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PENNSYLVANIAN STRATIGRAPHY AND CONODONT BIOSTRATIGRAPHY IN THE CERROS DE AMADO, SOCORRO COUNTY, NEW MEXICO

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Abstract—We measured seven overlapping sections on different fault blocks to construct a complete, 805-m-thick Pennsylvanian section in the Cerros de Amado of Socorro County. At the base of the Pennsylvanian section, the Sandia Formation unconformably overlies Precambrian basement and is a 162-m-thick cyclic succession of siliciclastics (notably quartzose sandstone and conglomerate) and limestones (mostly coarse-grained bioclastic wackestone/packstone). The overlying Gray Mesa Formation is 233 m thick and, following Rejas, we divide it into three members named by Thompson: Elephant Butte Member (oldest; 95 m of limestone and shale with a prominent 10-m-thick sandstone bed near the base), Whiskey Canyon Member (35 m of mostly very cherty limestone) and Garcia Member (103 m of diverse limestone, conglomerate, sandstone and shale). The overlying Atrasado Formation is 290 m of interbedded silicilclastics (mostly shale and arkosic sandstone) and varied limestones. We recognize most of the formation rank units of Thompson and Rejas as members of the Atrasado Formation (ascending order): Bartolo, Amado, Tinajas (new name), Council Spring, Burrego, Story, Del Cuerto and Moya. The Bursum Formation caps the Pennsylvanian section in the Cerros de Amado and is as much as 120 m of red-bed siliciclastics and limestones.

Fusulinids are not common in the Pennsylvanian section in the Cerros de Amado and provide sparse age data for parts of the Gray Mesa, Atrasado and Bursum formations, so we undertook sampling for conodonts. They indicate the following ages: (1) Atokan—47 m above the base of the Sandia Formation; (2) early Desmoinesian (Cherokee)—Elephant Butte, Whiskey Canyon and lower Garcia members of Gray Mesa Formation; (3) late Desmoinesian (Marmaton)—upper Garcia Member of Gray Mesa Formation and Bartolo Member of Atrasado Formation; (4) early Missourian—Amado Member of Atrasado Formation; (5) late Missourian—Tinajas and Council Spring members of Atrasado Formation; (6) middle Virgilian—top of Burrego, and all of Story, Del Cuerto and Moya members of Atrasado Formation. The conodont ages are consistent with the few fusulinid horizons we located, and fusulinids indicate that the Bursum Formation in the Cerros de Amado is early Wolfcampian in age.

A striking aspect of the entire Cerros de Amado Pennsylvanian section is the degree to which coarse siliciclastics are present at various levels, and the presence of several unconformities, indicating a strong tectonic influence on local sedimentation throughout the Middle-Late Pennsylvanian.

INTRODUCTION

The Cerros de Amado are rugged hills developed in faulted and folded upper Paleozoic strata exposed along the eastern flank of the Rio Grande rift about 8 km northeast of Socorro, New Mexico (Fig. 1). Much of the bedrock in the Cerros de Amado consists of Pennsylvanian sedimentary rocks, and, indeed, a complete Pennsylvanian section for this part of central New Mexico can be pieced together across different fault blocks. In this article, we present such a section, compiled from seven different, overlapping sections (Fig.1). This complete and detailed section allows us to evaluate and revise the lithostratigraphic nomenclature of the Pennsylvanian strata in the Cerros de Amado. Furthermore, we have sampled these strata for conodonts, so we present a preliminary conodont biostratigraphy of the Pennsylvanian section in the Cerros de Amado.

PREVIOUS STUDIES

Herrick (1904a, b) provided the first recognizable descriptions of Pennsylvanian strata in the Cerros de Amado, identifying the Sandia Beds (also called by him Sandia Formation or Sandia Series) overlain by the "Coal Measures" (or "Coal Measure Formation"), also called by him the "Massive Grey Limestone with Quartzite Beds" (Fig. 2). Herrick (1904a) also described a *Lepidodendron* flora from the Sandia Formation in the Arroyo de la Presilla (cf. Lucas et al., 2003, this guidebook).

Darton (1928) referred the entire Pennsylvanian section in the Cerros de Amado to the Magdalena Group (Fig. 2). He provided a general description of what he believed to be a complete Pennsylvanian section exposed along the Arroyo de la Presilla (secs. 11-12, T3S, R1E), but this 287-m-thick section is only part of the

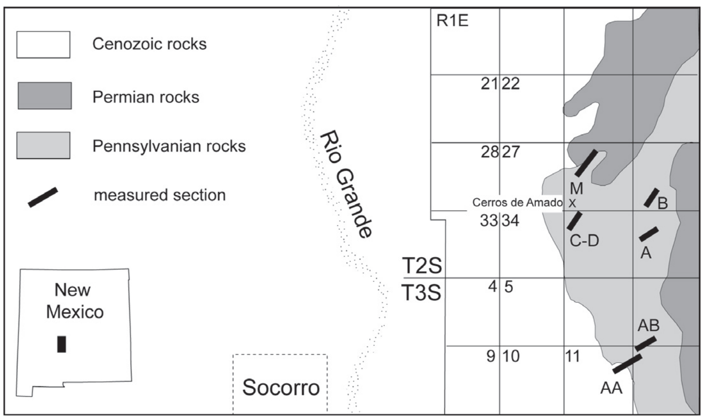

FIGURE 1. Simplified geologic map of the Cerros de Amado area (geology modified from Wilpolt and Wanek, 1951) showing locations of measured sections of Pennsylvanian strata. Measured sections are: A = Cerros de Amado A (Fig. 11); AA = Arroyo de la Presilla A (Fig. 3); AB = Arroyo de la Presilla B (Fig. 6); B = Cerros de Amado B (Fig. 12); C-D = Cerros de Amado C and D (Figs. 7-8); M = Minas de Chupadera (Fig. 13). Grid shows legal land survey; numbered squares are sections, nominally one mile (1.6 km) on a side.

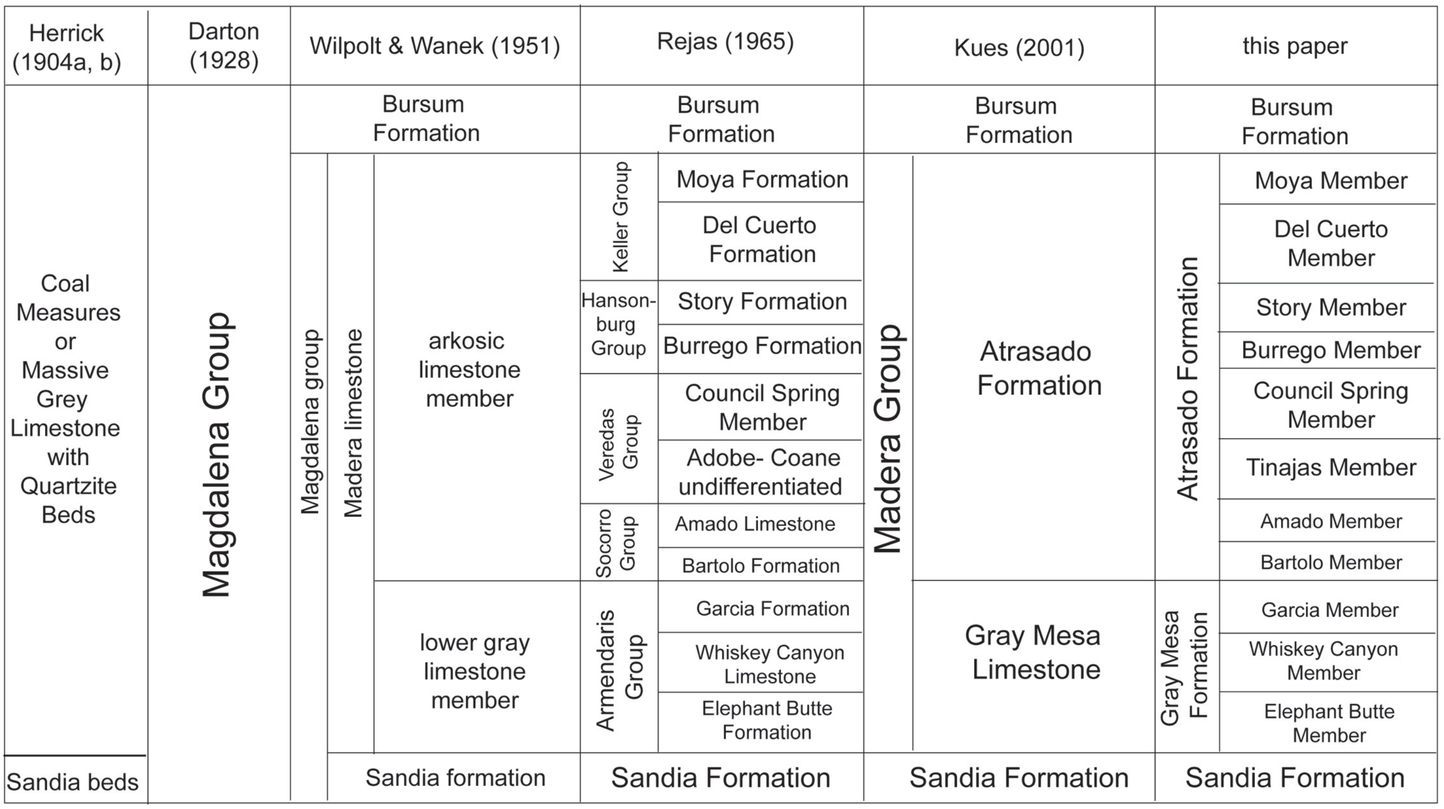

FIGURE 2. Comparison of previously used Pennsylvanian lithostratigraphic nomenclature in the Cerros de Amado and the nomenclature advocated in this article.

local Pennsylvanian succession. Darton (1928, p. 68) also noted "impressions of the bark of a large plant, *Lepidodendron obovatum* "in the Sandia Formation but apparently did not realize that he had rediscovered Herrick's (1904a) *Lepidodendron* locality.

Wilpolt and Wanek (1951) mapped a large area in Socorro County that includes the Cerros de Amado. They used a nomenclature for the Pennsylvanian rocks (Fig. 2) that had largely been developed by workers of the U. S. Geological Survey, from Gordon (1907) to Read and Wood (1947), and assigned the entire Pennsylvanian section to the Magdalena Group divided into the Sandia formation, Madera limestone and Bursum formation (the latter considered by them to be of Permian age). They further divided the Madera informally into a lower gray limestone member and an upper, arkosic limestone member.

Beginning with Hambleton (1959, 1962), several student theses completed at the New Mexico Institute of Mining and Technology (Rejas, 1965; Jaworski, 1973; Maulsby, 1981; Bauch, 1982; Brown, 1987) used nomenclature for the Pennsylvanian strata in the Cerros de Amado that Thompson (1942) had first proposed for the Pennsylvanian section in the Mud Springs Mountains of Sierra County and the Oscura Mountains of Socorro County. Thus, Hambleton (1959, 1962) studied a section near the Ojo de Amado (SE ¼ sec. 27, T2S, R1E) and assigned the strata to the Bolander Group, Coane, Adobe, Council Spring, Burrego and Story formations of Thompson (1942). He compared and correlated this section to Missourian strata in the northern Oscura Mountains and in the Lucero uplift of Valencia County. Much of his analysis focused on the algal bioherms in the Cerros de Amado section.

Kottlowski (1960, p. 55-56) briefly reviewed the Pennsylvanian section in the Cerros de Amado, based primarily on the data in Wilpolt and Wanek (1951). He thus assigned the section to the Sandia Formation (194 m thick), limestone member of the Madera (291 m thick) and the arkosic member of the Madera (at least 165 m thick). Although Kottlowski (1960) noted that fusulinid data are sparse in these strata, he still assigned the Sandia and lower part of the Madera limestone member to the Derryan (= Atokan), most of the limestone member of the Madera to the Desmoinesian and the arkosic member to the Missourian-Virgilian. Kottlowski (1960) also noted the work of Hambleton (1959) with approval, and referred (p. 56) to the top of the Pennsylvanian section in the Cerros de Amado (strata immediately beneath the Bursum Formation) as a "cherty phase" of the Moya Formation.

Rejas (1965) mapped a large part of the Cerros de Amado area, assigned the oldest Pennsylvanian strata to the Sandia Formation, and applied Thompson's (1942) stratigraphic nomenclature as well as some new names of his own (Socorro Group, divided into Bartolo Formation and Amado Limestone) to the overlying Pennsylvanian strata up to the Bursum Formation (Fig. 2). He was unable to differentiate Thompson's (1942) Adobe and Coane formations, so he referred to that stratigraphic interval as the "Adobe-Coane undifferentiated." This differed from Hambleton (1959, 1962), who had distinguished as the Coane Formation a 43-m-thick section of mostly shale above strata he termed

Desmoinesian Bolander Group; the overlying Adobe Formation according to Hambleton is 26 m thick and mostly shale, with a few prominent limestone beds.

Siemers (1978, p. 174-185; 1983) described a complete Pennsylvanian section in the Cerros de Amado measured in secs. 2-3, T3S, R1E and secs. 26 and 35, T2S, R1E. With a total thickness of 578.3 m, he assigned the section to the Sandia Formation and Madera Limestone, also identifying Atokan, Desmoinesian, Missourian and Virgilian time intervals (though no explicit data were presented to support the age assignments). Siemers (1978) thus broke ranks with the other New Mexico Tech students by not applying Thompson's (1942) lithostratigraphic nomenclature to the Pennsylvanian strata in the Cerros de Amado. Indeed, Siemer's (1978) section is fairly generalized—most units are more than 3 m thick and some are as much as 25 m thick. Furthermore, he noted (p. 23) that "the only consistent lithologic breaks recognized within the Pennsylvanian system throughout the Socorro region are between a lower terrigenous unit, a medial limestone unit, and an upper mixed limestone-terrigenous unit." Most of Siemers (1978, 1983) work was focused on petrography and interpretation of depositional environments.

Maulsby (1981) mapped an area east and northeast of the area mapped by Rejas (1965) that he termed the Rancho de Lopez area (secs. 19-22, 27-29, 32-33, T2S, R2E and secs. 3-6, T3S, R2E). Like Rejas (1965), he applied Thompson's (1942) nomenclature, mapping the Burrego, Story, Del Cuerto and Moya formations, which are the portions of the Pennsylvanian section that crop out in his map area.

Bauch (1982) mapped an area south of the area mapped by Rejas (1965), in the center of the Loma de las Cañas quadrangle (secs. 1-14, T3S, R1E and secs. 7-8 and 17-18, T3S, R1E). He also followed Rejas (1965) in applying Thompson's (1942) nomenclature to the post-Sandia Formation section. The only difference from Rejas (1965) is that Bauch did not separate the Del Cuerto and Story formations, calling them "Del Cuerto-Story undifferentiated" because of the local pinchout of the upper limestone interval of the Story Formation into clastics of the Burrego (below) and Del Cuerto (above) (Bauch, 1982, fig. 15).

Mapping in the Sierra de la Cruz area just northeast of the Cerros de Amado, Colpitts (1986) referred the Pennsylvanian strata to the Madera Limestone of the Magdalena Group and to the overlying Bursum Formation. In contrast, Brown (1987), mapping near the area mapped by Colpitts (1986), used the same stratigraphic nomenclature as Rejas (1965) for the Pennsylvanian section.

Lucas and Estep (2000) and Tidwell et al. (2000) advocated using the terms Gray Mesa and Atrasado formations for the strata in the Cerros de Amado that had previously been termed Madera Formation (Group). However, they presented only limited lithostratigraphic data and mostly focused on documenting new fossil occurrences. Kues (2001) also advocated using the terms Gray Mesa and Atrasado formations for the strata in the Cerros de Amado that had previously been termed Madera Formation (Group) (Fig. 2).

Most recently, Cather and Colpitts (2005) mapped the Loma de las Cañas quadrangle, which includes the Cerros de Amado. They assigned the Pennsylvanian section to the Sandia Formation (90-175 m thick), Gray Mesa Formation of Madera Group (approximately 150 m thick) and to the Atrasado Formation of the Madera Group (approximately 250 m thick). They noted that the Atrasado Formation includes the Bartolo, Amado, Adobe-Coane, Council Spring, Burrego, Story, Del Cuerto and Moya "units" of Rejas (1965).

LITHOSTRATIGRAPHY

Lithostratigraphic Nomenclature

As is clear from the historical review above, the lithostratigraphic nomenclature applied to the Pennsylvanian section in the Cerros de Amado comes from two main sources: (1) a generalized formation- and group-rank nomenclature developed during the first half of the 20th century for Pennsylvanian strata in central New Mexico, principally by workers of the U. S. Geological Survey (e.g., Herrick, 1900; Gordon, 1907; Darton, 1922, 1928; Wilpolt et al., 1946; Read and Wood, 1947); and (2) a very detailed group- and formation-rank nomenclature proposed by Thompson (1942) for Pennsylvanian strata in central and southern New Mexico, and much used by those who have subsequently studied and/or mapped the Pennsylvanian rocks in the Cerros de Amado (e.g., Hambleton, 1959, 1962; Kottlowski, 1960; Rejas, 1965; Maulsby, 1981; Bauch, 1982; Brown, 1987; Cather and Colpitts, 2005).

All workers apply the term Sandia Formation to the lowest Pennsylvanian formation-rank stratigraphic unit in the section (Fig. 2)—a cyclic succession of siliciclastics (notably quartz sandstone and conglomerate) and carbonates (especially coarse-grained bioclastic wackestone). Similarly, all workers use the term Bursum Formation for the stratigraphically highest Pennsylvanian strata in the section (Fig. 2)—a mixed succession of red-bed clastics and marine limestones (note, though, that the Bursum was long regarded as of earliest Permian age). Like Cather and Colpitts (2005), we follow Lucas and Estep (2000), Tidwell et al. (2000) and Kues (2001), who advocated using the terms Gray Mesa and Atrasado formations for the strata in the Cerros de Amado that had previously been termed Madera Formation (Group) by many workers (Fig. 2). Key points to justify these decisions include:

1. Gray Mesa and Atrasado apply to mappable lithosomes across much of central New Mexico, from the Oscura Mountains through the Cerros de Amado, the Los Pinos, Manzano and Sandia Mountains and the Lucero uplift. They are formal terms for the lower gray limestone and upper arkosic limestone members of the Madera Limestone mapped by Wilpolt et al. (1946) and Wilpolt and Wanek (1951), among others. We thus follow Kues (2001) in advocating the use of only two formation names for the Pennsylvanian strata between the Sandia and the Bursum formations in central New Mexico.

2. Gray Mesa and Atrasado are the oldest mappable formation rank unit names formally proposed for these units (Kelley and Wood, 1946). Krainer and Lucas (2004) recently provided detailed descriptions of the type sections of the Gray Mesa and Atrasado formations.

3. The formation names Myers (1973) introduced for what he termed the Madera Group in the Manzano Mountains—Los Moyos and Wild Cow formations—are, as Kues (2001) noted, obviously synonyms of the Gray Mesa and Atrasado formations of Kelley and Wood (1946). Los Moyos Formation and Wild Cow Formation thus should be abandoned and replaced by Gray Mesa Formation and Atrasado Formation, respectively, so we do not extend Myers' formation names into the Cerros de Amado area.

With regard to the lithostratigraphic nomenclature of the Pennsylvanian section proposed by Thompson (1942), we have restudied the type sections of his units in the Derry Hills and Mud Springs Mountains of Sierra County, and in the northern Oscura Mountains of Socorro County (Lucas et al., 2008, 2009). We are in general agreement with Hambleton (1959, 1962) and Rejas (1965), who first advocated applying much of Thompson's (1942) nomenclature to the Pennsylvanian section in the Cerros de Amado (Fig. 2). Key points to note here are:

1. Thompson's (1942) group-rank names are of no value as lithostratigraphic terms in the Cerros de Amado (or elsewhere). His Armendaris Group (Elephant Butte, Whiskey Canyon and Garcia formations) is an unused senior synonym of most of the Gray Mesa Formation, but resurrecting Armendaris Group would serve no useful purpose and would only cause confusion, given that Gray Mesa Formation has become a well-established term during the last decade. Thompson's Bolander Group cannot be recognized in the Cerros de Amado, either because it is missing at an unconformity or because of facies changes between its type section in the Mud Springs Mountains and the Cerros de Amado, a distance of ~ 120 km. Thompson's Veredas, Hansonburg and Keller groups apply to parts of the Atrasado Formation, but do not divide it into mappable formation-rank units or logical groupings of similar strata. Instead, they clearly are chronostratigraphic units based on Thompson's fusulinid biostratigraphy: Veredas Group = early Missourian, Hansonburg Group = late Missourian and Keller Group = Virgilian. Therefore, we do not use Thompson's (1942) group-rank nomenclature for Pennsylvanian strata in the Cerros de Amado (Fig. 2).

2. Thompson's (1942) formation-rank units are best treated as lithostratigraphic units of member rank. Thus, his Elephant Butte, Whiskey Canyon and Garcia formations are recognizable members of the Gray Mesa Formation in the Cerros de Amado (Rejas, 1965). Some of Thompson's (1942) other formation names –Council Spring, Burrego, Story, Del Cuerto and Moya—are recognizable as members of the Atrasado Formation in the Cerros de Amado (Fig. 2).

3. The base of the Atrasado Formation is the base of a unit that Rejas (1965) named the Bartolo Formation, and we formalize this name here as the Bartolo Member of the Atrasado Formation. The overlying Amado Formation of Rejas (1965) is also formalized by us here as a member of the Atrasado Formation; the Amado Member is one of the most distinctive stratigraphic markers in the Pennsylvanian section in the Cerros de Amado area. However, the stratigraphic interval (in the lower part of the Atrasado Formation) that Rejas (1965) referred to as the "Adobe-Coane (undifferentiated)" bears no lithologic resemblance to the type sections of Thompson's Adobe and Coane formations. Therefore, we propose a new member name for this unit, the Tinajas Member of the Atrasado Formation (see below).

Finally, we follow all workers since the 1940s in terming the uppermost unit in the Pennsylvanian section in the Cerros de Amado the Bursum Formation (Fig. 2). The Bursum Formation was long considered the oldest Permian stratigraphic unit in central New Mexico, but redefinition of the Carboniferous-Permian boundary by conodont biostratigraphy moved that boundary to a higher stratigraphic level (Davydov et al., 1998), so that the Bursum Formation is now latest Pennsylvanian in age. We recognize the Red Tanks and the Bruton members of the Bursum Formation in the Cerros de Amado (Lucas and Krainer, 2004; Krainer and Lucas, this volume). We only briefly discuss the Bursum Formation here, as it is discussed in detail by Krainer and Lucas elsewhere in this guidebook.

Sandia Formation

We measured a complete section of the Sandia Formation along the northern bank of the Arroyo de la Presilla at our Arroyo de la Presilla A section (Figs. 3, 4A). Here, the Sandia Formation is 162 m thick, rests on granitic Precambrian basement and consists of a cyclic succession of siliciclastic and carbonate strata --nonmarine and marine strata formed during well-developed transgressive-regressive cycles. The lower 46 m are almost entirely composed of siliciclastic sediments with only one thin limestone bed. The next 46 m are composed mostly of siliciclastic sediments with several intercalated fossiliferous limestone horizons. The uppermost 70 m are dominantly siliciclastic beds with thin limestone intervals in the upper part.

We recognize the following lithotypes in the Sandia Formation in the Arroyo de la Presilla A section (Fig. 3): conglomerate (2.5% of the section), coarse sandstone (23.5%), fine-grained sandstone/coarse siltstone (11.2%), shale/fine siltstone (11.5%), covered (44.3%) and limestone (7%). The base of the formation is a 2-m-thick conglomerate bed that grades upward into pebbly sandstone and sandstone; stratigraphically higher conglomerate beds are thinner, about 1 m thick. These conglomerates are quartz rich, poorly to moderately sorted and relatively fine grained, with a maximum grain size of about 3 cm; the grains are mostly subrounded, but angular to subangular near the base. At the base of the formation a thin lag with boulders up to 20 cm in diameter is developed. The conglomerate beds have erosive bases and are indistinctly to distinctly trough cross-bedded.

The lower contact of the Sandia is a profound unconformity. The Sandia lies directly on coarse-grained Precambrian granitic rock along the Arroyo de la Presilla (NE ¼ NE ¼ sec. 11 and W ½ NW ¼ sec. 12) and also along a ridge about 1.6 km to the north (central part of NE ¼, sec. 2, T3S, R1E). These exposures lie in upturned fault blocks.

In the Sandia Formation, coarse-grained sandstone is commonly trough cross-bedded, rarely displays planar cross-bedding and may be pebbly. The sandstone is quartz-rich, reddish and individual quartz grains are up to 1-2 cm in diameter. Sandstone intervals are up to 4.7 m thick, upward fining, and composed of multistoried channel fills. Individual sandstone beds contain

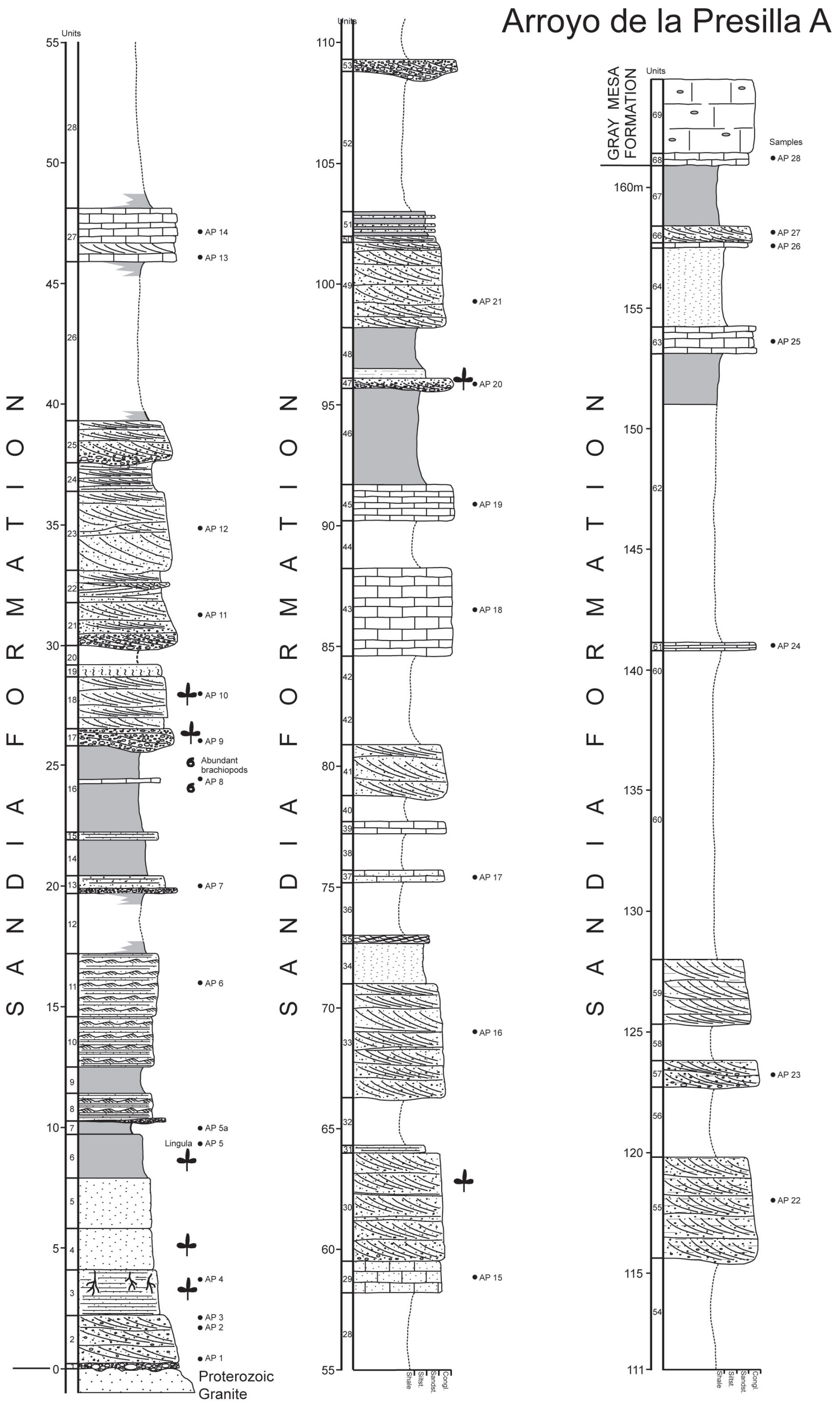

FIGURE 3. Measured section of the Sandia Formation at the Arroyo de la Presilla A section. Section measured in the NE ¼ NE ¼ sec. 11 and NW ¼ NW ¼ sec. 12, T3S, R1E. For legend to lithologic symbols see Figure 7. Thin section and microfossil sampling levels are indicated by sample numbers to right of lithologic units (for example, “AP 23”).

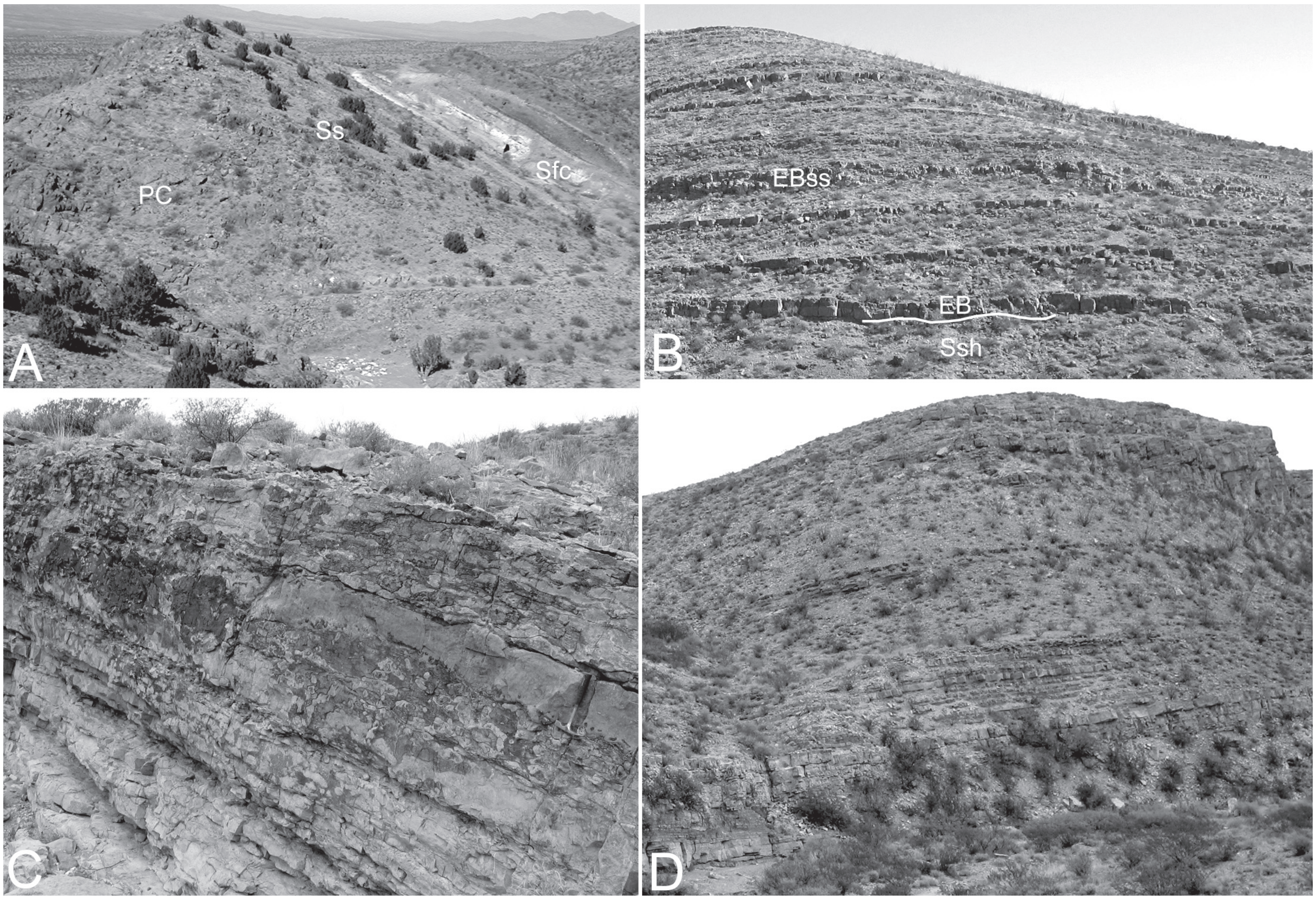

FIGURE 4. Outcrop photographs of the Sandia and Gray Mesa Formations in the Cerros de Amado. **A**, Photograph looking north at lower part of Arroyo de la Presilla A section (lower part of Sandia Formation overlying Proterozoic granite); **PC** = Proterozoic granite; **Sfc** = "fire clay" in lower Sandia Formation (note old mine adit; the *Lepidodendron* locality of Herrick [1904a] is at the base of the "fire clay"); and **Ss** = sandstone/conglomerates at base of Sandia Formation; **B**, Contact of Sandia Formation and overlying limestone-dominated section of Elephant Butte Member of Gray Mesa Formation at the Arroyo de la Presilla B section; **EB** = Elephant Butte Member, **Ssh** = uppermost clastic beds of Sandia Formation, **EBss** = thick sandstone interval in lower part of Elephant Butte Member. **C,** Typical cherty limestone beds of Whiskey Canyon Member of Gray Mesa Formation at base of Cerros de Amado D section. **D,** Most of the Garcia Member of the Gray Mesa Formation exposed at the Cerros de Amado C section.

fossil plant fragments, including some stem fragments > 1 m long. The sandstone intervals display erosive bases, and rarely (unit 53) mudstone clasts (rip-up clasts) up to 10 cm in diameter are present. The sandstone is composed mostly of quartz grains and cemented by authigenic quartz overgrowths (Fig. 5A, F, H).

The "fire clay" of Herrick (1904a) in the lower part of the section (Figs. 3, unit 7, 4A) is a light gray, 0.5- m- thick fissile shale that contains plant fossils. It is underlain by dark gray, laminated, silty claystone containing *Lingula* and plant fossils. Below that, the yellowish-brownish siltstone (unit 4) contains abundant impressions of *Lepidodendron* (Herrick, 1904a; Darton, 1928; Lucas et al., 2003, this guidebook).

Thick siltstone/fine-grained sandstone intervals occur in the lower part of the Sandia Formation section, above and below the "fire clay." The thickness of these intervals is from 1.2 to 4.7 m. Thinner siltstone/fine-grained sandstone layers are also developed on the top of conglomerate/sandstone units (up to 1.3 m thick) and rarely as thin (0.3 m) intercalations in shale. The most common lithofacies are horizontally laminated and ripple-laminated siltstone to fine-grained sandstone. Small-scale trough cross-bedding is also observed. Rarely, fine-grained sandstone is bioturbated.

From 21 to 26 m above the base of the Sandia Formation, greenish-brownish silty shale is poorly exposed with a thin micaceous sandy siltstone intercalated in the lower part and a thin fossiliferous limestone in the upper part (Fig. 3, unit 16). The shale immediately below and particularly above the limestone contains abundant marine fossils such as crinoids, bryozoans, brachiopods and rugose corals. In the middle and upper part of the section, shale intervals are mostly covered and up to 6.6 m thick in the middle part and up to 12.8 m thick in the upper part. Marine fossils such as crinoids and brachiopods occur in a 4-m-thick brownish shale in the middle part of the section (unit 46).

In the lower part of the section, there is only one thin, poorly exposed limestone bed (10-20 cm thick). The limestone is coarse-grained, poorly-sorted bioclastic wackestone to packstone that contains brachiopods and bryozoans (Fig. 5B).

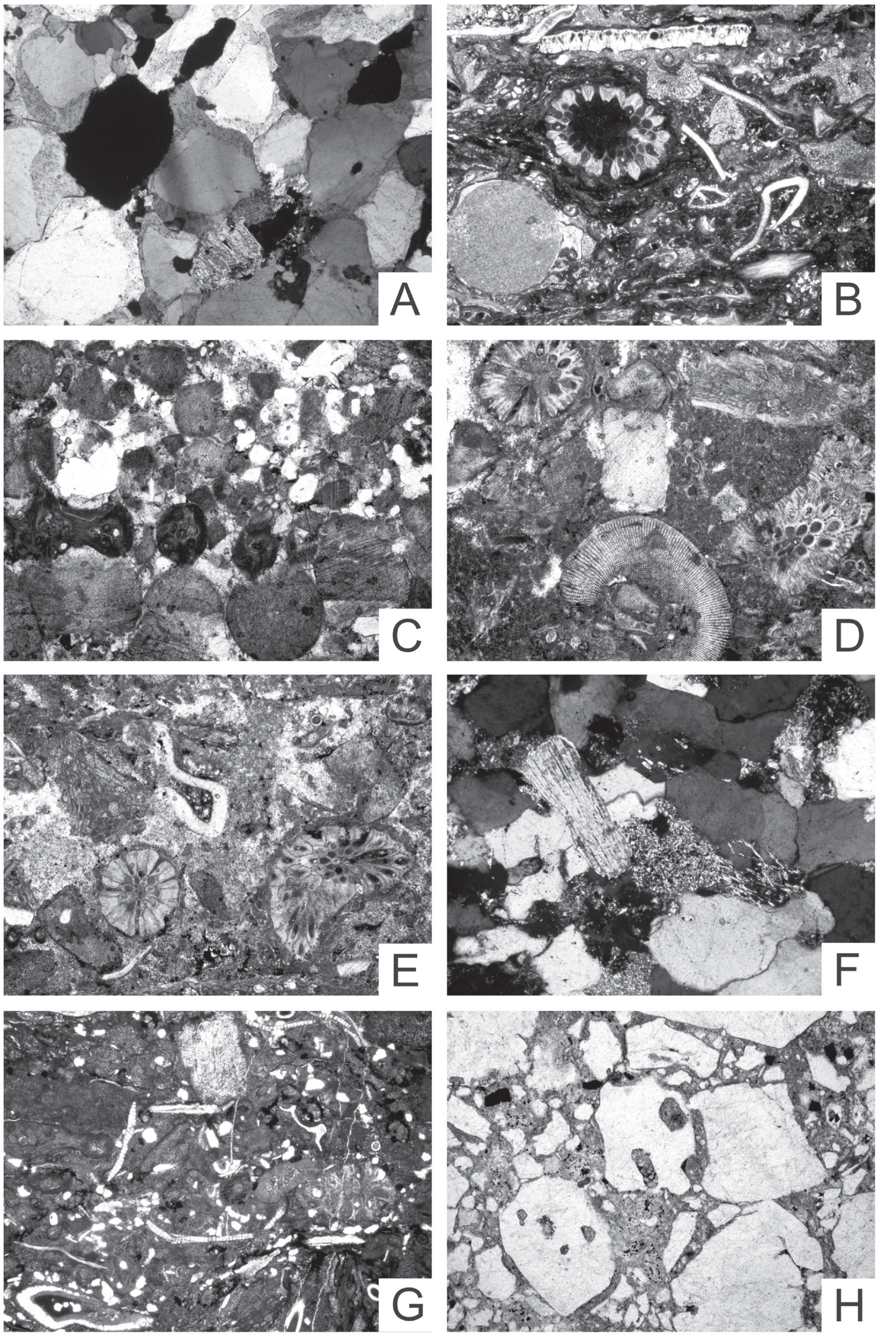

FIGURE 5. Thin section photographs of selected sandstone and limestone beds of the Sandia Formation at the Arroyo de la Presilla A section. **A**, Coarse-grained sandstone composed of abundant quartz grains, rare detrital feldspars that are mostly altered to clay minerals and very rare granitic rock fragments. The detrital grains are cemented by authigenic quartz overgrowths. Sample AP 1 (base of Sandia Formation, polarized light, width of photograph 3.2 mm). **B**, Bioclastic wackestone to packstone, coarse-grained and poorly sorted, containing abundant crinoids and bryozoans fragments, brachiopod shells, and subordinate brachiopod spines, trilobite fragments and gastropods. Matrix is dark gray micrite. Sample AP 8 (width of photograph is 6.3 mm). **C**, Crinoidal packstone, coarse-grained, poorly sorted, composed of abundant abraded crinoid fragments and up to about 20 % detrital quartz grains. Subordinate bryozoans, brachiopods and trilobites are present. The grains are cemented by calcite. Sample AP 13 (width of photograph is 6.3 mm). **D-E**, Bioclastic wackestone and packstone, coarse-grained, poorly sorted, containing abundant crinoids and bryozoan fragments, and subordinate brachiopods, trilobites and ostracods. A few small detrital quartz grains are present. The rock contains micritic matrix and some calcite cement. Sample AP 14 (width of photographs is 6.3 mm). **F,** Fine- to medium-grained sandstone composed of abundant quartz, rare muscovite (left) and feldspars. Many of the feldspars are altered to clay minerals forming pseudomatrix (center). Some quartz grains display authigenic overgrowths. Sample AP 16 (polarized light, width of photograph is 1.2 mm). **G**, Bioclastic wackestone, coarse-grained, poorly sorted, with up to approximately 10% quartz grains. Bioclasts are abraded and include abundant crinoids and bryozoans, brachiopods, a few ostracods, brachiopod spines and trilobites. Matrix is micrite. Sample AP 19 (width of photograph is 6.3 mm). **H**, Coarse-grained sandstone, poorly sorted, containing angular to subrounded quartz grains including volcanic quartz (center), rare feldspars and other detrital grains, and high amounts of matrix. Sample AP 27 (width of photograph is 3.2 mm).

In the middle and upper part of the Sandia Formation, limestone intervals are 0.3-2.2 m thick, commonly gray to dark gray and brownish weathered with bed thicknesses of 5-30 cm. Typically, the limestones are coarse-grained, sandy and fossiliferous with abundant fragments of crinoids, brachiopods, bryozoans and (subordinately) solitary corals. Rarely the limestone displays cross-bedding (unit 27) or appears massive. Two lithotypes are observed: bioclastic wackestone to packstone (Fig. 5D-E, G) and crinoidal wackestone to packstone (Fig. 5C). In the upper part of the section (unit 61), fusulinids and gastropods are present in a strongly altered, dark brown- to black-stained limestone bed. Quartz grains are also present in amounts up to 10%. The rock contains micritic matrix, and locally some calcite cement. The uppermost thin limestone bed (unit 65) is a recrystallized, non-laminated, fine-grained dolomitic mudstone containing abundant spicules and rare smaller foraminifers.

Gray Mesa Formation

Overview

In the Mud Springs Mountains of Sierra County, Thompson (1942) proposed the name Armendaris Group for all strata between the top of the Derry series (homotaxial to the Sandia Formation) below and the base of the Bolander Group above. The Armendaris Group is (was) divided (in ascending order) into the Elephant Butte Formation (including the Warmington Limestone Member at the base), the Whiskey Canyon Limestone and the Garcia Formation. The Bolander Group of Thompson encompassed gray to light gray fossiliferous limestone, several beds of fossiliferous gray shale, and one well-developed conglomerate and pebbly sandstone at the type section (Thompson 1942). Thompson did not divide the Bolander Group into formations. The Armendaris and Bolander groups (*sensu* Thompson 1942) refer to the Gray Mesa Formation as it is being used here. In the Cerros de Amado, Rejas (1965) recognized the Armendaris Group and its three formations. However, he referred to the stratigraphic interval that should represent the Bolander Group of Thompson (1942) as the Socorro Group and divided it into the Bartolo Formation and Amado Limestone (Fig. 2).

In the Cerros de Amado, we recognize the base of Rejas' (1965) Bartolo "Formation" as the base of the Atrasado Formation above the Gray Mesa Formation, as the Bartolo interval is the first thick, clastic-dominated unit above a thick, dominantly limestone section (also see Cather and Colpitts, 2005). This is the way the Gray Mesa-Atrasado contact is picked elsewhere, particularly at the type sections in the Lucero uplift (Krainer and Lucas, 2004). Similarly, we picked the base of the Gray Mesa Formation at the first cherty limestone bed that is above the highest quartzose sandstone bed in the Sandia Formation. This is how the contact has been chosen by earlier workers in the Cerros de Amado area (e.g., Rejas, 1965; Cather and Colpitts, 2005) and at the lectostratotype section of the Sandia Formation (Krainer and Lucas, 2005), and it provides a mappable boundary between the two formations.

At the Arroyo de la Presilla B section, we measured most of the Gray Mesa Formation (Figs. 4B, 6). The measured section is 192.6 m thick; the lowermost 8 m represent the uppermost Sandia Formation. The rest of the section is the Gray Mesa Formation, which can be divided into the Elephant Butte Member (95 m), Whiskey Canyon Member (35 m) and much of the Garcia Member (55 m).

Elephant Butte Member

This lowest member of the Gray Mesa Formation consists of different types of limestone, covered shale intervals, two thin sandstone beds, two thin limestone conglomerate beds, and a prominent, 10-m-thick sandstone interval in the lower part (Figs. 4B, 6, units 32-35), which displays an erosive base overlain by a coarse, pebbly quartzitic sandstone that is indistinctly cross-bedded. Strata we assign to the Elephant Butte Member in the Cerros de Amado occupy the same stratigraphic position and are lithologically similar (note the near absence of cherty limestone and the presence of quartzose clastics) to the Elephant Butte "Formation" at its type section in the Mud Springs Mountains (Thompson, 1942, fig. 3). As shown in Figure 4B, the Elephant Butte Member produces stepped gray hillsides having a series of limestone ledges of roughly equal thickness.

In the lower part of the Elephant Butte Member, below the prominent sandstone interval, a 0.6-m-thick cross-bedded quartzose sandstone bed and a 0.3-m-thick carbonate conglomerate bed with limestone nodules up to 3 cm in diameter are present. In the middle of the member, a 0.9-m-thick cross-bedded calcareous sandstone bed is present (unit 52), and 20 m higher in the section a 0.8-m-thick intraformational limestone conglomerate with limestone clasts up to 3 cm is present (unit 68). Covered intervals (0.3-6.7 m thick) most likely represent shale, which is rarely exposed and of gray color. The thickness of the limestone units ranges from individual beds 0.1 m thick to intervals of multiple limestone beds 6.4 m thick. We distinguish the following limestone types: (1) thin, wavy-bedded limestone with bed thickness of mostly 10-20 cm; (2) thick-bedded limestone, with bed thicknesses commonly of 20-50 cm; (3) thick-bedded, coarse, crinoidal limestone; (4) massive to indistinctly bedded algal limestone, 0.9-1.8 m thick; and (5) wavy bedded to nodular cherty limestone, which is thin bedded (mostly 10-20 cm).

Fossils observed in the field are algae (particularly in the massive algal limestone facies), crinoids (abundant in the crinoidal limestone facies), brachiopods, bryozoans and solitary corals. Fusulinids are rare. In many limestone units fossils are silicified. It is interesting that *Chaetetes*, which is common in the lower part of the Gray Mesa type section in the Lucero uplift (Krainer and Lucas, 2004), is completely absent in the Elephant Butte Member at the Arroyo de la Presilla B section.

Whiskey Canyon Member

We recognize the Whiskey Canyon Member as an interval about 25 m thick of very cherty limestone beds (e.g., Fig. 4C),

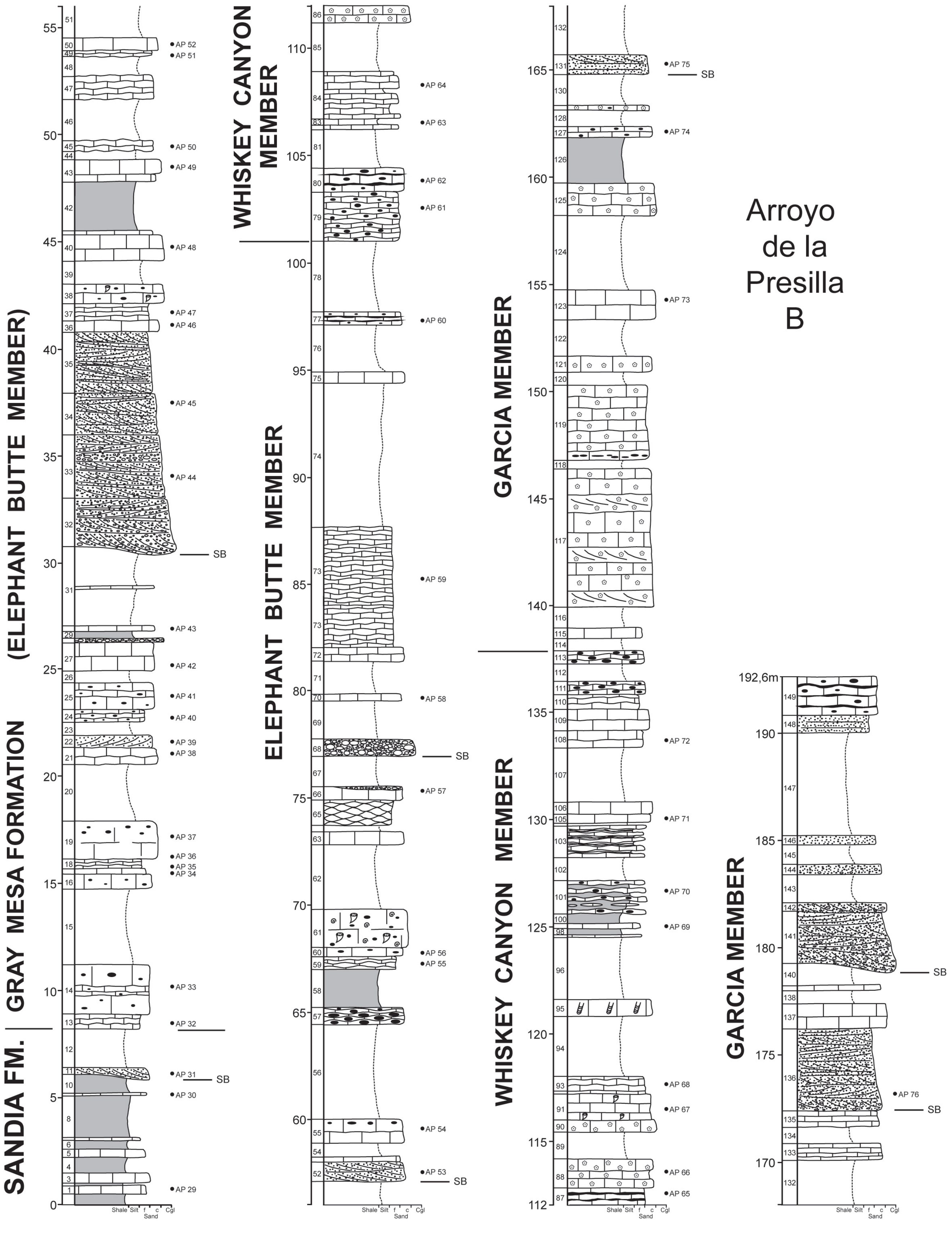

FIGURE 6. Measured section of most of the Gray Mesa Formation at the Arroyo de la Presilla B section. Section measured in the NW ¼ NW ¼ sec. 12 and SW ¼ SW ¼ sec. 1, T3S, R1E. For legend to lithologic symbols see Figure 7. Thin section and microfossil sampling levels are indicated by sample numbers to right of lithologic units (for example, "AP 39").

some with abundant rugose corals, near the middle of the section of the Gray Mesa Formation (Fig. 6). In the Cerros de Amado, it occupies the same stratigraphic position and is lithologically similar (mostly very cherty limestone) to Thompson's (1942, fig. 3) type section of the Whiskey Canyon limestone in the Mud Springs Mountains of Sierra County. Thick, siliceous limestone beds in this member commonly form cliffs (Fig. 4C). The base of the Whiskey Canyon Member is the first bed of very cherty limestone above strata of the Elephant Butte Member, which has few cherty limestone beds (Fig. 6).

In the Cerros de Amado, the Whiskey Canyon Member is composed of different types of bedded limestone and some covered (shale) intervals. The cherty limestone is composed of thin and wavy cherty limestone alternating with brownish cherty silty layers. It is very fossiliferous, with abundant crinoids, brachiopods, rugose corals, bryozoans and local fusulinid packstones. The member also contains thick-bedded algal and crinoidal limestone, locally with minor chert, fusulinids and bryozoans.

Garcia Member

We measured all or part of the Garcia Member in three sections (Figs. 6-8). Given that the top unit of the Cerros de Amado D section (Fig. 7, unit 24) is the same as unit 30 of the Cerros de Amado C section (Fig. 8), the total thickness of the Garcia Member is about 103 m. The stratigraphic position and the mixed clastics and carbonates of the Garcia Member in the Cerros de Amado are very much the same as the type section of the Garcia "Formation" in the Mud Springs Mountains of Sierra County (Thompson, 1942, fig. 4). The base of the Garcia Member is the first non-cherty limestone bed above very cherty limestone at the top of the underlying Whiskey Canyon Member (Figs. 6-7).

In the Cerros de Amado, Rejas (1965) divided the Garcia "Formation" into a lower clastic member and an upper carbonate member, but we do not see an obvious subdivision of the member along those lines in our measured sections. The Garcia Member is composed of different types of limestone, conglomerate, sandstone, shale and covered (shale) intervals (Figs. 4D, 6-8). This member erodes to ledges of varying thicknesses separated by rubble-strewn slopes underlain by shale. Massive limestone near the base of the member forms a cliff (Figure 4D).

At the Arroyo de la Presilla B section (Fig. 6), the most common limestone type is thick-bedded, crinoidal limestone. Less abundant is thick-bedded, fossiliferous limestone containing algae, gastropods and some chert, and thin-bedded micritic fossiliferous limestone.

Conglomerate/sandstone units are 0.4 to 2.5 m thick. Conglomerate beds (mostly limestone clasts) are cross-bedded, and grade upward into cross-bedded sandstone. The sandstone is fine- to coarse-grained, arkosic, partly micaceous, partly pebbly, and displays trough cross-bedding, crude horizontal lamination or appears massive. The bases of the conglomerate and sandstone units are erosional. The thicker conglomerate-sandstone units show an upward-fining trend, and are overlain by covered shale intervals with limestones on top. Compared to the quartzose conglomerates and sandstones of the Elephant Butte Member, the conglomerates and sandstones of the Garcia Member are arkosic and contain abundant granitic debris.

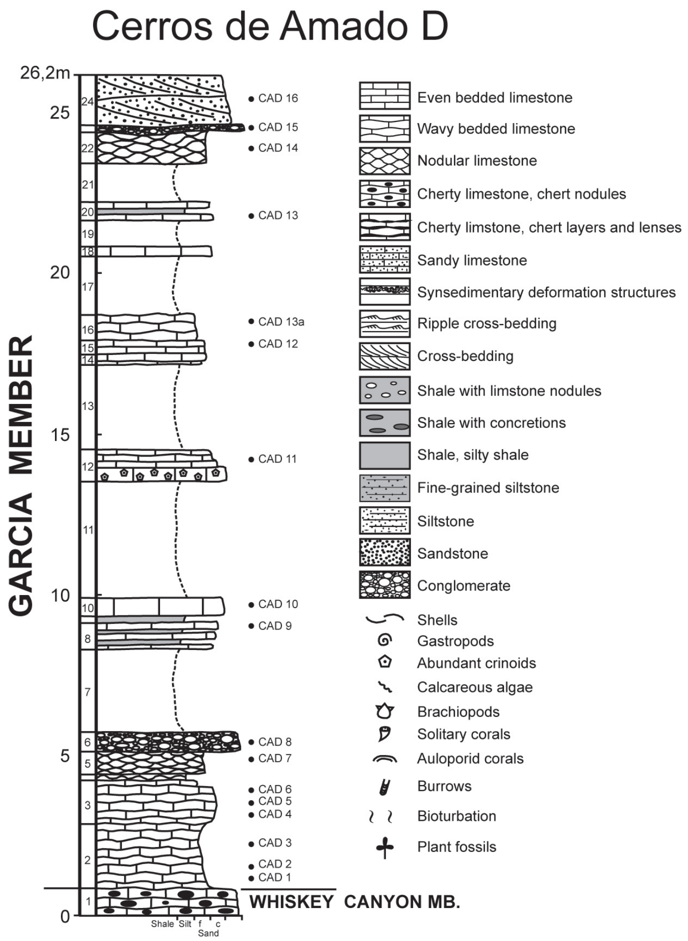

FIGURE 7. Measured section of part of the Gray Mesa Formation at the Cerros de Amado D section. Section measured in the SW ¼ NW ¼ sec. 35, T2S, R1E. Thin section and microfossil sampling levels are indicated by sample numbers to right of lithologic units (for example, "CAD 9").

The Cerros de Amado D section (Fig. 7) includes the top of the Whiskey Canyon Member and the basal 25 m of the overlying Garcia Member. The uppermost Whiskey Canyon Member is represented by very cherty, thinly and wavy bedded limestone and is overlain by a 4.5-m-thick interval of thin, wavy to nodular, bedded gray limestone at the base of the Garcia Member, which is fossiliferous, containing crinoids, brachiopods, bryozoans and algae. Individual limestone beds contain abundant fusulinids. This limestone unit is erosively overlain by poorly-sorted carbonate-clast conglomerate. Above follows a 20-m-thick succession of covered intervals and fossiliferous limestone, either as individual limestone beds separated by thin shale intervals or limestone intervals up to 1.2 m thick composed of medium- to thin-bedded fossiliferous limestone containing abundant crinoids, subordinate brachiopods, solitary corals and bryozoans. Bedding is even to wavy. The top of the succession is formed by a 1-m-thick nodular limestone containing bryozoans. The nodular limestone is erosively (disconformably) overlain by a thin lag of poorly- sorted limestone nodules up to 5 cm in diameter floating in sandy matrix. This lag is overlain by a 1.6-m-thick reddish, trough cross-bedded and horizontally laminated arkosic pebbly sandstone. This sandstone (unit 24) corresponds to unit 30 of the Cerros de Amado C section (Fig. 8).

We assign the lower 93.5 m of the Cerros de Amado Section C to the Garcia Member (Fig. 8). The lowermost 26 m (units 1-38) consist of thin conglomerate, sandstone, siltstone and limestone beds intercalated with covered (shale) intervals. The conglomerate beds contain limestone clasts, crinoid debris, and shell fragments. In the higher part of this succession, a 0.2-m-thick conglomerate (unit 37) laterally grades into a large, trough cross-bedded channel sandstone up to 1 m thick. This channel is more than 20 m wide and erosively overlies gray shale. The sandstone is mostly coarse-grained and contains abundant crinoidal debris and shell fragments. Stratigraphically higher, 0.1-0.2-m-thick sandstone beds with horizontal lamination and small-scale cross-bedding are separated by thin greenish siltstone-shale intercalations.

In the Garcia Member, shale is gray and 0.1 to 0.9 m thick where exposed. For the most part, the shale is not well exposed, forming covered intervals up to 1.5 m thick. Limestone is intercalated as individual limestone beds 0.1 to 0.3 m thick or as bedded limestone intervals up to 1.1 m thick. It is gray, micritic and contains abundant fossils, particularly crinoids. Subordinate brachiopods, bryozoans, solitary corals and algae are present. Beds are even to wavy, and some are composed of coarse crinoidal limestone.

In the Cerros de Amado C section (Fig. 8), the middle part of the Garcia Member (units 39-108) begins with a 2.8-m-thick interval composed of thin-bedded, dark gray lime mudstone that is partly laminated, bioturbated and lacks fossils.

This interval is overlain by alternating beds of gray marly shale and dark gray lime mudstone. Common sedimentary structures are horizontal lamination and burrows, and small scale cross-bedding is rare. Fossils such as brachiopods and crinoids are rare. In the lower part of the succession, 0.2-m-thick pebbly sandstone is exposed. In the middle, 1.4-m-thick pebbly sandstone is present, overlain by a fine-grained conglomerate.

The upper part of the Garcia Member at the Cerros de Amado C section (Fig. 8, units 109-152) is 30.5 m thick and is composed of fossiliferous limestone, intercalated covered (shale) intervals, and two limestone conglomerate beds. Limestone intervals are 0.2 to 2.4 m thick and composed rarely of one limestone bed or more commonly of wavy-bedded limestone intervals with bed thicknesses ranging from 10 to 30 cm. Two indistinctly bedded to massive limestone intervals are present. The limestone is gray to dark gray and fossiliferous, containing crinoids, brachiopods, bryozoans and solitary corals. Algae are abundant in the upper half of this succession. Fusulinids occur near the top of unit 116 and in unit 118 (cf. Lucas and Estep, 2000). Two fine-grained limestone conglomerates are developed. The lower is 0.6 m thick and displays normal grading. The upper is 0.3 m thick, fossiliferous and contains shark teeth (NMMNH [New Mexico Museum of Natural History] locality 3389: Lucas and Estep, 2000). Gray shale is exposed only in a 0.9-m-thick interval in the uppermost part, intercalated with thin lenses and beds of wavy-bedded limestone.

Atrasado Formation

In the Lucero uplift, Kelley and Wood (1946) characterized the Atrasado Member of the Madera Formation as a 152-213-m-thick succession of medium-gray, thin-bedded, shaly limestone with a few massive beds, interbedded with thick gray shale. According to these authors, the Atrasado member differs from the Gray Mesa member in having greater portions of shale, somewhat more sandstone and red beds, and far less chert in limestone. Kues (2001) raised the Atrasado Member to formation rank. The type section lies near Major Ranch in the Lucero uplift, where the Atrasado Formation is 112.5 m thick (Krainer and Lucas 2004).

In the Mud Springs Mountains of Sierra County, the type section of the Bolander Group of Thompson (1942) is 62 m of varied fossiliferous limestones, most nodular or cherty, that comprise the upper part of the Gray Mesa Formation (Lucas et al., 2009). Unable to recognize this unit in the Cerros de Amado, Rejas (1965) coined the name Socorro Group for strata he perceived as age equivalent to the Bolander Group, and divided it into the Bartolo Formation and Amado Limestone. Here, Bartolo Formation and Amado Limestone of Rejas (1965) are lowered to member status, and we consider the Bartolo Member the basal member of the Atrasado Formation, conformably overlying the Garcia Member of the Gray Mesa Formation. We also do not use the term "Socorro Group" of Rejas (1965), abandoning it as a chronostratigraphic, not lithostratigraphic term, much like the group names proposed by Thompson (1942).

In the Cerros de Amado, the Atrasado Formation is well exposed and ~ 290 m thick. We divide the Atrasado Formation into the following members (in ascending order): Bartolo, Amado, Tinajas (new), Council Spring, Burrego, Story, Del Cuerto and Moya.

Bartolo Member

We formalize the term "Bartolo Formation" of Rejas (1965) as the Bartolo Member of the Atrasado Formation. The name is for the Arroyo de Tío Bartolo near the type section of the unit, which is the type section described by Rejas (1965, p. 101-102) in the NE ¼ sec. 35, T2S, R1E. At the type section, the Bartolo Member is 67 m thick and mostly olive gray calcareous shale with a few beds of brownish gray sandstone and sandy crinoidal limestone. The base of the Bartolo Member (which is the base of the Atrasado Formation) is the lowest thick shale slope above the limestone-dominated Garcia Member of the Gray Mesa Formation.

At the Cerros de Amado C section (which is essentially the same section published by Lucas and Estep, 2000, fig. 2), the Bartolo Member is completely exposed, overlies the Garcia Member of the Gray Mesa Formation and is overlain by the Amado Member (Figs. 8, 9A). At this section, the Bartolo Member is 69 m thick and composed of thick shale intervals and intercalated horizons of conglomerate, sandstone and fossiliferous limestone. The Bartolo Member tends to form rounded, sparsely vegetated slopes on which the sandstone and limestone layers stand out as ledges (Fig. 9A). The greenish-gray shale intervals are 5.3 to 19.4 m thick, partly covered, probably dominantly nonmarine in the lower part of the member and dominantly marine in the upper

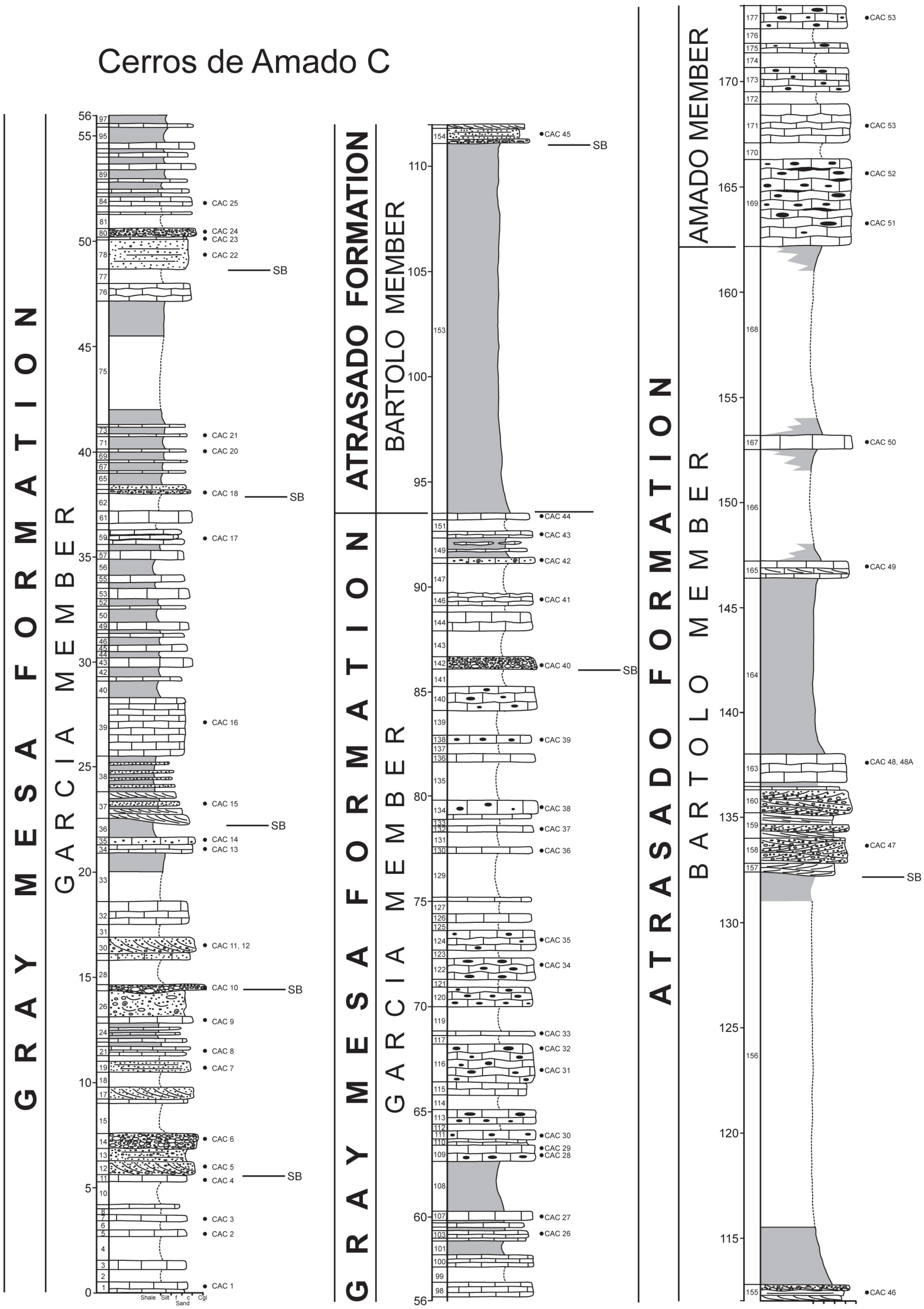

FIGURE 8. Measured section of parts of the Gray Mesa and the Atrasado formations at the Cerros de Amado C section. Section measured in the NW ¼ NW ¼ sec. 35, T2S, R1E. For legend to lithologic symbols see Figure 7. Thin section and microfossil sampling levels are indicated by sample numbers to right of lithologic units (for example, "CAC 10").

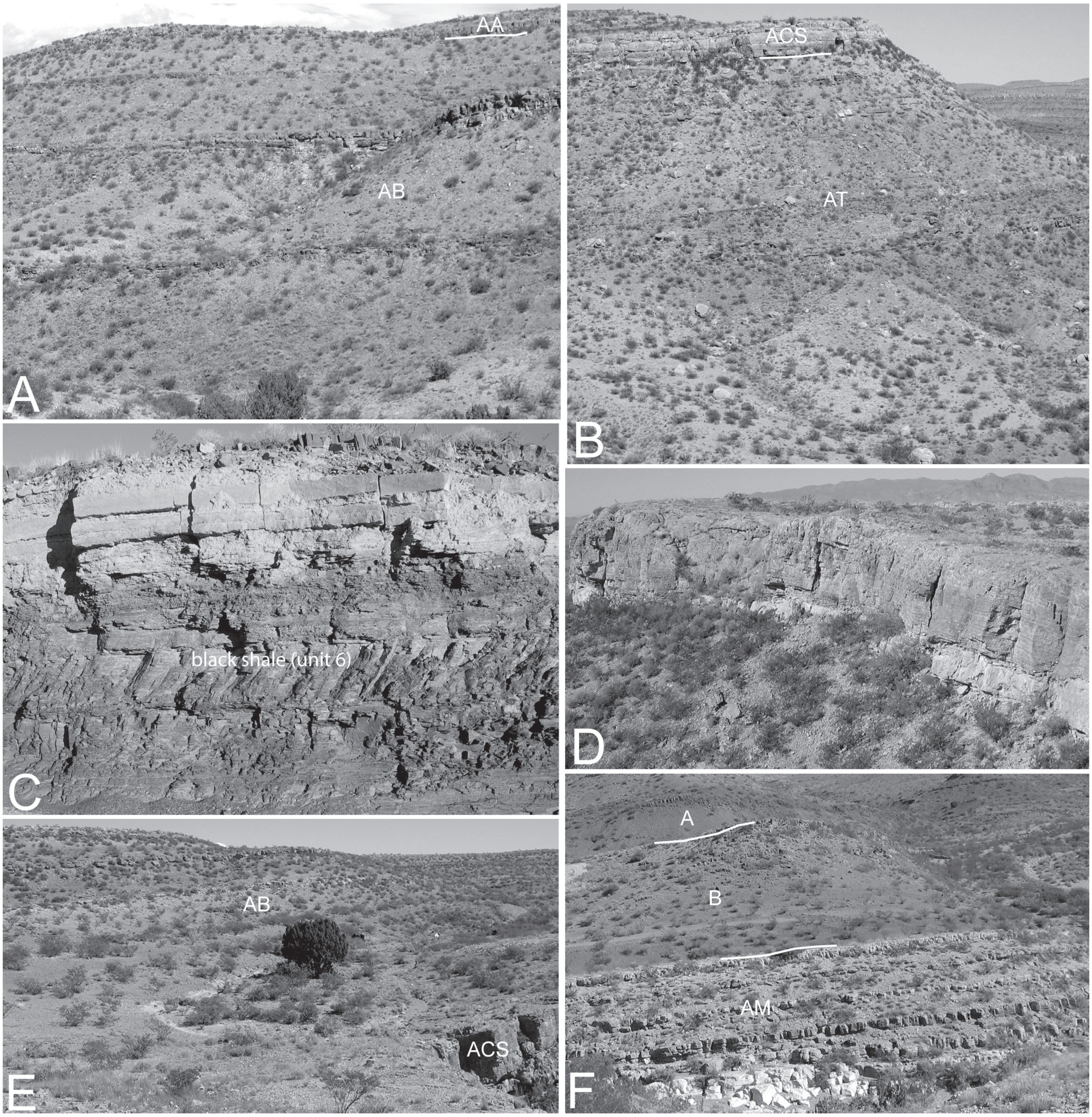

FIGURE 9. Photographs of outcrops of the Atrasado Formation in the Cerros de Amado. **A**, Slope-forming Bartolo Member (**AB**) beneath ridge crest formed by Amado Member (**AA**) at the Cerros de Amado C section. **B**, Slope-forming type section of Tinajas Member (**AT**) beneath mesa capped by Council Spring Member (**ACS**) at Cerros de Amado B section. **C**, Lacustrine black shale and overlying limestone beds in lower part of Tinajas Member at Cerros de Amado B section. **D**, Algal bioherm developed in Council Spring Member at Ojo de Amado. **E**, Top of Council Spring Member (**ACS**) and overlying Burrego Member (**AB**) at the Minas de Chupadera section. **F**, Moya Member of Atrasado Formation (**AM**), Bursum (**B**) and Abo (**A**) formations at the Minas de Chupadera section.

part of the member. Two horizons of conglomerate and sandstone are present. The lower horizon (units 155-156) is 1.7 m thick and begins with a thin sandy, fine-grained conglomerate at the base. This basal sandy conglomerate shows normal grading and is overlain by siltstone with crude horizontal stratification. The upper part is composed of several brownish, trough cross-bedded sandstone beds that contain rip-up clasts and are locally bioturbated. The horizon shows an upward coarsening trend and is overlain by a 19.4-m-thick, partly covered shale interval which is overlain by the upper conglomerate-sandstone unit (units 157-160).

This unit begins with 0.6 m of greenish and brownish fine-grained micaceous sandstone, overlain by reddish-brown, trough cross-bedded sandy conglomerate containing limestone clasts up to 4 cm in diameter and quartz grains up to 2-3 cm in diameter. The conglomerate is poorly sorted, mostly trough cross-bedded, and displays rare planar cross-bedding and reactivation surfaces. Some large-scale trough cross-bedding (lateral accretion) is observed. Thin intervals of lenticular, cross-bedded sandstone are intercalated. The uppermost conglomerate contains a few fossil shell fragments and is overlain by a 0.2-m-thick fossiliferous limestone bed.

The thin limestone bed is overlain by a thin shale interval, followed by a 1.3-m-thick limestone bed that is indistinctly thick bedded (unit 163). The limestone is dark gray, coarse-grained and fossiliferous, yielding abundant large crinoid fragments and brachiopods, and subordinate bryozoans and calcareous algae embedded in micritic matrix. On top, abundant *Chaetetes*-colonies with diameters up to about 30 cm are developed.

Both coarse clastic intervals extend laterally over at least several hundred meters with only minor changes in thickness (sheet sandstone/conglomerate bodies).

The limestone is overlain by 8.4 m of covered shale slope, followed by a 0.8-m-thick fossiliferous limestone bed, which is coarse grained and partly cross-bedded (unit 165). The limestone is dark gray and brownish weathered on the surface. The most common fossils are large crinoid fragments, brachiopods and bryozoans. On top of this limestone bed, small colonies of auloporid corals are present.

This fossiliferous limestone interval is overlain a by 5.3-m-thick covered slope (shale), followed by a 0.7-m-thick brownish weathered, dark gray micritic limestone bed (unit 167). The overlying covered slope interval is 9 m thick and represents the top of the Bartolo Member.

The lowermost 54 m of the Cerros de Amado A section (Fig. 11) are strata of the Bartolo Member; the lower part (~ 15 m) of the Bartolo is not exposed. The facies of the Bartolo Member is similar to that of the Cerros de Amado C section (Fig. 8). The basal 14 m are composed of greenish-brownish micaceous silty shale and fine-grained siltstone intercalated with thin (5-10 cm), fine-grained sandstone layers. The sandstone layers of the lowermost 1 m appear massive, and higher up the sandstones display small-scale current ripples. Rarely, small concretions are present in the shale. The interval between 3 and 6 m shows an upward-coarsening trend. This fine-grained clastic interval is overlain by a coarse-grained clastic interval, which is 5.3 m thick and composed of three sandstone horizons separated by covered intervals (units 7-11). An upward coarsening trend is observed. The lowermost sandstone has an erosional base and is 0.6 m thick, brownish-gray, coarse-grained, trough cross-bedded, and thickens laterally to 0.8 m. The sandstone contains a few limestone clasts up to 2-3 cm in diameter and shale rip-up clasts. The next sandstone horizon follows a 1.5-m-thick covered interval and is 1.4 m thick and consists of trough cross-bedded, coarse-grained sandstone with quartz pebbles up to 1 cm and limestone clasts up to 2-3 cm in diameter.

The uppermost horizon overlies a 0.4-m-thick covered interval and is 1.4 m thick. It is a fine-grained sandy conglomerate, grading upward into sandstone. This horizon is also trough cross-bedded. The basal, conglomeratic part contains quartz and limestone pebbles up to 3-4 cm in diameter. The sandstone on top of this interval contains a few oncoids. This coarse clastic interval is overlain by a 0.8-m-thick covered slope and 3.2 m of limestone (units 13-17). The lowermost limestone bed is 0.6 m thick, coarse-grained and very fossiliferous, containing abundant brachiopod shells and crinoid fragments. A thin-bedded fossiliferous limestone interval is exposed above a thin covered interval, overlain by 1.6 m of indistinctly bedded limestone (bioclastic packstone: Fig. 10A) and 0.3 m of coarse crinoidal limestone containing *Chaetetes* (units 15-17).

The coarse clastic and overlying limestone interval (Fig. 11, units 18-29) correspond to the similar interval at Cerros de Amado section C (Fig. 8, units 157-160 are the clastic interval, and units 161-163 are the limestone interval). Both intervals are thicker at section A. The facies and composition of the clastic sediments is very similar; the fossiliferous limestone is also very similar. *Chaetetes* is present at both sections.

At Cerros de Amado section A (Fig. 11), the limestone interval (units 13-17) is overlain by 6.6 m of covered slope. Only the uppermost 1 m is exposed, and it is greenish-gray shale/fine-grained siltstone, which is overlain by a 0.8-m-thick, coarse-grained, very fossiliferous limestone bed. This limestone bed (unit 19) is trough cross-bedded and contains abundant brachiopod shell fragments, crinoids and bryozoans. It is overlain by a 0.2-m-thick coquina containing abundant crinoids, brachiopod shells, bryozoans, and also burrows. We correlate this limestone bed with the fossiliferous limestone interval of unit 165 at Cerros de Amado section C.

Above an 8.8- m-thick covered slope (shale), another 0.8-m-thick, coarse-grained fossiliferous limestone bed is exposed containing abundant crinoid and brachiopod fragments (unit 22). On top of this bed small auloporid coral colonies are present (very similar to those on top of unit 165 in section C).

The uppermost part of the Bartolo Member at Cerros de Amado section A is composed of greenish-gray micaceous shale to fine-grained siltstone (partly covered) intercalated with 0.2-to-0.5-m-thick, ripple-laminated, fine-grained sandstone horizons (units 23-29). Two horizons of fossil plants occur within this unit, the lower about 2 m above the base, and the upper about 6.5 m below the top. The upper horizon yielded a well-preserved fossil flora rich in *Neuropteris*. The Bartolo Member at section A is very similar to that of section C, but slightly thicker, and the clastic facies is somewhat coarser-grained.

At the Minas de Chupadera (also called Miñas de Chupadero: R. Colpitts, written commun., 2009) section (Fig. 13), the uppermost 5.4 m of the Bartolo Member consist of thin, medium-grained brownish sandstone,and a fossiliferous gray limestone bed overlain by a covered slope. The limestone bed contains crinoids, brachiopods and rare solitary corals, many silicified. The boundary between the sandstone and overlying limestone bed is sharp.

Amado Member

We formalize the term "Amado Limestone" of Rejas (1965) as the Amado Member of the Atrasado Formation. The type sec-

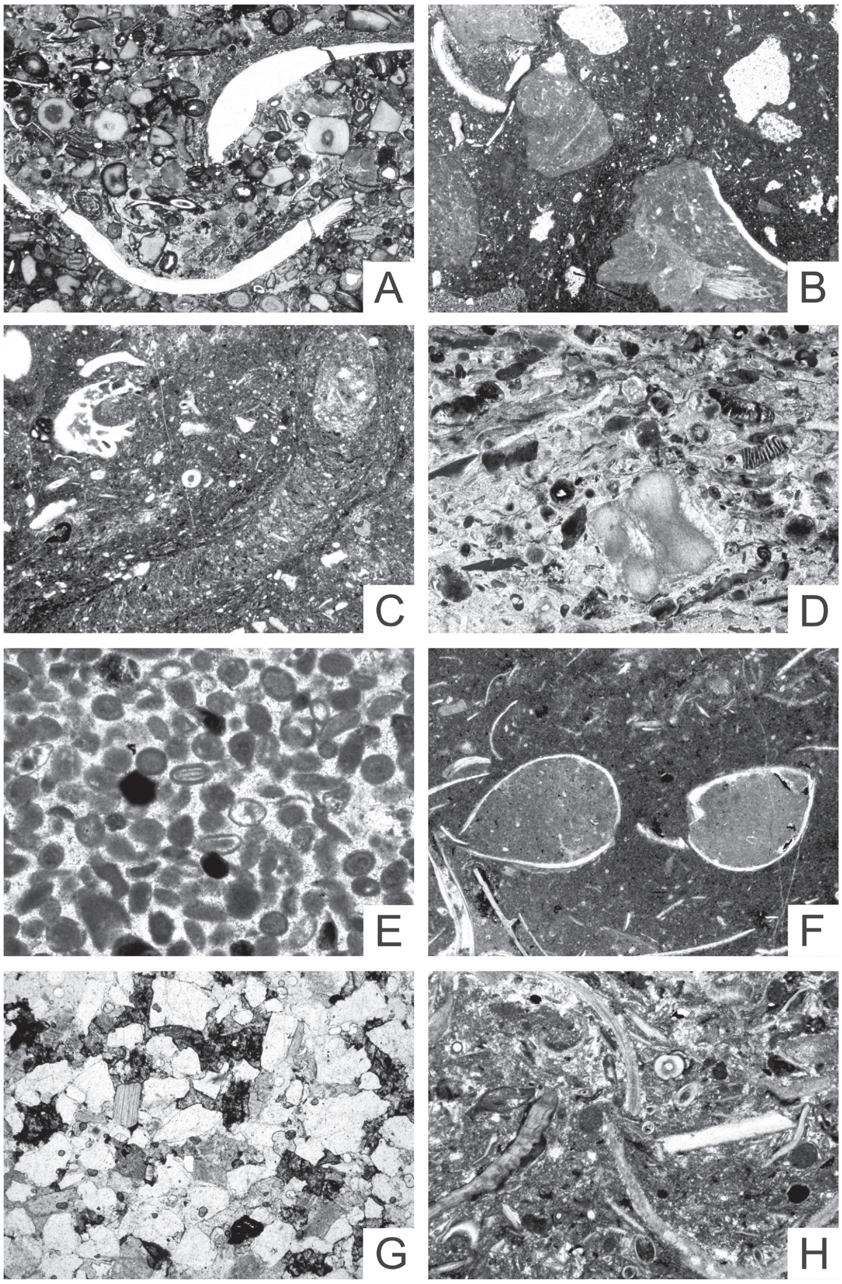

FIGURE 10. Thin section photographs of sandstone and limestone of the Atrasado Formation at the Cerros de Amado A section. **A**, Coarse-grained, poorly-sorted bioclastic packstone composed of abundant crinoid and brachiopod fragments, subordinate bryozoans, ostracods and brachiopod spines and a few angular detrital quartz grains. A few ooids are also present. Sample CAA 7, width of photograph is 12 mm (Bartolo Member). **B**, Fine-grained, matrix-supported conglomerate, poorly sorted, containing subangular to subrounded intraclasts of micritic limestone and silicified limestone floating in micritic matrix with abundant spicules and a few other bioclasts such as bryozoans, brachiopods, smaller foraminifers and ostracods. Sample CAA 15, width of photograph is 14 mm (Amado Member). **C**, Fine-grained bioclastic wackestone containing a few large skeletons such as calcisponges. Larger bioclasts float in a fine bioclastic matrix that contains echinoderms, bryozoans, and brachiopods in micritic matrix. Note the well-preserved burrow extending from the upper right to the lower left of the photograph. Sample CAA 18, width of photograph is 12 mm (Amado Member). **D**, Bioclastic packstone, poorly sorted and indistinctly laminated. Most abundant are crinoids fragments; subordinately, the rock contains bryozoans, brachiopods, ostracods, *Epimastopora*, smaller foraminifers and rare echinoid spines. A few micritic intraclasts are present. Sample CAA 20, width of photograph is 14 mm (Amado Member). **E**, Peloidal grainstone composed of abundant peloids, ooids and micritic intraclasts, and a few ostracods. The grainstone is well sorted and cemented by calcite, and some micrite is present. Sample CAA 26, width of photograph is 3.2 mm (Tinajas Member). **F**, Bioclastic wackestone to mudstone composed of micrite and abundant brachiopod shells. Other bioclasts such as gastropods, trilobites, ostracods and echinoderms are rare. Sample CAA 28, width of photograph is 9 mm (Tinajas Member). **G**, Medium-grained, moderately-sorted sandstone containing abundant quartz grains, many detrital feldspars (mostly altered K-fsp) and some rock fragments. Detrital micas are rare. Many quartz grains display authigenic quartz overgrowths. Sample CAA 34, width of photograph is 3.2 mm (Tinajas Member). **H**, Bioclastic wackestone to packstone, medium grained and poorly sorted, containing abundant brachiopod fragments, subordinate bryozoans, echinoderms, ostracods and smaller foraminifers, fecal pellets and a micritic matrix. Sample CAA 38, width of photograph is 6.3 mm (Tinajas Member).

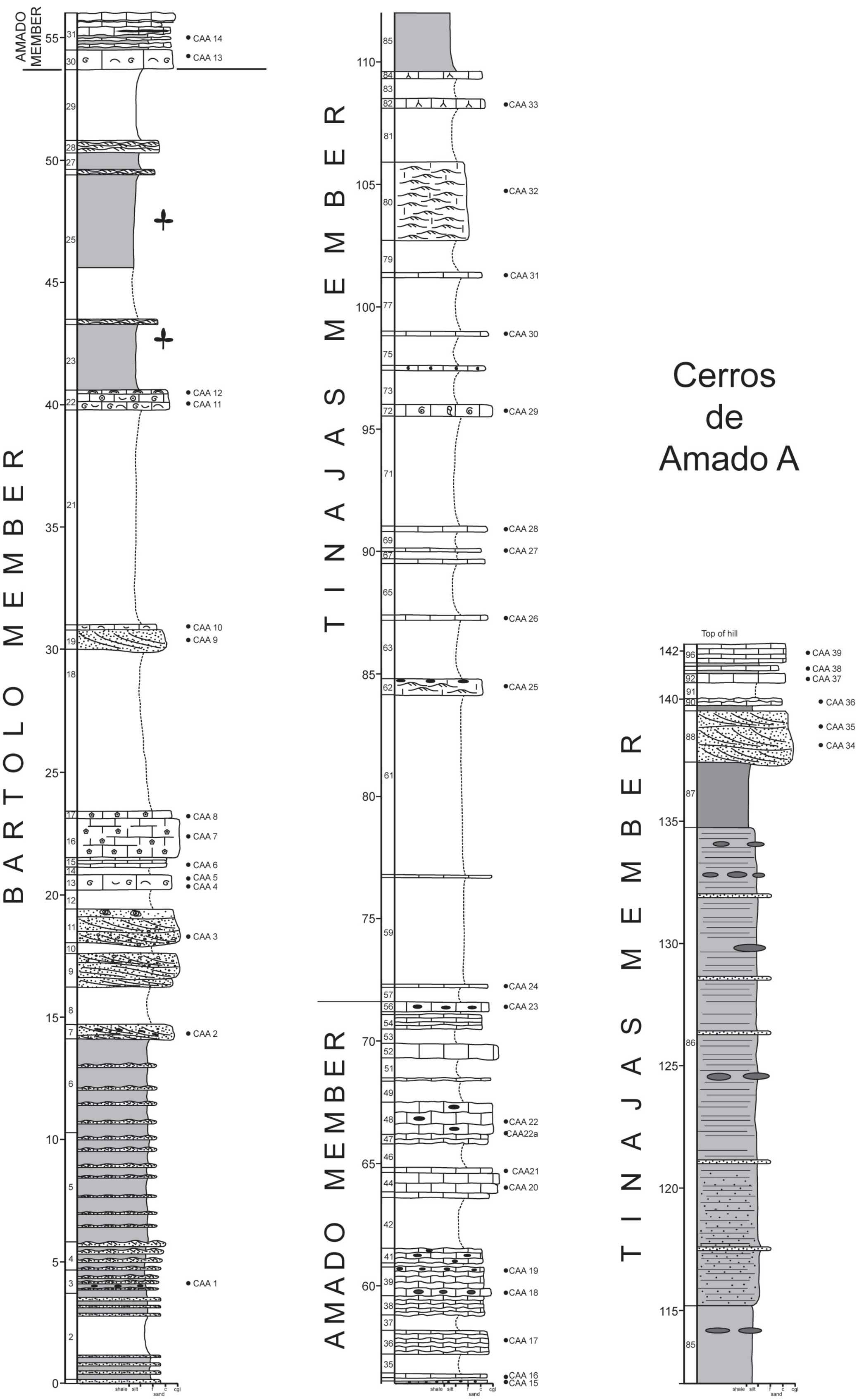

FIGURE 11. Measured section of part of the Atrasado Formation at the Cerros de Amado A section. Section measured in the S ½ NW ¼ sec. 36, T2S, R1E. For legend to lithologic symbols see Figure 7. Thin section and microfossil sampling levels are indicated by sample numbers to right of lithologic units (for example, "CAA 24").

tion of the Amado Member is the type section described by Rejas (1965, p. 104) near the Cerros de Amado in the NE ¼ NE ¼ sec. 35, T2S, R1E. Here, the Amado Member is 10.5 m thick and mostly cherty limestone (lime mudstone and wackestone) that yields abundant brachiopods and forms a prominent escarpment above largely covered slopes underlain by the Bartolo Member (Fig. 9A, top of ridge).

In the Cerros de Amado C section (Fig. 8), the uppermost covered shale interval of the Bartolo Member is overlain by the Amado Member, which is composed of 11.4 m of limestone with four intercalated covered intervals. The lowermost limestone interval is a 4.1-m-thick, indistinctly-bedded ledge with bed thicknesses of 10 to 30 cm. Bedding is wavy, and the limestone is gray, micritic and contains chert nodules and lenses. Fossils observed on outcrop are algae, some crinoids, brachiopods and bryozoans. Many fossils are silicified. This lowermost interval is overlain by a 0.8-m-thick covered slope, followed by 1.8 m of indistinctly bedded limestone similar to that below, but almost free of chert. It is a gray, fossiliferous micritic limestone containing crinoids, brachiopods and bryozoans. The overlying limestone units are all composed of indistinctly bedded cherty limestone, which is gray and fossiliferous, containing brachiopods and solitary corals (similar to the basal limestone unit).

In the Cerros de Amado A section (Fig. 11), the Amado Member is 17.9 m thick and composed of different types of limestone and thin, covered (shale) intervals. Limestone intervals are up to 2.1 m thick, and covered intervals are 0.1 to 2.1 m thick.

Individual limestone beds are 0.1 to 0.8 m thick, with even to wavy bedding planes. The typical microfacies is bioclastic wackestone.

Thin, wavy-bedded limestone intervals are up to 1 m thick, and medium to thick, wavy to even bedded limestone intervals are up to 1.2 m thick. Thin to thick bedded cherty limestone is wavy bedded, up to 1.2 m thick and contains thin layers, lenses and nodules of chert. Most common is bioturbated bioclastic wackestone (Fig. 10C). Another microfacies type is bioclastic packstone (Fig. 10D). All limestone types are gray, micritic and fossiliferous, mostly containing brachiopods, crinoids and bryozoans in varying amounts. Subordinate are algae, gastropods and corals. Unit 48 contains Syringopora and Chaetetes. Chaetetes is also present in unit 56. In the lower part of the Amado Member, a 0.2-m-thick, intraformational, fine-grained conglomerate is intercalated, containing abundant limestone and chert clasts (Fig. 10B). The limestone facies is very similar to that of the Cerros de Amado C section.

At the Minas de Chupadera section (Fig. 13), the Amado Member is 3.5 m thick and composed of a 0.5-m-thick, gray, micritic, fossiliferous limestone bed (bioclastic wackestone) containing brachiopods at the base, followed by a thin covered interval and 5 to 20 cm of wavy-bedded, fossiliferous, micritic limestone with thin shale intercalations. Algae are present near the top. A thin bed containing reworked micritic intraclasts is intercalated.

Tinajas Member

In the Cerros de Amado, Rejas (1965) referred to the clastic-dominated stratigraphic interval between the Amado and Council Spring formations as the "Adobe-Coane undifferentiated" (Fig. 2). We conclude that he did this for chronostratigraphic, not lithostratigraphic reasons, believing the "Adobe-Coane undifferentiated" to represent the oldest Missourian strata in the Cerros de Amado, as these strata do at their type sections in the northern Oscura Mountains (Thompson, 1942). However, at their type sections, the Coane Formation is 18 m of limestone and some thin interbedded shale, and the 14-m-thick Adobe Formation has some clastic beds of sandstone and shale, but includes substantial beds of limestone, some of which are algal bioherms. In contrast, in the Cerros de Amado, the "Adobe-Coane undifferentiated" is mostly shale and siltstone with only a few thin interbeds of limestone and sandstone. On a purely lithostratigraphic basis, the names Adobe and Coane should not be applied to these strata.

Instead, these strata represent a distinctive, slope-forming unit between the cliff- and ledge-forming Amado and Council Spring members of the Atrasado Formation. We thus coin a new member name, the Tinajas Member, for the stratigraphic unit in the Cerros de Amado that Rejas (1965) termed the "Adobe-Coane undifferentiated." The name is for the Arroyo Tinajas near the type section, which is our section Cerros de Amado section B (Figs. 9B-C, 12). At the type section, the base of the Tinajas Member is not exposed, so we identify our section Cerros de Amado A (Fig. 11) as a reference section for the lower contact.

At the type section, 72.4 m of the Tinajas Member are exposed. Correlation of the member between the sections Cerros de Amado A and B (unit 85 in section A is the same as unit 6 in section B) indicates a total thickness of the Tinajas Member of ~ 104 m. Of this thickness, most of the unit is slope-forming, olive-gray shale and siltstone (70% of the measured section) with much less sandstone (18%), limestone (7%) and distinctive and very fossiliferous black shale (5%) of lacustrine origin (Fig. 9C; Lerner et al., this volume). Sandstone beds in the Tinajas Member range from laminar to trough crossbedded and are arkosic. Most of the limestone beds are thin, nodular and algal.

At the Cerros de Amado A section (Fig. 11), the Amado Member is conformably overlain by a 72.4-m-thick succession of dominantly covered (shale) intervals and shale-siltstone with thin intercalated limestone and sandstone assigned to the Tinajas Member.

It can be lithologically divided into a 38-m-thick lower part, a 27.8-m-thick middle part and a 4.9-m-thick upper part. The lower part is composed of 0.3- to 7.3-m-thick covered (shale) intervals intercalated with several 0.1- to 0.7-m-thick limestone beds. In the upper part, a 3.2-m-thick, ripple-laminated calcarenite is exposed. Most common are thin beds of dark gray limestone composed of peloidal wackestone and grainstone (Fig. 10 E), bioclastic wackestone to mudstone (Fig. 10F) and ostracodal mudstone. In the lower part a thin interval of horizontally and ripple-laminated gray limestone with rare stromatolite layers is exposed. Chert nodules are present near the top of this unit. The lithotype is fine-grained, laminated, well sorted peloidal packstone. In the middle of the section, a dark gray, brownish-weathered limestone bed (a bioclastic wackestone) is developed that contains abundant gastropods and a few solitary corals (unit 72). In the upper part, a 3.2-m-thick interval of ripple-laminated limestone interval with a thin stromatolite layer near the base is exposed. The limestone is composed of fine-grained, laminated, partly cross-bedded peloidal wackestone to packstone. The uppermost two limestone beds are 0.4 and 0.3 m thick, dark gray (but weather orange-gray) and display fossil root structures. The limestone is partly peloidal mudstone, indistinctly laminated and partly bioturbated. Many ostracods are present floating in lime mudstone. Irregular voids that represent root structures are filled with sparitic calcite cement.

The middle part of the Tinajas Member begins with a 5.6-m-thick black shale interval that contains large concretions of dark gray micritic limestone with diameters up to 40 cm near the top (unit 85). The black shale is overlain by greenish-gray micaceous siltstone, partly covered, intercalated with a few thin (2-5 cm), fine-grained sandstone beds. In the middle and upper part dark gray micritic limestone concretions up to several dm occur. The uppermost 2.7 m are composed of black shale.

The upper part of the Tinajas Member begins with a 2.1-m-thick trough cross-bedded sandstone that erosively rests on underlying black shale (unit 88). The sandstone is coarse to medium grained in the lower part and fine grained in the upper part (fining upward). It is medium to well sorted, and the grains are mostly subrounded. Most abundant are monocrystalline quartz grains with subordinate polycrystalline quartz grains. Detrital feldspars are abundant (Fig. 10F). The sandstone is overlain by a 0.2-m-thick calcareous shale containing abundant crinoid debris, followed by a thin (0.3 m) fossiliferous nodular limestone. The limestone is composed of coarse-grained wackestone-grainstone, and is partly rudstone. Most abundant are fragments of bryozoans and echinoderms. Above a covered interval, two thin (0.4 and 0.2 m) fossiliferous limestone beds are exposed, separated by a thin shale interval. The lithotypes of these two limestone beds are bioclastic wackestone to packstone (Fig. 10H). The limestone bed is overlain by a thin shale interval and a 0.8-m-thick, bedded limestone interval that forms the top of the hill. This limestone is composed of indistinctly laminated, locally bioturbated peloidal mudstone and mudstone lacking fossils.

The Cerros de Amado B section (Fig. 12) is 76.7 m thick. The lower 72.4 m represent the Tinajas Member, overlain by 4.3 m of the Council Spring Member (limestone forming the top of the hill: Fig. 9B). The Tinajas Member can be lithologically divided into a lower part dominated by shale and siltstone (38.1 m) and an upper part characterized by thicker sandstone units (34.3 m).

In the lower part, the lower 5.6 m are composed of greenish, micaceous siltstone to fine-grained sandstone with intercalated thin shale intervals, thin laminated coarse-grained siltstone to fine-grained sandstone beds, very micaceous greenish silty shale containing fossil plants and a 0.7-m-thick interval of three thin nodular limestone beds with thin greenish shale between (units 1-5). The limestone is composed of fine-grained breccia containing subangular to rounded recrystallized micritic intraclasts floating in micritic matrix. This breccia is probably pedogenically overprinted.

The siltstone interval is overlain by a 5.2 to 7 m thick black shale (unit 6: Fig. 9C) that contains abundant conchostrachans and few small carbonate concretions throughout the succession. The black shale is fissile in the lower part and laminated in the

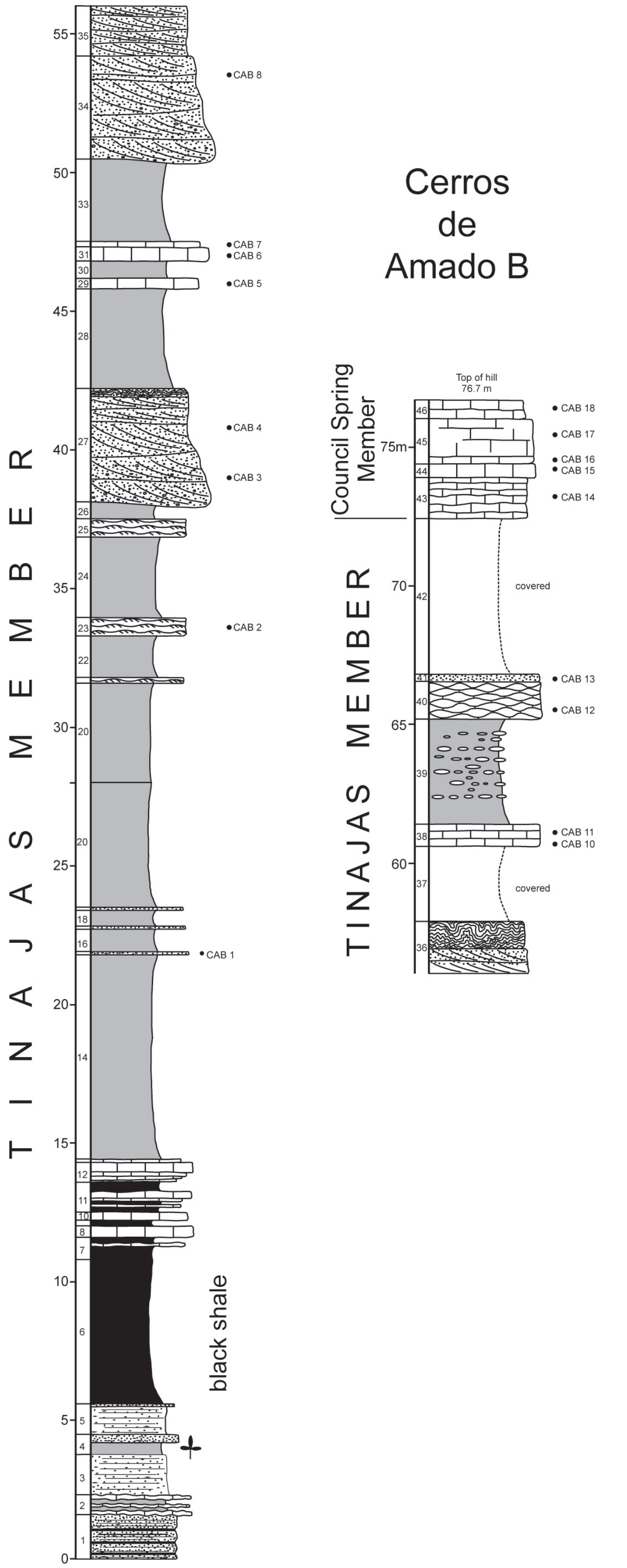

FIGURE 12. Measured section of part of the Atrasado Formation at the Cerros de Amado B section. Section measured in the SE ¼ SW ¼ sec. 25, T2S, R1E. For legend to lithologic symbols see Figure 7. Thin section and microfossil sampling levels are indicated by sample numbers to right of lithologic units (for example, “CAB 12”).

upper part. This shale is of lacustrine origin and is the Tinajas locality (NMMNH locality 4667) of Lerner et al. (this guidebook), which yields fossils of plants, crustaceans, bivalves and fishes (also see Lerner et al., 2001, 2007a, b, this guidebook; Lerner and Lucas, 2002, 2005; Kues et al., 2002; Martens and Lucas, 2005).

The black shale is overlain by brownish-gray (lower part) and greenish shale (upper part) with a 3-5-cm-thick, wavy limestone bed intercalated. This shale contains abundant euryhaline bivalves (*Dunbarella*). The thin limestone is composed of fine-grained bioturbated bioclastic wackestone with few larger bioclasts. The *Dunbarella* shale is overlain by two limestone beds (0.4 and 0.3 m thick), separated by a thin shale interval. The lower limestone bed consists of bioclastic wackestone and locally of bindstone. The upper limestone bed is a coarse-grained crinoidal wackestone.

The limestone beds are overlain by 1.1 m shale interval with abundant thin limestone lenses in the lower part and a 0.2-m-thick limestone (bioclastic wackestone) bed in the middle. The shale is brownish below the limestone bed, dark gray above and contains abundant brachiopods.

On top of this shale interval, dark gray, brownish-weathered, micritic, bedded limestone is developed. On outcrop solitary corals are observed. The limestone is composed of bioclastic and intraclast wackestone. The lower 15 m of the Cerros de Amado B section with the black shale are described in greater detail by Lerner et al. (this volume).

The limestone is overlain by a 23.7-m-thick succession of mostly greenish, partly brownish, shale to fine-grained siltstone, partly sandy in the upper part with ripple lamination (units 14-26). Intercalated are a few 0.1-0.2-m-thick, fine-grained sandstone beds. The sandstone beds are massive or display horizontal lamination and ripple lamination. The lowermost sandstone bed (unit 15) contains fossil plants (*Calamites*). In the upper part, two fine-grained, micaceous sandstone intervals with ripple lamination are intercalated, each 0.6 m thick.

The upper part of the Tinajas Member is 34.3 m thick and composed of alternating sandstone, shale, limestone conglomerate, nodular limestone and bedded limestone. Sandstone occurs as two thick, fining-upward intervals of trough cross-bedded, arkosic sandstone and fine-grained sandstone with soft sediment deformation on top. The base of each interval is an erosional scour. The lower sandstone interval is 4.1 m thick (unit 27), the upper measures 7.4 m (units 34-36). A third, 0.3-m-thick sandstone bed is exposed on top of a limestone conglomerate in the upper part of the Tinajas Member (unit 41).

Shale is greenish, commonly silty and mostly covered. In the upper part a 1.3-m-thick limestone conglomerate is exposed on top of nodular limestone. The conglomerate is composed of subangular, poorly sorted limestone clasts (including phylloid algal limestone) with diameters of mostly 2 to 5 cm, rarely > 10 cm. The conglomerate is clast supported and contains sandy matrix with detrital quartz, and it is overlain by a sandstone bed. The limestone is 0.4-0.8 m thick, wavy bedded, gray and contains algae and brachiopods. In the upper part of the Tinajas Member a 3.8-m-thick, poorly exposed nodular limestone is developed.

Our Minas de Chupadera section (Figs. 9E, 13) includes another characteristic section of the Tinajas Member, and it is mostly covered slopes and shale (83% of the section) with much less limestone (10%), arkosic sandstone (1%), carbonate sandstone (5%) and conglomerate (1%). The base of the Tinajas Member is the base of a 0.6-m-thick reddish sandstone bed on top of the Amado Member, and the top of the Tinajas Member is a bed of shale below the limestone at the base of the Council Spring Member.

The lower 22 m of the Tinajas Member are a poorly exposed gray shale slope with a 0.3-m-thick, gray, silty limestone bed intercalated in the middle and a 0.6-m-thick brownish siltstone to fine-grained calcareous sandstone displaying horizontal lamination, small-scale current ripples and dewatering structures in the upper part. Near the top of the slope, a 0.2-m-thick calcareous siltstone bed is exposed.

The upper part of the Tinajas Member is ~27 m thick and is mostly covered slopes (0.6 to 6.6 m thick) and several intercalated limestone intervals. These limestones either form single beds (0.2-0.7 m thick) or thin, indistinctly-bedded intervals (0.4-0.8 m thick) and one nodular limestone. Single beds are usually micritic, and rarely coarse crinoidal; indistinctly bedded intervals contain algae, crinoids and brachiopods. Also present is a thin bed of fine-grained, greenish and red sandstone that is massive or displays horizontal lamination and current ripples (units 22-23). A limestone conglomerate 0.4 m thick is present (unit 30), which contains limestone clasts up to 5 cm in diameter, a silty matrix and rests erosively on nodular limestone.

Council Spring Member

One of the most distinctive parts of the Atrasado Formation section in the Cerros de Amado is the Council Spring Member—a light gray/white limestone interval that forms resistant ledges, cliffs and ridges that cap much local topography (Fig. 9,B, D-E). This unit and overlying members of the Atrasado Formation (Burrego, Story, Del Cuerto and Moya members) identified by Rejas (1965), Maulsby (1981) Bauch (1982) and us in the Cerros de Amado are a stratigraphic succession of remarkably similar lithology when compared to the type sections of these units in the northern Oscura Mountains of Socorro County (Thompson, 1942, fig. 6-7).

Our sections Cerros de Amado B and Minas de Chupadera (Figs. 12-13) are characteristic sections of the Council Spring Member. At these sections, the Council Spring Member is less than 5 m thick and mostly algal wackestone. An extensive algal bioherm is also developed in the Council Spring Member near Ojo de Amado (Fig. 9D) and was originally described by Hambleton (1959, 1962).

At the Cerros de Amado B section (Fig. 12), the Council Spring Member is 4.3 m of thin bedded and indistinctly bedded to massive limestone that forms the top of the hill (Fig. 9B). The thin-bedded limestone at the base is dark gray and contains silicified brachiopods and crinoids. The massive part is composed of algal limestone (phylloid algal mound forming a biostrome), and the limestone beds on top are micritic and contain large crinoid fragments. The Council Spring Member is similar but thinner at our Minas de Chupadera section (Fig. 13).

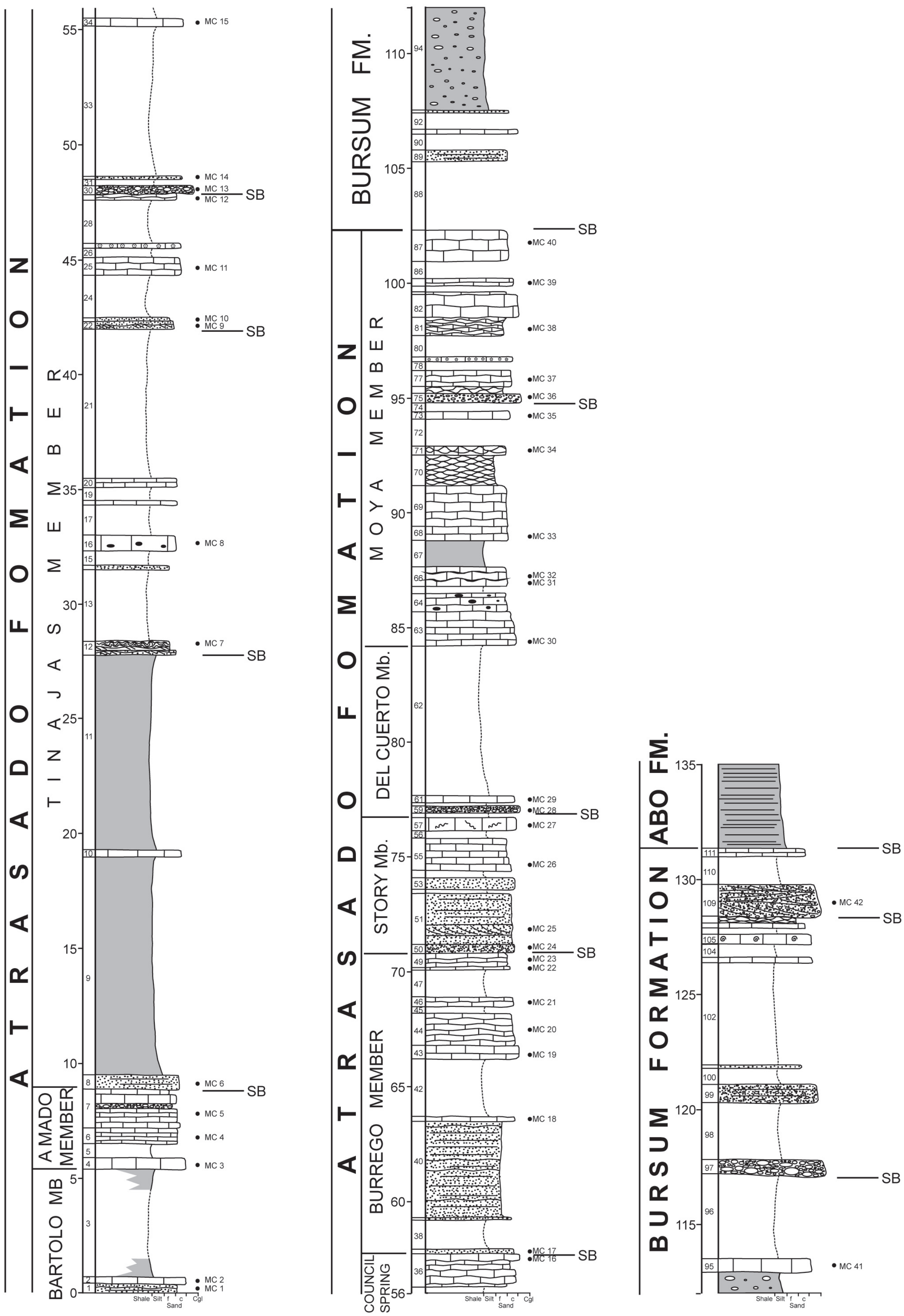

FIGURE 13. Measured section of part of the Atrasado Formation and the Bursum Formation at the Minas de Chupadera section. Section measured in the NW ¼ SW ¼ sec. 26, T2S, R1E. For legend to lithologic symbols see Figure 7. Thin section and microfossil sampling levels are indicated by sample numbers to right of lithologic units (for example, "MC 18").

At Ojo de Amado (SE ¼ NE ¼ sec. 27, T2S, R1E), the Council Spring Member thickens to 12.7 m and forms a phylloid algal mound that laterally extends over 150 m (Fig. 9D; Hambleton, 1959, 1962). The succession is composed of dark gray, wavy-bedded fossiliferous limestone with shale intercalations (4.1 m), overlain by a massive algal mound facies. The mound facies is up to 1.8 m thick and lenses out laterally. It is composed of phylloid algae that mostly seem to be in life position or toppled in situ. The mound is overlain by wavy bedded limestone containing some chert and fusulinids.

Burrego Member

The dominantly clastic unit above the Council Spring Member is the Burrego Member, approximately 13 m of mostly thin-bedded arkosic and micaceous sandstone, covered slopes (shale?) and limestone (Fig. 13). The limestone is partly cherty and contains silicified fossils. Fossils observed in the field are algae, crinoids and brachiopods. Algal limestone and crinoidal packstone occur near the top of the member. We identify the base of the Burrego Member as the first arkosic sandstone bed above algal limestone of the Council Spring Member. The unit forms a ledgy slope between the prominent ledges formed by the Council Spring Member (below) and the Story Member (above).

Story Member

In the northern Oscura Mountains, the type section of the Story Formation of Thompson (1942) is a bipartite unit—a clastic-dominated lower half overlain by a carbonate-dominated upper half. Like Rejas (1965), we identify the same kind of bipartite unit in the Cerros de Amado as the Story Member. Indeed, Rejas (1965) divided the Story "Formation" into a "lower clastic member" and an "upper limestone member." At the Minas de Chupadera section (Fig. 13), a typical section of the Story Member is exposed.

Here, the Story Member is ~ 6 m thick and mostly beds of sandstone in the lower half and limestone beds in the upper half. The lower part of the Story Member is mostly 3.3 m of arkosic calcareous sandstone, which is medium to coarse grained and partly cross-bedded. The sandstone is overlain by a 10-20-cm-thick, bedded limestone, which is partly algal and contains a few corals and some chert. The thin-bedded limestone is overlain by a 0.6-m-thick algal limestone bed. The sandstone, thin-bedded limestone and algal limestone bed can be interpreted to represent a transgressive cycle. As in the northern Oscura Mountains at Thompson's (1942) type section of the Story "Formation," the entire Story Member can be interpreted to represent one transgressive cycle with nearshore marine clastic sediments at the base overlain by shallow, open-marine limestone (Lucas and Krainer, this guidebook).

Del Cuerto Member

The Del Cuerto Member in the Cerros de Amado is another interval of mixed clastics and carbonates; it forms a slope between the limestone ledge at the top of the Story Member and the similar resistant limestones at the base of the Moya Member. Rejas (1965) divided the Del Cuerto Formation into three members, a lower member of slope-forming shale, a middle member of limestone and an upper member mostly of sandstone. However, the unit cannot be consistently subdivided in this way; for example, at the Minas de Chupadera section (Fig. 13), the middle of the Del Cuerto is shale dominated, and the lower part is sandstone and limestone. Thus, we employ no subdivisions of the Del Cuerto Member in the Cerros de Amado.

At the Minas de Chupadera section (Fig. 13), a typical section of the Del Cuerto Member is exposed. Here, the Del Cuerto Member is ~7 m thick and mostly a covered slope (presumably underlain by shale) and beds of pebbly sandstone and limestone.

Pebbly sandstone (0.3 m thick: unit 59) forms the base of the member and the base of a cycle and is overlain by a thin shale interval, a gray limestone bed and 6.5-m-thick covered interval.

Moya Member

The uppermost part of the Atrasado Formation in the Cerros de Amado is a relatively thick, cliff- and ledge-forming limestone interval, the Moya Member. The Minas de Chupadera section (Fig. 13) is a characteristic section of the Moya Member, which stands out above the slope forming Del Cuerto Member and below the slope-forming red beds of the overlying Bursum Formation (Fig. 9F). Here, the Moya Member is ~ 18 m thick and is mostly limestone (73% of the measured section), covered slopes presumably underlain by shale (23%) and minor arkosic sandstone (4%) The bed of arkosic and conglomeratic sandstone in the middle of the unit was used by Rejas (1965) to divide it into upper and lower members, but we do not subdivide the unit. Most of the limestone beds have some chert, and limestone types range from lime mudstones through coarse and crinoidal, but algal wackestone is the dominant limestone type.

Most of the limestone is wavy and thin bedded, but it is thick bedded near the top of the member. Nodular limestone is also present. Common fossils observed in the field are algae and crinoids. Fusulinids (large *Triticites*), solitary corals and bryozoans are also present near the top of the member. These fossils suggest that limestone formed in shallow, open marine settings with slight changes in water depth and energy.

Bursum Formation

Krainer and Lucas (this volume) provide a comprehensive review of the lithostratigraphy of the Bursum Formation in and around the Cerros de Amado (also see Rejas, 1965; Kottlowski and Stewart, 1970; Altares, 1990; Beck and Chapin, 1991 and Beck and Johnson, 1992, among others). In brief, the Bursum Formation in the Cerros de Amado is up to 120 m thick and composed of alternating shallow marine limestone and shale and nonmarine red beds. These alternating marine and nonmarine sediments locally form well-developed cyclic successions. However, strong vertical and lateral variations in thickness and facies are observed, and we assign Bursum strata of predominantly marine facies (mostly marine limestones and shales) to the Bruton Member, whereas dominantly nonmarine facies (red bed mudstones, sandstones and conglomerates) of the Bursum are the Red Tanks Member (Lucas and Krainer, 2004). These pronounced local variations indicate that sedimentation of the Bursum Formation in the Joyita Hills was strongly influenced by tectonic movements of the Ancestral Rocky Mountain orogeny (e.g., Kottlowski and Stewart, 1970; Beck and Chapin, 1991; Beck and Johnson, 1992; Krainer and Lucas, this volume).

The Bursum Formation section illustrated here as part of our Minas de Chupadera section (Fig. 13) is relatively thin (~ 28 m) and mostly nonmarine siliclastic red beds, so we assign it to the Red Tanks Member. Fusulinids from near the middle of the Bursum Formation at this section (Fig. 13, unit 95) are dominated by large, globose *Triticites* of early Wolfcampian (Newwellian *sensu* Wilde, 2006) age.

FUSULINID BIOSTRATIGRAPHY

Although some previous workers have assigned ages to the Pennsylvanian strata in the Cerros de Amado based on fusulinid biostratigraphy, few fusulinid fossils have actually been documented in print. Furthermore, our fieldwork indicates that fusulinids are only abundant in parts of the Pennsylvanian section in the Cerros de Amado (principally in the Gray Mesa and the Bursum formations), so their patchy distribution makes precise age control based on fusulinids problematic.

Needham (1937) reported "*Fusulina* [= *Beedeina*] *euryteine*s" from "large blocks of Pennsylvanian limestone in valley fill believed to be late Pliocene or Pleistocene in age" from north of the "Valle del Ojo de la Parida," but provided no more precise stratigraphic data. This indicates a Desmoinesian age for the outcrop sampled.

Rejas (1965) assigned a Desmoinesian (upper Cherokee) age to the Elephant Butte, Whiskey Canyon and Garcia "formations" based on fusulinids, but provided no precise data. Maulsby (1981) reported *Triticites* from the Burrego Formation.

Lucas and Estep (2000) reported fusulinids from the upper part of the Garcia Member of the Gray Mesa Formation (bed 118 of our Cerros de Amado C section: Fig. 8) as *Beedeina* ex gr. *leei* and *B.* ex gr. *euryteines* (or possibly *B. soccorroense*), indicative of a Desmoinesian age. Kues et al. (2002) reported *Triticites* of early-middle Missourian age from the Council Spring Member (bed 45 of our Cerros de Amado B section: Fig. 12). Several workers (e.g., Altares, 1990; Beck and Johnson, 1992) have documented early Wolfcampian (Newwellian *sensu* Wilde, 2006) fusulinids from the Bursum Formation in the Cerros de Amado.

We have collected fusulinids from various beds in our measured sections that are currently under study. A preliminary analysis of these samples is consistent with the conodont-based age determinations detailed below.

CONODONT BIOSTRATIGRAPHY

Numerous conodonts were obtained from samples collected during the process of measuring the sections of Pennsylvanian strata in the Cerros de Amado (Figs. 14-15). Samples were collected at irregular intervals through the stratigraphic sections where relatively coarse-grained carbonate beds and lenses occurred, usually in the upper parts of the shallow-water carbonate and shale cycles. This approach was used because of its moderate success in obtaining conodonts from similar cyclical units in the Pennsylvanian sections in the Big Hatchet Mountains of southwestern New Mexico. The conodont faunas are characterized by taxa that are indicative of shallow-water marine conditions. Variable proportions of elements of *Adetognathus, Hindeodus, Idiognathodus* and *Streptognathodus* occur in most samples, as well as less common specimens of *Ellisonia.* Fewer elements of the more offshore genera *Idioprioniodus* and *Neognathodus* were obtained, and no specimens of *Gondolella* were recovered.

Atokan-Desmoinesian (Moscovian) Conodonts

Conodont taxonomy and biostratigraphy are poorly developed for the Atokan-Desmoinesian time interval. Although revised zonations have been proposed for this time interval in Midcontinent North America (Barrick et al., 2004) and for the Moscovian in the Donets Basin and the Moscow Basin (Nemyrovska et al., 1999; Alekseev and Goreva, 2001, respectively), they provide relatively coarse time resolution. One reason for this lack of time resolution is the incomplete taxonomic framework for species of *Neognathodus* and *Idiognathodus.* Although some papers documenting conodonts from short increments of time in North America have been published (Lambert, 1992, base of Desmoinesian; Stamm and Wardlaw, 2003, Verdigris cyclothem), these do not provide sufficient range data for correlation. Attempts to determine ranges on a cycle-by-cycle basis for the Atokan-Desmoinesian interval have been made, but the results rely heavily on poorly described taxa often left in open nomenclature (Ritter et al., 2001, Paradox Basin, Utah; Boardman et al., 2004, southern Midcontinent). Species characterization and species ranges are somewhat better established for Eurasian faunas (Alekseev and Goreva, 2001) and are employed here as appropriate.

Sandia Formation (Arroyo de la Presilla A section)

Only one sample, unit 27, 47 m above the base of the formation, yielded sufficient conodonts from the Sandia Formation for age determination. This level yielded small numbers of *Idiognathodus* elements that are most like *I. incurvus* Dunn, 1966. A few specimens of *Declinognathodus marginodosus* (Grayson, 1984) and *Idiognathoides sulcatus* Higgins & Bouckaert, 1968 were recovered. This assemblage is Atokan in age. The specimens of *I. incurvus* resemble closely those illustrated by Barrick et al. (2004, pl. 2) as "*I. incurvus* descendents," which suggests a late Atokan age. Based on the range of *D. marginodosus* in Eurasia (Nemyrovska et al., 1999, fig. 2; Goreva and Alekseev, 2001, table 8), the fauna is likely latest Baskirian to earliest Moscovian in age.

Gray Mesa Formation, Elephant Butte Member

Samples from the Elephant Butte Member in the Arroyo de la Presilla B section (Fig. 6) produced two successive conodont faunas. The oldest fauna, from the lower 60 m of the member, is characterized by *Idiognathodus obliquus* Kossenko, 1978, *Dip-*

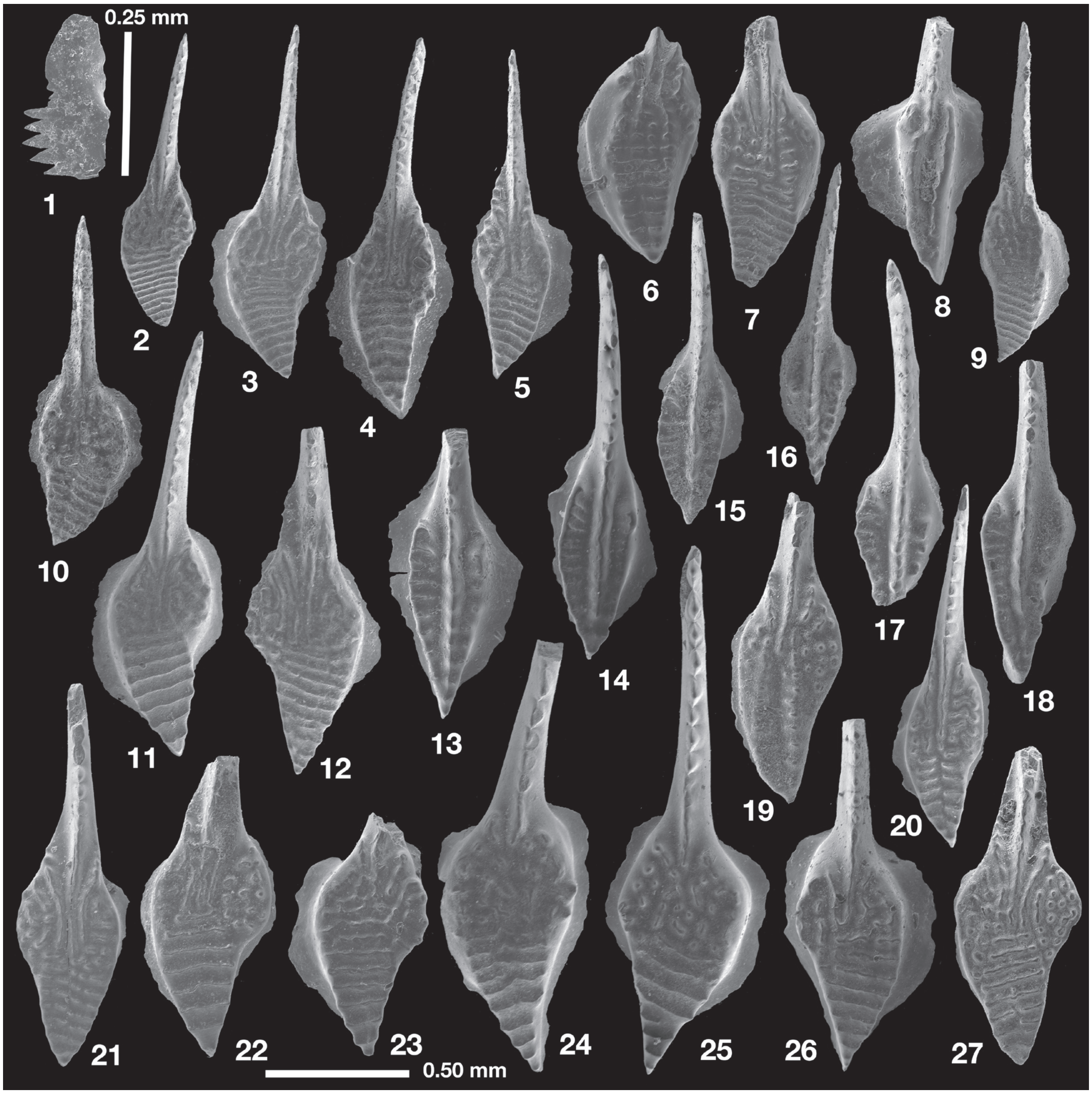

FIGURE 14. Selected conodonts from the Pennsylvanian strata in the Cerros de Amado. Specimens are in the collection of Texas Tech University. 1, *Diplognathodus coloradoensis* Murray & Chronic (Amado D8); 2-5, *Idiognathodus obliquus* Kossenko; 2 (Amado D8); 3 (Presilla B41), 4 (Presilla B68); 5 (Presilla B68); 6-7, *Idiognathodus incurvus* Dunn ; 6 (Presilla A27); 7 (Presilla A27); 8, *Declinognathodus marginodosus* Grayson (Presilla A27); 9, *Idiognathodus obliquus* (Presilla B122); 10, *Idiognathodus podolskensis* (Amado D15); 11-12, *Idiognathodus iowaensis* Youngquist & Heezen?; 11 (Amado C104); 12 (Amado C104); 13, *Neognathodus asymmetricus* Stibane? (Presilla B133); 14. *Neognathodus intrala* Stamm & Wardlaw (Amado D3); 15, *Neognathodus colombiensis* Stibane?(Presilla B34); 16-18, *Neognathodus roundyi* (Gunnell); 16 (Amado C148); 17 (Amado C130); 18 (Amado A13); 19-20, *Swadelina neoshoensis* Lambert, Heckel & Barrick; 19 (Amado A13); 20 (Amado C148); 21-22, *Idiognathodus delicatus* Gunnell 1931; 21 (Amado C130); 22 (Amado C130); 23, *Idiognathodus iowaensis*Youngquist & Heezen (Presilla B133); 24-25, *Idiognathodus robustus* Kossenko & Kozitskaya; 24 (Presilla B133); 25 (Presilla B133); 26, *Idiognathodus iowaensis* Youngquist & Heezen (Presilla B133); 27. *Idiognathodus* sp. (Amado C13).

lognathodus coloradoensis (Murray & Chronic, 1963), and rare forms of *Neognathodus bothrops* Merrill, 1972, and/or *N. columbiensis* (Stibane, 1967). Although *D. coloradoensis* ranges from at least as low as the Atokan into the middle Desmoinesian (von Bitter and Merrill, 1990), *I. obliquus* appears near the base of the Desmoinesian in the type area in Iowa (Lambert, 1992) and in eastern Oklahoma (Boardman et al., 2004). The upper range of *I. obliquus* in North America is less well determined, but it has not been reported above the Verdigris cyclothem near the top of the lower Desmoinesian Cherokee Group (Stamm and Wardlaw, 2003; Boardman et al., 2004). *Idiognathodus obliquus* is common in the Donets and Moscow basins, where it ranges from the lower

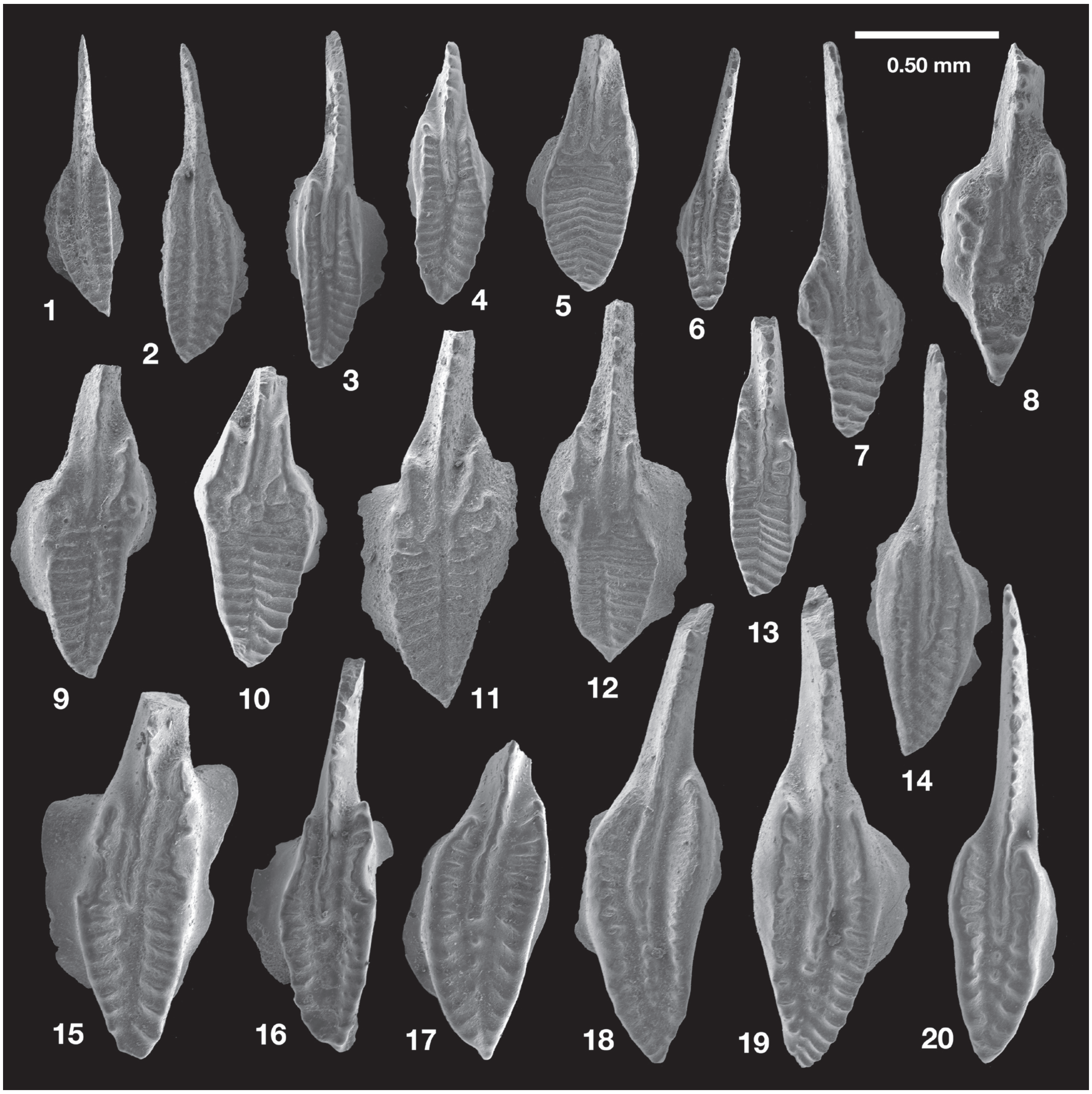

FIGURE 15. Selected conodonts from the Pennsylvanian strata in the Cerros de Amado. Specimens are in the collection of Texas Tech University. 1-2, *Streptognathodus ruzhencevi* Kozur; 1 (Chupadera 48); 2 (Chupadera 48); 3-4, *Streptognathodus virgilicus* Ritter; 3 (Chupadera 79); 4 (Chupadera 79); 5. *Idiognathodus tersus* Ellison (Chupadera 55); 6, *Streptognathodus cancellosus* Gunnell? (Amado A54); 7, *Idiognathodus sulciferus* Gunnell? (Amado C16)8; 8, *Idiognathodus eccentricus* (Ellison)?(Amado C168); 9-12, *Idiognathodus eudoraensis* Barrick, Heckel & Boardman; 9 (Chupadera 2); 10 (Chupadera 2); 11 (Amado B10); 12 (Amado B10); 13, *Idiognathodus tersus* Ellison (Chupadera 55); 14. *Streptognathodus pawhuskaensis* (Harris & Hollingsworth); 14 (Chupadera 27); 15 (Chupadera 34); 16 (Chupadera 34); 17, *Streptognathodus vitali* Chernykh (Chupadera 55); 18-19, *Streptognathodus firmus* Kozitskaya; 18 (Chupadera 2); 19 (Amado B10); 20, *Streptognathodus vitali* Chernykh (Chupadera 55).

Moscovian (lower Kashirian) into the upper Moscovian (middle Myachkovian).

The second conodont fauna from the Elephant Butte Member appears approximately 65 m above the base of the unit, in the upper part of the member. Many of the same species found below occur, but this level is marked by the appearance of rare elements that can be referred with question to *Neognathodus asymmetricus* (Stibane, 1967) as used by Barrick et al. (2004), which indicates an early Desmoinesian age.

Gray Mesa Formation, Whiskey Canyon Member

Only a few levels of the Whiskey Canyon Member were sampled for conodonts. At the Arroyo de la Presilla B section, the fauna is like that found in the upper part of the Elephant Butte Formation. *Idiognathodus obliquus* and *Neognathodus asymmetricus*? were the most important species recovered.

Gray Mesa Formation, Garcia Member

The lower 20 m of the Garcia Member contain a conodont fauna similar to that of the Whiskey Canyon Member, but with the appearance of *Idiognathodus podolskensis* Goreva, 1984 not far above the base. This species occurs in the upper Cherokee Group in eastern Oklahoma, where it ranges from the Inola Limestone through the Verdigris Limestone (Boardman et al., 2004). In the Moscow Basin, *I. podolskensis* ranges from the Podolian into the middle Myachkovian, through most of the middle part of the Moscovian (Goreva and Alekseev, 2001). A few examples of *Neognathodus intrala* Stamm & Wardlaw, 2003 were obtained just above the base of the Garcia at the Cerros de Amado D section. A few forms of *Idiognathodus* that possess widely spaced transverse ridges like *I. meekerenis* Murray & Chronic, 1963 occur, but this species assignment in uncertain.

At both sections, Arroyo de la Presilla B and Cerros de Amado C, a different conodont fauna, one dominated by species of *Idiognathodus* with few transverse ridges and prominent lobes, appears about 30 m above the base of the Garcia Member. Some forms are similar to *Idiognathodus iowaensis* Youngquist & Heezen, 1948 from the Midcontinent region (Barrick et al., 2004) and *I. robustus* Kossenko & Kozitskaya, 1978, as described by Stamm and Wardlaw (2003) from the Verdigris cyclothem and equivalent strata. In addition, more typical examples of *I. robustus* occur (see Boardman et al., 2004, for a discussion of this species). Other forms cannot be assigned to a formally named species at this time.

This fauna appears to be equivalent in age to upper part of the Cherokee Group in the Midcontinent region, best represented by the Verdigris cyclothem (Stamm and Wardlaw, 2003; Boardman et al., 2006). Barrick et al. (2004) show the *I. iowaensis* Zone encompassing the upper part of the Cherokee Group, but this species and others originally described by Youngquist and Heezen (1948) and Youngquist and Downs (1949) from the Verdigris cyclothem in Iowa are still poorly known. This *I. iowaensis* fauna persists through an interval of at least 75 m at the Cerros de Amado C section and to the top of the Garcia Member measured at the Arroyo de la Presilla B section, through a thickness of about 40 m.

The reported range of *I. robustus* differs between the Moscow Basin and the Donets Basin, making correlation difficult to Eurasia. In the Donets Basin, the type area of the species, *I. robustus* occurs with *I. podolskensis* in Myachkovian units and ranges above that species (Nemyrovska et al., 1999). But in the Moscow Basin, *I. robustus* occurs in the Kashirian, below the first appearance of *I. podolskensis* (Goreva and Alekseev, 2001).

Approximately 85 above the base of the Garcia Member at the Cerros de Amado C section (Fig. 8), *Neognathodus roundyi* (Gunnell, 1931) and forms that are commonly assigned to *Idiognathodus delicatus* Gunnell, 1931 appear. These two species are typical of the lower Marmaton Group in the Midcontinent region (Barrick et al., 2004). The highest conodont fauna from the Garcia Formation, which appears within a few meters of its top, contains a diverse association that includes *Swadelina neoshoensis* Lambert, Heckel, and Barrick 2003, and *N. roundyi*. This fauna can be assigned to the *Sw. neoshoensis* Zone of the Midcontinent region, which characterizes the upper, but not uppermost, part of the Marmaton Group (Barrick et al., 2004). Detailed correlation of late Desmoinesian conodont faunas with late Moscovian conodont faunas is problematic because of provincialism.

Atrasado Formation, Bartolo Member

Few conodonts were recovered from the thin limestones in the clastic-dominated Bartolo Member. Most specimens are elements of *Adetognathus, Hindeodus*, and *Ellisonia*, all shallow water species. One limestone about 35 m below the top of the member at Cerros de Amado section A (Fig. 11), contained *Swadelina neoshoensis* and *Idiognathodus* sp. A, both known from the *Sw. neoshoensis* Zone of the Midcontinent region. *Swadelina neoshoensis* was also recovered from a thin limestone 15 m below the top of the Bartolo Formation. No evidence of the latest Desmoinesian conodont zone, the *Swadelina nodocarinatus* Zone, was discovered.

Missourian-Virgilian (Kasimovian-Gzhelian) Conodont Faunas

The taxonomy and biostratigraphy of conodonts from Missourian-Virgilian strata in the Midcontinent region (Barrick et al., 2004) and Kasimovian-Gzhelian strata in Eurasia (Alekseev and Goreva, 2006) are better understood than for older Pennsylvanian faunas, and comparable zonations exist for each region. The most recent proposal for the level of the base of the Missourian in the Midcontinent region places the boundary at the Exline Limestone, which corresponds to the base of the *Idiognathodus eccentricus* Zone (Heckel et al., 2002). The base of the international stage, the Kasimovian, has yet to be placed, but recent work indicates that a level near the base of the Khamovikian will be chosen (Villa and Task Group, 2006). This decision would place the underlying Krevyakinian, which has been considered to be Kasimovian in age, into the top of the Moscovian Stage. The base of the Kasimovian would then correspond approximately to the base of the Missourian.

Heckel et al. (1998) recommended that the base of the Virgilian Stage be raised to the level of the Cass cyclothem in the Midcontinent region, somewhat higher than the usual levels at which this stage boundary has been placed. Recently, it has been recommended that the base of the international Gzhelian Stage be placed at a level to coincide with the first appearance of *Idiognathodus simulator* (Heckel et al., 2008). This base of the Gzhelian correlates with the Oread cyclothem in the Midcontinent region, a few cycles higher than the Cass cyclothem (Barrick et al., 2008).

Atrasado Formation, Amado Member

The few conodonts recovered from the lower beds of the Amado Member are mostly elements of *Hindeodus*, *Adetognathus* and tiny specimens of *Idiognathodus species*. These small specimens possess long carinas, a feature typical of Missourian species, and the few larger specimens appear to be examples of *I. eccentricus* (Ellison, 1941) and *I. sulciferus* Gunnell, 1933, both known from lowermost Missourian units in the Midcontinent region (Barrick et al., 2004). One sample near the top of the Amado Member at the Cerros de Amado A section produced a few small specimens of *Streptognathodus* that may be examples of *S. cancellosus* Gunnell, 1933, an early Missourian form (Barrick et al., 2004). Because the proposed base of the Kasimovian currently coincides approximately with the base of the Missourian, these faunas are early Kasimovian in age. This means that the Desmoinesian-Missourian boundary in the Cerros de Amado is at or near the base of the Amado Member of the Atrasado Formation (Fig. 16).

Atrasado Formation, Tinajas Member

Only a few undiagnostic conodonts were obtained from the thin limestones in the lower part of the clastic-dominated Tinajas Member at the Cerros de Amado A section (Fig. 11). In contrast, an extremely abundant fauna was recovered from the limestones just above the conchostracan-bearing black shale in the Cerros de Amado B section (Fig. 12). This fauna is dominated by elements of *Idiognathodus eudoraensis* Barrick, Heckel & Boardman, 2008 and a smaller number of elements of *Streptognathodus firmus* Kozitskaya, 1978. Because the examples of *S. firmus* are characterized by a reduced carina, this fauna is likely slightly younger than the Eudora cyclothem (Lansing Group, upper Missourian Series) in the Midcontinent region, where both species appear (Barrick et al., 2004, 2008).

Atrasado Formation, Council Spring Member

No diagnostic conodonts were obtained from the Council Spring Member at the Cerros de Amado B section (Fig. 12), but the base of the member at the Minas de Chupadera section (Fig. 13) yielded elements of *S. pawhuskaensis* (Harris & Hollingsworth, 1932), a species that ranges from the upper Missourian through much of the Virgilian. This, underlying and overlying conodonts suggest that the Council Spring Member is late Missourian, middle Kasimovian, in age.

Atrasado Formation, Burrego, Story and Del Cuerto Members

At the Minas de Chupadera section (Fig. 13), a sample from the middle of the Burrego Member produced a low diversity conodont fauna that includes specimens of *Streptognathodus pawhuskaensis*. The species *S. pawhuskaensis* is a long-ranging species and is characteristic of conodont faunas from the late Missourian into the middle Virgilian in the Midcontinent region and the middle Kasimovian into the middle Gzhelian in Eurasia.

In the Minas de Chupadera section (Fig. 13), the top limestone of the Burrego Member produced a sparse conodont fauna that contains the species *Streptognathodus ruzhencevi* Kozur, 1977. This species appears at the base of the *S. vitali* Zone in Eurasia, the second zone above the base of the Gzhelian (Chernykh, 2002; Alekseev and Goreva, 2006). A sample in the overlying Story Member yielded *S. vitali* Chernykh 2002 and *Idiognathodus tersus* Ellison, 1941, both characteristic Gzhelian species that occur with *S. ruzhencevi* in the middle Virgilian Queen Hill cyclothem in the Midcontinent region (Ritter, 1995; Boardman et al., 2006).

Atrasado Formation, Del Cuerto Member

In the Minas de Chupadera section (Fig. 13), the basal limestone of the Del Cuerto Member produced a sparse conodont fauna that contains the species *Streptognathodus ruzhencevi* Kozur, 1977. This species appears at the base of the *S. vitali* Zone in Eurasia, the second zone above the base of the Gzhelian (Chernykh, 2002; Alekseev and Goreva, 2006). A sample higher in the member yielded *S. vitali* Chernykh 2002 and *Idiognathodus tersus* Ellison, 1941, both characteristic Gzhelian species that occur with *S. ruzhencevi* in the middle Virgilian Queen Hill cyclothem in the Midcontinent region (Ritter, 1995; Boardman et al., 2006).

Atrasado Formation, Moya Member

In the Minas de Chupadera section (Fig. 13), the most diagnostic conodont fauna from the Moya Member came from a sample from near the middle of the unit. This sample contained *Streptognathodus pawhuskaensis* and *S. virgilicus* Ritter, 1995. The latter species is the index form for the *S. virgilicus* Zone, which characterizes middle Virgilian strata in the Midcontinent region (Ritter, 1995; Barrick et al., 2004) and middle Gzhelian strata in Eurasia (Alekseev and Goreva, 2006).

Bursum Formation

In the Minas de Chupadera section (Fig. 13), no identifiable conodonts were recovered from a few samples of the Bursum Formation.

CONCLUSION

Our detailed review of the Pennsylvanian lithostratigraphy in the Cerros de Amado (Fig. 16) supports most of the lithostratigraphic conclusions of Rejas (1965). It thus indicates the continuity of relatively thin lithosomes between the Mud Springs Mountains, northern Oscura Mountains and Cerros de Amado, distances of as much as 120 km. Conodont biostratigraphy provides precise age determinations for most of the Pennsylvanian section in the Cerros de Amado (Fig. 16).

Two things are striking about the Pennsylvanian section in the Cerros de Amado: (1) the abundance of clastic sediment, especially coarse-grained clastics, some of obvious nonmarine origin, intercalated in a dominantly marine carbonate section; and (2) the presence of unconformities in many parts of the section, usually where nonmarine clastric beds rest on marine strata, including the relatively long hiatus (= late Virgilian) between the Atrasado and Bursum formations. Clearly, as others have argued (e.g., Kottlowski and Stewart, 1970; Siemers, 1983), syndepositional tectonism was a major factor controlling Pennsylvanian sedimenta-

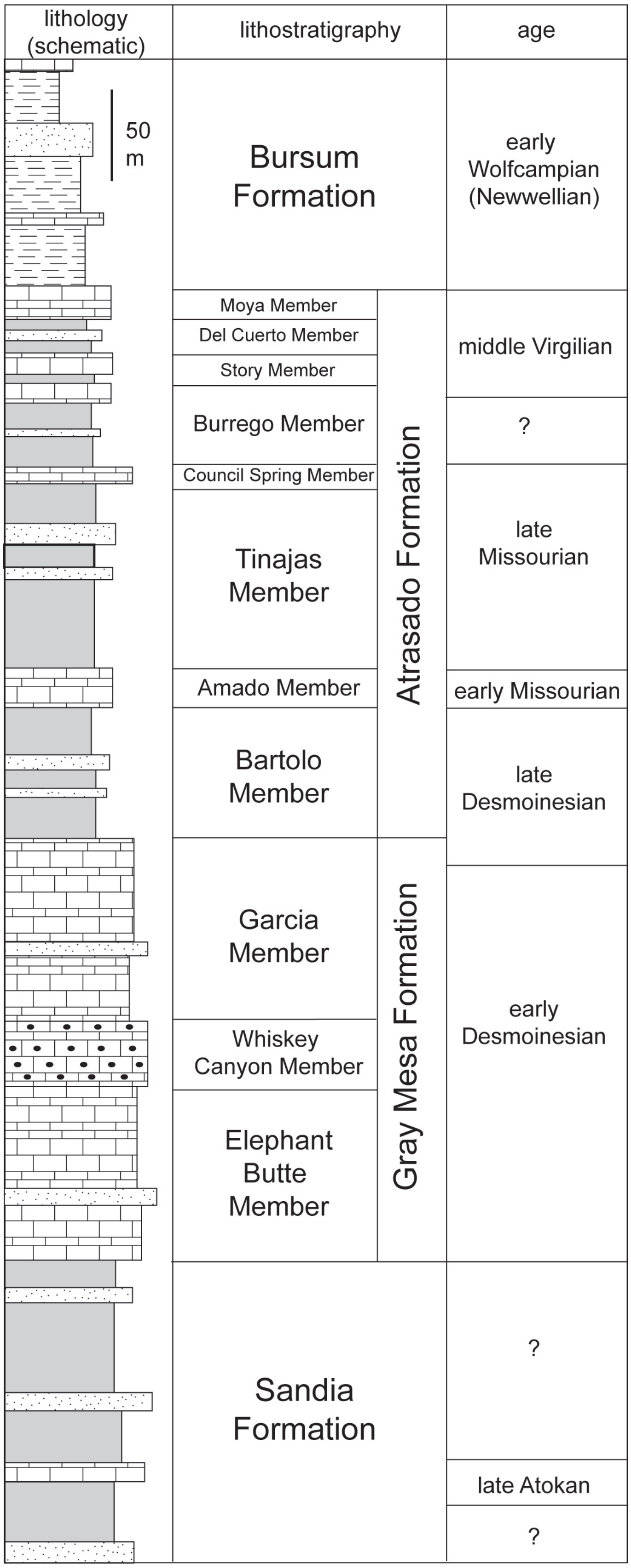

FIGURE 16. Summary of lithostratigraphic nomenclature and conodont-based age determinations of the Pennsylvanian strata in the Cerros de Amado.

tion in the Cerros de Amado. Discussion of this topic is beyond the scope of this article, but the detailed lithostratigraphy and biostratigraphy presented here will be the basis of such a discussion in a future contribution.

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