC 18. F, Moderately sorted sandstone (subarkose) from the base of the Shinarump Formation (Chinle Group) composed of dominantly quartz, a few feldspar grains and sparry calcite cement. Crossed polars, sample EC 18.

section are garnet, tourmaline and apatite. Some of the samples contain red-stained matrix; all samples contain coarse, pokilotopic calcite cement that randomly replaces detrital feldspars, rarely quartz. According to the classification scheme of Pettijohn et al. (1987) most of the samples plot in the field of litharenites; one sample (B 1) is classified as sublitharenite.

Most detrital grains (quartz, feldspars, granitic rock fragments, micas) are derived from granitic source rocks, subordinately from low-grade metamorphic rocks (phyllites). The presence of garnet may indicate the reworking of medium-grade, garnet-bearing metamorphic rocks. The texture of these rocks also indicates short distance of transport, and composition points to a dominantly granitic source rock, subordinately metamorphic rocks (phyllites). Sedimentary rock fragments represent reworked calcrete crusts.

Some differences exist between the sandstone composition of the El Cobre Canyon Formation at Arroyo del Agua and at El Cobre Canyon: at Arroyo del Agua the sandstones contain less detrital feldspars and plot in the field of lithic arenites, rarely sublitharenites, whereas at El Cobre Canyon sandstones contain more detrital feldspars therefore plotting also in the field of arkose (Fig. 10). These differences in composition are probably related to differences in the source rocks. No significant differences in petrography were recognized between the El Cobre Canyon and Arroyo del Agua formations at El Cobre Canyon.

CORRELATION TO THE ABO FORMATION

Most workers have long accepted correlation of the Cutler Group strata in the Chama basin to the Abo Formation section along the Jemez River (e.g., Wood and Northrop, 1946; Baars, 1962; Kues and Giles, 2004). However, careful study of the lithostratigraphy of the "Madera Group" and Abo Formation near Jemez Springs and a consideration of the vertebrate and plant-based biostratigraphy suggests a different correlation (Fig. 11). We will present all the data that support this correlation elsewhere, but in brief:

1. Strata of the upper part of the "Madera Group" at Guadalupe Box (these are strata Kues [2001] termed Atrasado Formation) are of Late Pennsylvanian age and are a mixture of marine limestones and shales and arkosic red-bed siliciclastics similar to sandstones of the Cutler Group in the Chama Basin. Strata of the lower part of the El Cobre Canyon Formation in the Chama Basin are of Late Pennsylvanian age.

2. The lower part of the Abo Formation near Jemez Springs contains a vertebrate fauna correlative to the fossil vertebrate assemblages from the upper part of the El Cobre Canyon Formation in the Chama Basin (Langston, 1953; Berman, 1993).

3. Along the Jemez River, there is a lithologic break within the Abo Formation similar to but not as pronounced as the break between the El Cobre Canyon and Arroyo del Agua formations in the Chama Basin. This is a change from brown, coarser-grained, sandstone-dominated strata to orange siltstones and sheet sandstones.

4. The De Chelly Sandstone (= Meseta Blanca Member of Yeso Formation) overlies the Abo Formation along the Jemez River and the Arroyo del Agua Formation near Coyote in the Chama Basin.

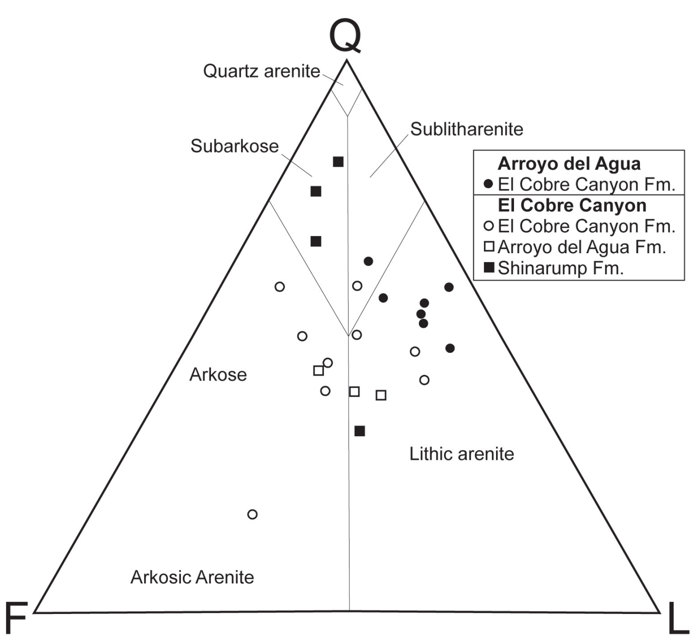

FIGURE 10. QFL diagram showing the composition of sandstones from the Cutler Group at Arroyo del Agua and El Cobre Canyon.

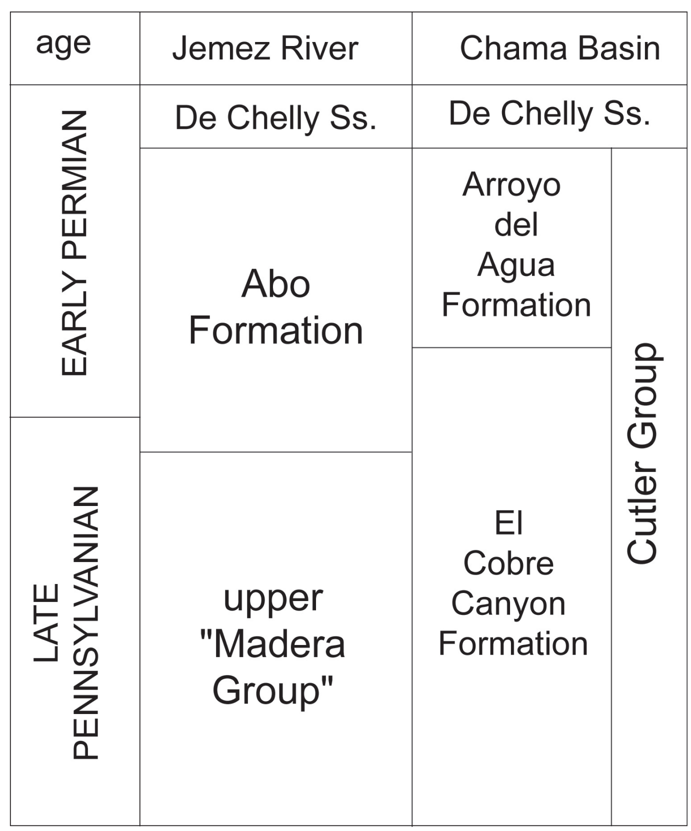

FIGURE 11. Correlation of Cutler Group strata in the Chama Basin to Abo Formation and "Madera Group" along the Jemez River.

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APPENDIX—DESCRIPTION OF MEASURED SECTIONS

El Cobre Canyon Formation Type Section

Measured along the western floor and wall of El Cobre Canyon in secs. 25-26, T24N, R5E. Base at UTM Zone 13, 378369E, 4016319 (NAD27) and top at 376985E, 4016278N. Strata dip 8° to S40°W.

unit	lithology	thickness (m)

Upper Triassic:
Chinle Group:
Shinarump Formation:

85. Conglomeratic sandstone; very pale orange (10YR8/2) and moderate yellowish brown (10YR5/4); quartzose; coarse grained; not calcareous; clasts are chert, jasper and quartzite pebbles; trough crossbedded. not measured

unconformity
Permo-Pennsylvanian:
Cutler Group:
Arroyo del Agua Formation:

84. Sandy siltstone; mottled pale red (10R6/2) and light greenish gray (5GY8/1); not calcareous; blocky. 1.5
83. Sandy siltstone; same as unit 75. 6.0
82. Sandstone; yellowish gray (5Y8/1) and moderate reddish brown (10R4/6); arkosic; coarse grained; not calcareous; trough crossbedded; bench. 3.4
81. Sandy siltstone; moderate reddish brown (10R4/6); micaceous; not calcareous. 1.3
80. Sandy siltstone; same as unit 75. 6.0
79. Sandstone; same as unit 76. 3.3
78. Calcrete pebble conglomerate; pale yellowish brown (10YR6/2) and light olive gray (5Y6/1); bench. 0.7
77. Sandy siltstone; same as unit 75. 4.5
76. Sandstone; moderate reddish brown (10R4/6) and pale reddish brown (10R5/4); arkosic; coarse grained; not calcareous; trough crossbedded; multistoried. 2.6
75. Sandy siltstone; moderate reddish brown (10R4/6); slightly calcareous; some calcrete nodules; slope. 27.0
74. Sandstone; moderate reddish brown (10R4/6); arkosic; coarse grained; trough crossbeded. 1.5
73. Muddy siltstone; moderate reddish brown (10R4/6); calcrete nodules. 14.0
72. Conglomeratic sandstone; pale reddish brown (10R5/4) and moderate reddish brown (10R4/6); arkosic; coarse grained; conglomerate is siltstone and calcrete rip-ups; trough crossbedded; scour base; multistoried bench. 5.7
71. Muddy siltstone; same as unit 73. 5.2
70. Sandstone; yellowish gray (5Y8/1) and moderate reddish brown (10R4/6); arkosic; coarse grained; calcareous; trough crossbedded; multistoried. 2.8
69. Sandstone; moderate reddish brown (10R4/6); arkosic; micaceous; coarse grained; slightly calcareous; in ledges (0.3-m thick) separated by blocky siltstone like unit 68; some calcrete. 6.0
68. Sandy siltstone; same as unit 60; many calcrete nodules. 7.0
67. Sandstone; same as unit 63. 2.0
66. Sandy siltstone; same as unit 60. 6.0
65. Conglomeratic sandstone; sandstone is light greenish gray (5GY8/1) and moderate reddish brown (10R4/6); arkosic, coarse grained and calcareous; clasts are calcrete pellets; trough crossbedded. 1.2
64. Sandy siltstone; same as unit 60. 1.6
63. Sandstone; pale reddish brown (10R5/4) and moderate reddish brown (10R4/6); arkosic; coarse grained; trough crossbedded; scour base with 3 m of relief. 6.0
62. Sandy siltstone; same as unit 60. 0.8
61. Sandstone; same as unit 61. 0.7
60. Sandy siltstone; moderate reddish brown (10R4/6); not calcareous; blocky; calcrete nodules. 4.6
59. Sandy siltstone; same as unit 54; abundant calcrete. 4.0
58. Sandstone; moderate reddish brown (10R4/6); arkosic; coarse to very coarse grained; calcareous; some calcrete pebbles; trough crossbedded; scour base locally cuts down to unit 55. 3.0
57. Sandy siltstone; grayish red (10R4/2); calcareous; blocky. 1.0
56. Sandy siltstone; same as unit 54. 6.2
55. Sandstone; pebbly at base; moderate reddish brown (10R4/6) and pale red (10R6/2); arkosic; coarse to very coarse grained; calcareous; pebbles are siltstone and calcrete rip ups; trough crossbedded; bench. 1.7
54. Sandy siltstone; moderate reddish brown (10R4/6); calcareous; blocky. 8.7

El Cobre Canyon Formation:

53. Sandstone; pale reddish brown (10R5/4); fine grained; arkosic; very calcareous; laminar and bioturbated. 1.7
52. Sandy siltstone; same as unit 44. 1.6
51. Sandstone; same as unit 47. 0.6
50. Sandy siltstone; same as unit 44. 0.2
49. Sandstone; same as unit 47. 0.3
48. Sandy siltstone; same as unit 44. 1.0
47. Sandstone; pale reddish brown (10R5/4) and grayish red (10R4/2); fine grained; arkosic; calcareous; massive. 0.8
46. Sandy siltstone; same as unit 44. 1.5
45. Sandstone; pale reddish brown (10R5/4); arkosic; fine grained; calcareous; bioturbated. 0.6
44. Sandy siltstone; pale reddish brown (10R5/4); calcareous; calcrete; blocky. 2.0
43. Conglomeratic sandstone; pale reddish brown (10R5/4); coarse to very coarse grained; arkosic; clasts are quartzite and calcrete pebbles; very calcareous; trough crossbedded; scour base; bench. 2.7
42 Sandy siltstone; same as unit 44 except laminar. 1.8
41. Sandy siltstone; same as unit 44. 7.3
40. Sandstone; same as unit 38. 0.6
39. Sandy siltstone; same as unit 44. 3.8
38. Sandstone; pinkish gray (5YR8/1) and light brownish gray (5YR6/1); arkosic; coarse grained; very calcareous; ripple laminated. 0.3
37. Sandy siltstone; pale reddish brown (10R5/4); abundant calcrete nodules; blocky; slope. 2.7
36. Sandstone; same as unit 38; thin bioturbated ledge. 1.8
35. Sandy siltstone; same as unit 37; some thin sandstone lenses like unit 38. 3.2
34. Sandstone; same as unit 32. 0.5
33. Sandy siltstone; same as unit 31. 1.0
32. Sandstone; pinkish gray (5YR8/1) and light olive gray (5Y6/1); arkosic; calcareous; coarse grained; bioturbated. 1.0
31. Sandy siltstone; pale reddish brown (10R5/4); micaceous; numerous calcrete nodules; blocky slope; a few lenses of sandstone like unit 32. 4.0
30. Sandstone; yellowish gray (5Y8/1) and light olive gray (5Y6/1); arkosic; coarse grained; calcareous; trough crossbedded. 3.5
29. Sandstone; same as unit 27, bench. 2.9
28. Sandy siltstone; pale red (10R6/2) and pale reddish brown (10R5/4); laminar; calcareous. 0.8
27. Sandstone; yellowish gray (5Y8/1); arkosic; coarse grained; very calcareous; trough crossbedded; bench. 2.9
26. Sandy shale; light olive gray (5Y6/1); not calcareous; plant debris. 2.5
25. Conglomeratic sandstone; yellowish gray (5Y8/1) and moderate orange pink (10R7/4); arkosic; coarse grained; very calcareous; clasts are quartzite up to 6 cm diameter; trough crossbedded. 1.9
24. Sandy siltstone; same as unit 18. 1.6
23. Calcrete ledge; light olive gray (5Y6/1); some associated calcrete-pebble conglomerate. 1.3
22. Sandy siltstone; same as unit 18; blocky; slope. 3.1
21. Calcrete ledge; same as unit 23. 0.1
20. Sandy siltstone; same as unit 18. 0.7
19. Sandstone; pale red (10R6/2); arkosic; fine grained; very calcareous; massive; cuesta. 0.6
18. Sandy siltstone; pale reddish brown (10R5/4); micaceous; not calcareous; numerous rhizoliths. 7.5
17. Conglomerate; light olive gray (5Y6/1); calcrete pebbles in coarse-grained arkosic sandstone matrix; trough crossbedded; bench. 1.6

16. Sandy siltstone; same as unit 18. 3.3
15. Sandstone; same as unit 6. 0.2
14. Sandy siltstone; same as unit 7. 1.9
13. Sandstone; yellowish gray (5Y8/1) and moderate orange pink (10R7/4); arkosic; coarse grained; calcareous; trough crossbedded; multistoried bench. 2.4
12. Sandy siltstone; same as unit 7 except trough crossbedded. 2.2
11. Sandy siltstone; same as unit 7. 5.0
10. Sandstone; pale reddish brown (10R5/4); arkosic; coarse grained; not calcareous; trough crossbedded; top surface has desiccation tracks. 1.2
9. Sandy siltstone; same as unit 7. 2.2
8. Sandstone; pale reddish brown (10R5/4); arkosic; medium grained; very calcareous; some calcrete rip-ups; trough crossbedded; multistoried bench. 2.0
7. Sandy siltstone; grayish red (10R4/2) and pale reddish brown (10R5/4); micaceous; not calcareous; abundant rhizoliths. 1.6
6. Sandstone; light olive gray (5Y6/1); arkosic; micaceous; medium grained; calcareous; ripple laminated. 0.4
5. Conglomerate; light olive gray (5Y6/1); calcrete pebbles and a sparse matrix of arkosic sand grains; bench. 0.2
4. Sandy siltstone; pale reddish brown (10R5/4) and grayish red (10R4/2); micaceous; not calcareous; laminar. 5.5
3. Conglomeratic sandstone; same as unit 1. 3.2
2. Sandy siltstone; pale reddish brown (10R5/4); micaceous; calcareous; blocky. 7.7
1. Conglomeratic sandstone; pale reddish brown (10R5/4); arkosic; micaceous; very calcareous; coarse grained; clasts are gray quartzite;trough crossbedded; multistoried. 0.9

Arroyo del Agua Formation Type Section

Measured north of the Rio Puerco up the point of Mesa Montosa in the SW1/4 sec. 5 and SE1/4 sec. 6, T22N, R3E. Base of section at UTM Zone 13, 351263E, 4003225N (NAD27); top at 351651E, 4003821N. Strata are essentially flat lying.

unit	lithology	thickness (m)

Upper Triassic:
Chinle Group:
Zuni Mountains Formation:

63. Sandstone and conglomeratic sandstone; color mottled very pale orange (10YR8/1), pale red (10R6/2), pale reddish brown (10R5/4) and light brown (5YR5/6); fine to coarse grained; quartzose; pebbles are gray quartzite; not calcareous; massive. not measured

unconformity
Permo-Pennsylvanian:
Cutler Group:
Arroyo del Agua Formation:

62. Sandy siltstone; same as unit 60. 2.1
61. Sandstone; same as unit 59. 1.2
60. Sandy siltstone; moderate reddish brown (10R4/6); not calcareous; blocky; no calcrete nodules; some lenses of sandstone like unit 58. 4.3
59. Sandstone; very pale orange (10YR8/2); coarse grained; arkosic; some pebbles of quartzite; kaolinitic? 1.6
58. Sandstone; moderate red (5R5/4) with white (N9) speckles; arkosic; clayey and friable; trough crossbedded. 4.0
57. Conglomeratic sandstone; same as unit 53. 2.4
56. Muddy sandstone; pale reddish brown (10R5/4) with white (N9) speckles and bands; some calcrete nodules; arkosic. 4.7
55. Sandy siltstone; moderate reddish brown (10R4/6); not calcareous; blocky; no calcrete nodules. 2.4
54. Muddy siltstone; same as unit 43. 5.0
53. Conglomeratic sandstone; moderate reddish orange (10R6/6); arkosic; coarse grained; clasts are quartzite pebbles, trough crossbeds. 0.7
52. Sandstone; same as unit 39; units 52 and 53 form a prominent bench. 2.2
51. Sandstone and interbedded nodular calcrete; sandstone is coarse grained, yellowish gray (5Y8/1), arkosic, calcareous and lenticular; calcrete is moderate reddish orange (10R6/6) and yellowish gray (5Y8/1) and sandy. 5.4
50. Sandstone; same as unit 47. 1.9
49. Muddy siltstone; same as unit 43. 3.0
48. Sandstone; same as unit 39. 4.6
47. Sandstone; moderate reddish brown (10R4/6); arkosic; coarse to very coarse grained; some calcrete pebble rip-ups; slightly calcareous; trough crossbedded. 0.8
46. Muddy siltstone; same as unit 43. 1.5
45. Conglomeratic sandstone; same as unit 42. 0.3
44. Nodular calcrete; light brown (5YR6/4); forms a bench. 1.1
43. Sandy siltstone; moderate reddish brown (10R4/6); some sandstone lenses like unit 32; faintly laminated; no calcrete nodules; forms a slope. 3.2
42. Conglomerate; yellowish gray (5Y8/1) calcrete pebbles; trough crossbedded. 1.3
41. Muddy siltstone; moderate reddish brown (10R4/6); not calcareous; a few calcrete nodules; forms a slope. 9.3
40. Sandstone and conglomeratic sandstone; moderate reddish brown (10R4/6); arkosic; coarse grained; conglomerate is calcrete pebbles; trough crossbedded; forms a bench. 2.1
39. Sandstone; moderate reddish brown (10R4/6) with some white (N9) specks; arkosic; coarse grained; calcareous; laterally accreted trough crossbeds; forms a bench. 4.8
38. Muddy siltstone; same as unit 31; many calcrete nodules. 10.7
37. Sandstone; dark reddish brown (10R3/4); coarse grained; arkosic; calcareous; some quartzite pebbles; trough crossbedded; forms a ledge. 4.3
36. Sandy siltstone; same as unit 33. 1.7
35. Calcrete; moderate reddish brown (10R4/6); three blocky ledges with more nodular horizons in between. 3.7
34. Muddy siltstone; same as unit 31. 1.8
33. Sandy siltstone; moderate reddish brown (10R4/6); not calcareous; micaceous; with some sandstone lenses like unit 32; a few calcrete nodules; forms a slope. 4.9
32. Sandstone; moderate reddish brown (10R4/6); arkosic; micaceous; slightly calcareous; coarse grained; massive. 0.2
31. Muddy siltstone; moderate reddish brown (10R4/6); numerous calcrete nodules; blocky; forms a slope. 18.3
30. Sandstone; yellowish gray (5Y8/1) and moderate reddish brown (10R4/6); medium to coarse grained; arkosic; calcareous; micaceous; trough crossbedded; forms a bench. 3.1
29. Muddy siltstone; same as unit 31; numerous calcrete nodules. 1.8

El Cobre Canyon Formation:

28. Sandstone; same as unit 27 but less conglomeratic. 2.9
27. Conglomeratic sandstone; pale reddish brown (10R5/4); and moderate reddish brown (10R4/6); arkosic; very calcareous; clasts are quartzite and calcrete pebbles, especially in lower 0.5 m; trough crossbedded; units 23-27 form a thick bench. 3.9
26. Silty sandstone; moderate reddish brown (10R4/6); arkosic; fine to medium grained; not calcareous; blocky; numerous calcrete nodules; forms a recessed notch. 2.5
25. Sandstone; pale reddish brown (10R5/4) and dark reddish brown (10R3/4); arkosic; micaceous; coarse grained; not calcareous; some quartzite and calcrete pebbles; trough crossbedded; multistoried. 5.3
24. Sandstone and sandy siltstone; color banded pale reddish brown (10R5/4) and pinkish gray (5YR8/1); sandstone is coarse grained, micaceous, arkosic and friable; trough crossbedded. 5.5
23. Conglomerate and sandstone; conglomerate is pale yellowish brown (10YR6/2) calcrete pebbles up to 2 cm in diameter in a coarse to very coarse grained arkosic sandstone that is pinkish gray (5YR8/1); sandstone is coarse grained, micaceous, arkosic, yellowish gray (5Y8/1) and very calcareous; trough crossbedded; a few granite and quartzite cobbles. 1.8
22. Muddy siltstone; same as unit 20; some plugged calcrete lenses. 8.8
21. Sandstone; pale reddish brown (10R5/4) to grayish red (10R4/2); coarse grained; arkosic; some pebbly beds and lenses of siltstone with *Walchia* and other carbonized plant material; trough crossbedded; ledge. 0.9

20. Muddy siltstone; pale reddish brown (10R5/4) with greenish gray (5GY6/1) mottles; numerous rhizolith concretions. 3.8
19. Sandstone; same as unit 21. 1.7
18. Sandy siltstone and calcrete nodules; same as unit 16. 0.7
17. Conglomerate; pale reddish brown (10R5/4) with calcrete clasts that are moderate reddish brown (10R4/6) and up to 1 cm in diameter; some quartzite pebbles; trough crossbedded. 1.6
16. Sandy siltstone; pale reddish brown (10R5/4); numerous calcrete nodules. 1.7
15. Sandstone; pale reddish brown (10R5/4); arkosic; coarse grained; very calcareous; a few quartzite pebbles; trough crossbedded; units 10-15 form a thick bench. 2.8
14. Sandstone; pale reddish brown (10R5/4); arkosic; coarse grained; many quartzite pebbles; very calcareous; trough crossbedded. 0.7
13. Sandstone; same as unit 9; forms a notch. 1.7
12. Sandstone; pale reddish brown (10R5/4) and moderate orange pink (10R7/4); arkosic; coarse grained; calcareous; trough crossbedded in thin (0.2-0.3m) sets. 1.3
11. Sandstone; same as unit 14; scourbase. 2.0
10. Sandstone; yellowish gray (5Y8/1) and pale reddish brown (10R5/4); coarse grained; very arkosic; calcareous; a few quartzite pebbles; trough crossbedded. 2.2
9. Sandstone; banded pale reddish brown (10R5/4) and yellowish gray (5Y8/1); medium grained; arkosic; very calcareous; massive to tabular bedded. 4.3
8. Conglomerate and sandstone; pale reddish brown (10R5/4) and moderate orange pink (10R7/4); arkosic; coarse grained; very calcareous; conglomerate is cobbles of quartzite, gneiss and granite; fines upwards; trough crossbedded. 2.1
7. Sandstone; same as unit 2. 5.4
6. Sandy siltstone; same as unit 4. 2.2
5. Sandstone; grayish red (10R4/2); arkosic; fine to medium grained; calcareous; trough crossbedded; bench. 2.0
4. Sandy siltstone; moderate reddish orange (10R6/6); very calcareous; some calcrete nodules. 4.0
3. Sandstone; pale reddish brown (10R5/4); arkosic; medium grained; calcareous; massive; bench. 0.7
2. Sandstone; pale reddish brown (10R5/4) and grayish red (10R4/2); arkosic; coarse to very coarse grained; very calcareous; trough crossbedded; a few silica pebbles and calcrete rip-ups; units 2-7 form a ribbed cliff just above the Rio Puerco.
1. Covered slope. not measured

PLATE 12: PHOTOGRAPHIC STRATIGRAPHY OF THE CHAMA BASIN PALEOZOIC AND MESOZOIC STRATIGRAPHY

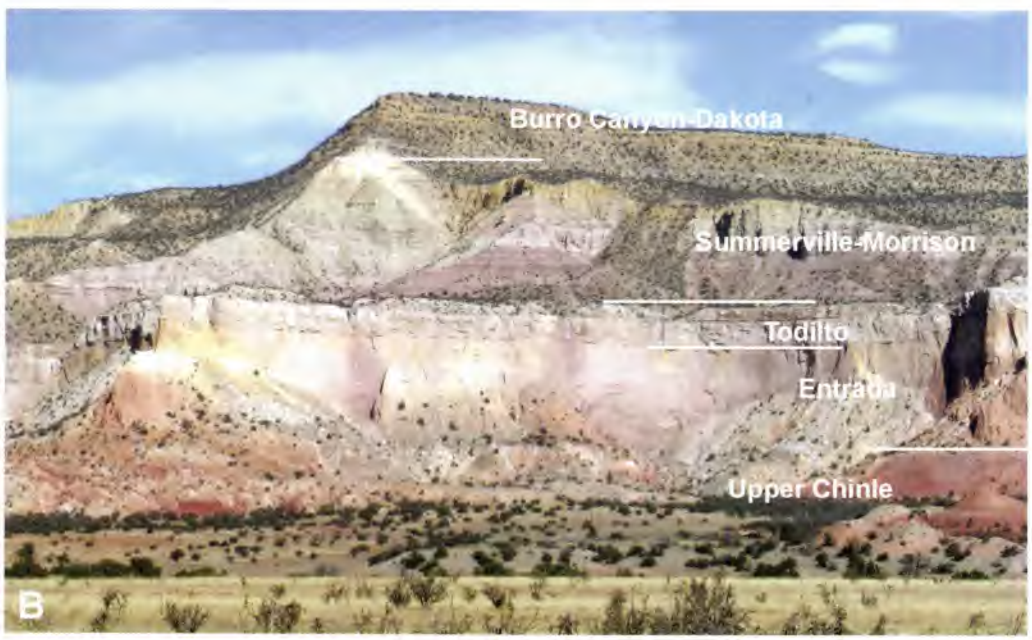

PLATE 12. Paleozoic and Mesozoic stratigraphy in the Chama Basin. A, Paleozoic and Mesozoic strata northwest of Coyote, New Mexico. Mesa Montosa is in the foreground and is composed of the Lower Permian Cutler Group's El Cobre Canyon and Arroyo del Agua formations. The mesa is capped by the Upper Triassic Shinarump, Salitral and Poleo formations of the Chinle Group. In the distance, the Jurassic Entrada Sandstone, Summerville-Bluff-Morrison formations and Cretaceous strata can be seen. B, Mesa Montosa immediately north of Ghost Ranch (not the same as Mesa Montosa near Coyote). Upper Triassic Petrified Forest Formation (Chinle Group) floors the valley and creates low red and purple hills in the foreground. The steep cliffs of the mesa are Jurassic Entrada Sandstone, Todilto and Summerville-Bluff-Morrison formations. Mesa Montosa is capped by the Cretaceous Burro Canyon-Dakota formations.

PLATE 13: PHOTOGRAPHIC STRATIGRAPHY OF THE CHAMA BASIN UPPER PENNSYLVANIAN TO LOWER PERMIAN STRATIGRAPHY

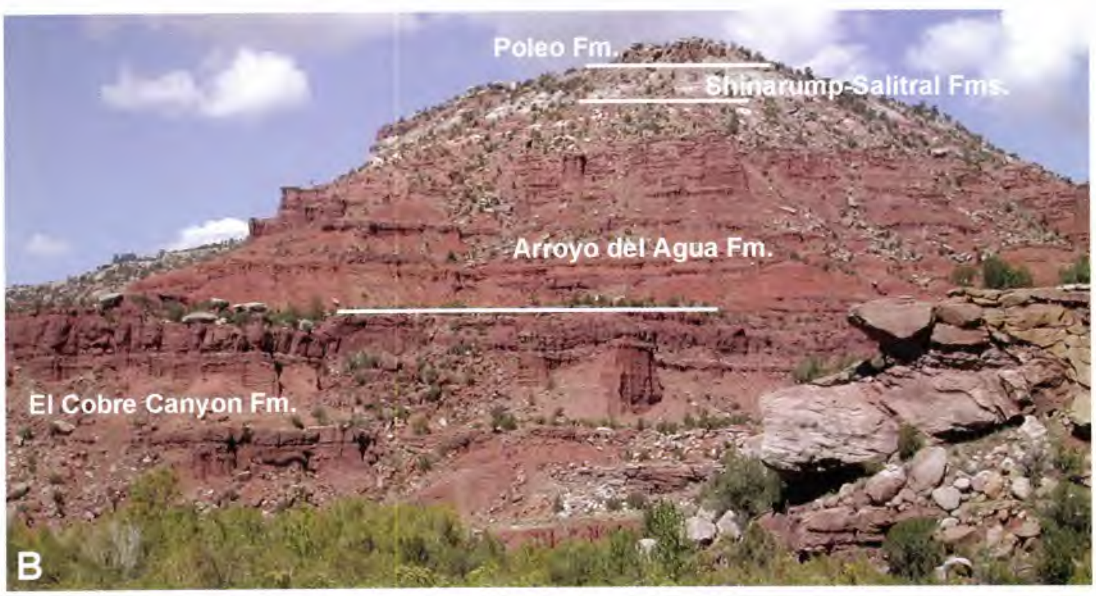

PLATE 13. Upper Pennsylvanian - Lower Permian strata in the Chama Basin. A, Western wall of El Cobre Canyon, northeast of Abiquiu. The El Cobre Canyon Formation of the Lower Permian Cutler Group floors the valley and creates low benches. The walls of the canyon are Arroyo del Agua Formation (Cutler Group), and are capped by the Upper Triassic Shinarump-Poleo formations of the Chinle Group. B, Flank of the side of Mesa Montosa, near Arroyo del Agua, New Mexico, showing the transition between the lower, sandier El Cobre Canyon Formation (Cutler Group) and the upper, siltier Arroyo del Agua Formation. The mesa is capped by the Upper Triassic Shinarump-Poleo formations of the Chinle Group.