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

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Abstract—The Pennsylvanian section in the Cerros de Amado of Socorro County is as much as 744 m thick and consists of three formations of marine and mixed marine-nonmarine origin. At the base of the Pennsylvanian section, the Sandia Formation unconformably overlies Precambrian basement and is a 162 m thick cyclic succession of siliciclastic (notably quartzose sandstone and conglomerate) and carbonate (mostly coarse-grained bioclastic wackestone/packstone) strata. The overlying Gray Mesa Formation is 233 m thick and divided into three members: Elephant Butte Member (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 up to 348 m of interbedded siliciclastics (mostly shale and arkosic sandstone) and varied limestones. Members of the Atrasado Formation (ascending) are Bartolo, Amado, Tinajas, Council Spring, Burrego, Story, Del Cuerto, and Moya. The lower Permian Bursum Formation overlies the Pennsylvanian section in the Cerros de Amado and is as much as 120 m of red-bed siliciclastics and limestones. Sparse fusulinid data and more extensive conodont records indicate the following ages: late Atokan (Sandia Formation), early Desmoinesian (most of the Gray Mesa Formation), late Desmoinesian (uppermost Gray Mesa Formation, Bartolo, and lowermost Amado members of Atrasado Formation), Missourian (most of Amado, Tinajas, Council Spring, and lower Burrego members of Atrasado Formation), and Virgilian (upper Burrego, Story, Del Cuerto, and Moya members of Atrasado Formation).

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 east-northeast of Socorro, New Mexico (Fig. 1). Much of the bedrock in the Cerros de Amado consists of Pennsylvanian sedimentary rocks (Fig. 2; Lucas et al., 2009a, 2013; Barrick et al., 2013; Krainer et al., 2017). Here, we review the lithostratigraphy and biostratigraphy of the Pennsylvanian strata in the Cerros de Amado (Figs. 2–11). Our goals are to present a concise summary and also to correct some earlier miscorrelations of some of these strata.

PREVIOUS STUDIES

Lucas et al. (2009a) presented a detailed review of previous studies of the Pennsylvanian section in the Cerros de Amado prior to 2009, obviating the need for such a review here. More recent published studies (e.g., Barrick et al., 2013; Lucas et al., 2013; Krainer et al., 2017) do not revise the overall lithostratigraphy of the Pennsylvanian section presented by Lucas et al. (2009a). The understanding of the Pennsylvanian stratigraphy in this area has evolved considerably since the pioneering observations of Herrick (1904a, b), particularly due to the important study of Rejas (1965), who mapped part of the Cerros de Amado area and applied Thompson's (1942) stratigraphic nomenclature as well as some new names of his own to the Pennsylvanian strata. Lucas et al. (2009a) published some of the stratigraphic observations of Rejas (1965), and their own data, to produce the lithostratigraphy of the Pennsylvanian strata reviewed here (also see Barrick et al., 2013; Lucas et al., 2013; Krainer et al., 2017). Here, we present new stratigraphic data on the Atrasado Formation and resolve some previous miscorrelations of Atrasado strata within the Cerros de Amado area.

SANDIA FORMATION

Lucas et al. (2009a) described a complete section of the Sandia Formation along the northern bank of the Arroyo de la Presilla (Fig. 4). Here, the Sandia Formation is 162 m thick, rests on Proterozoic granitic basement, and consists of a cyclic succession of siliciclastic and carbonate strata—nonmarine and marine strata that form well-developed transgressive 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.

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 and reddish, and individual quartz clasts are up to 1–2 cm in diameter. Sandstone intervals are up to 9 m thick, fine upward, and are composed of multistoried channel fills. Individual sandstone

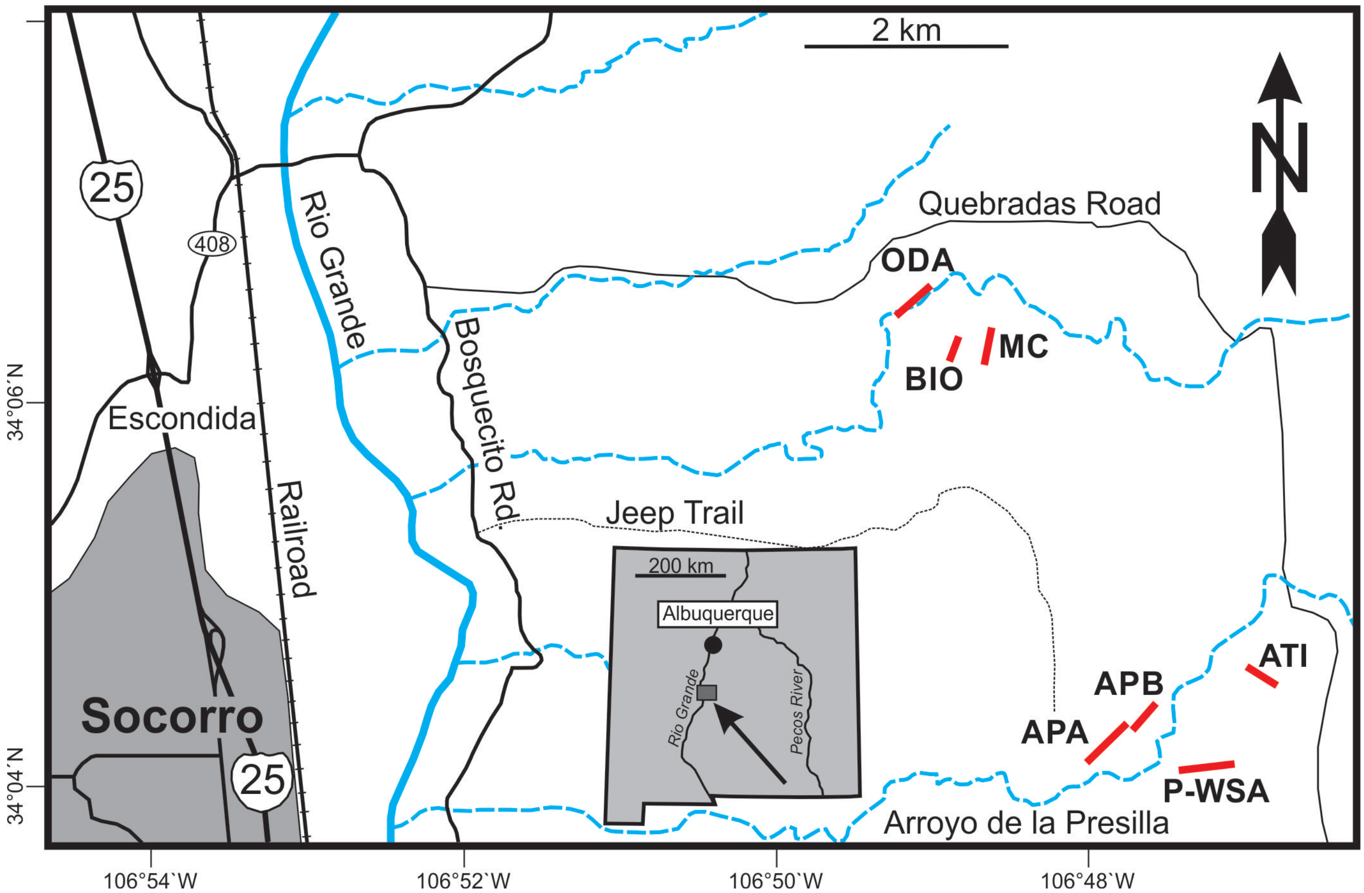

FIGURE 1. Map of the Cerros de Amado area showing locations of measured sections of Pennsylvanian strata illustrated here (Figs. 3–11). Measured sections are: APA = Arroyo de la Presilla A (Fig. 4); APB = Arroyo de la Presilla B (Fig. 5); ATI = Arroyo Tinajas (Fig. 7); BIO = Bioherm (Fig. 10); ODA = Ojo de Amado (Fig. 9); MC = Minas del Chupadero (Fig. 11); PWSA = Presilla WSA (Fig. 6).

beds contain 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 "fire clay" of Herrick (1904a; it is actually a fissile, laminated silty shale and siltstone) in the lower part of the section (Fig. 4, unit 7) is light gray, 0.5 m thick, and contains plant fossils. It is underlain by dark gray, laminated, silty claystone containing *Lingula* and plant fossils (unit 6). Below, a yellowish-brownish siltstone (unit 4) contains abundant impressions of *Lepidodendron* (Herrick, 1904a; Darton, 1928; Lucas et al., 2009b).

Thick siltstone/fine-grained sandstone intervals occur in the lower part of the Sandia Formation section, below and above the "fire clay." 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, a greenish-brown silty shale (unit 16) is poorly exposed and contains abundant marine fossils such as gastropods, crinoids, bryozoans, brachiopods, and rugose corals. In the middle and upper part of the Sandia Formation, 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, only one poorly exposed, thin (10–20 cm thick) limestone bed within unit 16 is present, which is fossiliferous and contains brachiopods and bryozoans. In the middle and upper part of the Sandia Formation, limestone intervals are 0.3–3.0 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, solitary corals, and shark's teeth (Ivanov et al., 2009).

GRAY MESA FORMATION

Lucas et al. (2009a) described a measured section of most of the Gray Mesa Formation at their Arroyo de la Presilla B section (Fig. 5). Other stratigraphic sections they described (Lucas et al., 2009a, figs. 7–8) include the upper strata of the Gray Mesa Formation not present (due to erosion) in the Arroyo de la Presilla B section, indicating a total thickness of the Gray Mesa Formation of 233 m in the Cerros de Amado.

The Arroyo de la Presilla B measured section is 193 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), lithostratigraphic units introduced by Thompson (1942).

Elephant Butte Member

This lower 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 (Fig. 5, units 32–35).

lithostratigraphic units		maximum thickness	age
Bursum Formation		120 m	Wolfcampian
Moya Member	Atrasado Formation	18 m	Virgilian
Del Cuerto Member	Atrasado Formation	23 m	Virgilian
Story Member	Atrasado Formation	19 m	Virgilian
Burrego Member	Atrasado Formation	51 m	Virgilian / Missourian
Council Spring Member	Atrasado Formation	13 m	Missourian
Tinajas Member	Atrasado Formation	161 m	Missourian
Amado Member	Atrasado Formation	12 m	Missourian
Bartolo Member	Atrasado Formation	67 m	Desmoinesian
Garcia Member	Gray Mesa Formation	103 m	Desmoinesian
Whiskey Canyon Member	Gray Mesa Formation	35 m	Desmoinesian
Elephant Butte Member	Gray Mesa Formation	95 m	Desmoinesian
Sandia Formation		162 m	Atokan

FIGURE 2. Summary of lithostratigraphic nomenclature and age determinations of the Pennsylvanian strata in the Cerros de Amado.

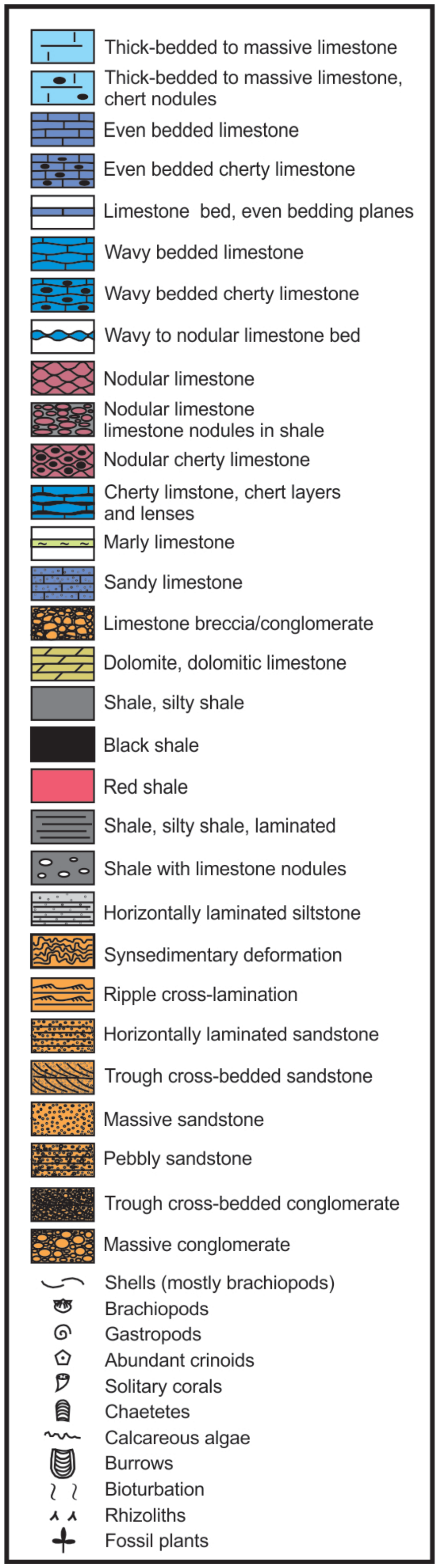

FIGURE 3. Lithologic legend for measured stratigraphic sections in Figures 4–7, 9–11.

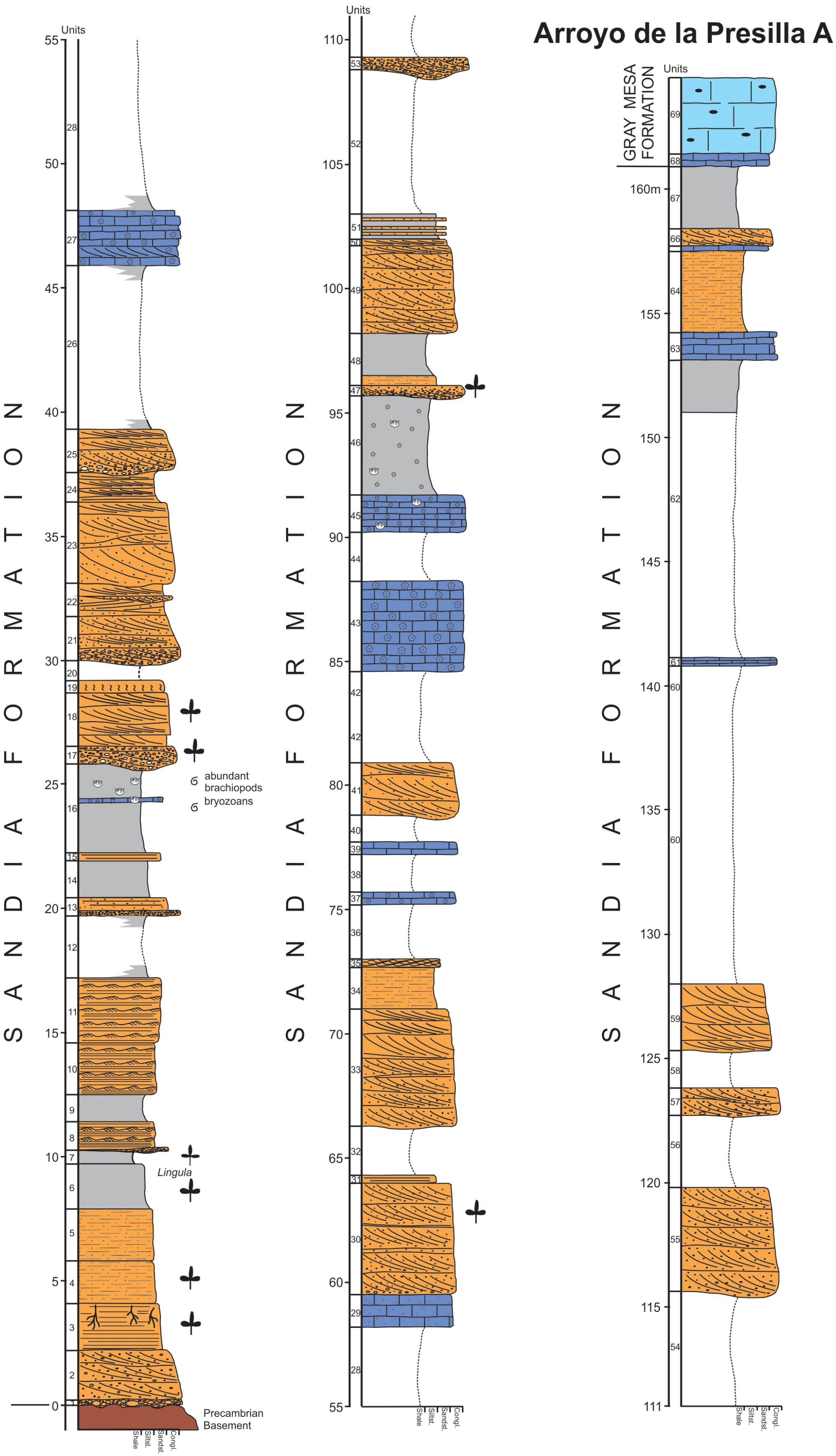

FIGURE 4. Measured section of the Sandia Formation at the Arroyo de la Presilla A section. See Figure 1 and Lucas et al. (2009a) for location of section. For legend to lithologic symbols, see Figure 3.

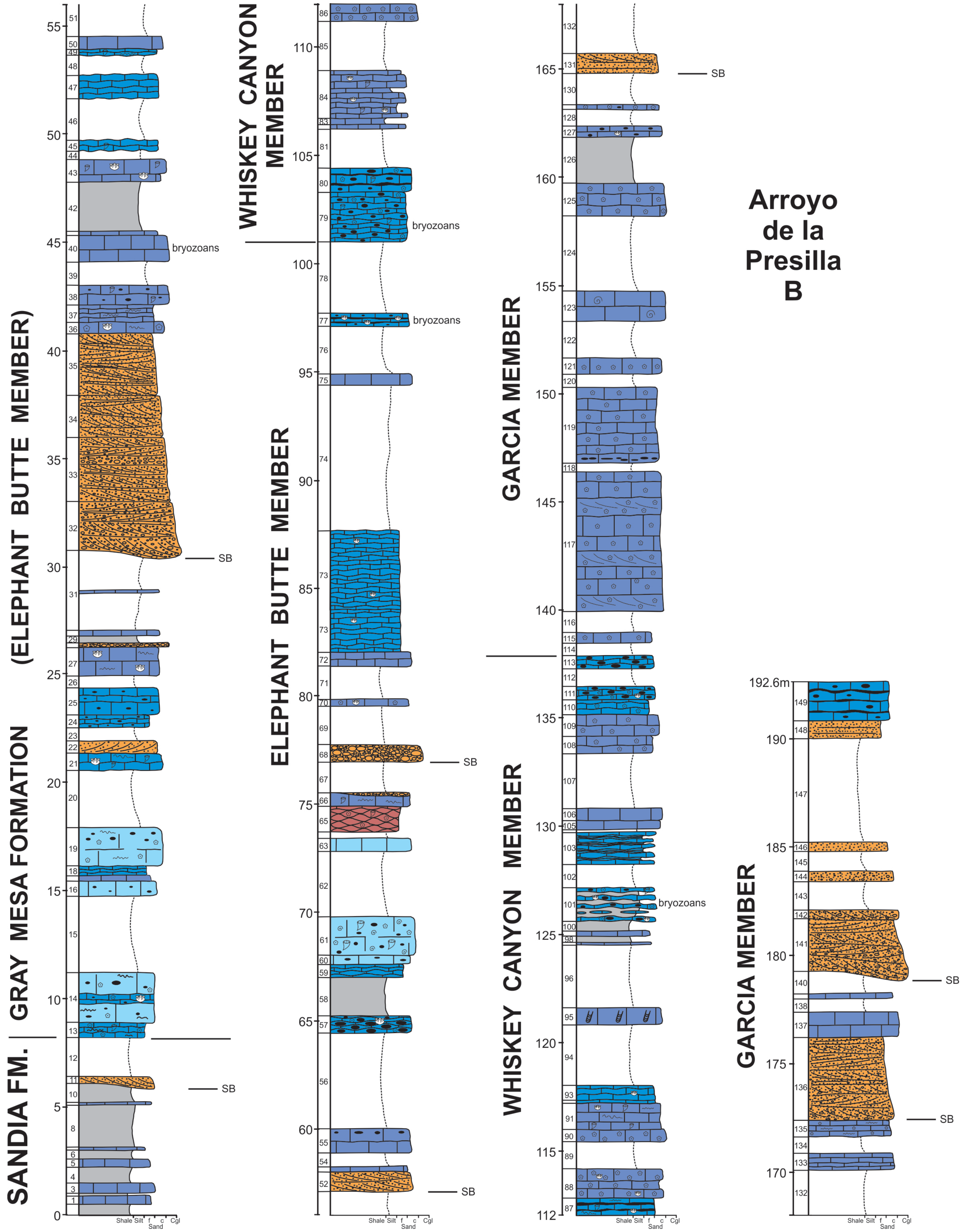

FIGURE 5. Measured section of most of the Gray Mesa Formation at the Arroyo de la Presilla B section. See Figure 1 and Lucas et al. (2009a) for location of section. For legend to lithologic symbols, see Figure 3. SB = sequence boundary.

In the lower part of the Elephant Butte Member, below the prominent sandstone interval, a 0.6 m thick, cross-bedded quartzose sandstone bed (unit 22) and a 0.3 m thick, carbonate conglomerate bed (unit 28) with limestone clasts 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 observed (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) medium-bedded, 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, with bed thicknesses of 20–50 cm; and (5) wavy-bedded to nodular cherty limestone, which is medium bedded (mostly 10–20 cm).

Whiskey Canyon Member

In the Arroyo de la Presilla B section (Fig. 5), the Whiskey Canyon Member is an interval about 35 m thick of generally cherty limestone beds, some with abundant rugose corals, near the middle of the Gray Mesa Formation. 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. Some layers contain as much as 50% chert. 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

Lucas et al. (2009a, figs. 6–8) measured all or part of the Garcia Member in three sections to determine a total thickness of the Garcia Member of about 103 m.

Most of the Garcia Member is present at the Arroyo de la Presilla B section (Fig. 5), where it is a unit of mixed clastics and carbonates. 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 0.4–2.5 m thick. Conglomerate beds 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. In contrast 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.

ATRASADO FORMATION

In the Cerros de Amado, the Atrasado Formation is well exposed and up to 348 m thick. We follow our earlier work (Lucas et al., 2009a; Barrick et al., 2013; Krainer et al., 2017) and divide the Atrasado Formation into the following members (in ascending order): Bartolo, Amado, Tinajas, Council Spring, Burrego, Story, Del Cuerto, and Moya. We present five stratigraphic sections of much or all of the Atrasado Formation (Figs. 6–11) that include a complete, previously unpublished section of the formation (Figs. 6–8).

The current presentation fixes miscorrelations of parts of the Atrasado Formation in the Ojo de Amado, Bioherm, and Minas del Chupadero sections (Figs. 9–11). These miscorrelations were in part due to major facies changes between these three sections, which are very close to each other geographically, and sections farther east, likely a reflection of syndepositional tectonism, as suggested by Rejas (1965). Thus, Lucas et al. (2009a) miscorrelated a thick interval dominated by clastic strata at the Minas del Chupadero section (Fig. 11, units 8–35) with the Tinajas Member father east, which it resembles, whereas the Burrego Member farther east is thinner and contains much marine limestone (Barrick et al., 2013). Recognizing that this interval is Burrego Member leads to a reassignment of the overlying units at Minas del Chupadero, Bioherm, and Ojo de Amado as indicated here (Figs. 9–11) that can be readily compared to the previous assignments of Lucas et al. (2009a), Barrick et al. (2013), and Krainer et al. (2017), as the lithologic columns for these sections have not changed. The new correlations indicated here also eliminate apparent contradictions in the conodont biostratigraphy discussed in earlier work (Barrick et al., 2013).

Bartolo Member

At the type section in the Cerros de Amado (see Lucas et al., 2009a), the Bartolo Member is ~67 m thick and composed of thick shale intervals (partly covered) and intercalated horizons of conglomerate, sandstone, and fossiliferous limestone (Rejas, 1965; Lucas et al., 2009a). In the Cerros de Amado, the Bartolo Member can be characterized as lower shale, middle shale-limestone, and upper sandstone-limestone units of roughly equal thickness. The lower shale is nearly uniform throughout. The middle shale-sandstone unit coarsens upward. The upper sandstone-limestone unit has variable architecture and contains several sedimentary sequences.

A complete section of the Bartolo Member at our Presilla WSA section (Fig. 6) is 89 m thick, well-exposed, and mostly composed of shale-siltstone and covered intervals. In the lower part, two limestone intervals (units 14, 16) are intercalated. The lower limestone bed (unit 14) is 0.1 m thick and contains abundant brachiopods. The upper limestone bed (unit 16) is 0.6 m thick and composed of dark gray, micritic limestone beds with *Zoophycos* and other trace fossils. In the upper half of the member, sandstone is interbedded with shale and minor limestone beds. In the Presilla WSA section (Fig. 6), the Bartolo Member can be lithologically divided into a lower part (units 12–17, 28.2 m thick), a middle part (units 18–29, 33.1 m thick), and an upper part (units 30–47, 27.8 m thick).

The lower part starts with thinly laminated dark gray to black shale (units 12–13), two limestone intervals (units 14, 16), and a thick interval of laminated greenish shale to siltstone (unit 17). The lower limestone bed is 0.1 m thick and contains abundant brachiopods. The upper limestone unit is 0.6 m thick and composed of dark gray, micritic limestone beds with *Zoophycos* and other trace fossils.

The middle part is composed of shale to siltstone and intercalated sandstone. The upper 30 m of the middle part show a coarsening-upward trend. Shale-siltstone is mostly thinly laminated and dark gray to black in the lowermost part, greenish in the middle and upper parts. Covered intervals in the upper part are 0.6 m and 3 m thick. The lowermost sandstone interval of the middle part (units 18–20) is exposed on top of a thick (23.2 m), greenish, laminated shale-siltstone interval (unit 17) of the lower part. The sandstone interval is 3 m thick and shows a fining-upward trend. The sandstone unit starts with a brownish, cross-bedded pebbly sandstone (unit 18, 1.2 m thick) containing small pebbles up to 1 cm and small rip-up clasts. The sandstone is poorly sorted and has an erosive base. The pebbly sandstone is overlain by horizontally laminated sandstone (unit 19) and fine-grained sandstone displaying small-scale cross-bedding (unit 20). The sandstone unit is overlain by a thick, greenish shale-siltstone interval (unit 21) with numerous thin (1–2 cm) siltstone beds intercalated.

In the Bartolo Member, siltstone beds are rare in the lower part and increasingly more abundant in the upper part, displaying a coarsening-upward trend. The upper part of the middle part is beds of laminated and ripple-laminated sandstone (units 22–25) overlain by a covered interval beneath a trough cross-bedded sandstone unit (0.9 m) with a scour base (unit 27). The sandstone unit shows a fining-upward trend, starts with pebbly sandstone containing small pebbles up to 2 cm, and grades into coarse- and finally fine-grained sandstone. The sandstone is arkosic in composition. Above a covered (shale) interval (unit 28, 0.6 m thick), a thin, pebbly sandstone is exposed (unit 29, 0.3 m thick).

The upper part of the Bartolo Member is composed of covered intervals (most likely representing shale-siltstone) and intercalated limestone and sandstone intervals. Covered intervals are 1.4–3.0 m thick. Four limestone intervals (units 31, 33–34, 36, and 39) are intercalated that are 0.6–2.7 m thick. The lowermost limestone interval (unit 31) is indistinctly wavy-bedded floatstone to rudstone containing crinoidal debris. The next two limestone units are composed of rudstone with abundant crinoid fragments and brachiopods (units 33–34, 36). The uppermost limestone bed (unit 39) displays a muddy texture (bioclastic mudstone to wackestone).

The lower two sandstone beds (units 38 and 41) of the upper part of the Bartolo Member are coarse-grained, pebbly, and display small-scale trough cross-bedding. The next sandstone bed (unit 43) is composed of a lower, fine-grained, greenish sandstone interval with plant fossils (? *Odontopteris*), overlain by sandstone displaying small-scale trough cross-bedding (unit 44). The uppermost sandstone interval (unit 46) is trough cross-bedded.

Amado Member

The type section of the Amado Member in the Cerros de Amado is 11.4 m of limestone with four intercalated covered intervals (Lucas et al., 2009a, fig. 8). In our Presilla WSA section, a complete section of the Amado Member is 11.7 m thick and composed of individual limestone beds (0.2–0.4 m thick) and bedded limestone units up to 1.7 m thick (Fig. 6). Thicker limestone units are commonly wavy bedded and contain abundant brachiopods, bryozoans, locally abundant crinoid fragments, and rare calcareous (mostly phylloid) algae (mostly bioclastic wackestone, subordinately floatstone, and rudstone). The upper limestone interval is composed of muddy limestone (wackestone) that is free of chert and has a thin (0.1 m) bed on top composed of abundant intraclasts. Limestone beds and intervals are separated by thin covered (shale) intervals that are 0.3–0.8 m thick.

At the Bioherm section (Fig. 10), the Amado Member is at least 8 m thick and consists of a cherty lower limestone overlain by thin-bedded shale and limestone capped by thick-bedded wackestone.

Tinajas Member

Lucas et al. (2009a, figs. 11–12) measured two overlapping sections on separate fault blocks as a type section of the Tinajas Member that indicates a total thickness of the Tinajas Member of ~104 m. 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. Sandstone beds in the Tinajas Member range from laminated to trough cross-bedded and are arkosic. Most of the limestone beds are thin, nodular, and algal. The black shale bed in the Tinajas Member (Lerner et al., 2009) is 3–7 m thick and is a persistent marker bed in the Cerros de Amado that allows unambiguous correlation of Tinajas Member stratigraphic sections that are kilometers apart (Figs. 6, 10).

At the Presilla WSA section (Figs. 6, 8), the Tinajas Member is considerably thicker (161 m) and can be divided into three thick intervals, here referred to as Units A, B, and C; these are different from the thinner, individual units otherwise referred to in the text. Unit A (34 m thick) is composed of shale/covered intervals and abundant intercalated thin limestone bedsand-subordinate dolomite and carbonate breccia, and sandstone beds are intercalated. Covered intervals are up to 5 m thick and most likely represent shale units. Exposed shale intervals are up to 4.8 m thick and have many dark gray micritic limestone beds and rare dolomite beds (mudstone to wackestone) intercalated that are mostly 10–20 cm thick. Limestone and dolomite beds commonly display even bedding planes, and rarely are wavy to nodular. In the lower part of Unit A, two intervals of dolomicrite are intercalated (units 70–71), exposed above a gray marly limestone (unit 69). The lower dolomite interval (unit 70) is 0.5 m thick and composed of two beds; the upper dolomite interval (unit 71) is 2.4 m thick and thin-bedded (mostly 1–4 cm, rarely up to 10 cm). Intercalated in the lower part of unit 71 is also a vuggy limestone bed that is 0.3 m thick. One gray argillaceous limestone bed (unit 76, 0.3 m) at the base of a carbonate breccia contains abundant burrows. The carbonate breccia (unit 77) that is exposed in the lower part of the Tinajas Member is 1.2 m thick and contains abundant micritic carbonate clasts (intraclasts) with diameters up to 5 cm. Two sandstone intervals are intercalated in Unit A. The sandstone interval near the base (unit 67) is 1.7 m thick, coarse grained, with pebbles up to 0.5 cm, and cross-bedded. The sandstone interval intercalated in the upper part of Unit A (unit 90) is 0.4 m thick and composed of laminated, fine-grained sandstone.

Unit B (Fig. 6, units 95–136) measures 59.7 m and starts with the Tinajas black shale that has a thickness of 3.2 m. Unit B is dominantly covered intervals and shale intervals with intercalated thin sandstone, dolomite, and limestone beds. Covered intervals are 0.6–9.8 m thick and most probably represent shale units. Exposed shale intervals are up to 3.2 m thick. Shale is green, gray, and black. Limestone and rare dolomite beds are present in the middle and upper parts. In the middle part, limestone beds are 0.4–1.2 m thick; two dolomite beds are 0.4 and 0.5 m thick. All limestone beds display a muddy texture (wackestone). Limestone of unit 114 contains calcareous algae, brachiopods, and crinoid fragments, including crinoid stem fragments that are up to 3 cm long. In the upper part of Unit B, intercalated limestone beds are 0.2–0.3 m thick, and beds display even bedding planes, muddy texture, and gray color (mudstone to wackestone). The uppermost limestone bed (unit 136) is 0.7 m thick and composed of crinoidal wackestone.

Unit C (Fig. 6, units 137–179) is composed of covered intervals and shale-siltstone intervals with intercalated sandstone, rare thin limestone beds, and nodular limestone. Covered intervals are 0.8–5.6 m thick and most likely represent shale-siltstone units. Shale-siltstone intervals are up to 9.9 m thick. Shale-siltstone is brownish and greenish, and reddish in the uppermost part. In the lower part of Unit C, intercalated sandstone beds are 10–25 cm thick, fine-grained, micaceous, horizontally laminated, and rarely ripple laminated. In the lower part of Unit C (units 140–147), the following sandstone lithologies are exposed: (1) coarse-grained, cross-bedded sandstone (unit 143, 1.6 m thick); (2) medium-grained, cross-bedded sandstone (unit 142, 0.4 m thick); (3) fine-grained sandstone displaying horizontal lamination, ripple lamination, and small-scale cross-bedding (units 140–141, 2 m); (4) fine-grained, ripple-laminated sandstone (unit 145, 0.8 m); and (5) thin, massive, fine-grained sandstone beds intercalated with thin shale units (unit 144, 1.2 m).

In the upper part of Unit C, fine-grained sandstones (units 163, 164, 171, 173, 178) displaying horizontal lamination, rarely ripple lamination, and massive texture are most common. Thickness is 0.3–1.0 m. Two sandstone units (units 162, 176, 0.6 and 1 m thick, respectively) display trough cross-bedding and a channel-fill geometry. Cross-bedded sandstone is medium and coarse grained. Near the top, a 1.6 m thick sandstone bed (unit 177) displays soft sediment deformation (dewatering structures). A shale interval (unit 139) that is 10 m thick is a distinctive unit. Siltstone-shale and sandstone of the uppermost 8 m are reddish. Intercalated limestone beds in Unit C are 0.2–0.7 m thick. The limestone beds are gray and display a muddy texture (mudstone-wackestone). Limestone of unit 151 contains intraclasts and gastropods that float in micrite. The uppermost limestone bed of the Tinajas Member (unit 166) is under- and overlain by nodular limestone that is composed of limestone nodules embedded in shale (1.5 and 2.5 m thick, respectively). On top of the upper nodular limestone, a thin, fine-grained conglomerate bed is exposed that contains limestone clasts up to 5 cm in diameter embedded in sandy matrix.

At the Bioherm section (Fig. 10), the Tinajas Member is thinner (81 m thick) but similar to other sections in being mostly shale/siltstone (including covered intervals) intercalated with relatively thin beds of limestone, dolomite, and sandstone. Tinajas Member sections to the east are thicker (Fig. 6; Lucas et al., 2009a, fig. 12) because of a relatively thick, clastic-dominated upper part of the member above the black shale bed. At Ojo de Amado, the base of the Council Spring Member is only about 13 m above the black shale bed. This indicates major thickness changes and likely unconformities within the upper part of the Tinajas Member in the Cerros de Amado.

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 to white limestone interval that forms resistant ledges, cliffs, and ridges that cap much local topography and can be traced laterally for kilometers (Fig. 8). This unit and overlying members of the Atrasado Formation (Burrego, Story, Del Cuerto, and Moya members) 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, figs. 6–7; Lucas and Krainer, 2009).

The Council Spring Member is present in all the Atrasado stratigraphic sections presented here and ranges from 6–13 m thick (Figs. 6–11). At all of these sections it is a limestone-dominated interval that consists mostly of chert-free wackestones, some of which contain abundant phylloid algae.

At the Presilla WSA section (Fig. 6), the Council Spring Member is 7.2 m thick (no top exposed) and composed of wavy-bedded limestone overlain by massive limestone and a thin-bedded limestone interval on top. The wavy-bedded limestone (units 180–181, bed thickness 5–30 cm) is 2.8 m thick and contains abundant crinoid fragments including stem fragments up to about 5 cm and some brachiopods (dominantly crinoidal wackestone). The massive limestone (unit 182) contains phylloid algae (algal mound facies), some brachiopods, and crinoid fragments. The thickness is 3.6 m. The massive limestone is overlain by bedded limestone (wackestone) that is 0.8 m thick.

At the Arroyo Tinajas section (Fig. 7), the Council Spring Member is exposed above the uppermost Tinajas Member with an exposed thickness of 5.9 m. As at the Presilla WSA section, the Council Spring Member is composed of wavy-bedded limestone overlain by massive limestone and a thin, bedded

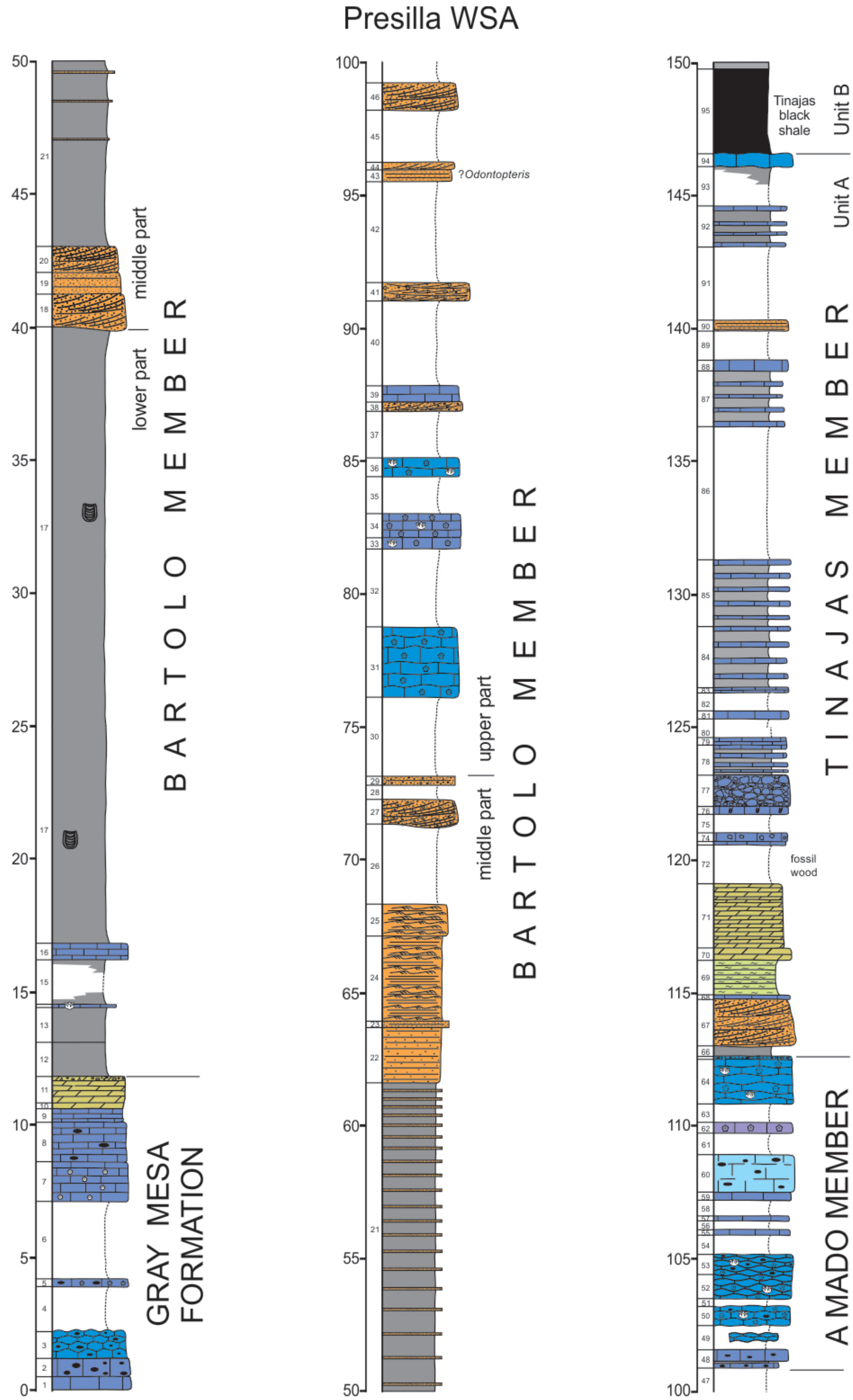

FIGURE 6. Measured section of parts of the Gray Mesa and Atrasado formations at the Presilla WSA section. See Figure 1 for location of section. Base of section at UTM 334687, 3771059 and top of section at 335229, 3771115 (zone 13, datum NAD 83). For legend to lithologic symbols, see Figure 3.

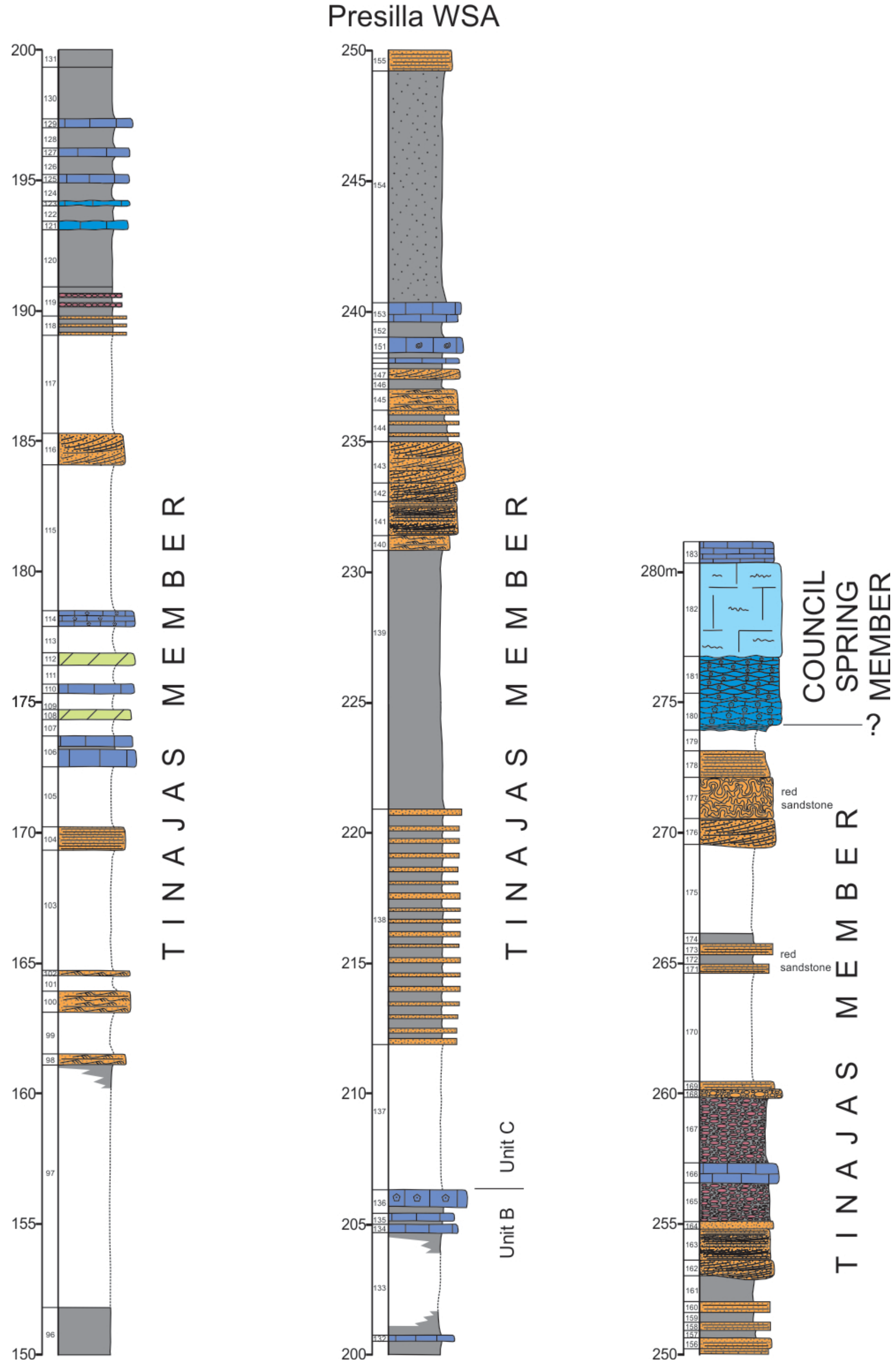

FIGURE 6. (Continued).

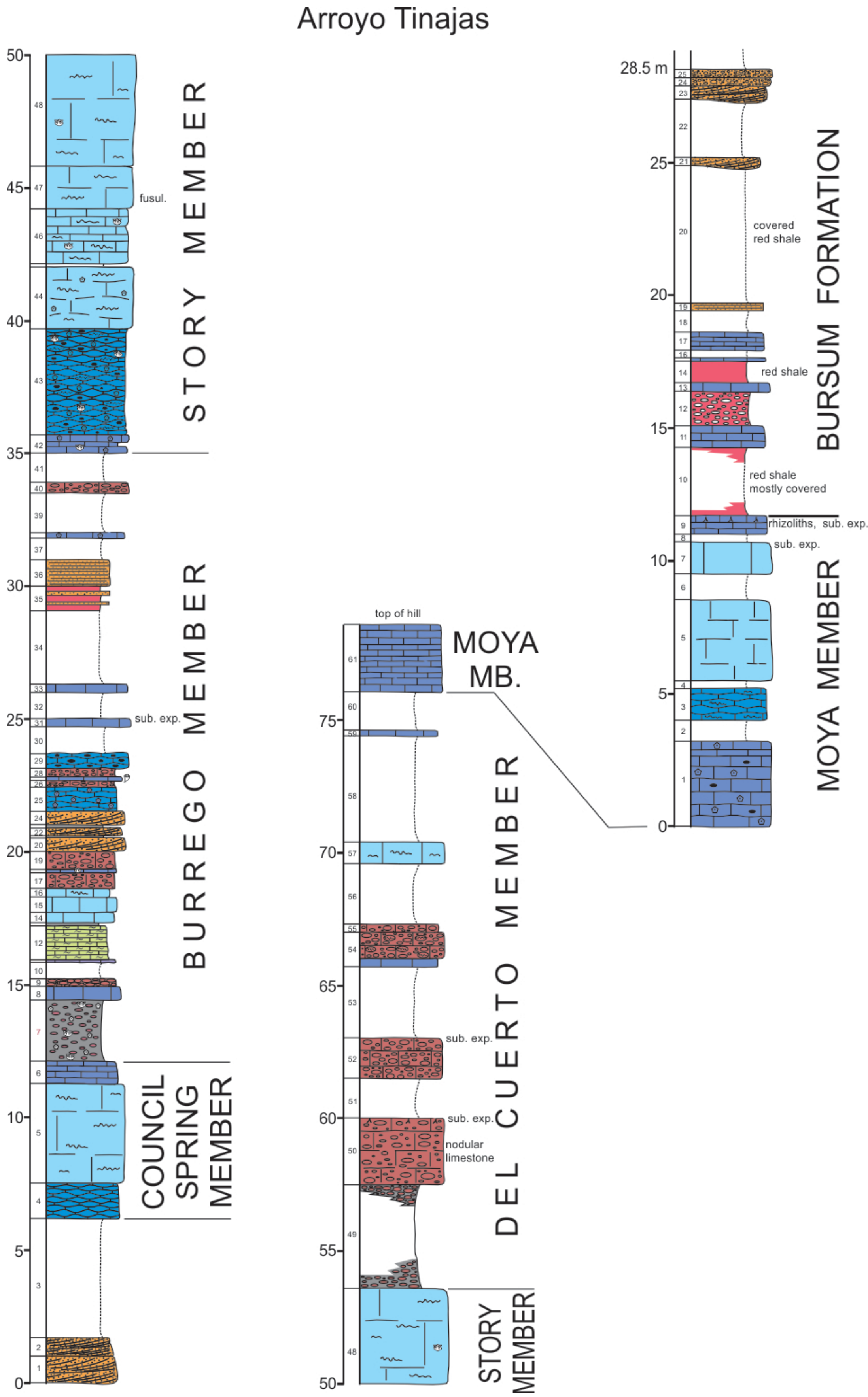

FIGURE 7. Measured section of part of the Atrasado Formation at the Arroyo Tinajas section. See Figure 1 for location of section. Base of section at UTM 335237, 3772086 and top of section at 335646, 3771863 (zone 13, datum NAD 83). For legend to lithologic symbols, see Figure 3.

limestone interval on top. The wavy-bedded limestone is 1.3 m thick and composed of wackestone. Bed thickness is 5–20 cm. Locally nodular bedding is observed. The massive limestone (unit 51) contains phylloid algae and some crinoid fragments (algal mound facies) and is overlain by 0.8 m of bedded limestone (wackestone) with bed thicknesses of 10–20 cm.

At the Bioherm section (Fig. 10), the Council Spring Member thickens to 13 m and forms a phylloid algal mound that laterally extends over 150 m (Hambleton, 1959, 1962; Krainer and Lucas, 2016). The mound facies is composed of phylloid algae that mostly seem to be in life position or toppled in situ (unit 55). The top of the mound is an even-bedded limestone (unit 56) overlain by a thick-bedded to massive limestone (units 57-58).

The Bioherm section (Fig. 10) also provides data to present a more confident correlation of the Ojo de Amado (Fig. 9) and Minas del Chupadero (Fig. 11) sections than we presented previously (Lucas et al., 2009a; Barrick et al., 2013; Krainer et al., 2017). This revised correlation places the Council Spring Member stratigraphically lower in these sections and confirms its Missourian age based on microfossil data collected farther east (Lucas et al., 2009a).

Burrego Member

The mostly clastic unit above the Council Spring Member is the Burrego Member, which is as much as 51 m of mostly slope-forming shale and siltstone with some ledge-forming beds of arkosic sandstone, conglomerate, and limestone. Characteristic Burrego lithologies seen at all sections presented here are red-bed mudstone and cross-bedded arkosic sandstone. Locally, red-bed mudstone intervals of the Burrego Member contain calcareous paleosols (Lucas and Tanner, 2021).

At the Arroyo Tinajas section (Fig. 7), the Burrego Member is 23 m thick and is a characteristic mixed siliciclastic-carbonate succession composed of alternating shale-siltstone/covered intervals, sandstone, and limestone. Covered intervals are 0.6–2.8 m thick.

Shale-siltstone intervals are poorly exposed and range in thickness from 0.1–2.3 m. The shale-siltstone interval at the base contains limestone nodules. Sandstone is exposed as three coarse-grained arkosic beds (units 20, 22, 24) that are 0.3–0.5 m thick, display trough cross-bedding, and are separated by 0.1 m thick shale beds. In the upper part of the member, fine-grained sandstone (1 m thick) with horizontal lamination and rare ripple lamination, and two thin, fine-grained sandstone beds intercalated in shale-siltstone, are exposed. Shale-siltstone and sandstone display reddish color.

Among limestone units, the following lithotypes can be distinguished: (1) individual limestone beds (0.1–0.5 m thick) with even bedding planes, composed of mudstone-wackestone locally containing brachiopods, crinoid fragments, rare phylloid algae, solitary corals, and siliceous sponges; the top of the unit 31 limestone is a subaerial exposure surface; (2) thin-bedded marly limestone near the base (1.3 m thick); (3) medium-bedded limestone (bed thickness 0.3–0.6 m) with slightly wavy bedding planes, composed of wackestone and phylloid algal wackestone; (4) wavy-bedded, non-cherty limestone (bed thickness 10–30 cm), composed of crinoidal wackestone (0.9 m thick); (5) wavy-bedded cherty limestone composed of wackestone (0.6 m thick); and (6) nodular limestone intervals (0.3–0.7 m thick), partly poorly exposed, commonly composed of wackestone. The lowermost nodular limestone (unit 7) contains bryozoans, brachiopods, and crinoid fragments.

At the Ojo de Amado section (Fig. 9), the Burrego Member is ~50 m thick, though possible faults in the upper part of the member make that thickness an estimate. Particularly striking in this section is the lower 25 m of the Burrego Member, which is arkosic sandstone, most of it trough cross-bedded and some of it conglomeratic. At the Bioherm section (Fig. 10), the Burrego Member is ~50 m thick and is a more lithologically diverse unit consisting of red-bed mudstone, siltstone, sandstone, and conglomerate as well as two substantial limestone intervals. At the Minas del Chupadero section (Fig. 11), the Burrego Member is 47 m thick and is mostly covered slopes with only thin beds of sandstone and limestone exposed.

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), Lucas et al. (2009a) identified the same kind of bipartite unit in the Cerros de Amado as the Story Member, and Rejas (1965) divided the Story "Formation" into a "lower clastic member" and an "upper limestone member." However, we have since redefined the Story Member, restricting it to the carbonate-dominated upper half and assigned the underlying clastic-dominated interval to the Burrego Member (e.g., Lucas et al., 2014).

At the Arroyo Tinajas section (Fig. 7), the Story Member is 19 m thick and starts with even-bedded limestone (unit 42, 0.6 m) that is coarse grained and fossiliferous, containing brachiopods and crinoid debris (rudstone). This basal interval is overlain by indistinctly wavy-bedded cherty limestone (unit 43, 4 m) containing fossils such as brachiopods, crinoid fragments, and phylloid algae. The fossils are partly silicified. The cherty limestone is overlain by indistinctly wavy-bedded to massive limestone that contains phylloid algae and crinoidal debris (2.3 m), followed by even-bedded (bed thickness 20–40 cm) phylloid algal limestone with some brachiopods (2.1 m). The upper 9.4 m of the Story Member consist of indistinctly bedded to massive phylloid algal limestone with few brachiopods (phylloid algal mound facies). Fusulinids occur 0.5 m above the base of this algal mound facies.

At the Ojo de Amado section (Fig. 9), the Story Member is 20 m thick and consists of diverse limestone types and minor interbedded shale. At the Minas del Chupadero section (Fig. 11), the Story Member is 22 m thick and is diverse limestone beds, covered intervals, and two sandstone intervals.

Del Cuerto Member

The Del Cuerto Member in the Cerros de Amado is another

FIGURE 8. Photograph of much of the Presilla WSA section, looking east.

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.

The Del Cuerto Member is usually <10 m thick, but a 23 m thick section is present at our Arroyo Tinajas section (Fig. 7).

Here, the Del Cuerto Member is composed of covered intervals representing reddish shale, partly with limestone nodules, and limestone intervals that are dominantly nodular. Covered intervals are 1.5–4.0 m thick. Limestone intervals are 0.2–2.5 m thick. The lowermost limestone interval is nodular limestone (or probably a limestone breccia/conglomerate) displaying a subaerial exposure surface at the top with rhizoliths. The next limestone unit also displays a nodular texture with a subaerial exposure surface developed at the top. The next unit starts with a thin limestone bed (wackestone), overlain by nodular limestone (wackestone) containing phylloid algae. The upper two limestone units are individual limestone beds (0.2 m and 0.8 m). The lower of these limestone beds (0.8 m) is a phylloid algal wackestone-floatstone, and the upper limestone bed (0.2 m) is a bioclastic wackestone.

Del Cuerto Member sections to the west are thinner than the section at our Arroyo Tinajas section. At the Ojo de Amado section (Fig. 9), the Del Cuerto Member is ~12 m thick and can be divided into a sandstone-dominated lower half and a limestone-dominated upper half. At the Minas del Chupadero section (Fig. 11), a 6 m thick interval identified as the Del Cuerto Member is mostly covered and has a thin conglomeratic sandstone overlain by a thin limestone bed at its base.

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 del Chupadero section 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. 11). 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 Moya Member (unit 75) 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 mudstone through coarse and crinoidal wackestone to packstone, but phylloid algal wackestone is the dominant limestone type.

At the Arroyo Tinajas section (Fig. 7), the Del Cuerto Member is overlain by 2.5 m of even-bedded limestone (bed thickness 20 cm) that partly contains abundant phylloid algae and rarely chert nodules. At the offset section, the Moya Member is 11.7 m thick and starts with 3.2 m of medium-bedded phylloid algal limestone with abundant crinoid fragments, including stems that are up to several cm long. The fossils are partly silicified. Above a covered interval (0.8 m) follow slightly wavy-bedded limestone (algal wackestone), a thin covered interval (0.2 m), indistinctly bedded-massive phylloid algal limestone (phylloid algal mound facies) with a thickness of 3 m, a covered interval (1 m), a massive limestone interval (wackestone) probably with a subaerial exposure surface at the top (1.2 m), a covered interval (0.3 m), and bedded limestone (wackestone) with a subaerial exposure surface and rhizoliths at the top (0.7 m).

Bursum Formation

At the Arroyo Tinajas section (Fig. 7), the Moya Member is overlain by the Bursum Formation. The partly covered lowermost part of the Bursum Formation is approximately 7 m thick and is overlain by approximately 10 m of mostly covered red shale-siltstone and intercalated sandstone. Shale/covered intervals are up to 5.2 m thick. The lowermost sandstone (unit 19) is 0.3 m thick and composed of fine-grained micaceous sandstone. The next sandstone interval (unit 21) is also 0.3 m thick and composed of trough cross-bedded, coarse-grained, arkosic sandstone. The uppermost sandstone interval (units 22–25) is 1.1 m thick and starts with coarse-grained, pebbly, trough cross-bedded, arkosic sandstone that is overlain by conglomeratic sandstone. The conglomeratic sandstone is poorly sorted, also arkosic in composition, and contains clasts with diameters up to approximately 5 cm. Limestone beds in the Bursum Formation are bedded wackestones.

BIOSTRATIGRAPHY AND AGE

Fusulinids are only abundant in parts of the Pennsylvanian-Permian 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. Gray Mesa fusulinids are of Desmoinesian age (Lucas and Estep, 2000), whereas Council Spring fusulinids are of early/middle Missourian age (Lerner et al., 2009). We have observed large *Triticites* in the upper Atrasado Formation that likely are of Virgilian age. Several workers (e.g., Kottlowski and Stewart, 1970; Altares, 1990; Beck and Johnson, 1992) have documented early Wolfcampian (Newwellian) fusulinids

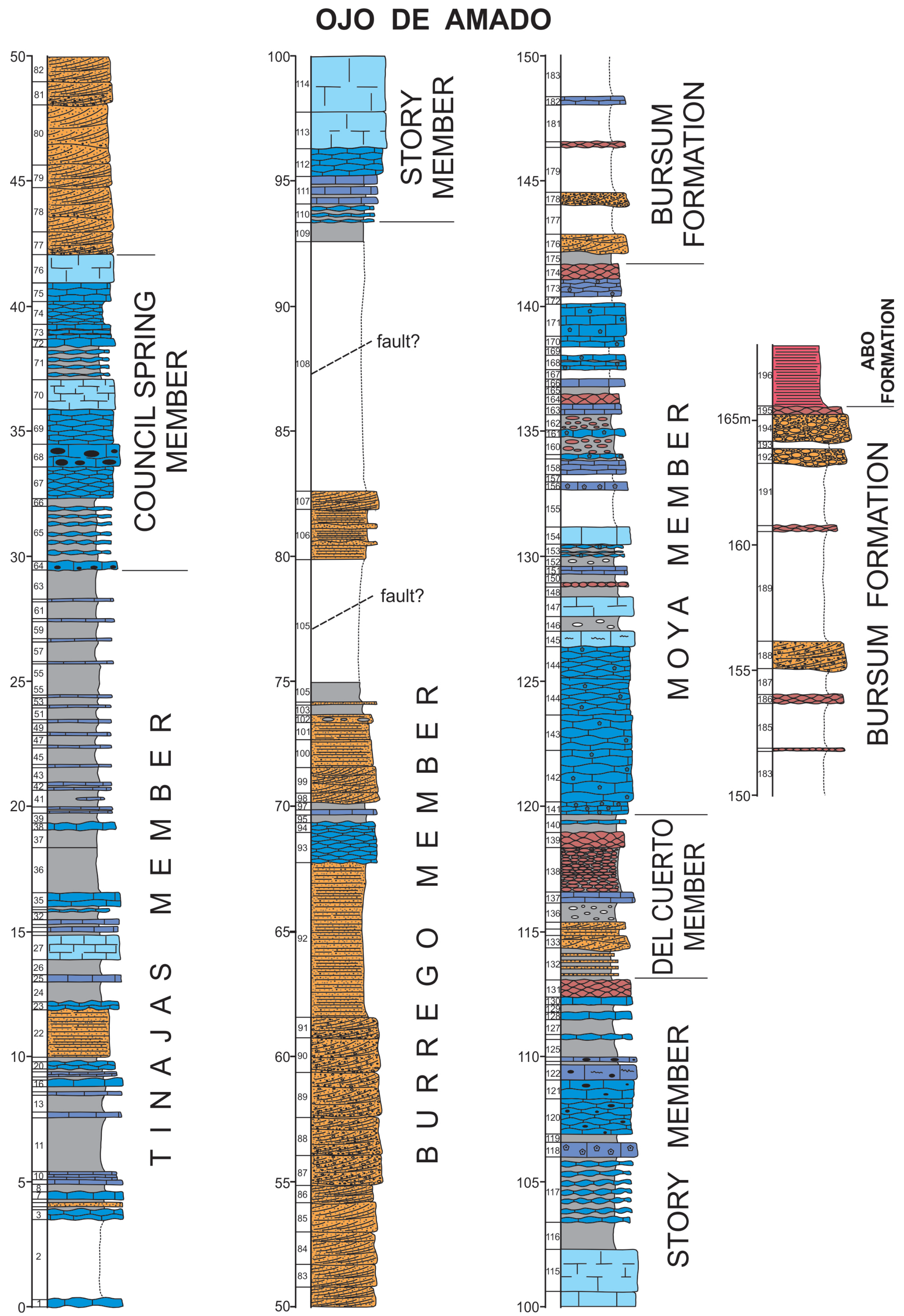

FIGURE 9. Measured section of parts of the Atrasado and Bursum formations at the Ojo de Amado section. See Figure 1 and Lucas et al. (2009a) for location of section. For legend to lithologic symbols, see Figure 3. Note that lithostratigraphic nomenclature has been revised from Barrick et al. (2013) and Krainer et al. (2017).

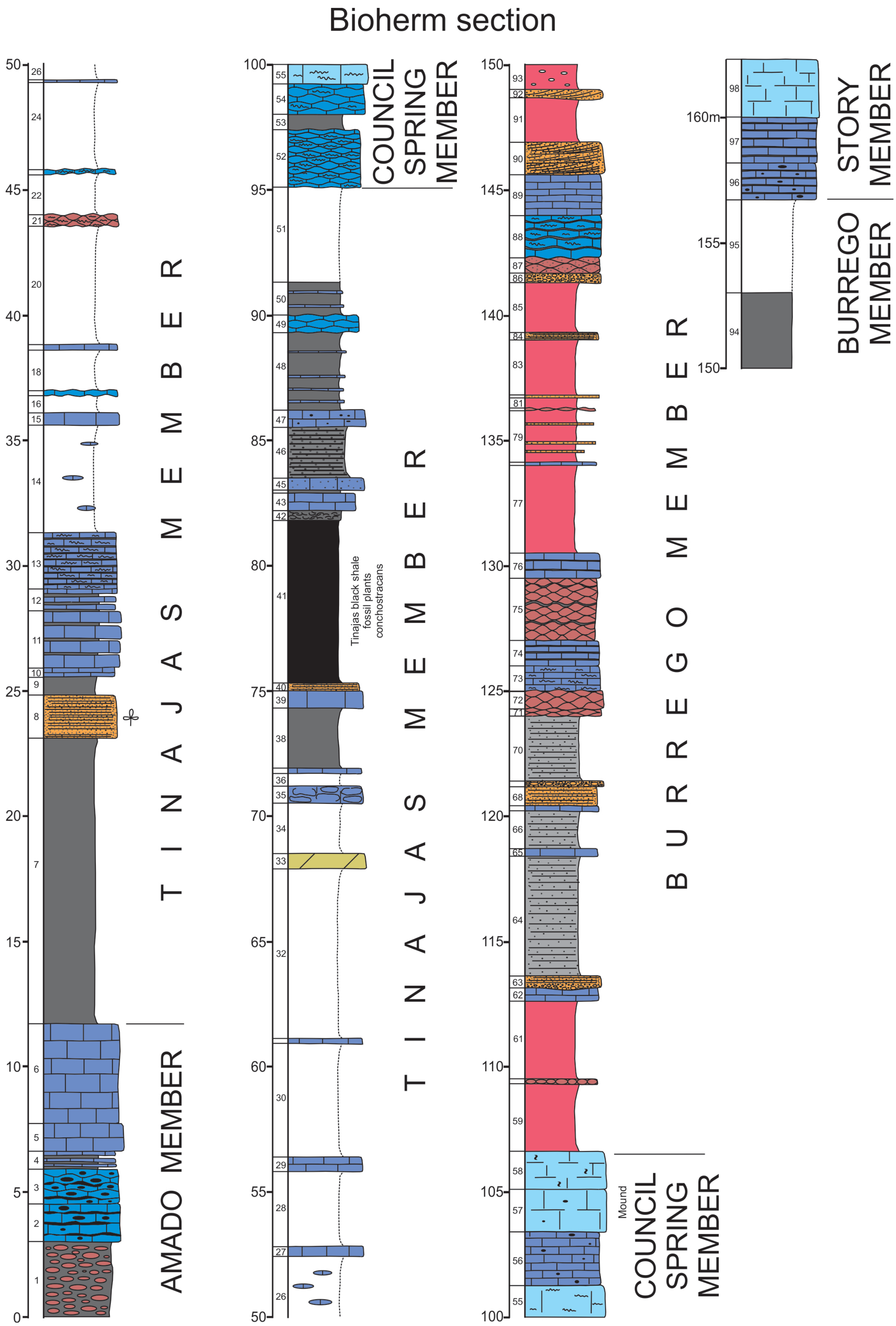

FIGURE 10. Measured section of parts of the Atrasado Formation at the Bioherm section. See Figure 1 and Krainer et al. (2017) for location of section. For legend to lithologic symbols, see Figure 3. Note that lithostratigraphic nomenclature has been revised from Krainer et al. (2017).

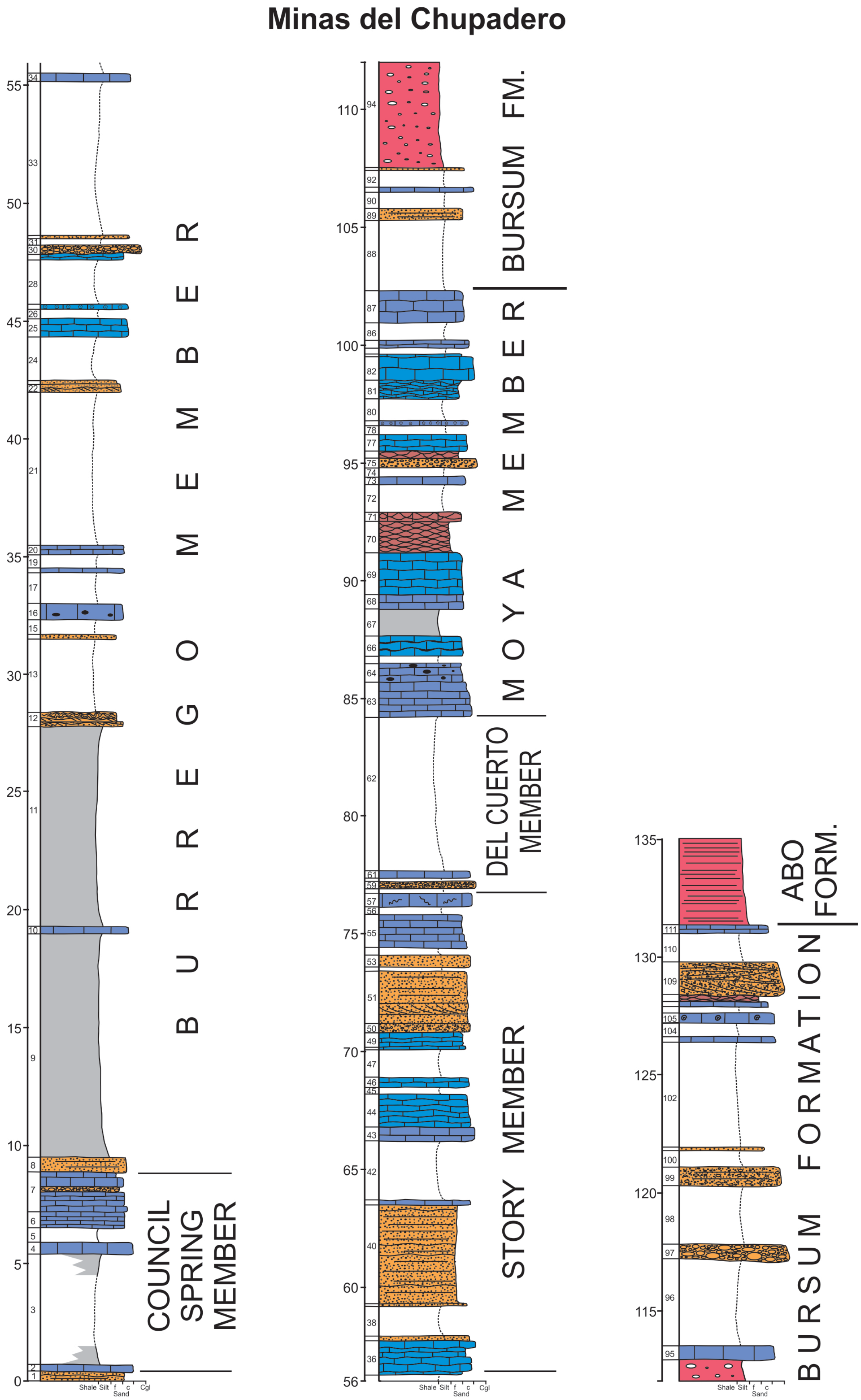

FIGURE 11. Measured section of part of the Atrasado Formation and the Bursum Formation at the Minas del Chupadero section. See Figure 1 and Lucas et al. (2009a) for location of section. For legend to lithologic symbols, see Figure 3. Note that lithostratigraphic nomenclature has been revised from Lucas et al. (2009a), Barrick et al. (2013), and Krainer et al. (2017).

from the Bursum Formation in and near the Cerros de Amado.

Numerous conodonts were obtained from samples collected during the process of measuring the sections of Pennsylvanian strata in the Cerros de Amado (Lucas et al., 2009a; Barrick et al., 2013). The revised correlation of the Ojo de Amado–Minas del Chupadero section (Figs. 9, 11) changes the position of the base of the Virgilian in the Cerros de Amado. Thus, the fusulinid-based Missourian age of the Council Spring Member is confirmed and the base of the Virgilian is in the Burrego Member (Fig. 2). Conodonts indicate the following ages: late Atokan (Sandia Formation), early Desmoinesian (most of the Gray Mesa Formation), late Desmoinesian (uppermost Gray Mesa Formation, Bartolo, and lowermost Amado members of Atrasado Formation), Missourian (most of the Amado, all of the Tinajas and Council Spring, and the lower Burrego members of Atrasado Formation), and Virgilian (upper Burrego, Story, Del Cuerto, and Moya members of Atrasado Formation; Fig. 2).

CONCLUSIONS

Our review of the Pennsylvanian lithostratigraphy and biostratigraphy in the Cerros de Amado (Fig. 2) supports the following conclusions:

1) The Pennsylvanian section in the Cerros de Amado of Socorro County is 744 m thick and consists of three formations of marine and mixed marine-nonmarine origin (ascending): Sandia, Gray Mesa, and Atrasado formations.
2) The Sandia Formation unconformably overlies Precambrian basement and is a 162 m thick cyclic succession of siliciclastic (notably quartzose sandstone and conglomerate) and carbonate (mostly coarse-grained bioclastic wackestone/packstone) strata.
3) The overlying Gray Mesa Formation is 233 m thick and divided into three members: Elephant Butte Member (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).
4) The overlying Atrasado Formation is 348 m of interbedded siliciclastic and carbonate strata divided into eight members (ascending): Bartolo, Amado, Tinajas, Council Spring, Burrego, Story, Del Cuerto, and Moya.
5) The lower Permian Bursum Formation overlies the Pennsylvanian section in the Cerros de Amado and is as much as 120 m of red-bed siliciclastics and limestones.
6) Sparse fusulinid data and more extensive conodont records indicate the following ages: late Atokan (Sandia Formation), early Desmoinesian (most of the Gray Mesa Formation), late Desmoinesian (uppermost Gray Mesa Formation, Bartolo, and lowermost Amado members of Atrasado Formation), Missourian (most of Amado, Tinajas, Council Spring, and lower Burrego members of Atrasado Formation), and Virgilian (upper Burrego, Story, Del Cuerto, and Moya members of Atrasado Formation).

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