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PENNSYLVANIAN STRATIGRAPHY IN THE SIERRA LADRONES, SOCORRO COUNTY, NEW MEXICO

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Abstract—The Pennsylvanian stratigraphic section in the Sierra Ladrones of northern Socorro County can be assigned to the (ascending) Sandia, Gray Mesa, and Atrasado formations. The Sandia Formation is 105 m thick and consists of a lower part that is mostly conglomerate, conglomeratic sandstone, sandstone, limestone, and covered intervals, and an upper part that is covered intervals, shale/siltstone, and intercalated thin beds of sandstone and limestone. The Gray Mesa Formation is 234 m thick and of fairly uniform lithology throughout, so subdivision into three members, as can be done at some other outcrop areas, is not possible. The Gray Mesa Formation is covered intervals (likely shale or nodular limestone), shale, and mostly limestone of diverse lithologies; most limestone beds have chert nodules or layers. The Atrasado Formation is 261 m thick and can be divided into the eight members present in other outcrop belts (ascending): Bartolo, Amado, Tinajas, Council Spring, Burrego, Story, Del Cuerto, and Moya members. The overlying Bursum Formation is considered by some to be of Pennsylvanian age, but we regard it as early Permian. It is up to 92 m thick, a mixture of siliciclastic red beds and marine limestones, and is overlain by the lower Permian Abo Formation. Fusulinids indicate the Sandia Formation is of late Atokan age, and the Gray Mesa Formation is of early Desmoinesian age. Missourian and Virgilian fusulinids are present in the Atrasado Formation, and it is likely that the Bartolo Member and part of the Amado Member are Desmoinesian, as they are to the southeast and east. Some previous workers overstated the thickness of the Pennsylvanian section in the Sierra Ladrones as 820–840 m thick, but it is about 550 m thick in the Navajo Gap area. The overstated thicknesses were the basis for identifying a Pennsylvanian Lucero basin that did not exist.

INTRODUCTION

The Sierra Ladrones is a fault block mountain range of the Basin and Range Province located in northern Socorro County, New Mexico (Fig. 1). Upper Paleozoic strata crop out around the basement core of the range, especially along its western edge and in Navajo Gap, which lies between the range and Mesa Sarca to the northwest. Most of these strata are of Pennsylvanian age and have been identified as the thickest Pennsylvanian section in Socorro County (e.g., Siemers, 1978, 1983) and the basis for identification of a Pennsylvanian Lucero basin (e.g., Wengerd, 1959; Kottlowski, 1960, pl. 3). However, we note that there are numerous faults in the Sierra Ladrones, especially along its northwestern edge in the Navajo Gap area, that make it difficult to put together a complete Pennsylvanian stratigraphic section.

We studied the Pennsylvanian section in the Sierra Ladrones between 2018 and 2021. Here, we present the initial results of that research as a complete, revised lithostratigraphy of the Pennsylvanian section there. This lithostratigraphic study recognizes a much thinner section than did some earlier workers and thus undermines the case for a Pennsylvanian Lucero basin, as postulated by Kottlowski (1960).

METHODS AND DATA

In the Sierra Ladrones, we measured nine stratigraphic sections of the Pennsylvanian rocks (Fig. 1, Table 1). These sections were measured with a 1.5 m staff and pocket field transit, and hand samples were collected for petrographic and micropaleontological analysis. We present here a synopsis of a longer and more detailed work under preparation.

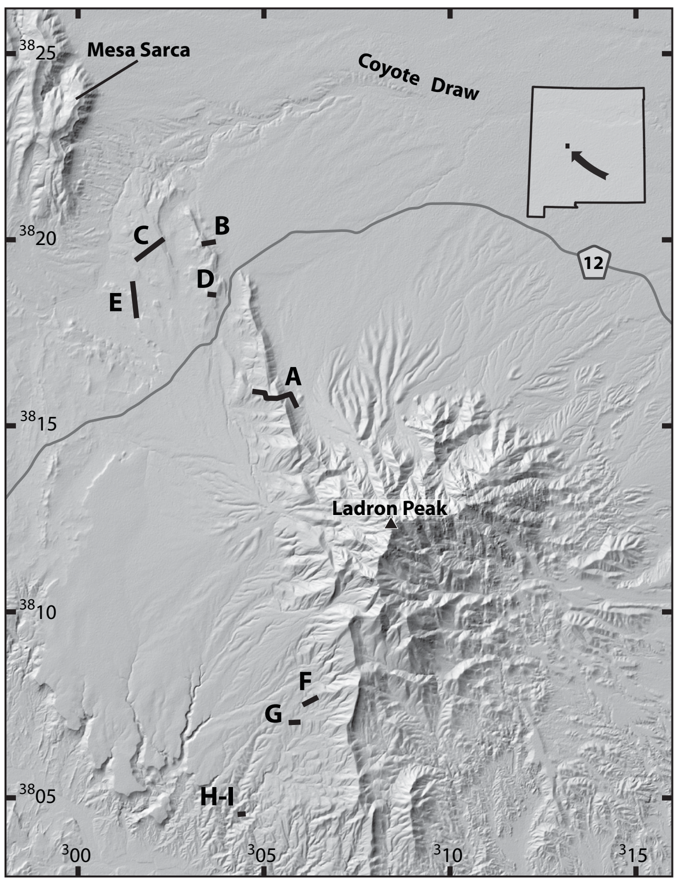

FIGURE 1. Index map showing locations of stratigraphic sections of Pennsylvanian rocks in the Sierra Ladrones (Figs. 2–6; Table 1). 5000 m UTM grid tics, zone 13S, NAD83.

TABLE 1. Locations of the measured stratigraphic sections of Pennsylvanian rocks in the Sierra Ladrones. Datum for GPS coordinates is NAD 83, zone 13S.

Section	Base (UTM)	Top (UTM)
A	305903, 3815490	304708, 3815921
B	303713, 3819954	303348, 3819886
C	302321, 3820016	301573, 3819453
D	303684, 3818515	303502, 3818519
E	301483, 3818880	301593, 3817894
F	306465, 3807704	306062, 3807496
G	305999, 3807042	305681, 3807024
H	304529, 3804588	304357, 3804546
I	304357, 3804546	304286, 3804534

PREVIOUS STUDIES

Most of the information on the Pennsylvanian strata in the Sierra Ladrones is in unpublished theses by Noble (1950), Cheetham (1950), Martin (1971), and Hammond (1987). Kelley and Wood (1946) presented some stratigraphic data on the Pennsylvanian section in the northern Sierra Ladrones. Wengerd (1959) published some generalized stratigraphic data, and Kottlowski (1960) published Cheetham's measured stratigraphic section of Pennsylvanian strata in the southern Sierra Ladrones.

SANDIA FORMATION

We measured one complete stratigraphic section of the Sandia Formation in the Sierra Ladrones (section A: Fig. 2). Here, the Sandia Formation rests directly on Precambrian granite or on a thin (<3 m thick) interval of quartz sandstone and quartz-pebble conglomerate that we assign to the Mississippian Espiritu Santo Member of the Arroyo Peñasco Formation. At measured section A, the Sandia Formation is 105 m thick and can be divided into a lower part that is 57.7 m thick (Fig. 2, units 4–38), and an upper part (Fig. 2, units 39–55) with a thickness of 46.9 m.

The lower part is composed of conglomerate, conglomeratic (pebbly) sandstone, sandstone, limestone, and covered intervals. Conglomerate and conglomeratic sandstone are the dominant lithology in the lower 20 m of the section. The Sandia Formation basal bed is a crossbedded, quartz-pebble conglomerate that has an erosive base that is locally cut down into the granitic basement. This basal conglomerate is 4.2 m thick and is overlain by crossbedded sandstone with a thickness of 0.7 m. Above a covered interval, crossbedded quartz-pebble conglomerate is exposed (1 m thick), followed by 2.6 m of cover (most likely siltstone), horizontally laminated pebbly sandstone (1.3 m thick), a covered interval (4.9 m thick), trough-crossbedded pebbly sandstone containing oxidized wood fragments (3.6 m thick) and trough-crossbedded sandstone (0.7 m thick). The top of this lowermost part of the Sandia Formation is formed by mixed siliciclastic-carbonate pebbly sandstone that displays multistorey trough-crossbedding (2.6 m thick).

This dominantly coarse-grained lower part is overlain by a succession of covered intervals and intercalated sandstone and limestone units. The covered intervals are 0.5–5.1 m thick and likely represent fine-grained siliciclastic sediments (mostly siltstone). Intercalated sandstone intervals are 0.2–0.8 m thick and are horizontally laminated and massive, mixed siliciclastic-carbonate sandstone (units 14, 16, 18), quartzose sandstone (units 26, 30, 34), and trough-crossbedded, mixed siliciclastic-carbonate sandstone (unit 36). Limestone intervals are 0.3–1.1 m thick and are wavy-bedded, cherty limestone (crinoidal packstone), wavy-bedded limestone containing brachiopods, and thin, even-bedded limestone (wackestone) with brachiopods.

The upper part of the Sandia Formation is composed of thick, covered intervals and shale/fine-grained siltstone units, and intercalated thin sandstone and limestone intervals. Covered intervals are 1.7–7.4 m thick and likely are shale/siltstone intervals. Greenish and greenish-gray shale is present in the lower part, forming 2.2–4.1 m thick intervals. In the upper part, black shale intervals with thicknesses of 2.5–9.7 m are exposed.

Intercalated sandstone intervals are 0.2–1.2 m thick and consist of horizontally laminated, greenish, micaceous fine-grained sandstone, mixed siliciclastic-carbonate sandstone that contains carbonaceous debris, and a coarse-grained, trough-crossbedded sandstone unit that forms the top of the Sandia Formation. In the middle of the upper part, two sandy limestone beds (wackestone) that contain brachiopods are intercalated in shale (each 0.4 m thick). Limestone is represented by one muddy limestone interval (wackestone; 1.2 m thick) and a massive limestone bed near the top that is 1.1 m thick and contains *Chaetetes*.

GRAY MESA FORMATION

We measured a complete section of the Gray Mesa Formation in the Sierra Ladrones at section A that is 234 m thick (Fig. 2). To the southeast, in the Cerros de Amado area east of Socorro, the Gray Mesa Formation can be divided into three members (ascending: Elephant Butte, Whiskey Canyon, and Garcia; Lucas et al., 2009). However, at section A, subdivision of the Gray Mesa Formation into members is difficult because lithology is relatively uniform throughout the succession. A possible subdivision (Fig. 2) is Elephant Butte Member, units 56–111 (89.7 m); Whiskey Canyon Member, units 112–139 (45.5 m); and Garcia Member, units 140–200 (98.8 m). These members are evident at some outcrops but not necessarily mappable. Nevertheless, we do not advocate recognition of members of the Gray Mesa Formation in the Sierra Ladrones.

The Gray Mesa Formation at section A contains numerous covered intervals (probably covered shale or nodular limestone units) that are 0.3–8.9 m thick. Shale units are rarely exposed, colored gray to dark gray, and 0.1–4.6 m thick. In thicker shale units, thin limestone beds and lenses are intercalated. A few shale units (0.3–2.4 m thick) contain abundant limestone nodules. One pebbly carbonate sandstone bed (unit 66; 0.3 m thick) is intercalated in the lower part of the Gray Mesa Formation. Also, in the lower part a coarse-grained, pebbly, trough crossbedded sandstone with an erosive base (channel fill) is developed. The thickness of this channel fill sandstone is 1.5–3 m (unit 79).

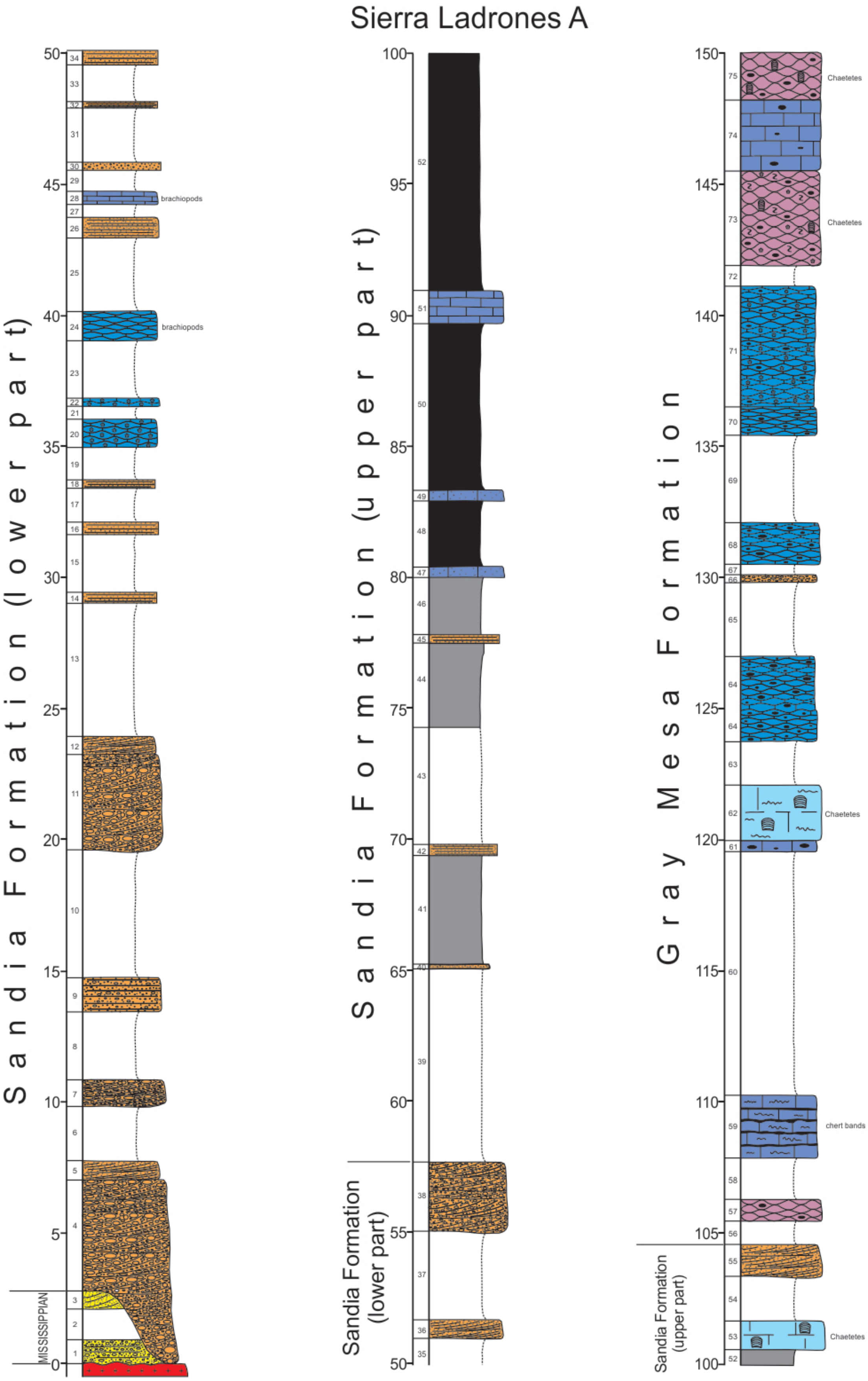

FIGURE 2. Measured stratigraphic section A of the Sandia, Gray Mesa, and Atrasado (part) formations in the Sierra Ladrones. See Figure 1 and Table 1 for location of section, and Figure 5 for lithologic legend.

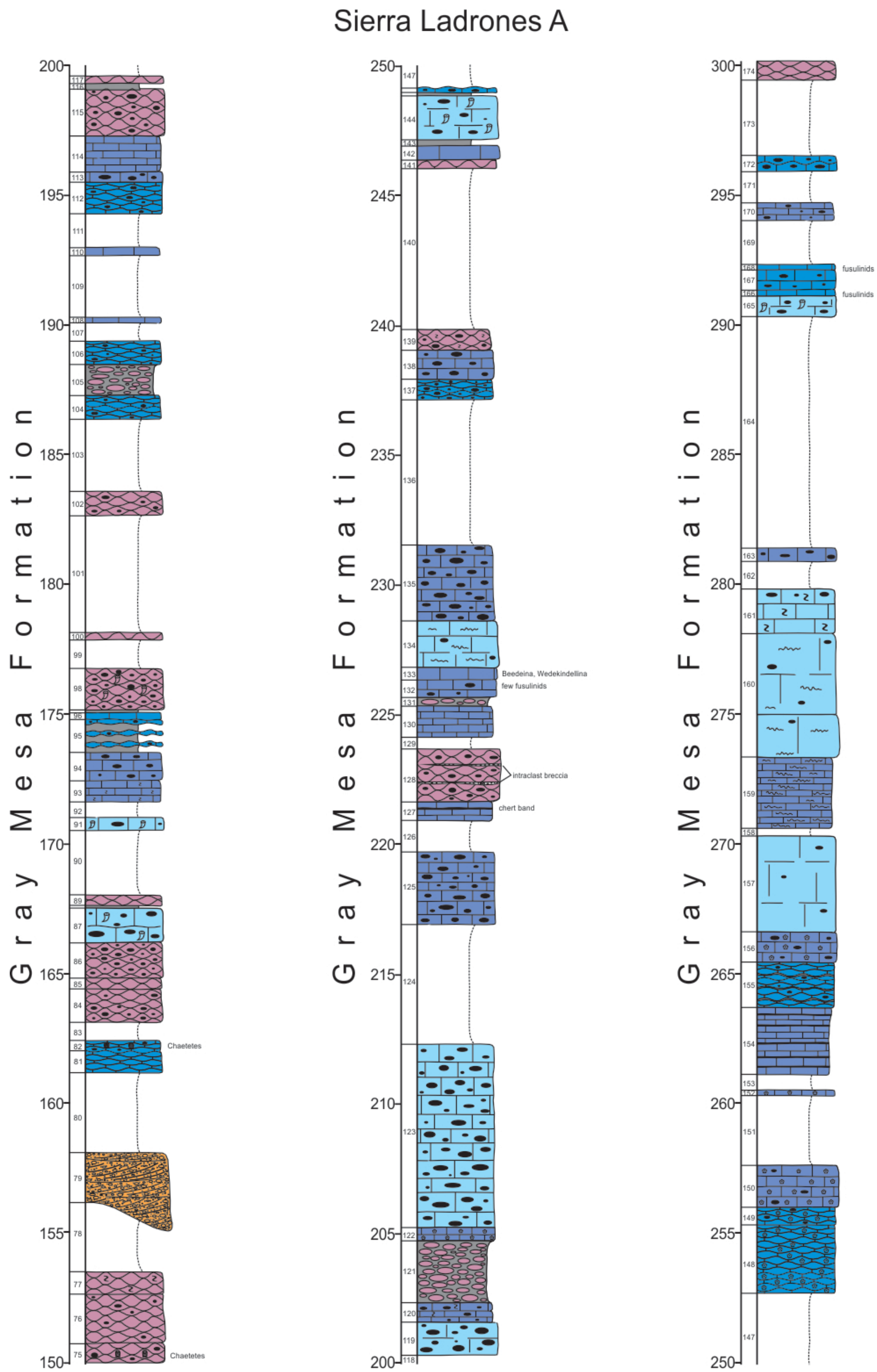

FIGURE 2. (Continued)

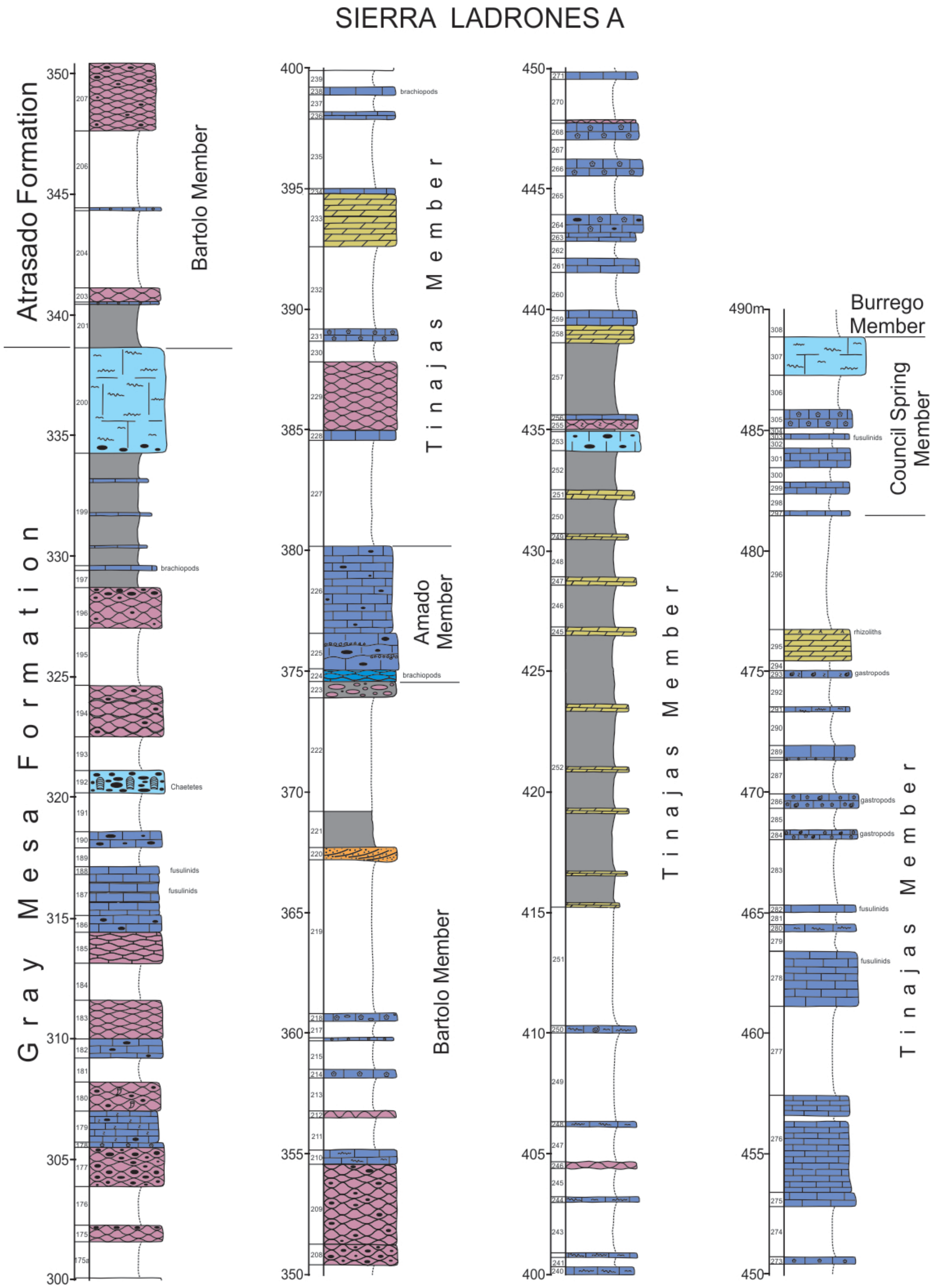

FIGURE 2. (Continued)

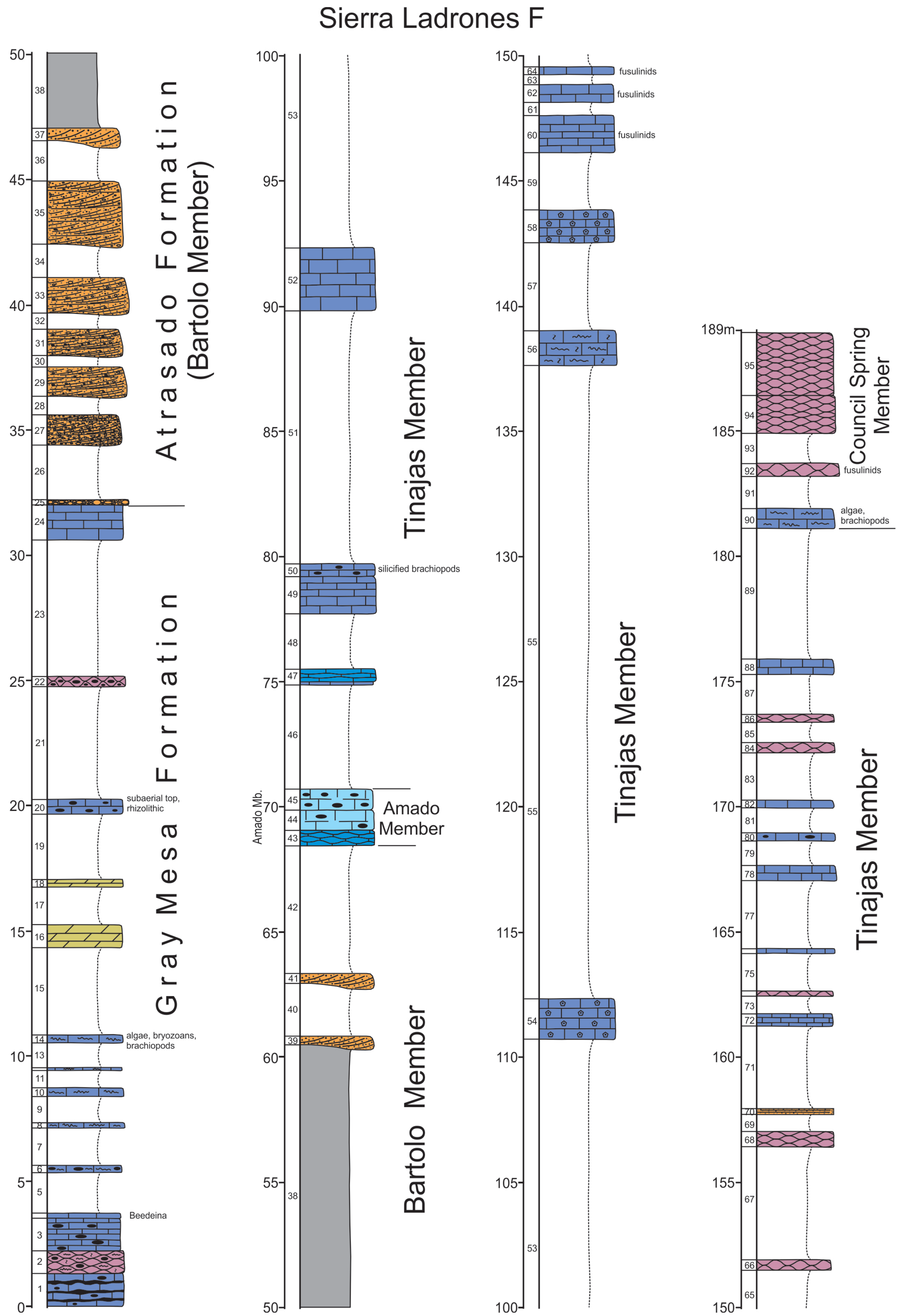

FIGURE 3. Measured stratigraphic section F of the parts of the Gray Mesa and Atrasado formations in the Sierra Ladrones. See Figure 1 and Table 1 for location of section, and Figure 5 for lithologic legend.

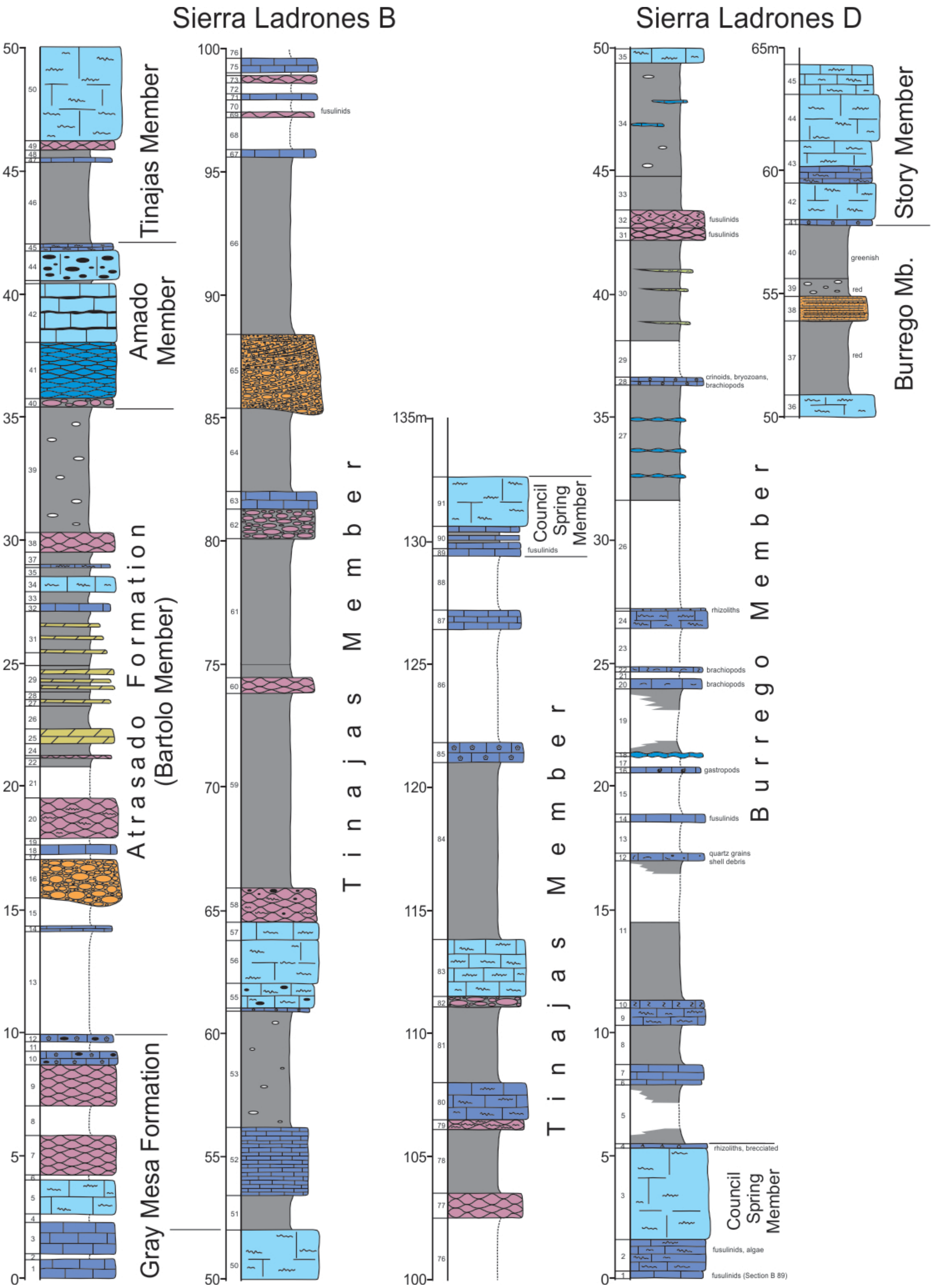

FIGURE 4. Measured stratigraphic Sections B and D of parts of the Gray Mesa and Atrasado formations in the Sierra Ladrones. See Figure 1 and Table 1 for location of sections, and Figure 5 for lithologic legend.

The dominant lithology of the Gray Mesa Formation at section A is limestone, including lithotypes that are well known from other outcrops of the Gray Mesa Formation in central New Mexico:

1) Individual limestone beds are 0.2–0.9 m thick, and mostly display even bedding planes, rarely wavy bedding planes. All limestone beds are characterized by muddy texture (bioclastic mudstone to wackestone, rare crinoidal wackestone to packstone), are both non-cherty and cherty, and locally very cherty with abundant *Chaetetes*.
2) Thin-bedded (5–20 cm) limestone has even bedding planes, is mostly non-cherty, and commonly has a muddy texture (wackestone), and is partly bioturbated, locally containing phylloid algae (unit 159) and fusulinids. A few thin-bedded limestone units contain chert nodules and thin chert bands. Thickness ranges from 0.7 to 2.6 m.
3) Medium- to thick-bedded limestone units with even bedding planes (1.3–7.1 m thick) commonly contain chert nodules and, subordinately, thin chert bands. Individual units contain phylloid algae and solitary corals.
4) Indistinctly thick-bedded to massive limestone units are composed of wackestone and algal wackestone to floatstone. Individual units contain solitary corals or *Chaetetes*. In most of these units, chert nodules are present, and individual units are 1.3–4.8 m thick.
5) Wavy bedded limestone units (bed thickness mostly 10–20 cm) have a muddy texture (bioclastic wackestone, crinoidal wackestone), rarely containing *Chaetetes*. Individual units are 0.4–4.6 m thick, and most of them contain chert nodules.
6) Nodular limestone units are mostly cherty to very cherty (abundant chert nodules, rare thin chert bands), and rarely non-cherty. Limestone displays a muddy texture (dominantly wackestone), and in the lower part some units contain *Chaetetes* and solitary corals. The thickness of individual units ranges from 0.4 to 3.6 m.

The upper part of the Gray Mesa Formation is present in our section F as its basal 32 m (Fig. 3). The succession starts with bedded cherty limestone (bioclastic wackestone) with chert nodules and thin chert bands (1.3 m thick), overlain by nodular bioturbated cherty limestone (algal wackestone; 0.9 m), thin, even bedded cherty limestone (bioclastic wackestone; 1.3 m) with large chert nodules and a thin (0.2 m) fusulinid limestone bed that contains *Beedeina*. Above follows a mostly covered succession with thin intercalated limestone and rare dolomite intervals. The following lithotypes are exposed: (1) algal limestone beds (algal wackestone to floatstone) 0.1–0.3 m thick—one bed contains small chert nodules and one bed contains bryozoans and brachiopods; (2) cherty limestone with a rhizolithic, subaerial top (0.6 m thick); (3) nodular cherty limestone (bioclastic wackestone) 0.4 m thick; (4) medium-bedded limestone (bioclastic wackestone) 1.4 m thick; and (5) thin-bedded dolomite (dolomicrite) 0.3 and 0.9 m thick. Covered intervals are 0.7–5.5 m thick.

ATRASADO FORMATION

We assembled two complete stratigraphic sections of the Atrasado Formation from overlapping sections: (1) at Navajo Gap, from sections B–E (Figs. 4–5); and (2) in the southwestern part of the Sierra Ladrones from sections F–H (Figs. 2, 3, 6). The total thickness is 261 m. Sections H and I correspond to the uppermost part of Cheetham's (1950) measured section, published in Kottlowski (1960, fig. 7). Sections G and I are poorly exposed and may be disturbed by faulting in covered intervals.

To the southeast, in the Cerros de Amado of east-central Socorro County, the Atrasado Formation consists of eight members that reflect its overall stratigraphic architecture of relatively thin (generally <10 m thick) intervals of limestone that are laterally extensive, intercalated with thicker units of mixed siliciclastic and carbonate strata that change facies and thickness relatively rapidly on strike (Rejas, 1965; Lucas et al., 2009; Krainer et al., 2017). Hammond (1987) first recognized this stratigraphic architecture in Atrasado Formation strata in the Sierra Ladrones. We assign Atrasado strata in the Sierra Ladrones to the (ascending) Bartolo, Amado, Tinajas, Council Spring, Burrego, Story, Del Cuerto, and Moya members.

Bartolo Member

The Bartolo Member is a mixed siliciclastic-carbonate interval that is a slope former at the base of the Atrasado Formation. At many sections east of the Rio Grande, the lowermost Bartolo is an interval of sandstone and conglomerate, the Coyote Bed (Coyote sandstone of Herrick, 1900, a unit abandoned by the U.S. Geological Survey), that unconformably overlies the Gray Mesa Formation at an evident sequence boundary (e.g., Lucas et al., 2016). In the Sierra Ladrones, the Bartolo Member is present in our sections A, B, and F (Figs. 2–4).

The Bartolo Member at section A (units 201–223; 36 m thick) consists of covered intervals, shale, crossbedded sandstone, and limestone. Covered intervals are 0.7–6.4 m thick and most likely represent shale. Exposed shale units are yellowish and 1.5 and 1.8 m thick. In the upper part, crossbedded carbonate grainstone is intercalated that is 0.5 m thick.

Thin limestone beds (0.1–0.3 m thick) display even to slightly wavy bedding planes, rarely are nodular, and are composed of bioclastic wackestone and crinoidal wackestone to packstone. Individual beds contain chert nodules. Thicker limestone units (0.6–3.3 m thick) are mostly represented by cherty nodular limestone with muddy texture (bioclastic mudstone to wackestone), and rarely by phylloid algal limestone (phylloid algal wackestone to floatstone). The top of the Bartolo Member is shale (0.7 m thick) that contains abundant limestone nodules (wackestone) containing brachiopods.

The Bartolo Member at section B is much thinner (25.5 m) than at section A (36 m) and section F (36.4 m). The Bartolo Member starts with a covered (shale) interval that may be faulted. Above follow shale/covered (shale) intervals with intercalated limestone and dolomite and one sandstone-conglomerate in the lower part.

Covered intervals are 0.2–4.2 m thick. Shale-siltstone intervals range in thickness from 0.3–5.1 m. The uppermost shale interval contains a few limestone nodules. Limestone is individual micritic limestone beds (0.1–0.6 m thick; bioclastic wackestone), partly containing calcareous algae (algal wackestone to floatstone), and nodular limestone (bioclastic wackestone), partly also containing algae, 0.1–1.7 m thick. In the middle of the member several thin, micritic dolomite beds (dolomicrite; 0.1–0.6 m thick) are intercalated in shale. The conglomerate in the lower part is up to 1.8 m thick, has an erosive base, and is trough crossbedded and composed of limestone cobbles.

At section F, the Bartolo Member (units 25–42) is 36.4 m thick and entirely siliciclastic. The succession starts with a thin limestone-cobble conglomerate with coarse-grained quartzose sandy matrix (0.2 m thick), overlain by alternating covered/shale intervals and sandstone. This sandstone interval and the underlying conglomerate is assigned to the Coyote Bed, which is at the base of the Atrasado Formation in the Los Pinos and southern Manzano Mountains to the east (Lucas et al., 2016). The covered intervals are 0.5–5.1 m thick and most likely represent shale-siltstone intervals. The shale interval unit 38 (13.5 m thick) is partly covered and composed of mostly pale, yellow, and olive gray shale-siltstone. Sandstone units are coarse grained, trough crossbedded, and 0.3–2.5 m thick. Sandstone of unit 27 contains some limestone cobbles in the upper part.

Amado Member

The Amado Member is a relatively thin (usually <10 m thick) interval of limestone that is laterally persistent. Cherty limestone and limestone rich in brachiopod fossils are characteristic. It is present in our Sierra Ladrones sections A, B, and F (Figs. 2–4).

At section A, the Amado Member (units 224–226) is 5.6 m thick, whereas at section B (units 43–45) it is 6.3 m thick. At sections A and B, the Amado Member basal unit is wavy bedded limestone (wackestone) that contains abundant brachiopods (0.5–0.6 m thick), overlain by massive to slightly wavy bedded cherty limestone (wackestone) with thin lenses of intraclast breccia (0.8–1.5 m thick) and bedded limestone with even bedding planes and muddy texture (wackestone) and minor chert nodules (0.9–3.6 m thick). At section F, the Amado Member (units 43–45) is thin (2.3 m) and composed of wavy bedded, chert-free limestone (bioclastic wackestone; 0.6 m thick), overlain by indistinctly bedded to massive cherty limestone (wackestone) that is 1.7 m thick.

Tinajas Member

Like the Bartolo Member, the Tinajas Member is a mixed clastic-carbonate unit that is a slope former. It is the thickest member of the Atrasado Formation. In the Sierra Ladrones, the Tinajas Member is present in our sections A, B, and F (Figs. 2–4).

At section A, the Tinajas Member (units 227–296) is 94 m thick, whereas at section B (units 46–88) it is 85 m thick, and at section F (units 46–89) it is 110 m thick. This member is a succession of numerous covered (shale) intervals, shale units, and intercalated thin to rarely thicker limestone and dolomitic limestone/dolomite intervals. Covered intervals range in thickness from 0.4 to 25.3 m. Shale units are 0.1 to 18.9 m thick. The thick shale unit at section B contains many intercalated thin, flaggy, ripply micritic dolomite beds.

Limestone includes thin limestone beds (0.2–0.8 m thick) with even to slightly wavy bedding planes that are rarely nodular and rarely cherty. Limestone beds are composed of micritic limestone, including bioclastic wackestone, algal wackestone to floatstone, and algal-crinoidal wackestone. Bedded limestone units are 0.3–0.8 m thick, thin bedded with even bedding planes, and composed of bioclastic wackestone and crinoidal wackestone to packstone. Chert nodules are rare. Nodular limestone units are 0.4–2.8 m thick and micritic (wackestone). Intercalated dolomicrite intervals are thin bedded and 0.7–2.2 m thick. In section F, there is one 0.2 m thick coarse-grained sandstone bed (unit 70).

Council Spring Member

Like the Amado Member, the Council Spring Member is a relatively thin and laterally persistent unit composed almost entirely of limestone. Chert-free algal limestone is characteristic. The Council Spring Member in the Sierra Ladrones is a conspicuous and consistent interval of limestone up to 10.6 m thick present in our sections A, B, D, F, and G (Figs. 2–4, 6).

At section A, the Council Spring Member (units 297–307) is 8 m thick and is composed of limestone intercalated with covered intervals. Limestones are mostly wackestone but include crinoidal packstone and algal limestone as the uppermost bed of the Council Spring Member.

At section B, the lower 3.2 m of the Council Spring Member (units 89–91) is exposed. It consists of fusulinid packstone (0.3 m) overlain by three beds of wackestone and intercalated shale (0.9 m) capped by recrystallized, massive white algal limestone.

At section D, the Council Spring Member (units 1–4) is 5.5 m thick. Its basal bed is a 0.3 m thick fusulinid packstone that is the same bed as unit 89 in section B. Overlying fusulinid-algal wackestone is 1.3 m thick overlain by a 3.7 m thick bed of massive algal limestone. The top bed of the Council Spring Member is a brecciated limestone with rhizoliths indicative of subaerial exposure that is 0.1–0.2 m thick.

At section F, the Council Spring Member (units 90–95) is 5.7 m thick. Its basal bed is a 0.5 m thick fusulinid wackestone equivalent to bed 89 at section B and unit 1 at section D. A 1.2 m thick covered interval overlies the basal bed and is overlain by ~4 m of nodular wackestone.

At section G, the Council Spring Member (units 2–6) is 3.7 m thick and is composed of bedded and massive algal limestone (bioherms of algal wackestone to floatstone; 2.9 m), overlain by a covered interval (0.5 m) and a thin nodular limestone unit (0.3 m) composed of bioclastic wackestone. The medium-bedded algal limestone (unit 4) contains brachiopods, and on its top rhizoliths are present that indicate a subaerial exposure surface.

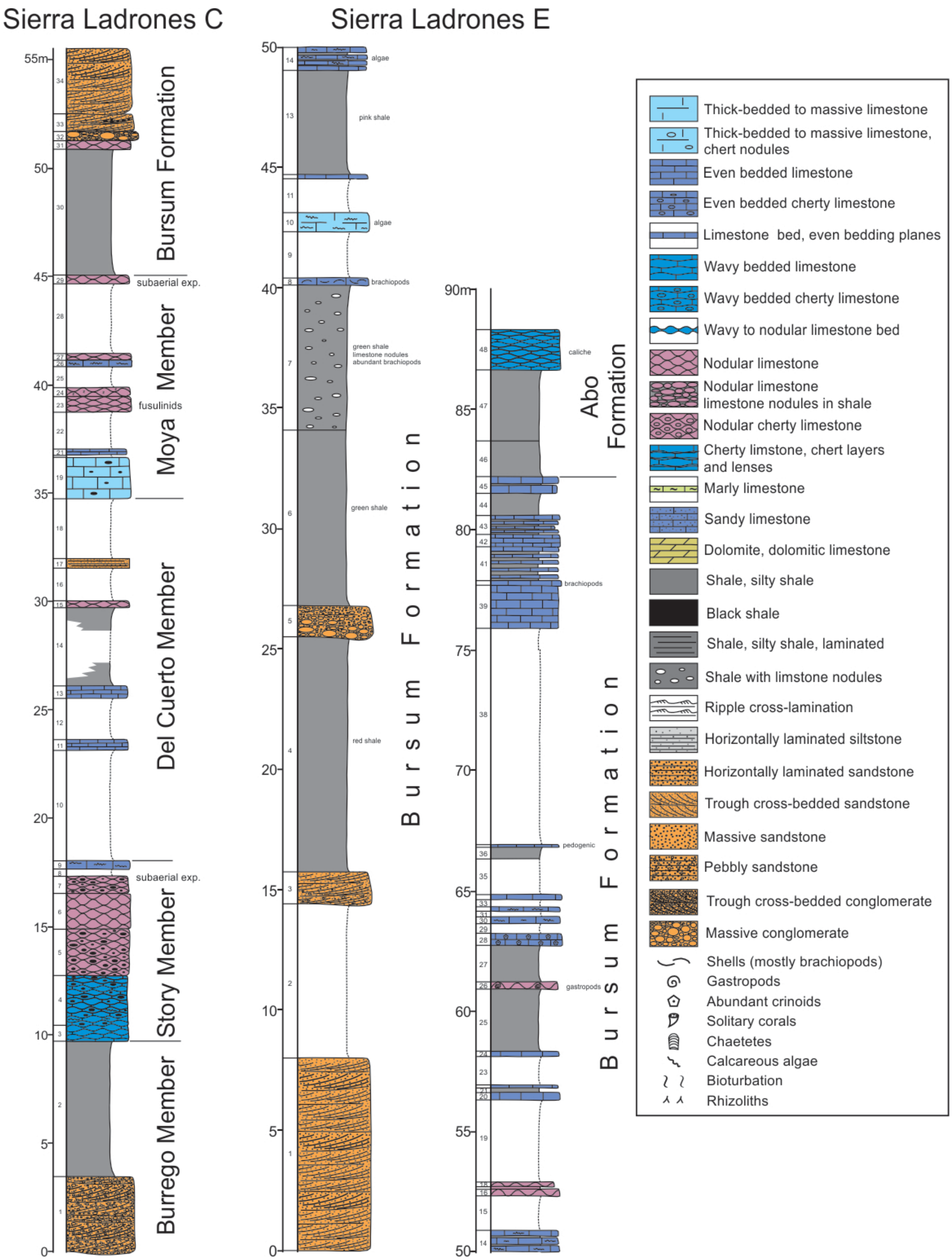

FIGURE 5. Measured stratigraphic sections C and E of the Atrasado (part) and Bursum formations in the Sierra Ladrones. See Figure 1 and Table 1 for location of sections.

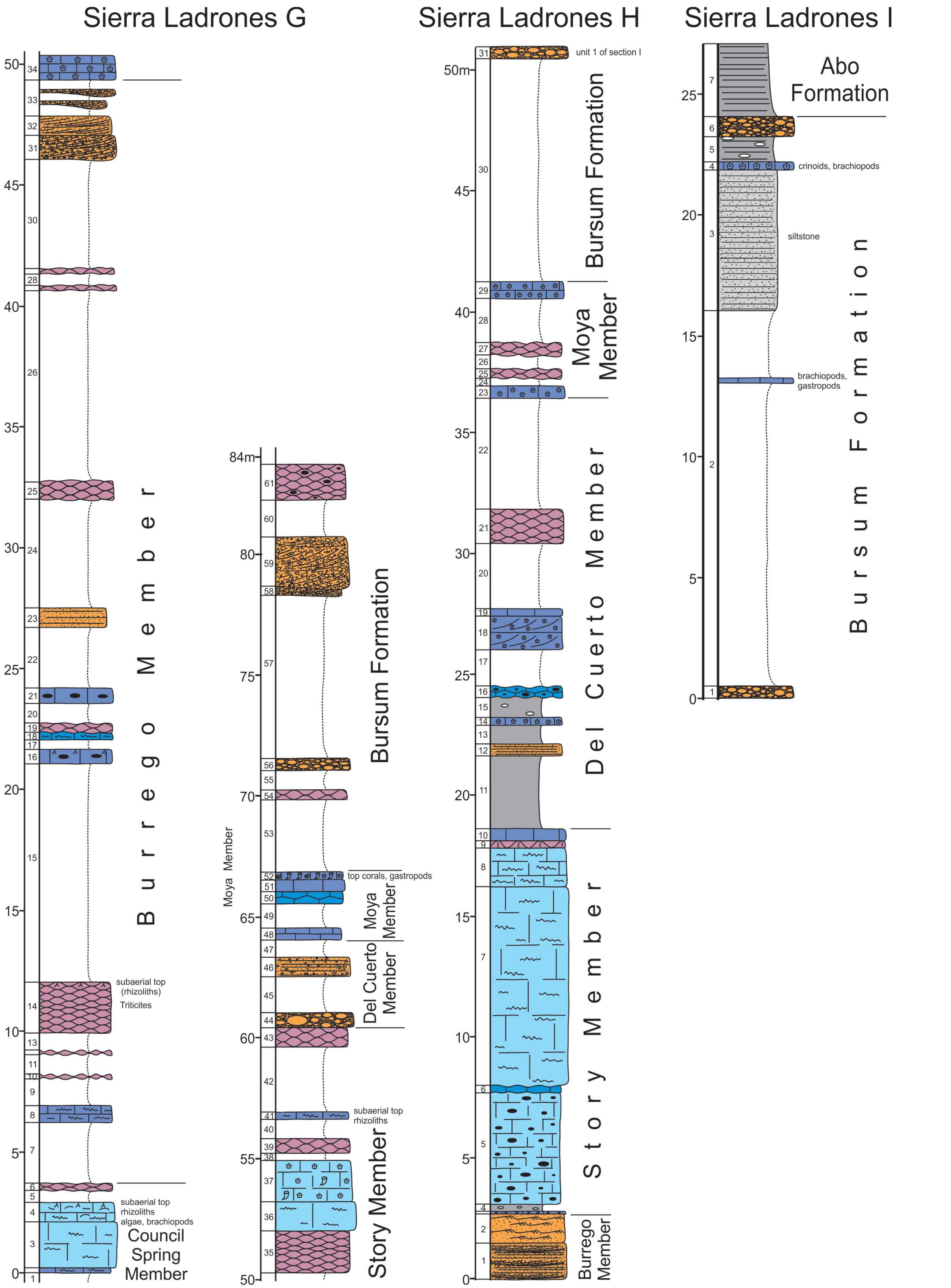

FIGURE 6. Measured stratigraphic sections G, H, and I of the Atrasado (part), Bursum, and Abo (part) formations in the Sierra Ladrones. See Figure 1 and Table 1 for location of sections, and Figure 5 for lithologic legend.

Burrego Member

The Burrego Member is a mixed carbonate/clastic unit that is a slope former between the limestone sheets of the Council Spring (below) and Story (above) members. In the Sierra Ladrones, it is present in our sections C, D, and G (Figs. 4–6).

At section C, only the uppermost part of the Burrego Member is exposed. It is trough-crossbedded, pebbly arkosic sandstone (3.4 m), overlain by poorly exposed red mudstone (6.3 m thick).

A complete section of the Burrego Member at section D (units 5–40) is 52.3 m thick. The dominant lithology is shale that is poorly exposed or covered, mostly gray, partly yellowish, and, in the upper part, red and greenish. One red shale interval contains calcrete nodules. Shale/covered shale intervals are 0.4–5.7 m thick. Intercalated in the shale are the following lithotypes:

1) Small limestone nodules and nodular limestone lenses containing brachiopods and bryozoans.
2) Thin lenses of marly limestone.
3) Individual limestone beds that are 0.2–0.4 m thick, mostly with even, rarely with wavy, bedding planes, and mostly micritic (fusulinid wackestone to packstone, wackestone with gastropods, and wackestone containing many productid brachiopods).
4) Bedded limestone intervals that are 0.3–0.9 m thick, even bedded, micritic, and contain abundant phylloid algae (algal wackestone to floatstone). One thin-bedded limestone interval contains abundant crinoid fragments, bryozoans, and brachiopods.
5) In the upper part of the member, a thin nodular limestone (fusulinid wackestone to packstone, 0.5 m thick) is exposed, overlain by bioturbated nodular limestone (wackestone with a few fusulinids, 0.7 m thick).
6) One thin limestone bed is exposed in the lower part that is 0.3 m thick and is composed of abundant carbonate grains, a few detrital quartz grains, and comminuted shell debris.
7) In the upper part, a horizontally laminated red micaceous sandstone is intercalated in red mudstone (0.8–1 m thick).

Another complete stratigraphic section of the Burrego Member at section G (units 7–33) is 45.6 m thick and mostly covered. Exposed strata are mostly thin limestone intervals and a few sandstone intervals in the upper half. Covered intervals are 0.4–9 m thick and represent shale-siltstone units. Limestone is represented by different lithologies, including: (1) algal limestone (0.3 and 0.8 m thick); (2) micritic cherty limestone beds (0.6 and 0.7 m thick)—the lower bed displays rhizoliths on top indicating subaerial exposure; and (3) nodular micritic limestone (0.2–2.1 m thick). The thick nodular limestone unit 14 contains fusulinids and rhizoliths on top (subaerial exposure surface). Sandstone is represented by horizontally laminated micaceous sandstone (0.8 m thick) and by coarse-grained, partly pebbly, arkosic sandstone displaying trough crossbedding (uppermost 3.3 m).

Story Member

Similar to the Council Spring Member, the Story Member in the Sierra Ladrones is a relatively thin interval, dominantly of limestone, that is a persistent unit over many km of strike. It is present in our sections C, D, G, and H (Figs. 4–6).

At section C, the Story Member (units 3–9) is 8.3 m thick. It is almost entirely composed of limestone with one thin covered (shale) interval (0.3 m) in the upper part. The lower part is composed of thin and wavy bedded limestone (wackestone) without chert (0.7 m), overlain by thin and wavy bedded, very cherty limestone that contains phylloid algae (algal wackestone to floatstone; 2.3 m thick). Wavy bedded limestone is overlain by nodular cherty limestone (2.1 m), nodular, noncherty limestone (1.7 m), and cherty nodular limestone (0.8 m). Nodular limestone is micritic and mainly composed of bioclastic wackestone. A subaerial exposure surface is developed on top of the uppermost nodular limestone. Above a thin covered interval (0.3 m), algal limestone (algal wackestone to floatstone; 0.4 m) is exposed.

At section D, the Story Member (units 41–45) is 6.5 m thick at the top of a distinctive bluff. It is algal limestone beds with a 0.2 m thick crinoidal wackestone at the base.

At section G, the Story Member (units 34–43) is 11.1 m thick and composed of different types of limestone and two covered intervals in the upper part. Limestone includes: (1) crinoidal limestone (crinoidal wackestone to packstone), medium-bedded, partly containing rugose corals, 1.0 and 1.7 m thick; (2) massive algal limestone (1.2 m) and a thin algal limestone bed with rhizoliths on top (0.3 m); and (3) nodular micritic limestone, partly cherty, partly bioturbated, composed of bioclastic wackestone (0.6–1.7 m thick).

At section H, the Story Member (units 3–10) is 15.9 m thick. Its base is a thin crinoidal limestone bed (crinoidal packstone) that is 0.1 m thick and overlain by shale with limestone nodules (0.3 m thick). Above follow indistinctly bedded to massive cherty micritic limestone (wackestone; 4.6 m), wavy bedded limestone (wackestone; 0.3 m), massive algal limestone (bioherm; 6.2–8.3 m), medium-bedded algal limestone (1.5 m), bioturbated nodular micritic limestone (0.3 m), and a micritic limestone bed (wackestone; 0.5 m).

Del Cuerto Member

The Del Cuerto Member is a dominantly clastic unit that forms a slope between two persistent limestone intervals, Story Member below, and Moya Member above. It is present at our sections C, G, and H (Figs. 5–6).

At section C, the Del Cuerto Member (units 10–18) is 16.7 m thick. It is composed of covered intervals, poorly exposed pink shale, intercalated thin limestone intervals and one sandstone unit. Covered intervals are 1.5–5.1 m thick. The poorly exposed pink shale interval measures 3.6 m. Limestone is represented by thin-bedded micritic limestone intervals (wackestone) that are 0.5 and 0.6 m thick, and one nodular, bioturbated micritic limestone interval that is 0.3 m thick. In the upper part, one thinly laminated, medium- to fine-grained arkosic sandstone (thickness of 0.4 m) is intercalated.

Strata in the upper part of section G are poorly exposed and the picks for members are somewhat speculative. According to the observations depicted in Figure 6, the Del Cuerto Member (units 44–47) is very thin, only 3.6 m thick. The member base is a limestone-pebble conglomerate (0.6 m) followed by a covered interval (shale-siltstone), horizontally laminated conglomeratic sandstone and coarse-grained sandstone, mixed siliciclastic-carbonate in composition (0.8 m) and a covered (shale-siltstone) interval (0.7 m).

At section H, the Del Cuerto Member (units 11–22) is a 17.8 m thick succession of shale and covered (shale) intervals with intercalated limestone and rare sandstone. Shale is red and yellowish and partly contains limestone nodules. Shale units are 0.8–3 m thick. Covered intervals are 1.5–4.6 m thick and also represent shale-siltstone units. A thin mixed siliciclastic-carbonate sandstone bed that is 0.5 m thick is intercalated in shale in the lower part. Limestone includes a thin limestone bed composed of crinoidal grainstone to packstone (0.3 m), crossbedded crinoidal limestone (grainstone to packstone; 1.4 m thick), a thin limestone bed (bioclastic wackestone; 0.3 m thick), nodular cherty limestone (wackestone; 0.5 m), and nodular chert-free limestone (wackestone; 1.4 m thick).

Moya Member

The Moya Member is a succession of alternating limestone and covered (shale) intervals at the top of the Atrasado Formation. It is present in our section C (Fig. 5) and may be present in sections G and H (Fig. 6), although strata in the upper part of the latter two sections are poorly exposed. At section C, the Moya Member (units 19–29) is 10.3 m thick. Covered intervals are 0.1–3.2 m thick. Limestone intervals are 0.3–1.9 m thick and include the following lithotypes: (1) thin-bedded micritic limestone with even bedding (wackestone; 0.3 m thick); (2) algal limestone (algal wackestone to floatstone; 0.3 m thick); (3) medium-bedded cherty micritic limestone (wackestone; 1.9 m thick); and (4) nodular micritic limestone (bioclastic wackestone, rarely fusulinid wackestone; 0.3–0.7 m thick). A subaerial exposure surface is developed on top of the uppermost nodular limestone interval.

At section G, the Moya Member (units 48–54) is covered intervals with intercalated limestone beds, with a total thickness of 7 m. The member starts with even, thin bedded limestone (bioclastic wackestone; 0.5 m), followed by a covered interval (1.0 m), wavy bedded limestone (0.5 m), a massive micritic limestone bed (wackestone; 0.5 m), a limestone bed that contains many rugose corals and gastropods near the top (0.3 m), a covered interval (3 m), and nodular micritic limestone (wackestone; 0.4 m) on top.

At section H the Moya Member (units 23–29) is 4.8 m thick. It is covered intervals and intercalated limestone beds discontinuously exposed in the floor of a drainage. Limestone includes medium-bedded crinoidal limestone (packstone) at the base and top (0.5 and 0.7 m thick) and two micritic nodular limestone intervals (wackestone; 0.4 and 0.5 m thick) in the middle. Covered intervals are 0.3–1.8 m thick.

BURSUM FORMATION

We regard the Bursum Formation in the Sierra Ladrones as mostly being early Wolfcampian age (its age in the nearby Lucero uplift; Lucas and Krainer, 2004), though we have no direct evidence of its age in this area. We consider early Wolfcampian to be Permian, but some workers consider it Late Pennsylvanian, so we describe the Bursum Formation here.

Sections C and E (Fig. 5) encompass a complete section through the Bursum Formation and the overlying basal Abo Formation. The Bursum Formation is approximately 92 m thick and can be divided into a lower part that is composed of shale/covered intervals, sandstone and conglomerate, and an upper part composed of shale/covered intervals and intercalated limestone.

At section C the lowermost Bursum Formation (exposed thickness is 10.4 m) is composed of red mudstone to siltstone (5.8 m thick), overlain by nodular limestone (crinoidal wackestone, 0.5 m), thin limestone pebble conglomerate with a scour base (0.3 m) and trough crossbedded sandstone with lenses of conglomerate and hematitic rip-up clasts in the lower part (3.8 m thick).

At section E, the lower part of the Bursum Formation (units 1–5; 27 m) is a thick sandstone interval (approximately 8 m thick) that is coarse-grained and displays multistorey trough crossbedding. This sandstone interval correlates with unit 34 of section C. The sandstone is followed by a covered interval (6.4 m) and a very coarse-grained, pebbly sandstone displaying trough crossbedding. This sandstone is lenticular, extending laterally over a distance of approximately 30 m (representing a shallow channel). The sandstone is overlain by red mudstone (9.8 m thick) and a limestone pebble/cobble conglomerate that is 1.3 m thick and shows an upward-fining trend.

The upper part of the Bursum Formation (units 6–45; 55 m thick) is composed mostly of shale and covered (shale) intervals with intercalated thin limestone beds and rare, thicker-bedded limestone units. Covered intervals are 0.2–9 m thick; the thickness of shale intervals ranges from a few cm up to 7.3 m. Shale is greenish, pink, yellowish and, in the uppermost part, reddish. Green shale of unit 7 contains limestone nodules and abundant brachiopods.

Individual limestone beds are 0.1–0.8 m thick. Most of them display even bedding planes, and, subordinately, individual limestone beds are nodular. All limestone beds are micritic (bioclastic mudstone to wackestone), many beds contain phylloid algae (phylloid algal wackestone to floatstone), one bed contains abundant brachiopods (unit 8), and one bed contains gastropods (unit 26). One thin limestone bed (unit 37) shows evidence of pedogenic overprinting and contains root structures.

Thicker limestone units are 0.5–1.9 m thick, are thin- to medium-bedded with even bedding planes and partly with thin shale breaks between the limestone beds. Limestone is micritic, and partly contains abundant algae (phylloid algal wackestone to floatstone) and crinoids (crinoidal wackestone to packstone). The uppermost marine limestone beds are pedogenically overprinted (root structures). Based on lithology, the

Bursum Formation of sections C/E can be assigned to the Red Tanks Member (Lucas and Krainer, 2004; Krainer and Lucas, 2004).

At section G, the Atrasado Formation (Moya Member) is overlain by the lower part (approximately 14 m) of the Bursum Formation. The section is mostly covered. The covered intervals are 0.8, 1.5, and 6.8 m thick and most likely represent shale-siltstone units. Exposed are a limestone-pebble conglomerate (0.5 m) near the base, coarse-grained sandstone and pebbly sandstone displaying crossbedding (2.4 m), and nodular limestone (bioclastic wackestone) with few chert nodules (1.5 m).

Sections H and I (Fig. 6) also may encompass a mostly covered section of some (or all) of the Bursum Formation. At section H, the basal 9.2 m of the Bursum Formation is covered (shale-siltstone) and probably faulted. Above this covered interval a limestone-pebble/cobble conglomerate that is 0.5 m thick is exposed (unit 1 of section I). This section is 35.1 m thick, either due to faulting low in the section, or it may be that the Bursum-Abo contact is picked too low in this section. However, late Cenozoic alluvial fan deposits above the top of the section make it impossible to further evaluate the lithostratigraphy.

The exposed thickness of section I is 26.9 m. The Bursum Formation measures 24 m, and the overlying 2.9 m are assigned to the Abo Formation. The Bursum Formation starts with a limestone-cobble conglomerate that fines upward and contains granitic debris. The conglomerate is 0.5 m thick and correlates to unit 31 of section H, indicating that the apparent total thickness of the Bursum Formation of sections H and I is 33.2 m. The basal conglomerate is overlain by a thick covered (shale) interval (15 m). In the upper part of this covered interval, approximately 13 m above the base, a thin limestone bed (0.3 m) is exposed that contains brachiopods and gastropods. Above the covered interval purple-red mottled siltstone is exposed that is 6.3 m thick, overlain by a thin limestone bed (0.3 m) that contains crinoid fragments and brachiopods, red mudstone-siltstone with limestone nodules (1.1 m), limestone-cobble conglomerate with brachiopod shell fragments and displaying crude horizontal lamination, overlain by red mudstone-siltstone of the Abo Formation.

BIOSTRATIGRAPHY

Fusulinids provide the only available biostratigraphic data on the ages of the Pennsylvanian strata in the Sierra Ladrones. Thompson et al. (1956) and Stewart (1968) presented the only published fusulinid data. They documented the early Missourian index fusulinid *Eowaeringella* from unit 46 in our section B, which is in the Tinajas Member. Thompson et al. (1956) also documented Missourian *Triticites* from unit 71 and adjacent strata in our section B. These Missourian age assignments to the Tinajas Member fit regional biostratigraphic data (e.g., Lucas et al., 2009; Allen and Lucas, 2018).

Wengerd (1959) and Martin (1971) reported fusulinids from the Sierra Ladrones Pennsylvanian strata identified by W. Stewart. These are *Fusulinella* from the upper Sandia Formation (late Atokan), *Beedeina* and *Wedekindellina* from the Gray Mesa Formation (Desmoinesian), and *Triticites* of Missourian and Virgilian age from the Atrasado Formation. Our fusulinid data, under study, are consistent with these earlier reported fusulinid age determinations.

LUCERO BASIN

The concept of a late Paleozoic Lucero basin was largely based on an overestimation of the thickness of the Pennsylvanian section in and near the Sierra Ladrones. We note that the overall structure in the Sierra Ladrones is extensional and a part of the western side of the Rio Grande rift, so there is extensive normal faulting in the area. In addition, the Atrasado Formation is a repetitive shale/carbonate unit that could easily be extended and mistakenly measured. In particular, the Tinajas Member is characterized by cycles of shale/carbonate, and possible repeat sections due to faulting might not be easily recognized. As pointed out to us by J. Devera and J. Nelson, in the Navajo Gap area there is also strike-slip faulting. These faults are left-lateral and are a part of a much more complex picture of the structure than the multiple normal fault blocks in the Sierra Ladrones. Thus, given the structural complexity and the potential to repeat parts of the Atrasado Formation that are not easily recognized as fault repeats, some earlier workers overestimated the thickness of the Pennsylvanian sections in the area of the Sierra Ladrones.

This led to reconstruction of a Lucero basin by Kottlowski (1960, pl. 3) based on three data points: (1) Mesa Sarca (primarily sec. 30, T4N, R3W), where, according to Kottlowski (1960), Kelley and Wood (1946) reported the Pennsylvanian section to be 2490 ft (759 m) thick, but Kottlowski misquoted them, as their section there is only 628 m thick for the Sandia-Atrasado interval; (2) the northern Sierra Ladrones (primarily sec. 14, T3N, R3W), where Kelley and Wood (1946) estimated the Pennsylvanian section as 2260 ft (689 m) thick; and (3) southern Ladron Mountains (secs. 20, T2N, R2W and 25-26, T2N, R3W), where Cheetham (1950) reported a Pennsylvanian section 2700 ft (823 m) thick.

However, our well-constructed Pennsylvanian section in the Navajo Gap area is only about 550 m thick (Hammond, 1987, reported a similar Pennsylvanian section thickness of 573 m at Navajo Gap). Cheetham's (1950) section to the south has a much thicker estimate of the Atrasado Formation thickness than our sections largely because he appears to have added multiple fault blocks to the section in very structurally complex and much covered terrain. Indeed, Cheetham's (1950) thickness of the Atrasado Formation interval in his section is about 460 m, more than twice our measured thickness of the Atrasado Formation. We thus conclude that thicknesses of the Pennsylvanian section >600 m in the Sierra Ladrones are overestimates.

The Pennsylvanian section in the Sierra Ladrones is much thinner than the Pennsylvanian section in the Cerros de Amado, northeast of Socorro, where the Pennsylvanian section is 744 m thick (see Lucas et al., this volume). Thus, if there were a "Lucero basin" its center would be much farther to the east, not in the Mesa Lucero region. We therefore conclude that there is no compelling evidence to support identification of a Pennsylvanian Lucero basin.

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REFERENCES

Allen, B.D., and Lucas, S.G., 2018, The Late Pennsylvanian (Missourian) index fusulinid *Eowaeringella* in the Manzanita Mountains of central New Mexico: New Mexico Geology, v. 40, p. 35–44.

Cheetham, A.K., 1950, Preliminary survey of some New Mexico Bryozoa [Senior thesis]: Socorro, Department of Geology, New Mexico School of Mines, 90 p.

Hammond, C.M., 1987, Geology of the Navajo Gap area between the Ladron Mountains and Mesa Sarca, Socorro County, New Mexico: a structural analysis [M.S. thesis]: Socorro, New Mexico Institute of Mining and Technology, 212 p.

Herrick, C.L., 1900, The geology of the White Sands of New Mexico: Journal of Geology, v. 8, p. 112–128 [also published in 1900 in New Mexico University Bulletin, v. 2, 17 p.].

Kelley, V.C., and Wood, G.H., 1946, Lucero uplift, Valencia, Socorro, and Bernalillo Counties, New Mexico: U.S. Geological Survey, Oil and Gas Investigations Preliminary Map 47, scale 1:63,360.

Kottlowski, F.E., 1960, Summary of Pennsylvanian sections in southwestern New Mexico and southeastern Arizona: New Mexico Bureau of Mines and Mineral Resources, Bulletin 66, 187 p.

Krainer, K., and Lucas, S.G., 2004, The Upper Pennsylvanian Red Tanks Member of the Bursum Formation at Carrizo Arroyo, central New Mexico: Transition from shallow marine to nonmarine facies: New Mexico Museum of Natural History and Science, Bulletin 25, p. 53–69.

Krainer, K., Vachard, D., Lucas, S.G., and Ernst, A., 2017, Microfacies and sedimentary petrography of Pennsylvanian limestones and sandstones of the Cerros de Amado Area, east of Socorro (New Mexico, USA): New Mexico Museum of Natural History and Science, Bulletin 77, p. 159–197.

Lucas, S.G., and Krainer, K., 2004, The Red Tanks Member of the Bursum Formation in the Lucero uplift and regional stratigraphy of the Bursum Formation in New Mexico: New Mexico Museum of Natural History and Science, Bulletin 25, p. 43–52.

Lucas, S.G., Krainer, K., and Barrick, J.E., 2009, Pennsylvanian stratigraphy and conodont biostratigraphy in the Cerros de Amado, Socorro County, New Mexico: New Mexico Geological Society, Guidebook 60, p. 183–212.

Lucas, S.G., Krainer, K., and Vachard, D., 2016, The Pennsylvanian section at Priest Canyon, southern Manzano Mountains, New Mexico: New Mexico Geological Society, Guidebook 67, p. 275–301.

Martin, J. L., 1971, Stratigraphic analysis of Pennsylvanian strata in the Lucero region of west central New Mexico [Ph.D. thesis]: Albuquerque, University of New Mexico, 196 p.

Noble, E.A., 1950, Geology of the southern Ladron Mountains, Socorro County, New Mexico [M.S. thesis]: Albuquerque, University of New Mexico, 81 p.

Rejas, A., 1965, Geology of the Cerros de Amado area, Socorro County, New Mexico [M.S. thesis]: Socorro, New Mexico Institute of Mining and Technology, 128 p.

Siemers, W.T., 1978, The stratigraphy, petrology, and paleoenvironments of the Pennsylvanian System of the Socorro region, west-central New Mexico [Ph.D. thesis]: Socorro, New Mexico Institute of Mining and Technology, 259 p.

Siemers, W.T., 1983, The Pennsylvanian System, Socorro region, New Mexico: Stratigraphy, petrology, depositional environments: New Mexico Geological Society, Guidebook 34, p. 147–155.

Stewart, W.J., 1968, The stratigraphic and phylogenetic significance of the fusulinid genus *Eowaeringella*, with several new species: Cushman Foundation for Foraminiferal Research, Special Publication no. 10, 29 p.

Thompson, M.L., Verville, G.J., and Lokke, D.H., 1956, Fusulinids of the Desmoinesian-Missourian contact: Journal of Paleontology, v. 30, p. 793–810.

Wengerd, S.A., 1959, Regional geology as related to the petroleum potential of the Lucero region, west-central New Mexico: New Mexico Geological Society, Guidebook 10, p. 121–134.

Salt casts (halite pseudomorphs) in the Arroyo de Alamillo Formation at Cerrillos del Coyote. Photo courtesy of Lewis Gillard.