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THE PENNSYLVANIAN SECTION IN THE LOS PINOS MOUNTAINS, SOCORRO COUNTY, NEW MEXICO

KARL KRAINER[1], SPENCER G. LUCAS[2], BRUCE D. ALLEN[3], JAMES E. BARRICK[4] , BRUCE BLACK[5] and PAUL A. MOORE[4]

[1]Institute of Geology, University of Innsbruck, Innrain 52, A-6020 Innsbruck, Austria, email: Karl.Krainer@uibk.ac.at;
[2]New Mexico Museum of Natural History, 1801 Mountain Road NW, Albuquerque, New Mexico 87104;
[3]New Mexico Bureau of Geology & Mineral Resources, 801 Leroy Place, Socorro, New Mexico 87801;
[4]Department of Geosciences, Texas Tech University, Box 41053, Lubbock, TX 79409;
[5]Black Oil Co., 206 W. 38th St., Farmington, NM 87401

Abstract—Pennsylvanian strata in the Los Pinos Mountains of Socorro County, New Mexico, nonconformably overlie Proterozoic granitic basement and are disconformably overlain by the lower Permian Bursum Formation. We assign the approximately 424 m thick Pennsylvanian section in the Los Pinos Mountains to the (ascending order) Sandia (172 m thick), Gray Mesa (45 m thick) and Atrasado (206 m thick) formations. The Sandia Formation is composed of a basal, siliciclastic unit of fluvial origin, overlain by marine mudstone with thin intercalated limestone, followed by a thick marine succession of dominantly mixed siliciclastic-carbonate, fossiliferous fine-grained conglomerate and sandstone with intercalated mudstone and limestone. This section of the Sandia Formation is unusually thick, and fusulinids and conodonts demonstrate that its upper 70 m are of Desmoinesian age. Limestone of the unusually thin Gray Mesa Formation is dominated by wackestone and floatstone with a diverse fossil assemblage indicating deposition in a low-energy, open, normal marine shelf environment. Limestones composed of microfacies that formed in high-energy settings are rare. The Atrasado Formation is composed of alternating siliciclastic-dominated and limestone-dominated intervals that can be arranged in eight lithostratigraphic members that are recognizable over a large part of central New Mexico. The Atrasado Formation is overlain by siliciclastic redbeds at the base of the Bursum Formation.

Several tectonic phases can be distinguished within the Pennslyvanian succession in central New Mexico (between Cedro Peak and the Cerros de Amado) based on occurrence of coarse sandstone and conglomerate in contrast to limestone. The main source of siliciclastic sediment was the Pedernal uplift to the east, and subordinately the smaller Joyita uplift to the southwest. The Sandia Formation represents the first tectonic phase of the Ancestral Rocky Mountain orogeny during the Atokan, starting locally during latest Morrowan time. At Sepultura Canyon the first tectonic phase lasted until the early Desmoinesian, documented by the Sandia sandstone facies. Dominantly marine limestone, the Gray Mesa Formation was deposited during a period of little tectonic activity. Four tectonic phases of rapid uplift of basement blocks are recorded by the clastic-dominated members of the Atrasado Formation. These tectonic phases are separated by three periods of tectonic quiescence during which mostly limestone was deposited.

INTRODUCTION

Situated 80 to 100 km south of Albuquerque, the Los Pinos Mountains are part of a north-northeast chain of mountains that border the east side of the Rio Grande Valley (Fig. 1). Geologically, the range is a basement-cored uplift that formed along the eastern margin of the Rio Grande rift during the late Cenozoic (Fig. 1). In this uplift, above a thick and complex basement core, sedimentary rocks of late Paleozoic (Pennsylvanian-Permian) age are exposed. The complete Pennsylvanian section was described in a generalized way in the older literature of New Mexico geology (Darton, 1922, 1928; Stark and Dapples, 1946). More recently, these rocks have been mapped at a scale of 1:24,000 (Myers et al., 1986; Allen et al., 2013a, 2014). Here, we present a detailed study of the Pennsylvanian strata in the Los Pinos Mountains based on the section exposed on their western flank, primarily in the area of Sepultura Canyon. Our goals are to detail the lithostratigraphy, sedimentary petrography, depositional environments and biostratigraphy of this Pennsylvanian section. Our interpretation of this section focuses on its lower part, which shows an unusual lithofacies relationship that has implications for regional tectonism of the Ancestral Rocky Mountain (ARM) orogeny.

PREVIOUS STUDIES

N.H. Darton (1922, pl. 38; 1928, p. 105-106, fig. 28E) published the first observations on the Pennsylvanian strata of the Los Pinos Mountains and referred to them as Magdalena group (Figs. 2-3). His report included a simple east-west cross section through the range (Fig. 2). Darton (1928, p. 106) noted that in the Los Pinos Mountains "the limestone of the Magdalena group shows a thickness of about 1,200 feet [366 m] and presents its usual characteristics," as seen in the Magdalena mining district west of Socorro, NM.

Wilpolt et al. (1946) mapped the geology of the Los Pinos Mountains as part of a regional investigation of geology and petroleum possibilities in north-central New Mexico. They used a lithostratigraphic nomenclature for the Pennsylvanian strata largely developed by workers of the U. S. Geological Survey, especially Gordon (1907) and Read and Wood (1947). Thus, Wilpolt et al. (1946) assigned the entire Pennsylvanian section to the Magdalena group divided into the Sandia formation and overlying Madera limestone. They considered the overlying Bursum formation to be Permian, and informally divided the Madera into a lower, gray limestone member and an upper, arkosic limestone member (Fig. 3).

Stark and Dapples (1946) described the geology of the Los Pinos Mountains, focusing mostly on the Precambrian rocks. They classified Pennsylvanian strata using then current series terminology. Their description of the Pennsylvanian strata (p. 1143-1153) presented generalized lithologic descriptions and organized the Pennsylvanian strata into "standard neritic cycles" (Wanless and Shepard, 1936) that they envisioned as marine depositional cycles in New Mexico and Texas. Stark and Dapples (1946) also proposed the name Aqua Torres Formation for strata now termed Bursum Formation (Lucas and Krainer, 2004; Krainer and Lucas, 2009). Their section of the "Derry series" [Atokan Stage] at "Turret Mesa" (p. 1165-1166; Turret Mesa is Sepultura Flat on current topographic maps) is essentially the same section as our Sepultura Canyon section of the Sandia Formation. They also described a section of the upper part of the Pennsylvanian strata at the southern end of the Los Pinos Mountains (p. 1169-1170).

Kottlowski (1960, fig. 12) presented Pennsylvanian stratigraphic sections from the southern Manzano Mountains southward through the Los Pinos Mountains based on Read et al. (1944) and Wilpolt et al. (1946) (Fig. 4). Kottlowski (1960, fig. 12) depicted the Pennsylvanian section at "Turret Mesa" to include substantial amounts of sandstone in the Derryan-Desmoinesian interval. He (p. 51) noted that "given definitions of the Sandia and Madera formations... the basal clastic

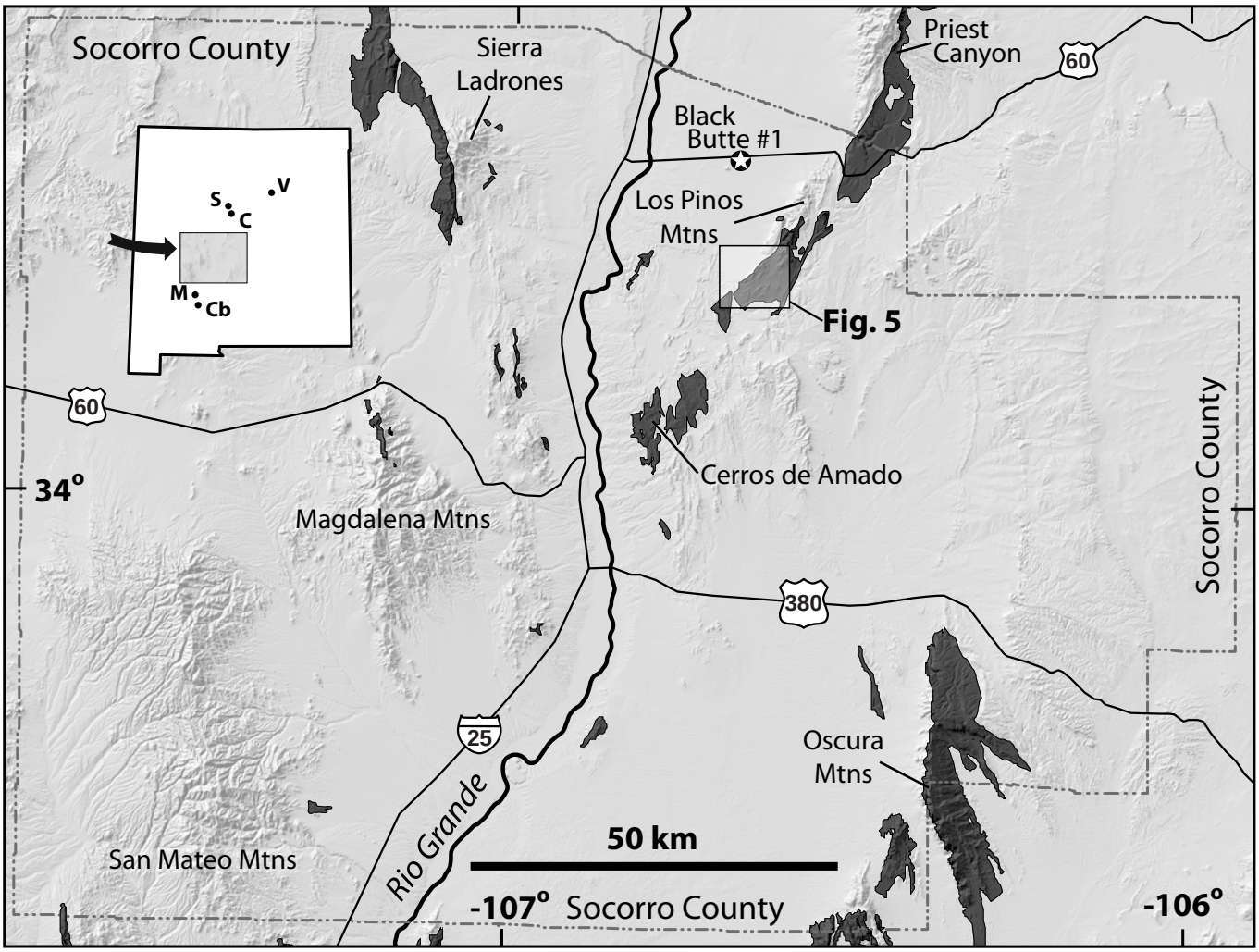


FIGURE 1. Index map of central New Mexico showing location of geologic map in Figure 5 and Pennsylvanian sections mentioned in the text. C = Cedro Peak, Cb = Caballo Mountains and Fra Cristobal Mountains to the north, M = Mud Springs Mountains, S = Sandia Mountains and type section of the Sandia Formation, V = Las Vegas. Dark gray area = Pennsylvanian outcrops.

phase attributed to the Madera limestone on Turret Mesa should be considered as part of the Sandia formation even if it does grade laterally into a limestone sequence. If facies are to be mapped, as is the stated intention when the Sandia and Madera formations are used, the contacts must be expected to cross time surfaces." We take this to mean that Kottlowki believed that much of the Desmoinesian interval at Turret Mesa should be assigned to the Sandia Formation on a lithological basis, even though these strata correlate to a portion of the Gray Mesa Formation elsewhere (see discussion below).

Siemers (1978, 1983) presented data and a review of the Pennsylvanian stratigraphy in Socorro County, but he presented no data from the Los Pinos Mountains. Myers et al. (1986) mapped the Becker SW quadrangle, which encompasses the Pennsylvanian stratigraphic sections we measured. They used the Pennsylvanian lithostratigraphic nomenclature proposed in the Manzano Mountains by Myers (1973), assigning the strata to the (ascending order) Sandia, Los Moyos, and Wild Cow formations (Fig. 3). Importantly, Myers et al. (1986) included measured stratigraphic sections of the Pennsylvanian strata and listed fusulinid biostratigraphic data. We have already explained in detail elsewhere (Lucas et al., 2014, 2016a) why Myers lithostratigraphic nomenclature should be abandoned and replaced with a nomenclature developed by Thompson (1942), Kelley and Wood (1946), Rejas (1965) and Lucas et al. (2009a).

Recently, Allen et al. (2013a) re-mapped the geology of the Becker SW quadrangle. They assigned the Pennsylvanian section to the Sandia, Gray Mesa and Atrasado formations, also recognizing eight members of the Atrasado Formation. This is the lithostratigraphic nomenclature we employ here (Fig. 3).

LITHOSTRATIGRAPHY AND PETROGRAPHY

We measured the complete Pennsylvanian succession (Sandia, Gray Mesa and Atrasado formations) at Sepultura Canyon and Cottonwood Well (Figs. 5-13). The total thickness of the three formations we recognize is approximately 424 m (Sandia Formation: 172 m; Gray Mesa Formation: 45 m; Atrasado Formation: 206 m).

Sandia Formation

Herrick (1900) introduced the name "Sandia series" for a succession of shale, sandstone, conglomerate, and minor sandy limestone in central New Mexico. The name refers to the Sandia Mountains, which form the skyline east of Albuquerque (Fig. 1). With minor modifications, most subsequent authors applied "Sandia Formation" in the Los Pinos Mountains and neighboring ranges, and we continue that usage here (Krainer and Lucas, 2013).

At Sepultura Canyon, the Sandia Formation (Figs. 6-7) is thicker than all other sections we have measured of this formation (172.2 m), even thicker than at the Cerros de Amado, east of Socorro (Lucas et al., 2009a; Krainer et al., 2017), at Priest Canyon in the southern Manzano Mountains (Lucas et al., 2016a) and at the type section of the Sandia Formation in the Sandia Mountains (Krainer et al., 2011; also see Krainer and Lucas, 2013). At Sepultura Canyon, the Sandia Formation is composed of sandstone and rare conglomerate (55.7% of the measured section thickness), shale-siltstone/covered (shale-siltstone) intervals (40.2%) and limestone, comprising 4.1% of the total measured thickness. It nonconformably overlies the Proterozoic Los Pinos Granite, a pale reddish gray to pink and intense red, medium to coarse-grained massive rock that contains dikes of pegmatite and

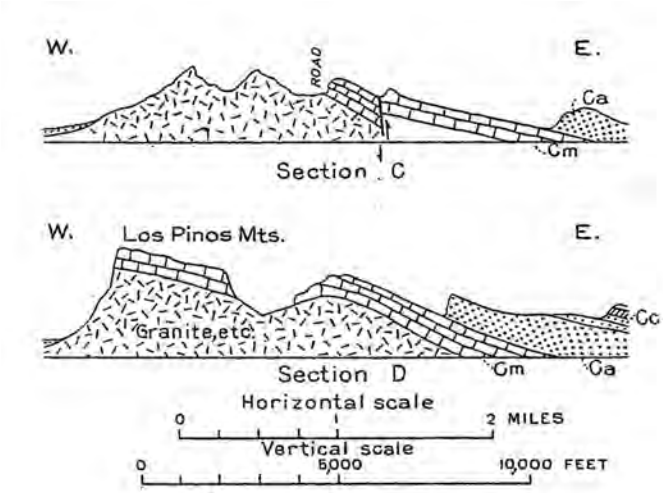


FIGURE 2. Darton's (1928, fig. 28) cross section through the Los Pinos Mountains. Cm = Magdalena group; Ca = Abo sandstone; and Cc = Chupadera formation.

aplite together with siliceous and iron-magnese oxide veins (Allen et al., 2013a).

We identify the top of the Sandia Formation as the stratigraphically highest quartzose sandstone, below beds of cherty limestone at the base of the Gray Mesa Formation (Fig. 7). This identification of the Sandia-Gray Mesa contact is consistent with lithostratigraphic definition of the Sandia-Gray Mesa contact used by Krainer et al. (2011) at the lectostratotype section of the Sandia Formation, and at other outcrops of the Sandia Formation in central New Mexico (Krainer and Lucas, 2013a).

For the sake of discussion, the Sandia Formation at Sepultura Canyon (Fig. 7) can be divided into three units: (1) a lower, siliciclastic unit (18.4 m) at the base; (2) a middle, dominantly shale-siltstone unit (11.4 m); and (3) an upper, thick succession of dominantly fine-grained, mixed siliciclastic-carbonate, fossiliferous conglomerate and sandstone with intercalated shale and limestone (142.5 m) (Fig. 7).

Lower Unit

The lower unit is composed of quartz-rich conglomerate and sandstone, and covered intervals (Fig. 7). The Proterozoic basement, which is locally composed of granite, is overlain by a poorly sorted breccia up to 1.6 m thick that fills an erosional surface that exhibits up to 1.2 m of relief. The breccia contains abundant angular quartz boulders and some metamorphic clasts with a maximum grain size of 30 cm that float in sandy matrix.

The overlying conglomerate (2.3 m) is clast-supported, displays crude crossbedding and is composed of subangular quartz grains. On top, a massive, pebbly sandstone (0.2 m) is exposed, followed by a covered interval (1 m). Above follows pebbly sandstone with a maximum grain size of 2 cm. This interval displays poorly developed crossbedding and is overlain by sandy conglomerate composed of poorly-sorted, subrounded quartz clasts and a covered interval (1.2 m), followed by crossbedded sandstone with thin pebbly layers containing rip-up clasts. Above are two covered intervals (2.8 and 3.7 m) separated by a thin pebbly sandstone bed (0.2 m). The top of this lower unit is formed by trough-crossbedded quartzose sandstone (1.8 m).

In the lower unit of the Sandia Formation section, fine-grained conglomerate is poorly-sorted, and the clasts are subangular to subrounded. Coarse-grained sandstone is moderately- to poorly-sorted, and medium- to fine-grained sandstone is dominantly moderately sorted. The grains in the sandstone are mostly subrounded. Both the conglomerate and sandstone are mainly composed of mono- and polycrystalline quartz grains (Figs. 9A-B). In conglomerate and coarse-grained sandstone, polycrystalline quartz is more abundant

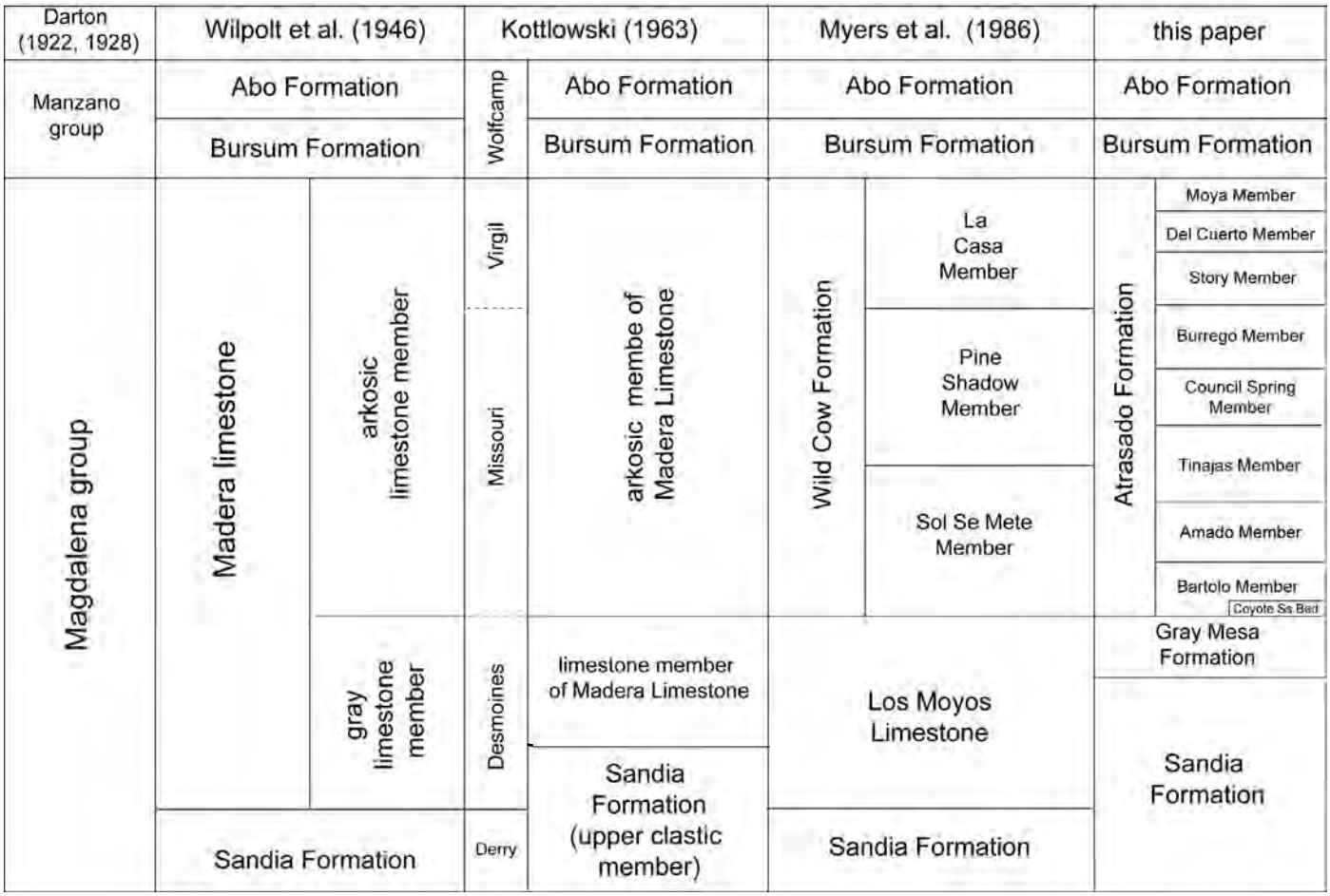


FIGURE 3. Development of Pennsylvanian lithostratigraphic nomenclature in the Los Pinos Mountains.

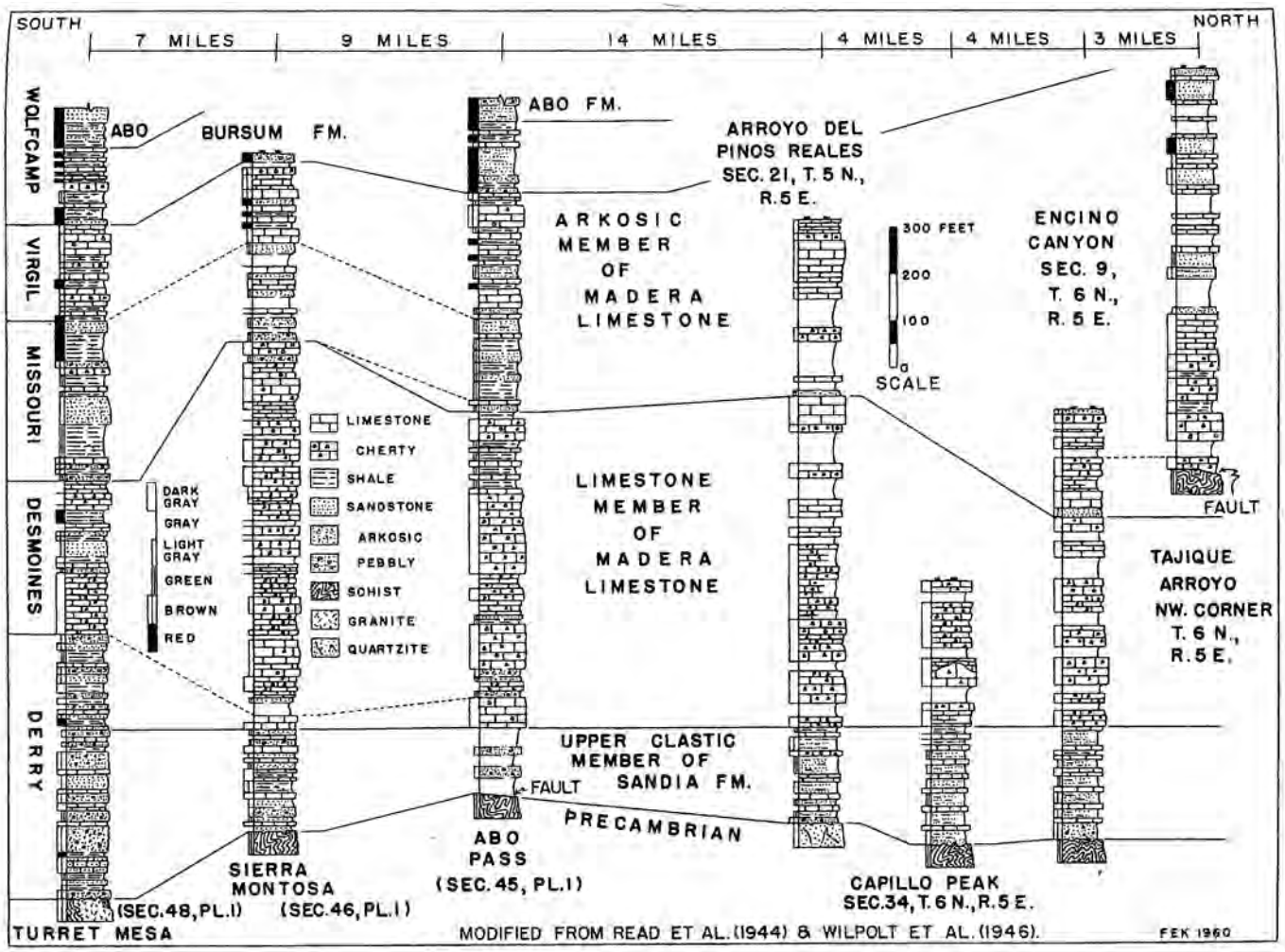


FIGURE 4. Sections of Pennsylvanian strata in the Manzano and Los Pinos mountains (from Kottlowski, 1960, fig. 12). Although Kottlowski did not depict intertonguing, abrupt thinning of the Gray Mesa at Turret Mesa is evident, and it appears that the Sandia-Gray Mesa contact is younger there than at the other localities.

than monocrystalline quartz. In medium- to fine-grained sandstone, monocrystalline quartz grains dominate. Other grain types are rare and include granitic and fine-grained schistose metamorphic rock fragments. Detrital feldspar grains are very rare to absent. Detrital mica and other grain types are absent.

Conglomerate and sandstone either contain matrix and rare quartz overgrowths on detrital quartz grains or, rarely, they are cemented by quartz that is present as well-developed authigenic overgrowths (Figs, 9A-B). Rarely, calcite cement is present. As the fine-grained conglomerates and sandstones are almost entirely composed of quartz grains with rare other grain types, they plot into the field of quartzarenite, and those at the base of the Sandia Formation into the field of sublitharenite in the classification scheme of Pettijohn et al. (1987) (Fig. 14).

Middle Unit

The lower unit is overlain by 11.4 m of dominantly shale-siltstone with intercalated greenish siltstone to fine-grained sandstone, bedded micaceous black limestone and two thin limestone beds (Fig. 7). These strata generally erode to a gentle slope and are well exposed only in gullies. Shale below the greenish siltstone to fine-grained sandstone is black to dark-gray, and is greenish above the greenish siltstone to fine-grained sandstone bed. The micaceous black limestone is bedded and contains a few brachiopods.

Two intercalated limestone beds are 0.2 m thick. Under the microscope the lower limestone bed appears as a fine-grained, mixed siliciclastic-carbonate sandstone (average grain-size 0.1-0.2 mm). The sandstone is composed of monocrystalline and a few polycrystalline quartz grains, many carbonate grains and detrital micas (mostly muscovite) that are oriented parallel to the bedding. Fossils include abundant shell fragments, mostly of ostracods, subordinately of brachiopods, some brachiopod spines and a few phosphatic shells (*Lingula*?).

Upper Unit

The fine-grained middle unit is overlain by a thick succession that is mostly composed of conglomerate and sandstone with intercalated shale and limestone (Fig. 7). These rocks crop out as a series of ledges on the steep slope that lies below the prominent "caprock" of Gray Mesa limestone (Fig. 6). Within the conglomerate and sandstone facies the following lithotypes can be distinguished:

- Fine-grained conglomerate, massive and trough crossbedded, poorly sorted, containing pebbles up to 5 cm in diameter. Pebbles are mostly quartz; in units 72 and 75 abundant reworked carbonate pebbles are also present. The conglomerate is fossiliferous, contains abundant crinoid fragments and subordinately other fossil fragments such as brachiopods and bryozoans. Individual conglomerate units are up to 2.8 m thick.
- The most common lithofacies is fine- to coarse-grained sandstone and pebbly sandstone displaying trough crossbedding. Individual units contain quartz clasts up to 3 cm in diameter. The composition is mixed siliciclastic-carbonate with abundant fossil fragments, particularly crinoidal debris, a few brachiopods and bryozoans. The thickness of individual units ranges from 0.5 to 13 m.
- Sandstone displaying horizontal lamination, mostly fine-grained and micaceous. Locally, thin pebbly layers and thin sandstone layers displaying small-scale trough crossbedding are intercalated. The maximum thickness of individual units is 2.9 m.

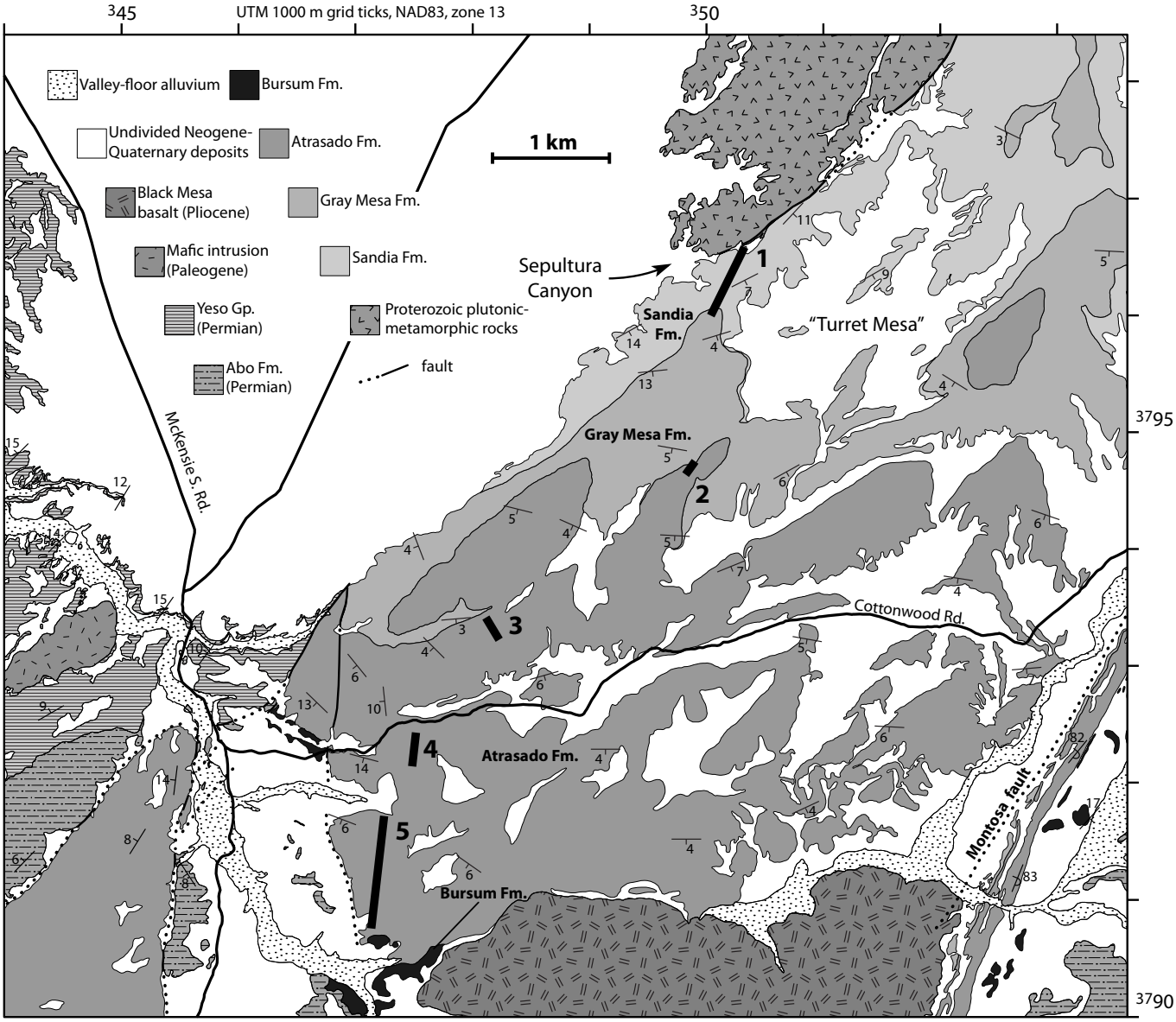


FIGURE 5. Geologic map of the Sepultura Canyon-Cottonwood Well area (after Allen et al., 2013a) showing location of the measured stratigraphic sections of Pennsylvanian rocks in Figures 7-8. Area of map shown on Fig. 1.

- Massive sandstone beds are intercalated in the lower part. Thickness is 0.3-0.4 m.

Shale-siltstone and covered intervals (most likely representing shale-siltstone) in the lower part measure 0.2-2.3 m and are up to 14.3 m thick in the upper part of the upper unit.

Six thin limestone intervals are intercalated. The lowermost limestone interval includes thin-bedded, nodular limestone (bioclastic wackestone; 0.7 m), a covered interval (0.8 m) and a massive muddy limestone bed (bioclastic wackestone to floatstone; 0.7 m). The second limestone interval is 1.5 m thick and represented by bedded wackestone to packstone. The third limestone interval includes two bedded, crinoidal limestone units (rudstone; 0.8 and 0.5 m thick) containing brachiopods. The two limestone intervals are separated by a thin covered interval (0.6 m). The fourth limestone interval measures 0.6 m and is a bedded limestone composed of bryozoan wackestone to floatstone. The fifth interval is bedded crinoidal limestone containing brachiopods, 0.5 m thick. The sixth interval is exposed near the top and is a 0.3 m thick, bedded limestone containing abundant brachiopods.

In the upper part of the Sandia Formation, some fining- and deepening-upward cycles (transgressive cycles) are developed. Each cycle starts with a conglomerate or pebbly sandstone at the base, grading into crossbedded sandstone, covered (shale-siltstone) and limestone on top (Fig. 7).

Petrographically, two types of conglomerate and sandstone are distinguished: arkosic sandstone and mixed siliciclastic-carbonate sandstone (packstone-rudstone). Arkosic sandstone is rare (Fig. 9C-D). The sandstone is medium to coarse grained and moderately to poorly sorted; detrital grains are mostly subangular to subrounded. The dominant grain types are mono- and polycrystalline quartz, and detrital feldspars that are almost entirely potassium feldspars (untwinned orthoclase, some microcline and perthitic feldspars). Most of the detrital feldspars appear fresh, but a few are altered. The sandstone contains small amounts of granitic rock fragments and fine-grained schistose metamorphic rock fragments. Micas are rare and mainly represented by muscovite, rarely by biotite. Fossils are rare and include bryozoans and echinoderms. Detrital quartz grains display authigenic overgrowths. Locally, coarse blocky calcite cement is present. The sandstone contains small amounts of matrix that is probably pseudomatrix formed by the alteration of detrital feldspars. Arkosic sandstones plot into the field of subarkose and arkose (Fig. 9C), rarely into the field of sublitharenite (Fig. 9D), (classification scheme of Pettijohn et al.,1987) (Fig. 14).

Mixed siliciclastic-carbonate sandstone (packstone-rudstone) is moderately to poorly sorted and contains siliciclastic grains in varying amounts (Fig. 9E, G). The sandstone grades into packstone and rudstone with only small amounts of siliciclastic grains (Fig. 9F, H). Siliciclastic grains are angular to subangular and mainly represented

FIGURE 6. Photograph of most of the Sepultura Canyon section (Fig. 7) looking east, showing very thick Sandia Formation section between Proterozoic basement and thin Gray Mesa Formation capping the plateau.

by mono- and polycrystalline quartz. Detrital feldspars are rare and dominantly potassium feldspars, including microcline. Plagioclase is very rare. The feldspar grains are altered and partly replaced by calcite. Other siliciclastic grains include muscovite, greenish grains (chlorite or glauconite), rare granitic rock fragments, phosphorite grains and opaque grains. A few carbonate grains (sedimentary rock fragments) are also present.

The sandstone contains abundant fossil fragments (Fig. 9E-H). Most common are fragments of crinoids, brachiopods and bryozoans. Fragments of brachiopod spines, ostracods, smaller foraminifers, small fusulinids, gastropods, trilobites and, probably, calcareous algae are subordinate to rare. Rarely, a diverse foraminiferal assemblage, including small fusulinids, is present. Locally, the skeletons are encrusted by cyanobacteria (*Girvanella*) and *Palaeonubecularia*, partly forming oncoids. The sandstone is partly poorly washed, containing carbonate matrix and calcite cement, partly well washed and cemented by coarse blocky calcite.

Intercalated limestone is composed of the following microfacies types:

- Bioclastic wackestone containing a diverse fossil assemblage, including recrystallized skeletons, abundant phylloid algae, and, subordinately, echinoderm fragments, ostracods, bryozoans, smaller foraminifers (including calcivertellids, *Earlandia, Syzrania, Tetrataxis, Tuberitina*), gastropods, brachiopods, rare fusulinids and trilobites. A few skeletons are encrusted by cyanobacteria and sessile foraminifers. Non-skeletal grains are peloids and rare micritic intraclasts. Locally, the wackestone is bioturbated and grades into floatstone containing larger fragments of recrystallized phylloid algae (Fig. 10A).
- Bryozoan wackestone to floatstone (Fig. 10B) contains abundant, partly large bryozoan fragments, and subordinately echinoderm fragments, brachiopods, ostracods and rare smaller foraminifers. A few detrital quartz grains are present, too.
- Grainstone, packstone and rudstone (Fig. 10C-D) contain abundant bryozoans and echinoderms, and subordinately brachiopods, gastropods, smaller foraminifers and rare fusulinids. The fossils are strongly fragmented. Non-skeletal grains include a few micritic intraclasts and rare, small detrital quartz grains. The rudstone is moderately to poorly sorted and poorly washed, containing some micritic matrix, and locally is well washed with coarse, blocky calcite cement.

Gray Mesa Formation

Kelley and Wood (1946) proposed the name Gray Mesa Member (of Madera Formation) for the unit that some previous authors informally called the gray limestone member. The name "Gray Mesa" refers to a landform that is labeled Mesa Aparejo on current maps, on the west side of the Rio Grande about 60 km northwest of the Los Pinos Mountains. Myers (1973) gave the name Los Moyos Limestone to strata that are essentially the same as the Gray Mesa in the Los Pinos Range. However, the name Gray Mesa has priority over Los Moyos, and the unit is readily mappable (Kues, 2001). Therefore, we follow Kues and Nelson et al. (2013b) and designate this prominent, distinctive unit as the Gray Mesa Formation.

The Gray Mesa is composed predominantly of limestone, with minor interbeds of shale and sandstone. This formation forms cliffs and bold ledges, including the "caprock" at the mouth of Sepultura Canyon (Fig. 6).

At Sepultura Canyon, the Gray Mesa Formation is only 45 m thick, much thinner than at several nearby localities (e.g., Priest Canyon 192 m: Lucas et al., 2016a; Cedro Peak; 119 m: Lucas et al. 2014; Arroyo de la Presilla 233 m: Lucas et al., 2009a; Krainer et al., 2017; also see Nelson et al., 2013b). Moreover, the Gray Mesa here cannot be divided into the three members recognized in sections to the south (Cerros de Amado) and north (Priest Canyon, etc.) (Figs. 6-7). The limestone facies contains the same lithologies as reported from other sections. Chert is common in some beds, particularly in the lower part of the formation. Siliciclastic sediments, which are intercalated in the Gray Mesa Formation at other locations (e.g., Priest Canyon), are absent at Sepultura Canyon.

The base of the Gray Mesa Formation is stratigraphically just above the stratigraphically highest quartzose sandstone bed at the top of the Sandia Formation. In our section (Fig. 7), the top of the Gray Mesa Formation is limestone just below a relatively thick succession of crossbedded sandstone, the Coyote Bed of the Bartolo Member at the base of the Atrasado Formation (Fig. 7, units 132-133).

The dominant lithology of the lower part of the Gray Mesa Formation at Sepultura Canyon is even and wavy bedded limestone with bed thicknesses of mostly 10-20 cm. One thicker limestone bed is present (0.9 m thick) near the top of the lower part. Even-bedded limestone is free of chert, and wavy bedded limestone contains abundant chert nodules that are mostly less than 10 cm in diameter. Fossils

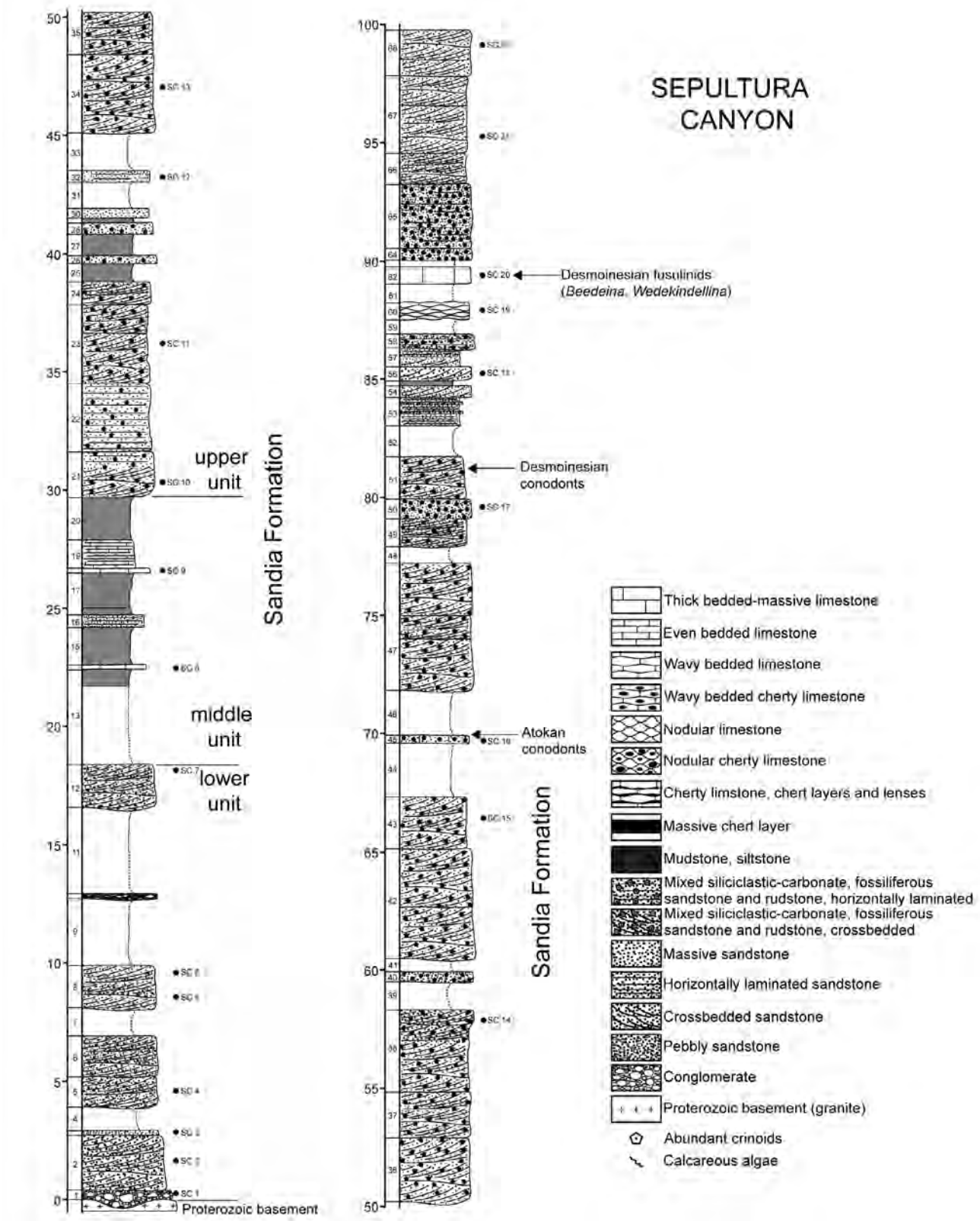


FIGURE 7. Measured stratigraphic section of the Sandia, Gray Mesa and Atrasado (lower part) formations at Sepultura Canyon. See Figure 5 and the Appendix for location of the section.

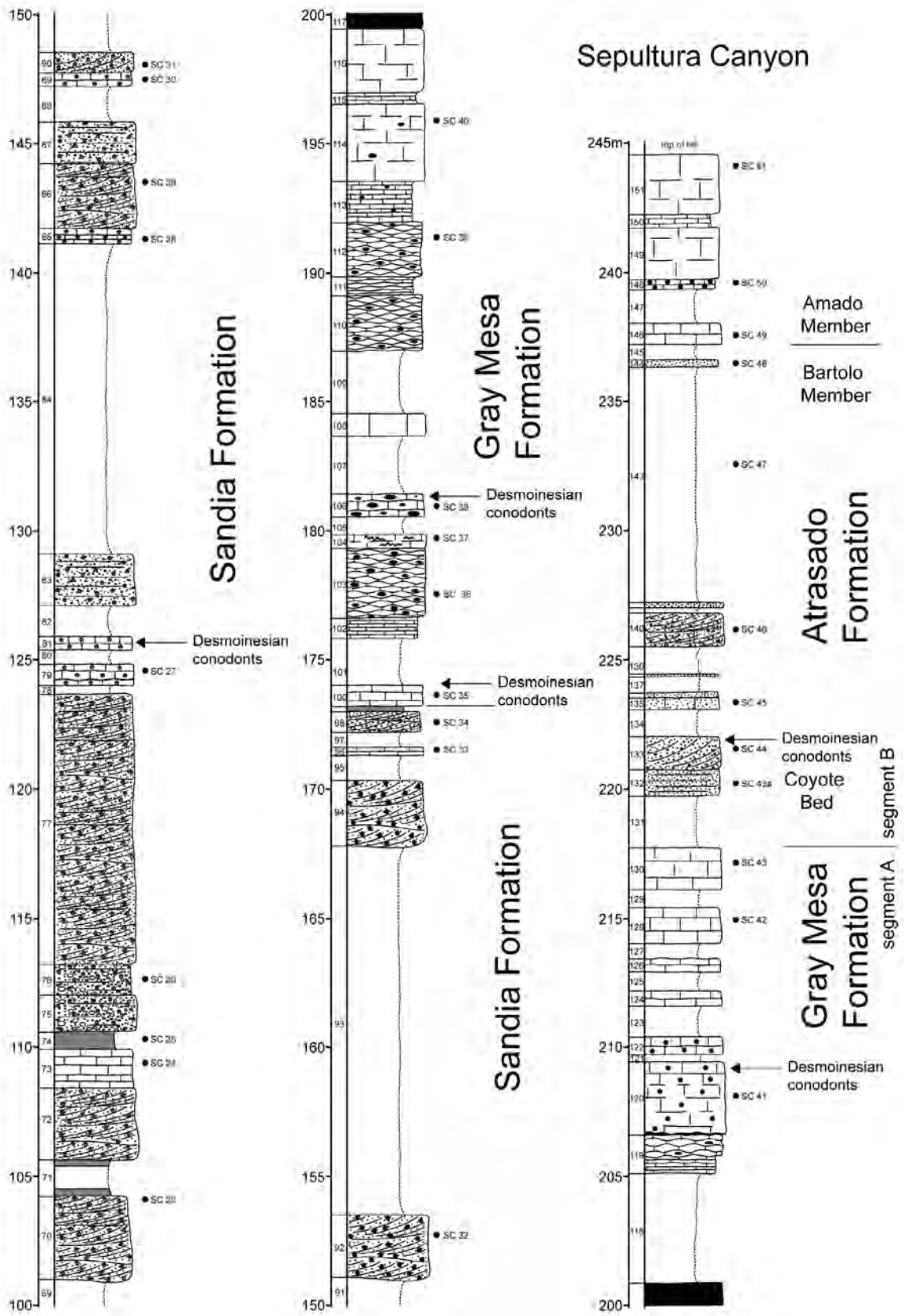


FIGURE 7 (continued). Measured stratigraphic section of the Sandia, Gray Mesa and Atrasado (lower part) formations at Sepultura Canyon. See Figure 5 and the Appendix for location of the section.

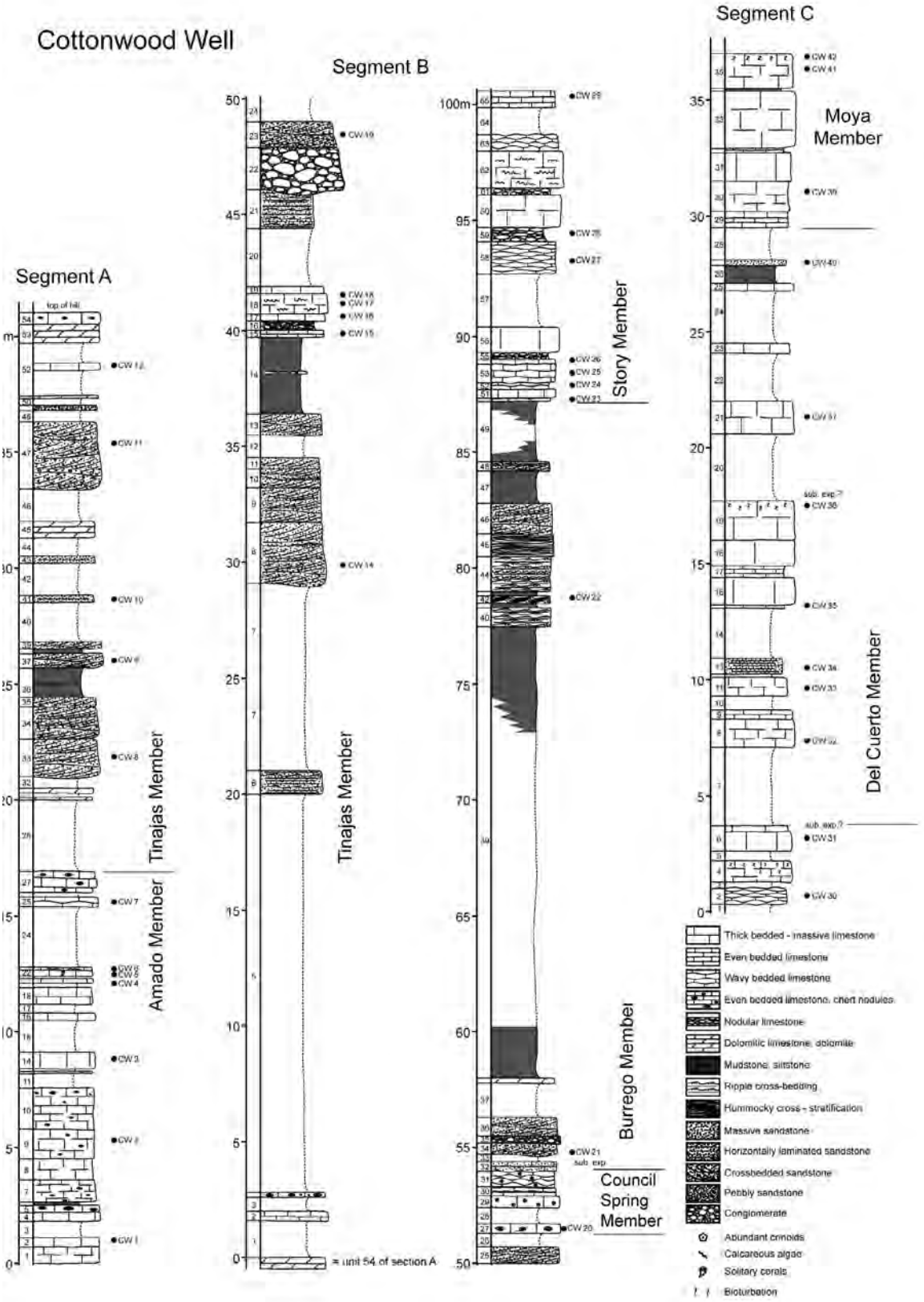


FIGURE 8. Measured stratigraphic section of the Atrasado Formation at Cottonwood Well. See Figure 5 and the Appendix for location of the section.

observed on outcrop are crinoidal debris, brachiopods and bryozoans. One limestone interval contains phylloid algae. The limestone intervals are separated by covered intervals that are 0.7-2.5 m thick.

The middle part of the Gray Mesa Formation at Sepultura Canyon is composed of thin, even and wavy bedded cherty limestone, indistinctly bedded limestone with little chert, and indistinctly bedded limestone free of chert. A massive chert interval (1.4 m thick) is also present.

The upper part of the Gray Mesa Formation at Sepultura Canyon starts with a covered interval, followed by thin, even and wavy bedded limestone with a few chert nodules and a thin (5 cm) chert band on top. This basal limestone interval is 1.5 m thick. The bulk of the upper part of the Gray Mesa Formation is composed of indistinctly, and mostly even-bedded limestone (bed thickness 20-40 cm). Individual limestone intervals are 0.5-4.3 m thick and are separated by covered intervals that are 0.3-4.3 m thick. Crinoidal limestone locally displays crossbedding. Fossils recognized in the field include crinoidal debris, brachiopods and bryozoans.

The microfacies and fossil assemblages of the Gray Mesa Formation at Sepultura Canyon are very similar to those of other sections that were described in detail recently, e.g., Cedro Peak in the Manzanita Mountains (Lucas et al., 2014), Priest Canyon in the southern Manzano Mountains (Lucas et al., 2016a), and the Cerros de Amado northeast of Socorro (Lucas et al., 2009a; Krainer et al., 2017). The dominant microfacies of the Gray Mesa Formation is bioclastic wackestone that locally grades into floatstone. Bioclastic wackestone to floatstone contains a diverse fossil assemblage dominated by echinoderm (crinoid) fragments, brachiopods and bryozoans, and, subordinately, smaller foraminfers, fusulinids, ostracods, gastropods and trilobites (Fig. 10F-G). Locally, abundant phylloid algae are present (phylloid algal wackestone to floatstone). Other microfacies types are rare and include bioclastic packstone (Fig. 10H), crinoidal packstone to grainstone, and bryozoan floatstone (see detailed descriptions of Gray Mesa microfacies in Lucas et al., 2014, 2016a, b). Oolitic grainstone also is present at the base of the Gray Mesa Formation in the Los Pinos Mountains (Fig. 10E).

Atrasado Formation

Kelley and Wood (1946) proposed the name Atrasado Member (of Madera Formation) for the unit previously called the arkosic limestone member. An intermittent stream about 10 km southwest of Mesa Aparejo (Gray Mesa) is the source of the name. However, the stream formerly called Atrasado Arroyo is now Arroyo Alamito. Myers (1973) introduced the name Wild Cow Formation for the same rocks in the Los Pinos Mountains; the name Atrasado enjoys priority and this unit is readily mappable at the scale of a formation (Kues, 2001). Following Kues and Nelson et al. (2013a), we apply the term Atrasado Formation to the strata of alternating limestone and siliciclastic rocks overlying the Gray Mesa Formation.

The Atrasado Formation in the southern Los Pinos Mountains is approximately 204 m thick, which is thinner than at Priest Canyon in the southern Manzano Mountains (272 m: Lucas et al., 2016a) or in the Cerros de Amado east of Socorro (290 m: Lucas et al., 2009a; Krainer et al., 2017). In the Los Pinos Mountains, the Atrasado Formation (Figs. 7-8) is composed of alternating siliciclastic-dominated and limestone-dominated members (in ascending order): Bartolo Member (siliciclastic-dominated; 19.5 m), Amado Limestone Member (limestone-dominated; 24 m), Tinajas Member (siliciclastic-dominated; 62 m), Council Spring Limestone Member (limestone-dominated; 2.2 m), Burrego Member (siliciclastic-dominated; 45.3 m), Story Limestone Member (limestone-dominated; 17.1 m), Del Cuerto Member (mixed limestone-siliciclastic; 25.8 m) and Moya Limestone Member (limestone-dominated; 7.5 m). The base of the Atrasado Formation is crossbedded sandstone above the limestone of the Gray Mesa Formation (with a thin covered interval intervening: Fig. 7). The stratigraphically highest limestone of the Atrasado Formation is overlain by red mudstone at the base of the Bursum Formation (Fig. 8).

In general, siliciclastic-dominated members of the Atrasado Formation are thicker than the limestone-dominated members and composed of shale/siltstone (mostly covered), intercalated sandstone and rare conglomerate. Intercalated limestone beds and thin limestone units are rare in these members. Limestone-dominated members are composed of different lithotypes of non-cherty limestone, less commonly of cherty limestone, and covered (shale/siltstone) intervals. Coarse-grained siliciclastic sediments are absent. The limestone members form cliffs and bold ledges and are widely continuous and uniform in thickness from the Oscura Mountains to the southern Sandia Mountains. The silicilastic members erode to slopes or step-and-ledge topography and are far more variable in thickness and lithology than the limestone members.

Bartolo Member

The Bartolo Member (19.5 m thick) starts with a covered interval (2 m), followed by alternating sandstone and covered (shale/siltstone) intervals. The basal 2-3 m of laminar and crossbedded sandstone are the Coyote Bed (see Lucas et al., 2014, 2016a). The sandstone facies are composed of the following lithotypes:

- Individual sandstone beds, medium to coarse grained, massive, 0.1-0.3 m thick
- Mixed siliciclastic-carbonate sandstone, massive, 0.4 m thick
- Horizontally laminated arkosic sandstone, coarse grained, 1 m thick.
- Trough-crossbedded, mixed siliciclastic-carbonate sandstone-rudstone, coarse grained, fossililferous, containing abundant crinoid fragments, and subordinately brachiopods and bryozoans. This lithotype is identical to that described from the Sandia Formation above.

Covered intervals of the Bartolo Member probably represent mudstone-siltstone and are 0.2-9.1 m thick. Regionally, the Bartolo is largely composed of greenish to olive-gray, non-calcareous silty shale and siltstone.

Amado Limestone Member

The Amado Member (24 m thick) is composed of limestone and a few covered intervals that probably contain mudstone, shale, and nodular limestone (Figs. 7-8). Within the limestone facies the following lithotypes are distinguished:

- Individual limestone beds, 0.1-0.7 m thick
- Thin- to medium-bedded limestone intervals, 0.5 m thick
- Thin-bedded crinoidal limestone, 0.4 m thick
- Medium-bedded limestone containing chert nodules, 0.7 m thick
- Indistinctly thick-bedded limestone lacking chert (0.7-0.9 m thick)
- Indistinctly thick-bedded limestone with a few chert nodules

Limestone is even bedded, and wavy bedding is very rare. Fossils observed in the field are brachiopods, crinoidal debris and, in the upper part, silicified corals and phylloid algae. Covered intervals are 0.1-2.6 m thick.

Tinajas Member

The Tinajas Member (62 m thick) is by far the thickest of the Atrasado members (Fig. 8). It is characterized by many covered intervals that are up to 17.2 m thick and that most likely represent mudstone/siltstone. Mudstone/siltstone is rarely exposed in the lower and upper part. The sandstone facies include individual sandstone beds and thicker sandstone units. We distinguished the following lithotypes:

- Thin, massive sandstone beds, fine and coarse grained, greenish, 0.2-0.3 m thick.
- Thin, horizontally laminated sandstone bed, fine grained, greenish, micaceous, 0.3 m thick.
- Thin arkosic sandstone beds, greenish, with small-scale trough crossbedding.
- Fine-grained micaceous sandstone, horizontally laminated and ripple laminated, burrows on top, 1 m thick.
- Thicker sandstone intervals, medium to coarse grained, displaying small-scale trough crossbedding and, locally, soft-sediment deformation structures, 0.5-1.5 m thick.
- Thicker sandstone intervals, coarse grained, pebbly, with thin conglomerate lenses (clasts up to 5 cm), displaying large-scale trough crossbedding and, locally, soft-sediment deformation structures. These sandstones are composed of abundant quartz clasts and many granite clasts.
- Greenish mudstone-siltstone is exposed in the lower part (1.3 m thick) and uppermost part (3.3 m thick with a thin layer of limestone nodules containing fossils).
- Covered intervals are 0.2-17.2 m thick and most likely represent mudstone-siltstone.

In the lower 26 m of the Tinajas Member, thin dolomitic limestone and limestone are intercalated. Dolomitic limestone is present as 0.1-0.2 m thick beds and 0.7-0.8 m thick, bedded intervals. Limestone is represented by a 0.2 m thick, very cherty limestone bed and a 0.5 m thick limestone bed containing a few chert nodules.

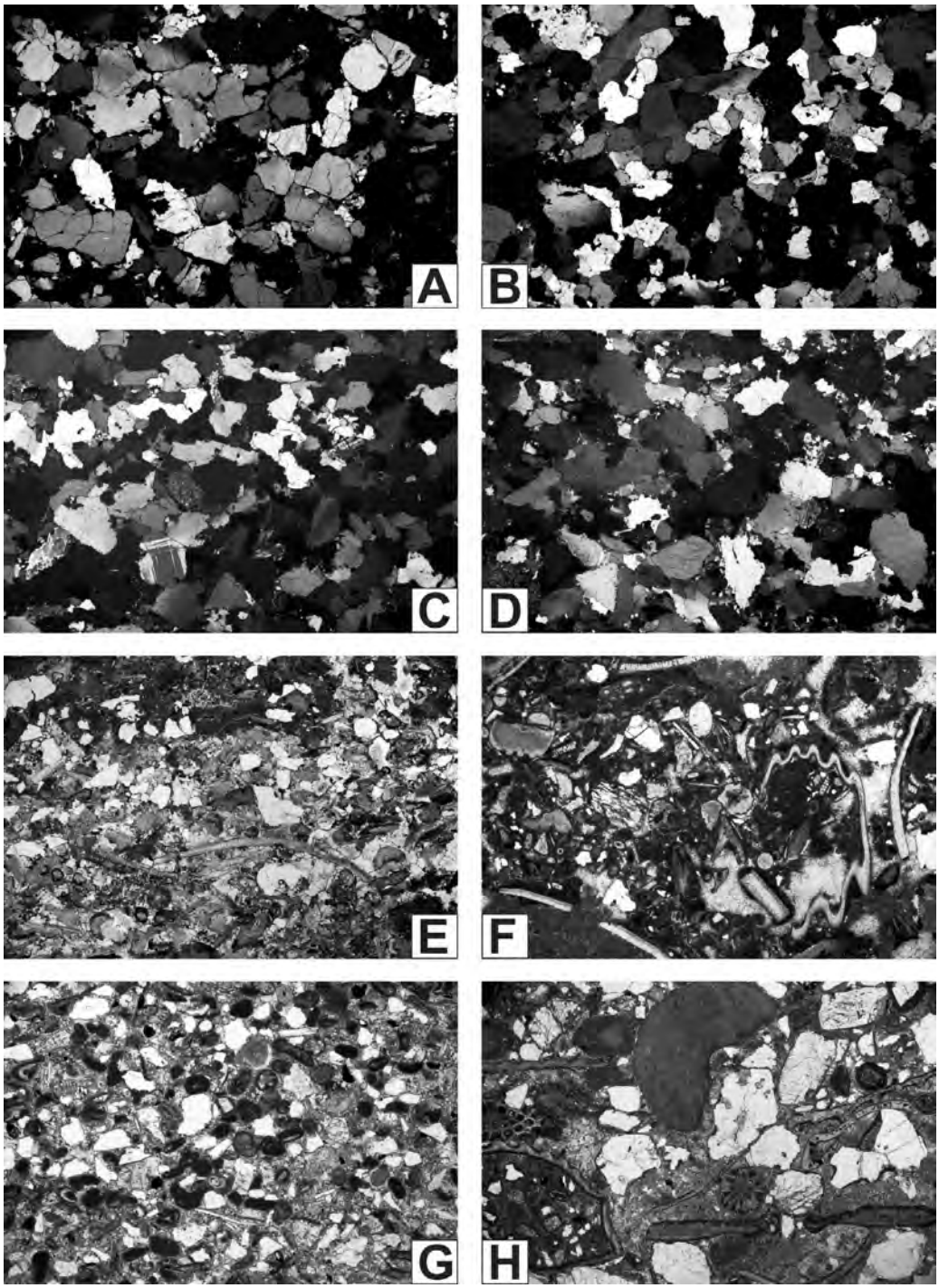


FIGURE 9. Thin section photographs of sandstone and rudstone of the Sandia Formation at Sepultura Canyon. Photos A-D under polarized light, E-H under plane light. Width of photographs: A, D, E, F, H = 9 mm; B, C, G = 4.6 mm. **A,** Coarse-grained, moderately sorted sandstone composed of abundant mono- and polycrystalline quartz and very rare granitic and metamorphic rock fragments (quartz arenite). Detrital quartz grains display authigenic overgrowths. Sample SC 2, Sandia Formation, lower part. **B,** Moderately sorted sandstone composed of mono- and polycrystalline quartz and rare granitic and metamorphic rock fragments (quartz arenite). Detrital quartz grains are cemented by quartz which occurs as authigenic overgrowths. Sample SC 6, Sandia Formation, lower part. **C,** Medium-grained sandstone composed of mono- and subordinate polycrystalline quartz, detrital feldspars, granitic and metamorphic rock fragments, rare mica (arkose). Detrital quartz grains display authigenic overgrowths. Sample SC 13, Sandia Formation, middle part. **D,** Coarse-grained, moderately sorted sandstone composed of mono- and polycrystalline quartz, detrital feldspars and granitic rock fragments (sublitharenite). Many quartz grains display authigenic overgrowths. Sample SC 18, Sandia Formation, middle part. **E,** Mixed siliciclastic-carbonate sandstone–rudstone composed of abundant crinoid fragments, brachiopods, bryozoans and many detrital quartz grains, cemented by calcite. Sample SC 11, Sandia Formation, middle part. **F,** Rudstone containing fragments of crinoids, brachiopods, bryozoans, rare fusulinids, trilobites, gastropods and some detrital quartz grains. Rudstone is poorly washed and contains both micritic matrix and calcite cement. Sample SC 17, Sandia Formation, middle part. **G,** Mixed siliciclastic-carbonate sandstone containing detrital quartz and feldspar grains, a few rock fragments and many fossil fragments such as echinoderms (crinoids), brachiopods, bryozoans, smaller foraminifers, some intraclasts and few peloids, cemented by calcite. Sample SC 24, Sandia Formation, upper part. **H,** Rudstone composed of fragments of crinoids, brachiopods, bryozoans, detrital quartz and feldspar grains and rare granitic rock fragments, cemented by calcite. Sample SC 34, Sandia Formation (top).

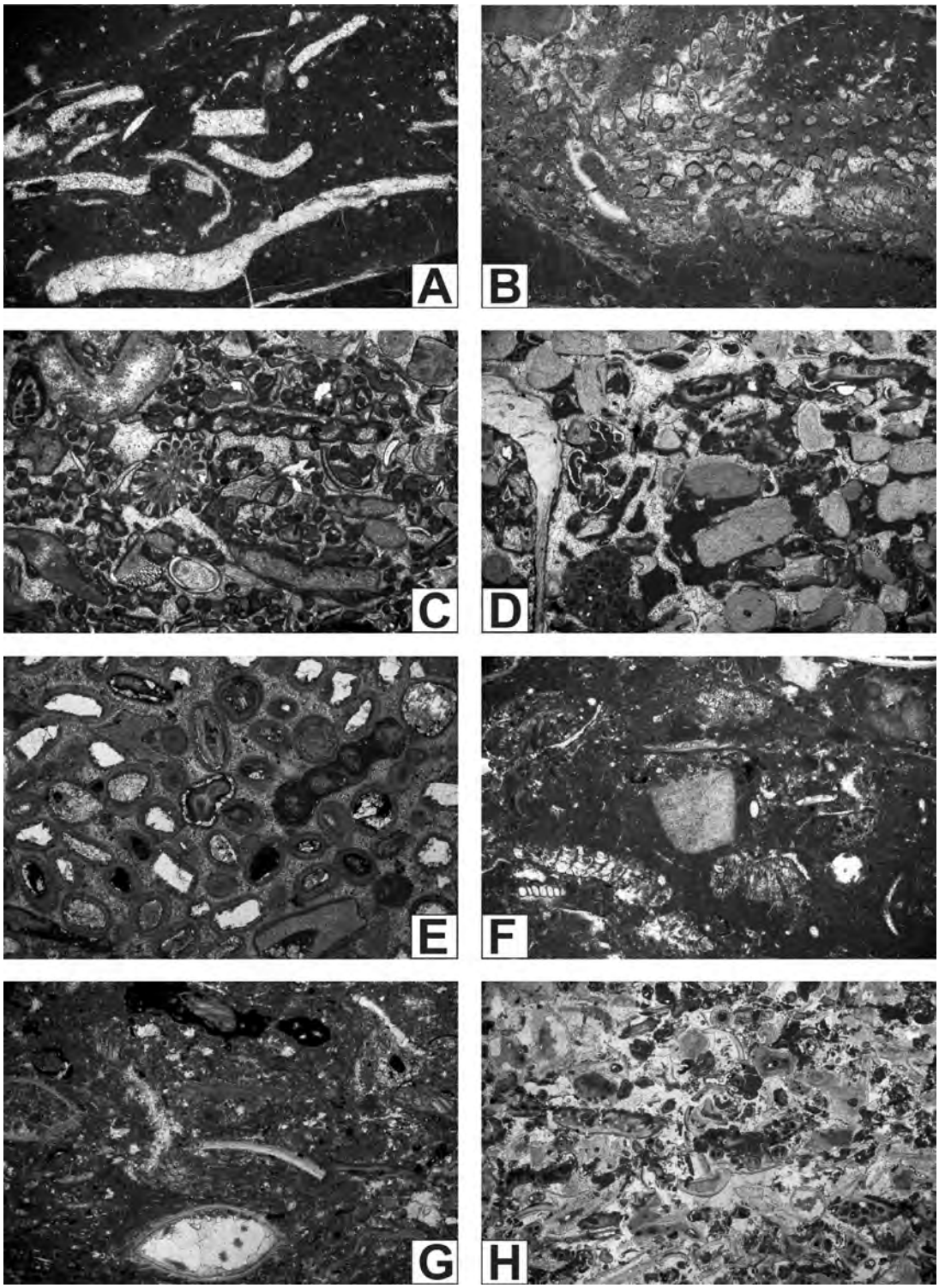


FIGURE 10. Thin section photographs of limestone of the Sandia Formation (A-D) and Gray Mesa Formation (E-H) at Sepultura Canyon. All photos under plane light. Width of photos is 9 mm, except for E which is 4.6 mm. **A,** Phylloid algal floatstone containing abundant fragments of recrystallized phylloid algae and few other skeletal grains such as echinoderms, bryozoans, brachiopods and ostracods. Sample SC 20, Sandia Formation. **B,** Bryozoan wackestone-floatstone containing up to a few cm large bryozoan colonies. Subordinate are fragments of brachiopods, echinoderms, ostracods. Sample SC 28, Sandia Formation. **C,** Grainstone-packstone containing a diverse fossil assemblage with echinoderms, bryozoans and brachiopods being most abundant. Sample SC 30, Sandia Formation. **D,** Rudstone composed of fragmented fossils of dominantly echinoderms (crinoids), bryozoans, brachiopods and a few other skeletal grains. Few intraclasts and many detrital quartz grains are present. Sample SC 27, Sandia Formation. **E,** Oolitic grainstone composed of abundant slightly recrystallized ooids displaying radial fibrous structures. Detrital quartz grains often are the nuclei of ooids. Fossils include echinoderms, brachiopods and bryozoans, rare other skeletal grains. Sample SC 35, Elephant Butte Member. **F,** Floatstone composed of few large fossil fragments floating in micritic matrix which contains small skeletal grains including bryozoans, brachiopods, smaller foraminifers and ostracods. Sample SC 36, Elephant Butte Member. **G,** Bioclastic wackestone containing a diverse fossil assemblage. Sample SC 43, Garcia Member. **H,** Packstone composed of abundant crinoid fragments, subordinately bryozoans, brachiopods and some other skeletal grains. Sample SC 41, Garcia Member.

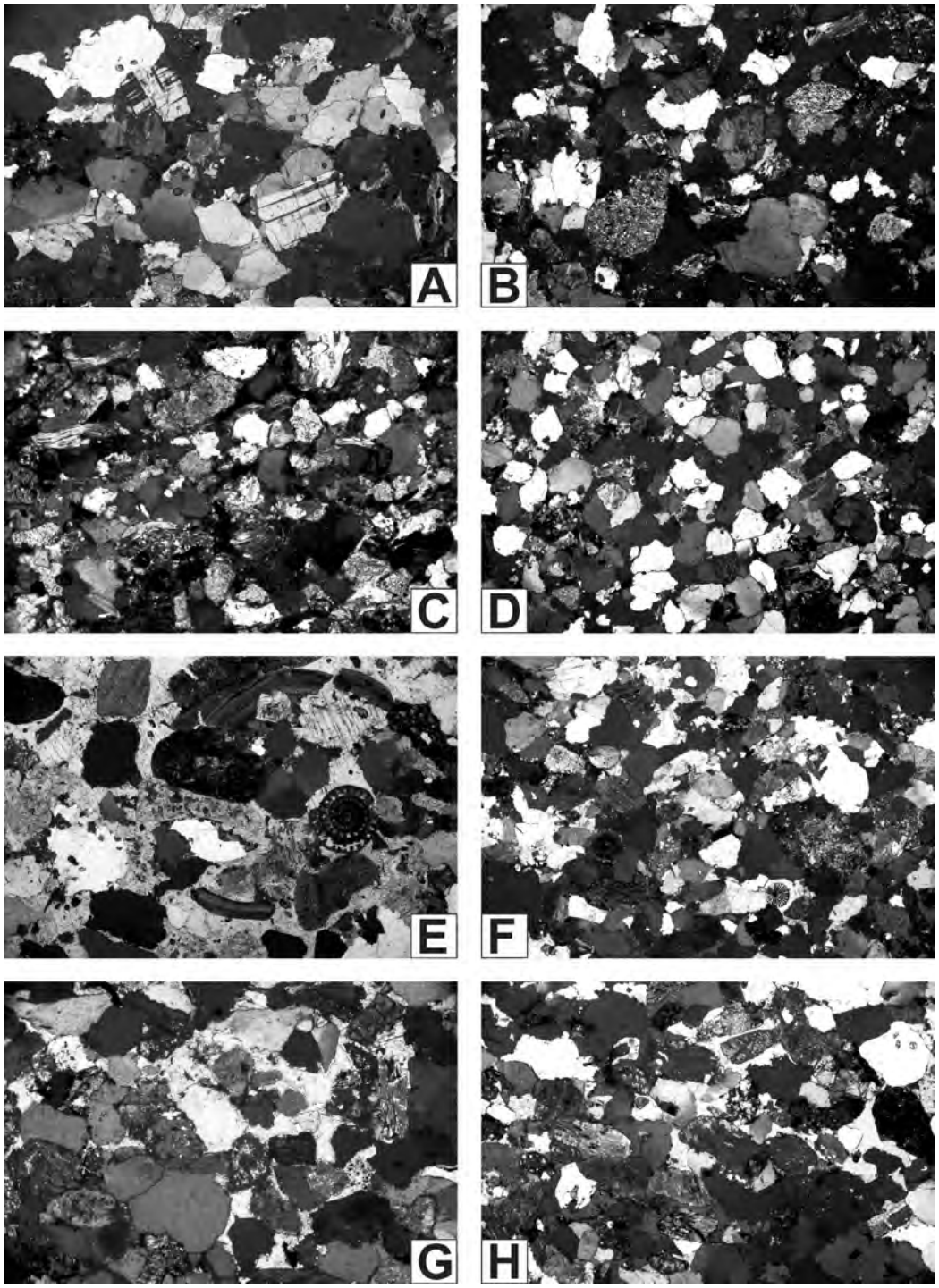


FIGURE 11. Thin section photographs of sandstone of the Atrasado Formation at Cottonwood Well. All photos under polarized light. Width of photos is 4.6 mm, for C and G 1.8 mm. **A,** Sandstone composed of mono- and polycrystalline quartz, detrital feldspars (mostly K-fsp) and some granitic and metamorphic rock fragments (subarkose). Few quartz grains display authigenic overgrowths. The detrital grains are cemented by coarse blocky calcite. Sample SC 43, Bartolo Member. **B,** Sandstone containing mono- and polycrystalline quartz, slightly altered detrital feldspars (mostly K-fsp) and granitic rock fragments (lithic arenite). Sample CW 8, Tinajas Member. **C,** Fine-grained sandstone composed of mono- and polycrystalline quartz, altered detrital feldspars (predominantly K-fsp) granitic and metamorphic rock fragments (sublitharenite). The detrital grains are cemented by coarse blocky calcite. Sample CW 9, Tinajas Member. **D,** Well-sorted sandstone composed of abundant mono- and polycrystalline quartz, many detrital feldspars (mostly K-fsp) and rock fragments (sublitharenite) cemented by coarse blocky calcite. Sample CW 14, Tinajas Member. **E,** Mixed siliciclastic-carbonate sandstone containing mono- and polycrystalline quartz grains, detrital feldspars, rock fragments and many fossils including crinoids, bryozoans, brachiopods and fusulinids. The detrital grains are cemented by coarse calcite. Sample CW 19, Burrego Member. **F,** Well-sorted sandstone composed of mono-and polycrystalline quartz, abundant detrital feldspars (dominantly K-fsp), granitic and metamorphic rock fragments (subarkose). Few fossils are present. The grains are cemented by coarse blocky calcite. Sample CW 21, Burrego Member. **G,** Sandstone composed of mono- and polycrystalline quartz, detrital feldspars (mostly K-fsp) and rock fragments cemented by coarse, poikilotopic calcite cement. Sample CW 34, Del Cuerto Member. **H,** Sandstone composed of mono- and polycrystalline quartz, detrital feldspars (mostly K-fsp), granitic and metamorphic rock fragments (subarkose), cemented by coarse, poikilotopic calcite cement. Sample CW 40, Del Cuerto Member.

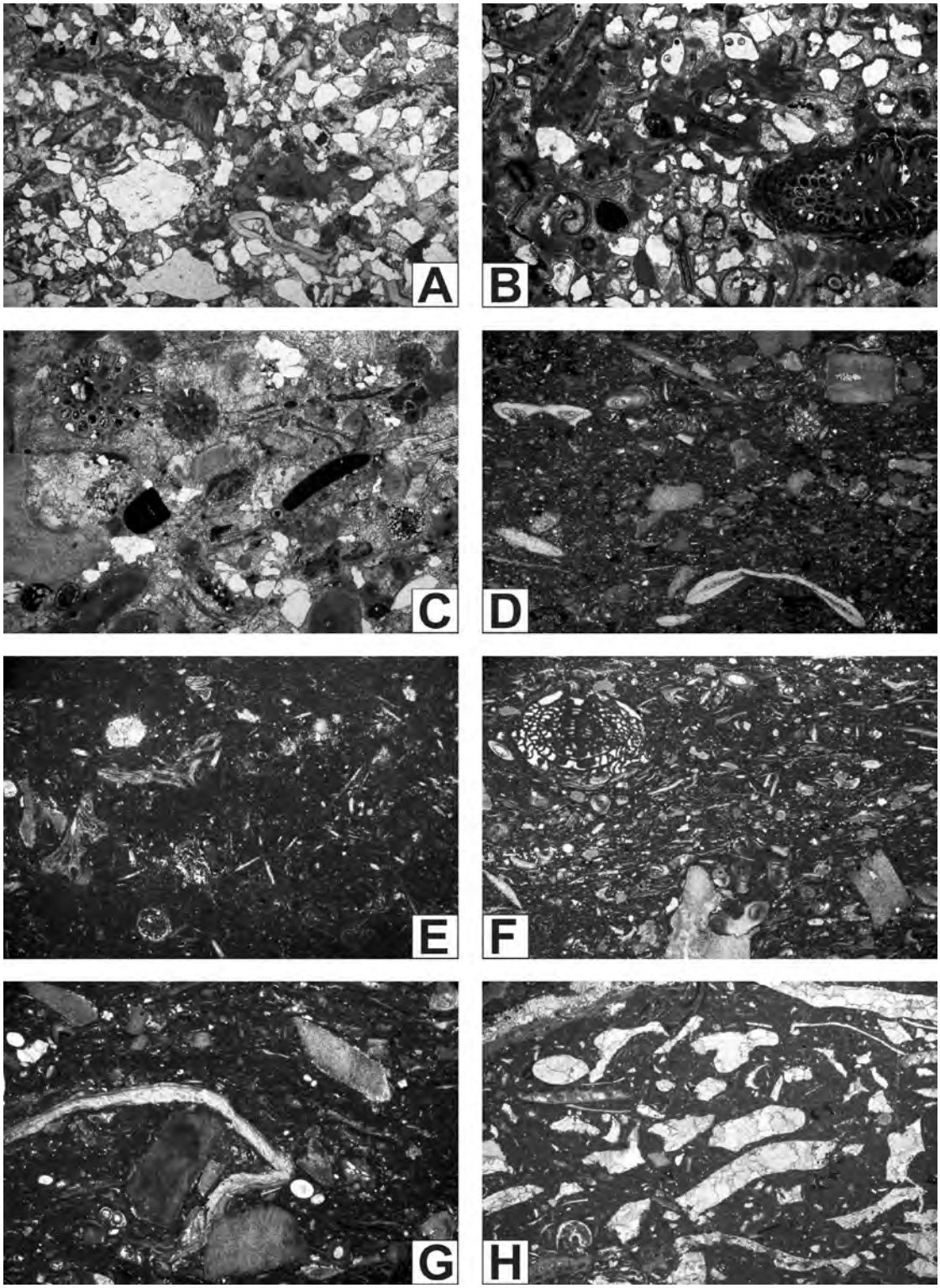


FIGURE 12. Thin section photographs of mixed siliciclastic-carbonate sandstone and limestone of the Atrasado Formation at Sepultura Canyon and Cottonwood Well. All photos under plane light; width of all photos is 9 mm. **A,** Mixed siliciclastic-carbonate sandstone containing abundant detrital quartz and many feldspar grains, granitic and metamorphic rock fragments and fossil fragments including crinoids, brachiopods, bryozoans and trilobites. Sample SC 44, Bartolo Member. **B,** Mixed siliciclastic-carbonate sandstone composed of mono- and polycrystalline quartz, detrital feldspars, granitic and metamorphic rock fragments, fossil fragments (crinoids, brachiopods, bryozoans) and ooids. Sample SC 47, Bartolo Member. **C,** Rudstone composed of abundant fossil fragments (mostly crinoids, brachiopods and bryozoans) and subordinate quartz and feldspar grains and rock fagments. Sample SC 46, Bartolo Member. **D,** Bioclastic wackestone containing a diverse fossil assemblage including crinoids, brachiopods, bryozoans and trilobites. Sample SC 50, Amado Member. **E,** Bioclastic wackestone with a diverse fossil assemblage. Sample SC 62, Amado Member. **F,** Bioclastic wackestone with a diverse fossil assemblage including crinoids, brachiopods, bryozoans and fusulinids. Sample SC 62B, Amado Member. **G,** Floatstone-rudstone containing a diverse fossil assemblage. Sample SC 62A, Amado Member. **H,** Phylloid algal floatstone containing completely recrystallized fragments of phylloid algae and subordinately fragments of brachiopods, bryozoans, crinoids and smaller foraminifers. Sample CW 6. Amado Member.

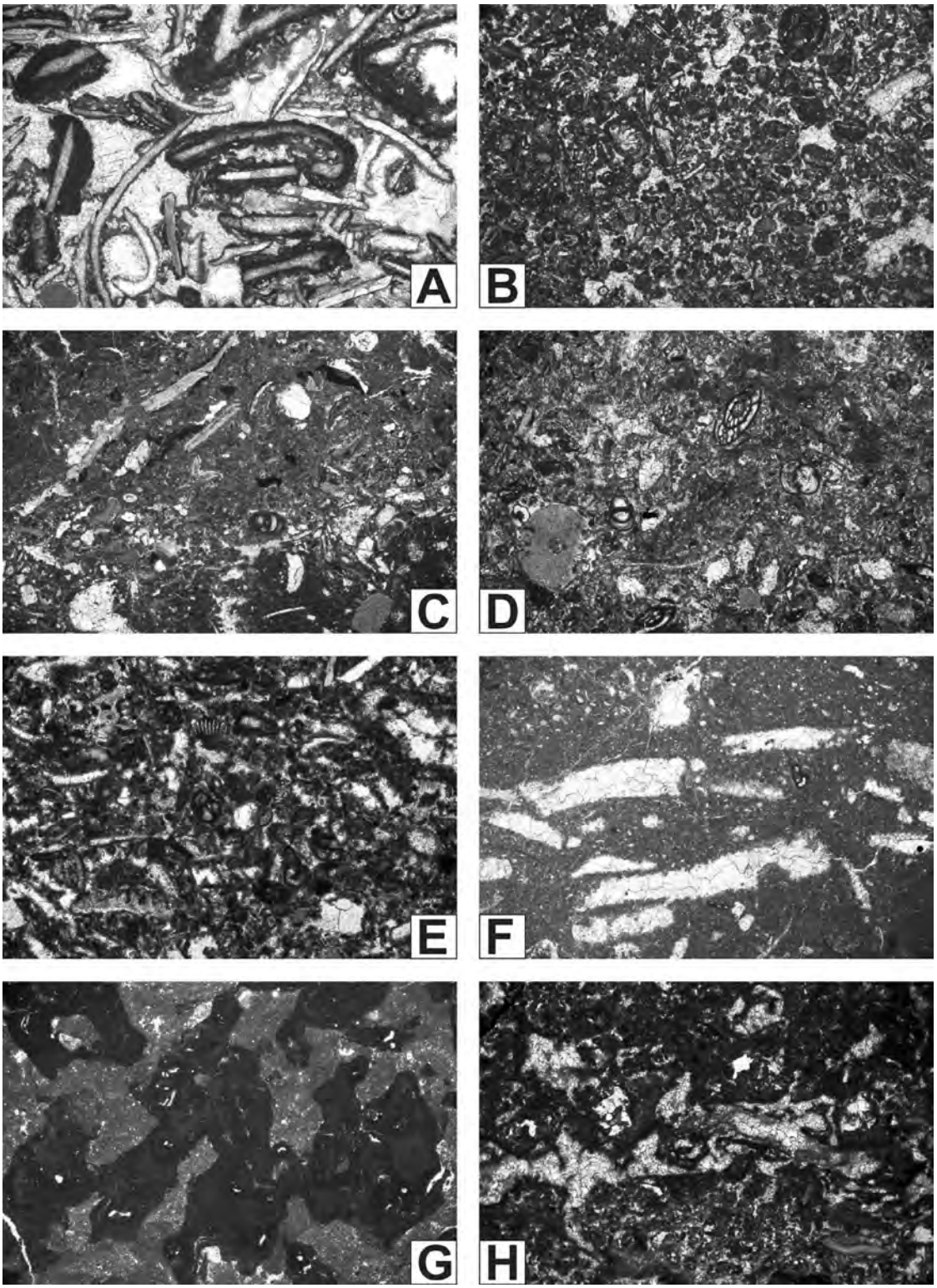


FIGURE 13. Thin section photographs of limestone of the Atrasado Formation at Cottonwood Well. All photos under plane light. Width of B, E, H is 4.6 mm, of all other photos 9 mm. **A,** Rudstone composed of recrystallized skeletons (?bivalves), gastropods, ostracods, brachiopods and smaller foraminifers. Some of the skeletons are encrusted by *Palaeonubecularia* and *Girvanella* forming oncoids. Sample CW 15, Council Spring Member. **B,** Wackestone-grainstone composed of intraclasts, recrystallized skeletons, smaller foraminifers and few other skeletal grains. Many skeletons display micritic envelopes. Sample CW 18, Council Spring Member. **C,** Bioclastic wackestone with a diverse fossil assemblage and few oncoids. Sample CW 25, Story Member. **D,** Bioclastic wackestone containing recrystallized skeletons, crinoids, brachiopods, bryozoans, fusulinids and ostracods. Sample CW 31, Story Member. **E,** Bioclastic packstone-grainstone composed of recrystallized skeletons, smaller foraminifers, echinoderms, ostracods, brachiopods and peloids. Sample CW 33, Del Cuerto Member. **F,** Phylloid algal floatstone containing recrystallized fragments of phylloid algae and a few other small fossils including smaller foraminifers, ostracods and echinoderms. Sample CW 35, Del Cuerto Member. **G,** *Tubiphytes* bindstone with large *Tubiphytes* binding lime mud. Sample CW 38, Del Cuerto member. **H,** Peloidal wackestone–bindstone containing abundant peloids and subordinately fossil fragments locally bound by cyanobacteria. Sample CW 42, Del Cuerto Member.

Council Spring Limestone Member

At Cottonwood Well, the Council Spring Member is thin (2.2 m thick), which is close to a minimum thickness for this member. The unit consists of bedded limestone and one intercalated interval (0.3 m thick) composed of shale with abundant limestone nodules (Fig. 8). Beds are 0.1-0.2 m thick in the lowermost interval, and approximately 0.3 m thick in the other intervals. One limestone interval contains abundant phylloid algae, which are characteristic of this member.

Burrego Member

At Cottonwood Well, the Burrego Member is rather thick (45.3 m) and dominantly siliciclastic, with minor intercalated limestone and dolomitic limestone (Fig. 8). Siliciclastic lithologies are mudstone-siltstone, which is yellowish, brownish and greenish, and mostly covered. Individual mudstone-siltstone intervals are 0.2-19.5 m thick. Intercalated sandstone units are 0.4-3.8 m thick and include: (1) fine-grained, horizontally laminated and ripple-laminated micaceous sandstone; (2) fine-grained sandstone with small-scale planar and trough-crossbedding; individual crossbedded sets are approximately 10 cm thick; and (3) coarse-grained, pebbly sandstone with trough crossbedding; individual sets are 20-40 cm thick. In the lower part of the Burrego Member, a prominent, coarse-grained conglomerate is intercalated (Fig. 8, segment B, unit 22). The conglomerate represents an incised channel fill, is up to 1.8 m thick and laterally grades into crossbedded sandstone. The conglomerate is clast supported, contains boulders up to 50 cm in diameter and sandy, arkosic matrix. The boulders are reworked limestone clasts. Approximately 7 m higher in the section, a thin (0.3 m) conglomerate is exposed, also representing a channel fill composed of reworked limestone clasts with diameters up to 10 cm (Fig. 8, segment B, unit 35).

Limestone is present as: (1) a 0.4 m thick limestone bed (Fig. 8, segment B, unit 27) containing oncoids with diameters up to 6 cm near the top; and (2) a 2 m thick unit composed of crinoidal limestone (wackestone) containing brachiopods (0.5 m), overlain by 0.4 m of bedded cherty limestone (crinoidal wackestone), 0.7 m of wavy bedded cherty limestone (crinoidal wackestone) and 0.4 m of bedded cherty limestone (wackestone) with a subaerial exposure surface on top (Fig. 8, segment B, units 29-31). A thin (0.2 m) dolomitic muddy limestone is intercalated in poorly exposed greenish mudstone-siltstone (Fig. 8, segment B, unit 38).

Story Limestone Member

The Story Member is 17.1 thick in the Cottonwood Well section and composed of various types of limestone, with a few covered intervals that are 0.3-2.3 m thick (Fig. 8). The following limestone lithologies are recognized: (1) nodular limestone composed of mudstone with abundant limestone nodules; (2) thin- to medium-bedded limestone (wackestone) with even bedding, locally bioturbated; (3) wavy bedded limestone; and (4) indistinctly bedded to massive limestone, partly containing phylloid algae. Chert is absent. Individual limestone beds are 0.3-1.6 m thick.

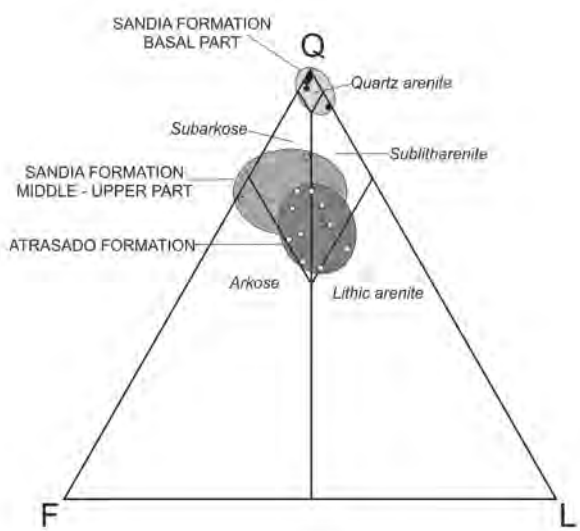


FIGURE 14. QFL diagram (sandstone classification scheme after Pettijohn et al., 1987) showing the composition of sandstone from the Sandia and Atrasado formations (Q = monocrystalline, polycrystalline quartz and chert; F = detrital feldspar grains; L = lithic grains including granitic, metamorphic and sedimentary rock fragments).

Del Cuerto Member

The Del Cuerto Member is 25.8 m thick in the Cottonwood Well section and is composed of covered intervals (mudstone-siltstone; 0.1-3.4 m thick) alternating with limestone intervals (0.3-4.6 m thick) and two thin sandstone intervals (0.2 and 0.7 m thick) (Fig. 8). Red mudstone-siltstone (0.8 m thick) is exposed in the upper part, below the thin sandstone interval. Limestone is represented by: (1) thin- to medium-bedded limestone (wackestone) with even bedding; and (2) indistinctly bedded to massive limestone, partly containing phylloid algae, and locally bioturbated near the top. On outcrop, fossils such as crinoidal debris, brachiopods and phylloid algae are rarely observed. On top of limestone unit 19 (Fig. 8, segment C) a subaerial exposure surface was observed. Sandstone is fine to medium grained, massive to horizontally laminated and brownish to reddish in color.

Moya Limestone Member

The exposed thickness of the Moya Member at Cottonwood Well is 7.5 m, and it is entirely composed of limestone (Fig. 8). Two limestone lithologies are distinguished: (1) thin- to medium-bedded limestone with even bedding (0.1-0.7 m thick); and (2) indistinctly thick bedded to massive limestone (1.2-2.5 m thick). The top of the uppermost limestone displays a subaerial exposure surface beneath red mudstone at the base of the overlying Bursum Formation.

Sandstone Petrography

Sandstones of the Bartolo, Tinajas, Burrego and Del Cuerto members display very similar textural and compositional properties (Fig. 11A-H). Sorting depends on the grain size: the finer grained the sandstone, the better the sorting. Detrital grains are mostly subangular to subrounded. The most common grain type is monocrystalline quartz. The amount of polycrystalline quartz, which also includes a few stretched metamorphic quartz grains, depends on the grain size. The coarser the sandstone, the higher the amount of polycrystalline quartz.

Detrital feldspars are a common constituent of all sandstones. Among the detrital feldspars, untwinned alkali feldspars (orthoclase) dominate. Microcline, perthitic feldspars and plagioclase are rare. Most of the feldspars are altered to some degree.

Sandstones contain small amounts of granitic and schistose metamorphic rock fragments. Individual sandstones also contain sedimentary rock fragments, including micritic grains and siltstone grains. The amount of detrital mica is higher in fine-grained than in coarse-grained sandstone. Most common is muscovite, and less abundant are biotite and chlorite. Opaque grains are present in all sandstones. Some of the sandstones of the Tinajas and Burrego members contain fossil fragments such as shell debris and spines of brachiopods, abraded fusulinids, echinoderms (crinoids), rare bryozoans and smaller foraminifers (*Globivalvulina*). Mixed siliciclastic-carbonate sandstones contain many fossil fragments of echinoderms (crinoids), brachiopods, bryozoans and rare trilobites (Fig. 12A- B). Locally, ooids are present (Fig. 12B).

Most of the studied sandstones are cemented by coarse blocky calcite, which locally is poikilotopic and commonly replaces detrital grains, particularly feldspars (Fig. 11A, C, D-H). Authigenic quartz overgrowths are rare. A few sandstones contain matrix. In one sandstone the pore space is filled with diagenetically formed chlorite. Most of the sandstones are classified as subarkose (Fig. 11A, F, H), subordinately as sublitharenite (Fig. 11C-D) and rarely, due to the amount of granitic and metamorphic rock fragments, as lithic arenite (Fig. 11B) sensu Pettijohn et al. (1987) (Fig. 14).

Limestone Microfacies

Bioclastic wackestone to floatstone is by far the most common microfacies of limestones of all Atrasado Formation members, particularly of the Amado, Council Spring, Story, Del Cuerto and Moya members (Figs. 12D-G, 13C-D). Other microfacies types are rare and include bioclastic mudstone-wackestone, peloidal wackestone-bindstone (Del Cuerto; Fig. 13H), phylloid algal floatstone (Amado, Del Cuerto; Figs. 12H, 13F), bioclastic wackestone-grainstone

(Amado, Council Spring; Fig. 13B), bioclastic packstone-grainstone (Del Cuerto; Fig. 13E), bioclastic rudstone (Bartolo, Council Spring, Del Cuerto; Figs. 12C, 13A) and locally bindstone (Del Cuerto; Fig. 13G).

All microfacies types contain a diverse fossil assemblage. The most common fossils are fragments of echinoderms (crinoids), brachiopods (including shells and spines) and bryozoans. Individual beds contain abundant recrystallized skeletons of phylloid algae, forming phylloid algal floatstone (Amado, Del Cuerto, Moya). Wackestone in the Story Member and packstone-grainstone in the Del Cuerto Member contain abundant smaller foraminifers, mostly calcivertellids. Other fossils present include ostracods, small gastropods, trilobites, bivalves, fusulinids, rare corals, calcisponges, *Epimastopora*, *Gyroporella*?, *Efluegelia* and *Tubiphytes*. Smaller foraminifers are represented by species of *Bradyina*, calcivertellids, *Climacammina*, *Earlandia*, *Endothyra*, *Eotuberitina*, *Globivalvulina*, *Hedraites*, *Hemigordius*, *Palaeonubecularia*, *Polytaxis*, *Spireitlina*, *Syzrania*, *Tetrataxis* and *Tuberitina*. Also present are many recrystallized, unidentifiable skeletons.

In wackestone to floatstone some of the skeletons are encrusted by *Palaeonubecularia*, and rarely by *Tuberitina* and bryozoans. In bioclastic wackestone-grainstone, skeletons are encrusted by *Palaeonubecularia* and *Girvanella*. In rudstone of the Council Spring Member, some of the skeletons are encrusted by *Palaeonubecularia*, *Hedraites* and *Girvanella*, forming oncoids. In wackestone-floatstone, many skeletons display thin micritic envelopes or are encrusted by thicker rims of cyanobacteria (Council Spring). In bioclastic wackestone-floatstone of the Story Member a few oncoids are present, formed by crusts of *Archaeolithophyllum lamellosum*, *Palaeonubecularia*, cyanobacteria, *Hedraites*? and rare *Tuberitina*.

In the Del Cuerto Member, bindstone is rare, composed of abundant encrusting organisms such as cyanobacteria and *Bacinella*. Also, *Tubiphytes*-*Palaeonubecularia*-cyanobacteria bindstone is locally present, encrusting and binding micrite.

BURSUM FORMATION

The Bursum Formation overlies the Atrasado Formation in the Los Pinos Mountains and is 40-60 m of interbedded siliciclastic red beds (mudstone, sandstone, conglomerate) and limestone (Krainer and Lucas, 2009; Allen et al., 2013a, b). Thus, the Atrasado-Bursum contact is readily mapped where the red beds overlie limestone of the Moya Member at the top of the Atrasado Formation (Allen et al., 2013a). Fusulinids indicate that the Bursum Formation in the Los Pinos Mountains is mostly or entirely of early Wolfcampian age, which is either latest Carboniferous or earliest Permian depending on how the base of the Permian is defined (Lucas, 2013). Here, we consider the lower Wolfcampian Bursum Formation in the Los Pinos Mountains to be of early Permian age.

BLACK BUTTE #1 WELL

A deep wildcat test hole drilled northwest of the Los Pinos Mountains provides an opportunity to compare thickness and character of rock units in the subsurface with those exposed in the mountains. The Stellar Energy Black Butte No. 1 well (projected section 6, T2N, R3E) was drilled in December 2009 to test the possible oil and gas potential in the southern part of the Albuquerque basin on lands of New Mexico Land Company (NMLC) LLC in the extreme northeastern part of Socorro County, New Mexico (Fig. 1). As secondary objectives, the well was also intended to look at the potential for freshwater aquifers, possible geothermal development potential, helium, CO_2 gas and possible uranium mineralization in the area.

The Black Butte prospect was a true wildcat. The prospect was defined by possible structural and fault closure seen on portions of three COCORP (Consortium for Continental Reflection Profiling) seismic lines (Lines 1, 1-A, and 2) on the NMLC LLC lands. These lines were part of the COCORP project designed to look at the deep crustal structure of the Rio Grande rift. Nevertheless, shallow seismic reflections are apparent on the profiles that appear to resolve geologic details for the uppermost crustal layers.

Prior to drilling the well the thickness of the Phanerozoic section was estimated based on Paleozoic outcrop data to the south in the Joyita Hills and to the east in the Manzano and Los Pinos mountains, and on the shallow reflections seen on the COCORP lines. Since no well control was available, reasonable seismic velocities were assumed for the suspected sedimentary section seen on the COCORP lines.

It was believed the well would be in Neogene Santa Fe Group and possible older basin fill to approximately 1000 ft. It was then expected to drill through the basal Tertiary unconformity into older, west-dipping Mesozoic or upper Paleozoic sediments. Approximately 2000 to 3000 ft of Phanerozoic sedimentary rocks were expected before reaching Precambrian basement near a depth of 4000 ft. Drilling began in December 2009 and was completed in January 2010. As expected, the well first drilled Santa Fe Group sands, gravels and red shales. At approximately 510 ft, black andesitic basalt (Oligocene La Jara Peak basaltic andesite) was encountered. The well drilled interbedded andesitic basalts and Santa Fe Group sands and gravels to 730 ft. At 730 ft the lithology changed to pale-colored, fine-grained igneous rocks (Oligocene rhyolitic tuffs). Intermediate-composition volcanic and volcaniclastic rocks of the upper Eocene-Oligocene Spears Formation (Datil Group) are present beneath the rhyolitic tuffs on the Becker SW and the La Joya quadrangles to the south-southwest, and may have been encountered during drilling before reaching Yeso Group sedimentary rocks (Rinehart et al., 2014).

A 9-5/8 inch surface casing was set at 995 ft, and drilling was resumed with an 8-1/4 inch bit. The unconformity at the base of the Tertiary section was penetrated, and the well drilled into the Yeso Group at approximately 1135 ft. The top of the Abo Formation was chosen by the mud loggers at 2124 ft, with a lithologic change to brick-red shale, mudstone and siltstone. The top of the Pennsylvanian Bursum Formation was originally called at approximately 2268 ft but may have been lower. The top of the Bursum Formation indicated in Figure 15 corresponds to the appearance of limestone and dark-colored shales in cuttings at a depth of approximately 2300 ft. The Abo Formation in the well is abnormally thin, ~45 m compared to 125 m on the Cerro Montoso quadrangle (Allen et al., 2014) and 275 m in the type area at Abo Pass (Myers, 1977). Most likely the well penetrated one or more normal faults, eliminating section.

Limestone was encountered at about 2510 ft, where circulation was abruptly lost. Circulation was partially regained at 2544 ft in fractured and vuggy limestone. Based on lithology, the mud log indicates the top of the Pennsylvanian "Madera Group" was reached at 2516 ft. Circulation was again lost in vuggy to cavernous limestone at 2578 ft, and the well was drilled blind with no returns until the well was cased at 2711 ft. On January 3, intermediate 7 inch casing was run to 2711 ft. After cementing, a cement bond log was run that showed cement behind casing from 2711 ft to approximately 2522 ft.

After the 7 inch casing was run, limestone with minor black shale and sandstone were drilled to the top of the Pennsylvanian Sandia Formation at a depth of approximately 2900 ft (Fig. 15). The Sandia was predominantly sandstone with limestone and black micaceous shale. Sandia lithologies were drilled to the top of the Precambrian unconformity, as indicated on the mud log at a depth of 3320 ft (Fig. 15). Precambrian basement lithologies noted on the mud log are dominantly metamorphic quartz mica schist and quartzite.The well reached total depth at 3724 ft on January 8, 2010. The well was logged by Weatherford including an open-hole Compensated Photo Density-Compensated Dual Neutron log in the interval from 2684 ft to 3718 ft on 8 January 2010. Petrophysical lithologic modeling assuming sandstone-shale- limestone-dolomite lithology was performed by Weatherford and is reproduced in Figure 15 from the top of the Precambrian to the top of the open-hole log.

The well logs (Fig. 15) reveal a relatively thick Sandia Formation and thin Gray Mesa Formation, as do our surface stratigraphic sections at Sepultura Canyon to the south (Fig. 1). Thus, the Proterozoic basement in the well is overlain by about 420 ft (128 m) of interbedded sandstone, shale and limestone. The sandstones are white to light gray, medium to coarse grained and quartz rich. The limestones are light gray to white and encompass wackestone, packstone and grainstone. These strata are readily referred to the Sandia Formation based on stratigraphic position and lithology.

In the well, strata above the Sandia Formation are an interval of limestone approximately 190 ft (58 m) thick that we refer to the Gray Mesa Formation. The 410 ft (125 m) of stratigraphic section between 2710 ft and the interpreted base of the Abo Formation at 2300 ft is considerably thinner than the expected combined thickness of the Atrasado and Bursum formations. The likely explanation, as with the thin Abo section above that, is that a normal fault has cut out a significant part of the Pennsylvanian section beneath the drill site. Fracturing of the rock and perhaps enhanced dissolution of carbonate strata in the vicinity of the fault(s), may explain the loss of drilling-fluid experienced during drilling of the interval ~2710 to 2500 ft. Rinehart et al. (2014) mapped a number of faults with Quaternary scarps in the

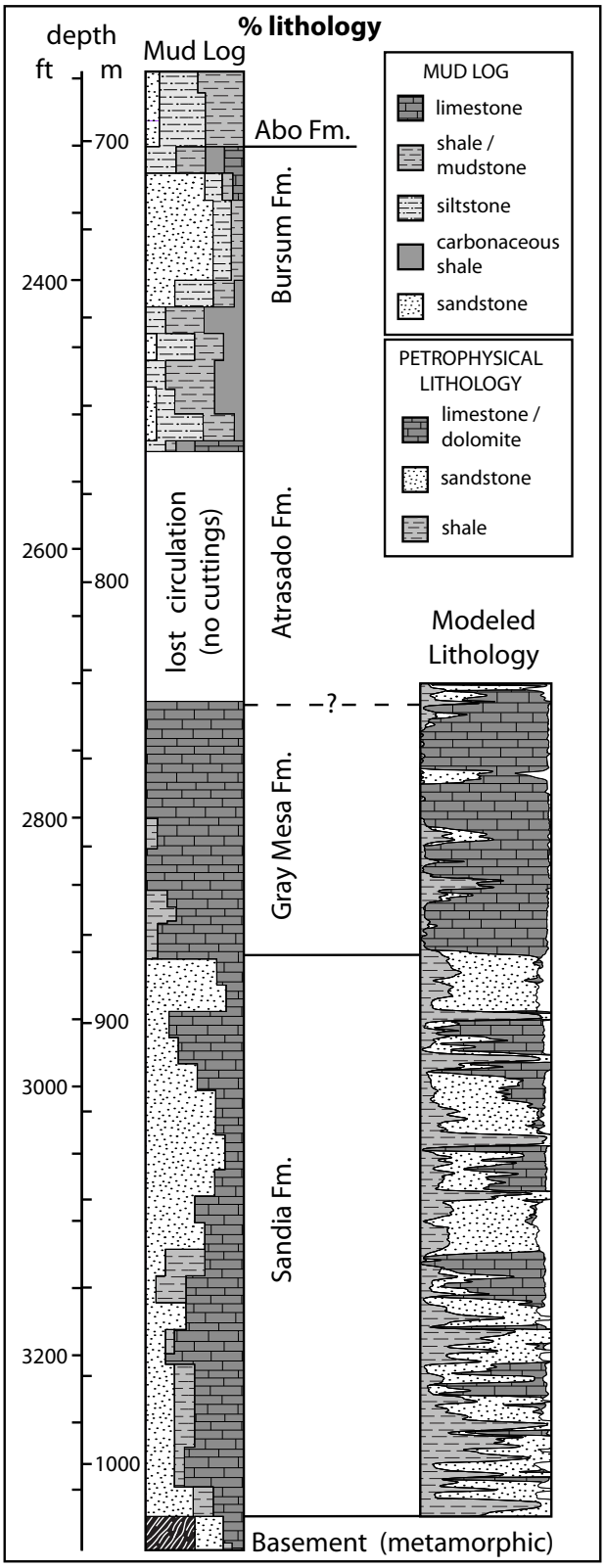


FIGURE 15. Lithologic logs from the Black Butte #1 borehole, transcribed from strip-chart logs generated by examination of cuttings (mud log) and open-hole geophysical logging conducted below a casing depth of 2700 ft. The lithology based on geophysical data represents solutions assuming a shale-sandstone-limestone-dolomite substrate.

immediate vicinity of the drill site, consistent with a fault explanation for apparent missing section at the Black Butte No. 1 borehole.

DEPOSITIONAL ENVIRONMENTS

Sandia Formation

Sediments of the Sandia Formation formed in various depositional environments ranging from fluvial to coastal to shallow marine siliciclastic and to carbonate and mudstone sediments of inner to outer shelf settings (Krainer and Lucas, 2013). At Sepultura Canyon, the basal siliciclastic unit of the Sandia Formation has a thin breccia at the base, overlain by mostly trough crossbedded, quartz-rich conglomerate and sandstone. We interpret these as fluvial channel deposits mostly due to their poor sorting and rounding.

The overlying shale-siltstone unit with intercalated thin limestone documents the first marine sediments, indicated by brachiopods in the black shale, and by ostracods and, particularly, brachiopods in the intercalated limestone beds. The low diversity fossil assemblage points to a restricted, shallow marine environment. The dominance of mudstone and intercalated muddy limestone beds shows that the sediments formed in a low-energy shelf environment.

The overlying thick succession of dominantly fine-grained, mixed siliciclastic-carbonate, fossiliferous conglomerate and sandstone with intercalated shale and limestone is entirely of marine origin. The several-meter thick successions of mostly trough crossbedded, fossiliferous fine-grained conglomerate and sandstone indicate deposition in a high-energy nearshore (shoreface) environment. These trough-crossbedded conglomerates and sandstones may represent two- and three-dimensional dunes that formed by fairweather longshore and onshore currents (Walker and Plint, 1992; Plint, 2010). They may also be the product of storm-induced currents. We did not observe hummocky crossbedded and swaley crossbedded sandstone, although such sediments, which form in mostly fine- and very fine-grained sandy sediments, are described from shoreface deposits and interpreted as storm-induced sediments (e.g., Walker and Plint, 1992; Plint, 2010). Intercalated mudstone and siltstone units are interpreted as offshore deposits.

The dominantly muddy texture and diverse fossil assemblage of the thin, intercalated limestone units indicate deposition in a shallow, dominantly low-energy shelf setting with normal salinity. Poorly washed rudstone indicating moderate water turbulence is rare. These limestone intervals represent short periods of relative sea-level highstands during which siliciclastic influx was very low to absent.

Gray Mesa Formation

Wackestone to floatstone containing a diverse fossil assemblage dominated by benthic sessile organisms is by far the most abundant microfacies of the Gray Mesa Formation, indicating deposition in a low-energy, open, normal marine shelf environment (see detailed discussion in Krainer et al., 2017). Microfacies pointing to deposition in high energy settings are very rare. Coarse silciclastic intercalations (conglomerate, sandstone) are absent. Covered intervals, which most likely represent mudstone-siltstone, are rare, indicating that siliciclastic influx was limited to fine-grained (muddy-silty) sediment. Silica of the chert nodules is mainly derived from siliceous sponges, indicated by the presence of calcified sponge spicules (see discussion in Krainer et al., 2017).

Atrasado Formation

The Atrasado Formation is characterized by the alternation of dominantly siliciclastic intervals (Bartolo, Tinajas, Burrego and Del Cuerto members) and dominantly carbonate intervals (Amado, Council Spring, Story and Moya members). Dominantly siliciclastic members display much stronger variations in thickness and lateral facies changes compared to the members composed dominantly of limestone (see also Krainer et al., 2017).

The Bartolo Member is thin (19.5 m) in the Los Pinos Mountains and contains relatively thicker sandstone units, including the Coyote Sandstone at the base. The Bartolo Member is much thicker (66 m) and very sandy at Priest Canyon but contains little sandstone at Cedro Peak (40 m) or in the Cerros de Amado. The Tinajas Member varies in thickness between 30 m at Bruton Canyon and 115 m at Priest Canyon, and contains much more sandstone at Ojo de Amado (in the Cerros de Amado) compared to other sections (Priest Canyon, Cedro Peak). In the Los Pinos Mountains, intercalated sandstone units are thin, mostly less than 1 m thick. The Burrego Member is very sandy at Cedro Peak (47 m thick) but has only a few sandstone beds intercalated at Priest

Canyon (23 m thick) or at the Cerros de Amado (only 13 m thick). In the Los Pinos Mountains the Burrego Member measures 45 m, contains sandstone units up to 3.8 m thick and a prominent, coarse-grained, nonmarine, channel-fill conglomerate. The Del Cuerto Member varies in thickness from 8.8 m at Cedro Peak to 35 m at Bruton Canyon; it is only 5 m thick at Ojo de Amado east of Socorro (Lucas et al., 2009a, 2013, 2014; Krainer et al., 2017). In the Los Pinos Mountains, the Del Cuerto Member is 35.8 m thick and composed of limestone and intercalated mudstone-siltstone with rare, thin sandstone beds intercalated.

Sandstone of the Bartolo, Tinajas, Burrego and Del Cuerto members is commonly mixed siliciclastic-carbonate in composition, containing abundant marine fossils, indicating deposition in a high-energy, nearshore environment. Subordinately, trough-crossbedded arkosic sandstone lacking fossils and carbonate rock fragments is present. Sandstone units composed of such arkosic sandstone may be of fluvio-deltaic origin. Thin intercalated limestone beds were deposited in a shallow, open to partly restricted marine environment and document relatively short periods during which siliciclastic influx was minor. We interpret lateral facies variations and differences in thickness within the clastic-dominated members to be the result of increased ARM tectonic activity, resulting in increased influx of siliciclastic sediment from reactivated uplifts.

The Atrasado Formation members that are dominantly composed of limestone with some shale and rare sandstone intercalated are generally thinner but more consistent in thickness and facies. For example, the Amado Member ranges in thickness from 9 m at Priest Canyon to 24 m in the Los Pinos Mountains. The Council Spring Member thickens from 2.2 m in the Los Pinos Mountains to 23 m at Priest Canyon. The Story Member varies in thickness from 6 m at Priest Canyon to 17 m in the Los Pinos Mountains and the Moya Member from 5 m at Cedro Peak to 8 m in the Los Pinos Mountains.

The microfacies of the limestones in all members are very similar and indicates deposition in a shallow, low- to high-energy shelf environment. Limestone facies are dominated by muddy textures (different types of wackestone to floatstone) that formed in a low-energy setting. Microfacies indicating high-energy conditions (grainstone and rudstone) are rare. All microfacies contain a diverse fossil assemblage pointing to an open, shallow marine shelf environment with normal salinty. Little variation in thickness and in facies demonstrates that sedimentation of the limestone-dominated members occurred during a period of tectonic inactivity on a wide shelf with little topography.

CONODONT BIOSTRATIGRAPHY

Sampling of the Sandia and Gray Mesa formations at the Sepultura Canyon section (Fig. 7) yielded numerous conodonts (Figs. 16-18). The stratigraphically lowest conodont fauna was obtained from a sandy carbonate bed 70 m above the base of the Sandia Formation (Fig. 7, unit 45). P_1 elements of *Hindeodus*, *Idioprioniodus*, and abundant (>50) *Idiognathodus* are present. One group of *Idiognathodus* elements comprises low, broad P_1 elements with large lobes, a form that was called *Idiognathodus* sp. G by Saelens (2014) and Treat (2014). The second group comprises narrower, higher, more curved P_1 elements with weakly developed lobes. Treat (2014) called similar forms I. sp. HI. Some specimens represent the *I. gibbus* Lambert, 1992 group. The few specimens of *Neognathodus* recovered possess a long carina and mostly triangular shapes and are likely examples of *Neognathodus colombiensis* (Stibane, 1967). The combination of *Idiognathodus* morphotypes suggests a latest Atokan age, based on collections from the Las Vegas, New Mexico, region (Treat, 2014), the Red House Formation in the Caballos Mountains (Saelens, 2014), and the Mud Springs Mountains (Lucas et al., 2016b).

A few meters higher (Fig. 7, unit 51; 82 m) a similar, but slightly younger conodont fauna was recovered. The abundant (>50) *Idiognathodus* P_1 elements are dominated by specimens that possess a wide, curved platform and both caudal and rostral lobes, probably members of the I. sp. H group of Treat (2014). A smaller number of *Idiognathodus* P_1 elements are narrower, only slightly curved and have a small rostral lobe. They resemble *I. amplificus* Lambert, 1992. In addition to *Adetognathus* and *Hindeodus* elements, a few specimens of *Neognathodus* with a biconvex outline and long carina occur, likely *N. bothrops* Merrill, 1972. This fauna may be earliest Desmoinesian in age. Only a few conodonts were obtained from unit 62 (Fig. 7, 89 m), but a few specimens of *Neognathodus* with a slightly reduced outer margin occur. A possible example of *Diplognathodus ellemerensis* Bender, 1980 was also recovered.

A more distinctive and diverse fauna was recovered from unit 81 (Fig. 7, 126 m). Some *Neognathodus* specimens resemble *N. colombiensis*, but the dorsal carina may be deflected very slightly to the outer side, which is reduced in width. Elements of *Idiognathodus amplificus* and the *I.* sp. HA group of Treat (2014) are present. Examples of *I. obliquus* Kossenko and Kozitskaya, 1978 (in Kozitskaya et al., 1978) also are present. This species has broad, strongly lobed platforms that are strongly curved so that the numerous fine transverse ridges run obliquely across the platform. The rostral lobe is strongly expanded, extending far dorsally, unlike the more restricted rostral lobes of the less curved *I.* sp. HA. The occurrence of *I. obliquus* suggests assignment to the upper part of the early Desmoinesian (Cherokee) *I. amplificus/I. obliquus* Zone of Barrick et al. (2013). A few specimens of the *I. iowaenis* Youngquist and Heezen, 1948 group and possibly *I. robustus* Kossenko and Kozitskaya, 1978 (in Kozitskaya et al., 1978), an association of species bearing coarse transverse ridges, occur a few meters higher (Fig. 7, unit 89, 148 m), which indicates a slightly younger, middle Cherokee age assignment (*I. rectus/I. iowaensis* Zone; Barrick et al., 2013) for that bed.

A small conodont fauna from unit 100 (Fig. 7, 173 m) has a few small *Idiognathodus* P_1 elements with coarse transverse ridges and *Neognathodus intrala* Stamm and Wardlaw, 2003. This distinctive species of *Neognathodus* possesses complete lateral margins, the outer one of which flares away from the ventral platform. This species has only been reported from the Verdigris (Lower Kittanning cyclothem of the northern Appalachian basin) to date, which is the youngest of the early Desmoinesian (Cherokee) cyclothems. A sample a few meters higher (Fig. 7, unit 106, 182 m) contains *Idiognathodus* elements like those in unit 100, but larger, which are similar to *I. attenuatus* Youngquist and Heezen, 1948.

A different, probably latest Cherokee, fauna occurs in unit 120 (Fig. 7, 207 m). Although the diverse fauna is dominated by shallow water conodonts (*Ellisonia*, *Adetognathus*, and *Hindeodus*), *Idiognathodus* elements are common. Many of the *Idiognathodus* elements resemble those identified by Stamm and Wardlaw (2003) as *I. robustus* and *I. podolskensis* Goreva, 1984, from the Verdigris (Lower Kittanning) cyclothem. However, *N. intrala* is absent, and forms of *Neognathodus* with a reduced outer margin occur, including ones like those incorrectly referred to *N. asymmetricus* Stibane, 1965 by Stamm and Wardlaw (2003).

The highest bed producing conodonts (Fig. 7, unit 133, 222 m) yielded just a few conodont elements. The presence of *Neognathodus roundyi* (Gunnell, 1931), with its strongly reduced outer margin, is characteristic of late Desmoinesian (Marmaton) conodont faunas. The few *Idiognathodus* specimens resemble *I. expansus* Stauffer and Plummer 1933, a late Marmaton species (Barrick et al., 2013). Two small P_1 elements with a medial groove are examples of *Swadelina neoshoensis* Lambert, Heckel and Barrick, 2003, another late Marmaton species. This confirms that the lowermost Atrasado Formation is of Desmoinesian age, as it is elsewhere.

FUSULINID BIOSTRATIGRAPHY

Myers et al. (1986) presented two measured sections in the Sepultura Canyon-Cottonwood Well area listing fusulinid identifications from various stratigraphic levels (Fig. 19). Their section 1 was measured to the northeast of our Sepultura Canyon section, but their section 2 was measured in the area of our Sepultura Canyon and Cottonwood Well sections. As noted above, Myers et al. (1986) reported the lowest occurrence of Desmoinesian fusulinids ~ 62 m above the base of the Pennsylvanian section (Figs. 7, 19). To the north, in their section 1, Desmoinesian fusulinids are found throughout a stratigraphic interval that encompasses strata we assign to the upper part of the Sandia Formation and the Gray Mesa Formation.

Stratigraphically higher in their section 2, Myers et al. (1986) report Virgilian *Triticites* from strata equivalent to the Story? through Moya members of the Atrasado Formation of our terminology (Fig. 19). No fusulinids were reported in the interval between the fusulinid-bearing beds of Desmoinesian age, and the beds containing Virgilian *Triticites* from the upper part of the Pennsylvanian section.

DISCUSSION

Perhaps the most unusual aspect of the Pennsylvanian section in the Los Pinos Mountains is the great thickness of the Sandia Formation, and the fact that the upper part of the formation is of Desmoinesian age (Figs. 7, 20). And, conversely, in the Los Pinos Mountains, the Gray Mesa Formation is very thin compared to sections to the north (Cedro

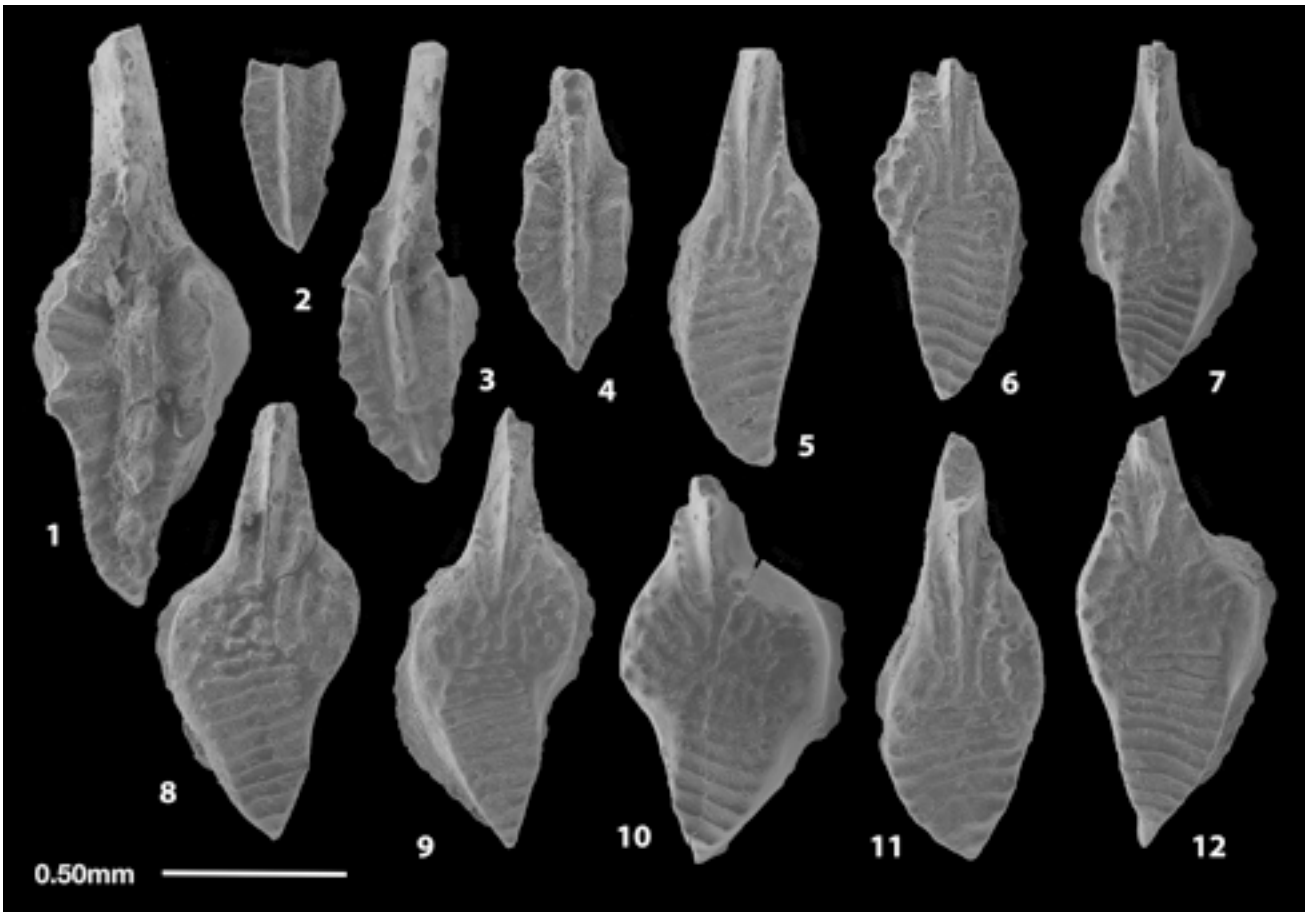


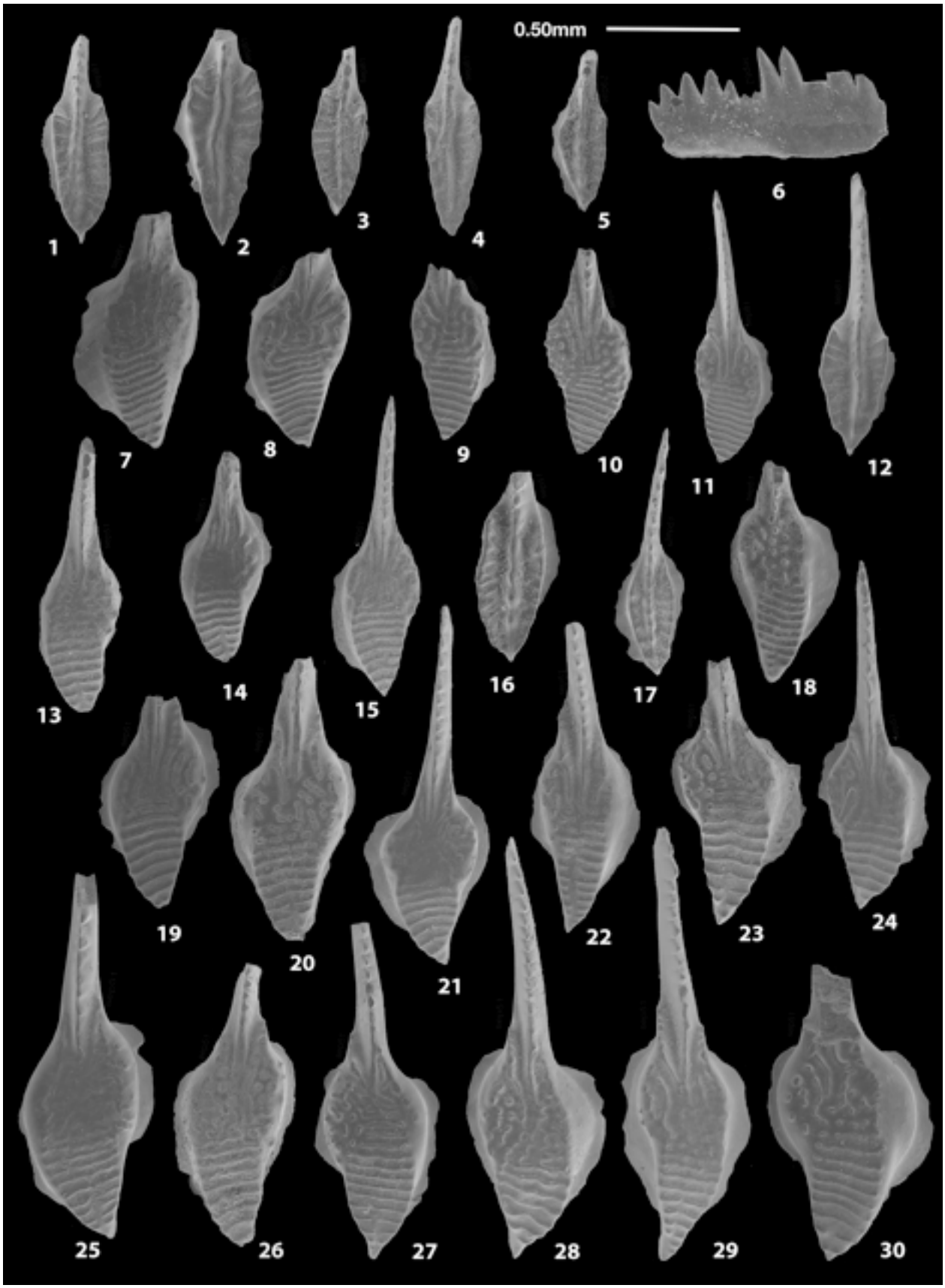
FIGURE 16. Selected conodonts from the Sepultura Canyon section. All specimens are upper views of P_1 elements. 50X magnification. Scale bar is 0.50 mm in length. Specimens are reposited at the New Mexico Museum of Natural History (NMMNH). 1. *Neognathodus colombiensis* (Stibane, 1967)? Bed 45 . 2. *Neognathodus colombiensis* (Stibane, 1967)? Bed 45 . 3. *Neognathodus colombiensis* (Stibane, 1967)? Bed 45 . 4. *Neognathodus colombiensis* (Stibane, 1967)? Bed 45 . 5. *Idiognathodus* sp. HI of Treat (2014). Bed 45 . 6. *Idiognathodus* sp. HI of Treat (2014). Bed 45 . 7. *Idiognathodus* sp. HI of Treat (2014). Bed 45 . 8. *Idiognathodus* sp. G of Saelens (2014). Bed 45 . 9. *Idiognathodus* sp. G of Saelens (2014). Bed 45 . 10. *Idiognathodus* sp. G of Saelens (2014). Bed 45 . 11. *Idiognathodus gibbus* Lambert 1992? Bed 45 . 12. *Idiognathodus* sp. HI of Treat (2014). Bed 45 .

Peak 119 m: Vachard et al., 2012, 2013; Lucas et al., 2014; Priest Canyon 192 m: Lucas et al., 2016a) and south (Cerros de Amado 233 m: Lucas et al., 2009a, Krainer et al., 2017). However, the limestone facies (microfacies and fossil assemblage) do not differ from the other sections.

Kottlowski (1960), quoted above, first drew attention to this, arguing that the stratigraphic interval with thick sandstone beds should be mapped as Sandia Formation regardless of its age. Wilpolt et al. (1946), however, mapped the Desmoinesian strata as "limestone member of the Madera formation." Myers et al. (1986) mapped it as Los Moyos Limestone. In their description of the Gray Mesa Formation, Allen et al. (2014) observed, "More detailed stratigraphic work is needed, but in areas the thick limestone beds near the base of the Gray Mesa appear to be represented laterally by siliciclastic deposits including thick beds of sandstone and pebbly sand, that for mapping purposes could arguably be assigned to the Sandia Formation."

The lowest occurrence (LO) of fusulinids in the Sepultura Canyon section is in unit 62 (Fig. 7) and was listed by Myers et al. (1986), who reported *Wedekindellina* sp. and *Beedeina* aff. *B. arizonensis* at that level (Fig. 19). This indicates that unit 62 is early Desmoinesian, but not basal Desmoinesian (cf. Wahlman, 2013). Indeed, our conodont data indicate that the base of the Desmoinesian in this section is lower, between units 45 and 51. Placing the base of the Gray Mesa Formation at unit 62 (as was done by Myers et al., 1986) means that about 80 m of overlying strata that encompass substantial beds of quartzose sandstone are included in the Gray Mesa Formation. However, such sandstone beds are characterstic of the Sandia Formation (Krainer and Lucas, 2013), so from a lithostratigraphic viewpoint these strata should be mapped as Sandia Formation, regardless of age. Indeed, mapping these strata as Los Moyos Limestone (= Gray Mesa Formation) by Myers

FIGURE 17 (facing page). Selected conodonts from the Sepultura Canyon section. All specimens are upper views of P_1, except figure 6. 50X magnification except for Figure 6. Scale bar is 0.50 mm in length. Specimens are reposited at the New Mexico Museum of Natural History (NMMNH). 1. *Neognathodus colombiensis* (Stibane 1967)? Bed 81. 2. *Neognathodus colombiensis* (Stibane 1967)? Bed 81. 3. *Neognathodus colombiensis* (Stibane 1967)? Bed 81. 4. *Neognathodus colombiensis* (Stibane 1967)? Bed 81. 5. *Neognathodus* sp. Bed 62. 6. *Diplognathodus ellesmerensis* Bender, 1980? 75X, caudal view. Bed 62. 7. *Idiognathodus obliquus* Kossenko and Kozitskaya, 1978. Bed 81. 8. *Idiognathodus obliquus* Kossenko and Kozitskaya, 1978. Bed 81. 9. *Idiognathodus obliquus* Kossenko and Kozitskaya, 1978. Bed 81. 10. *Idiognathodus obliquus* Kossenko and Kozitskaya, 1978. Bed 81. 11. *Idiognathodus obliquus* Kossenko and Kozitskaya, 1978. Bed 81. 12. *Neognathodus colombiensis* (Stibane 1967)? Bed 81. 13. *Idiognathodus* sp. H group of Treat (2014)? Bed 51. 14. *Idiognathodus* sp. H group of Treat (2014)? Bed 51. 15. *Idiognathodus amplificus* Lambert 1992? Bed 51. 16. *Neognathodus bothrops* Merrill, 1972. Bed 51. 17. *Neognathodus bothrops* Merrill, 1972. Bed 51. 18. *Idiognathodus amplificus* Lambert 1992? Bed 51. 19. *Idiognathodus* sp. H group of Treat (2014)? Bed 51. 20. *Idiognathodus* sp. H group of Treat (2014)? Bed 51. 21. *Idiognathodus* sp. H group of Treat (2014)? Bed 51. 22. *Idiognathodus amplificus* Lambert 1992? Bed 51. 23. *Idiognathodus amplificus* Lambert 1992? Bed 51. 24. *Idiognathodus* sp. H group of Treat (2014)? Bed 51. 25. *Idiognathodus* sp. H group of Treat (2014)? Bed 51. 26. *Idiognathodus* sp. H group of Treat (2014)? Bed 51. 27. *Idiognathodus* sp. H group of Treat (2014)? Bed 51. 28. *Idiognathodus* sp. H group of Treat (2014)? Bed 51. 29. *Idiognathodus amplificus* Lambert 1992? Bed 51. 30. *Idiognathodus* sp. H group of Treat (2014)? Bed 51.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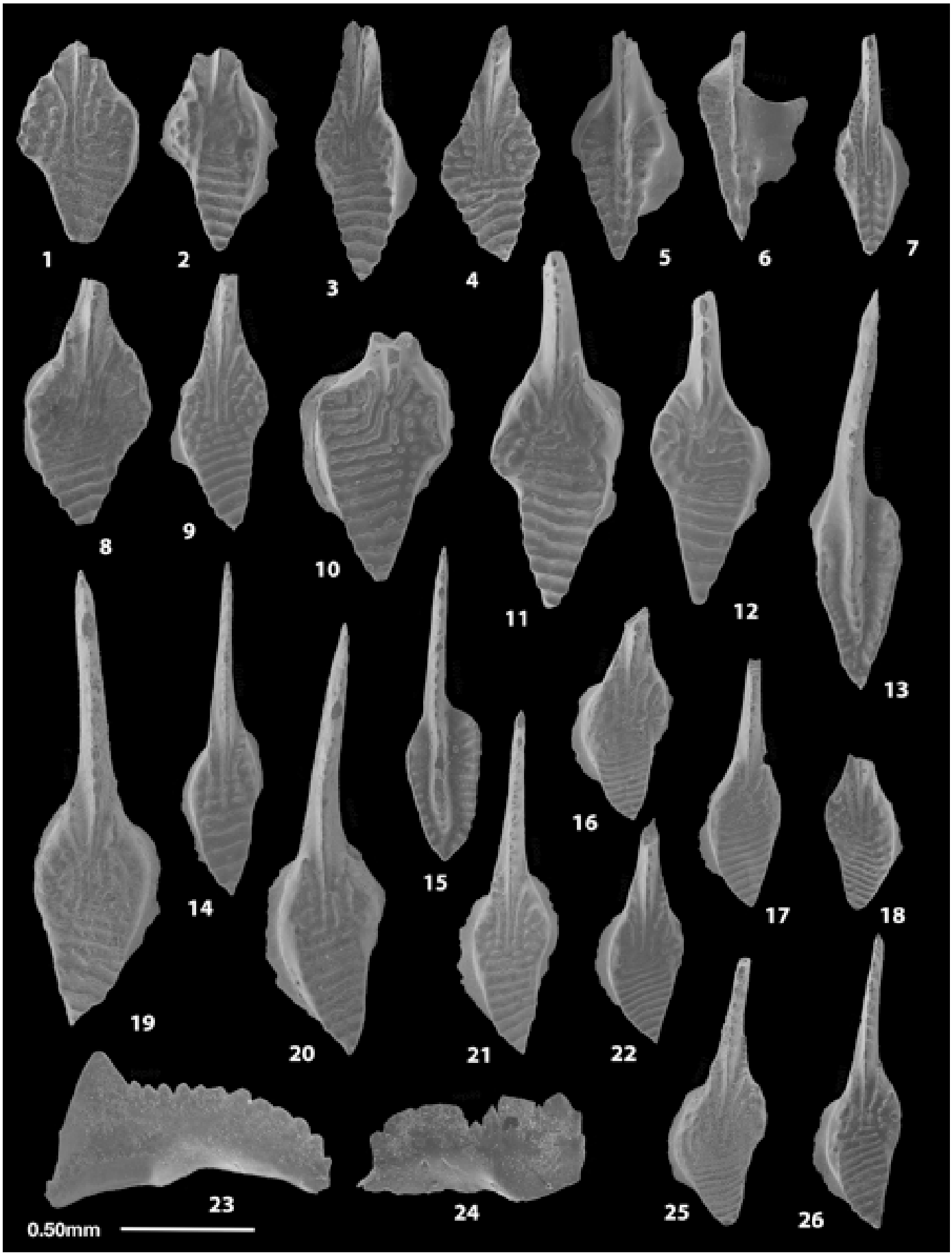
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FIGURE 18 (facing page). Selected conodonts from the Sepultura Canyon section. All specimens are upper views of P_1 elements except for figure 24. 50X magnification except for Figure 24. Scale bar is 0.50 mm in length. Specimens are reposited at the New Mexico Museum of Natural History (NMMNH). 1. *Idiognathodus robustus* Kossenko and Kozitskaya, 1978? Bed 120. 2. *Idiognathodus podolskensis* Goreva, 1984? Bed 120. 3. *Idiognathodus* sp. Bed 120. 4. *Idiognathodus robustus* Kossenko and Kozitskaya, 1978? Bed 120. 5. *Neognathodus* sp. Bed 120. 6. *Neognathodus roundyi* (Gunnell, 1931). Bed 133. 7. *Swadelina neoshoensis* Lambert, Heckel, and Barrick, 2003. Bed 133. 8. *Idiognathodus robustus* Kossenko and Kozitskaya, 1978. Bed 120. 9. *Idiognathodus podolskensis* Goreva, 1984? Bed 120. 10. *Idiognathodus robustus* Kossenko and Kozitskaya, 1978? Bed 106. 11. *Idiognathodus attenuatus* Youngquist and Heezen, 1948? Bed 106. 12. *Idiognathodus attenuatus* Youngquist and Heezen, 1948? Bed 106. 13. *Neognathodus intrala* Stamm and Wardlaw, 2003. Bed 100. 14. *Idiognathodus* sp. Bed 100. 15. *Neognathodus intrala* Stamm and Wardlaw, 2003. Bed 100. 16. *Idiognathodus* sp. HA group of Treat (2014). Bed 81. 17. *Idiognathodus* sp. HA group of Treat (2014). Bed 81. 18. *Idiognathodus obliquus* Kossenko and Kozitskaya, 1978. Bed 81. 19. *Idiognathodus robustus* Kossenko and Kozitskaya, 1978? Bed 89. 20. *Idiognathodus iowaensis* Youngquist and Heezen, 1948? Bed 89. 21. *Idiognathodus iowaensis* Youngquist and Heezen, 1948? Bed 89. 22. *Idiognathodus* sp. HA group of Treat (2014). Bed 81. 23. *Hindeodus minutus* (Ellison, 1941). Bed 89. 24. *Diplognathodus coloradoensis* (Murray and Chronic, 1965). 75X, caudal view. Bed 89. 25. *Idiognathodus* sp. HA group of Treat (2014). Bed 81. 26. *Idiognathodus* sp. HA group of Treat (2014). Bed 81.

et al. (1986) is a biostratigraphic/chronostratigraphic decision, not a lithostratigraphic decision. Like Allen et al. (2013a), we assign these strata to the Sandia Formation on a lithostratigraphic basis.

Regardless of which formation these strata are assigned to, it is unusual and significant that at Sepultura Canyon about 80 m of Desmoinesian strata contain substantial beds of sandstone and conglomerate. This distinguishes them from Desmoinesian strata to the north and south, which contain few or no beds of sandstone (one ~ 10 m thick sandstone bed is present in the lower part of the Gray Mesa Formation in the Cerros de Amado: Lucas et al., 2009a, fig. 6). This Demoinesian sandy interval thus indicates a local facies of Desmoinesian age not seen elsewhere in central New Mexico. This facies may most easily be explained by tectonic activity and proximity to the ARM Joyita uplift, over which the Gray Mesa Formation pinches out (Kottlowki and Stewart, 1970; Nelson et al., 2013b, fig. 9).

The Sandia Formation encompasses the lower part of the Pennsylvanian sedimentary succession across much of northern and central New Mexico, and represents synorogenic deposits related to the onset of the ARM orogeny. Krainer and Lucas (2013) pointed out that the Sandia Formation is characterized by distinct lateral facies changes and variations in thickness. The Sandia Formation is generally thin and dominantly siliciclastic in the northern part of New Mexico at sections close to the uplifts, and becomes thicker towards the south (Krainer and Lucas, 2013). At Sepultura Canyon the Sandia Formation is 173 m thick, thus representing one of the thickest Sandia sections, even thicker than the section at Arroyo de la Presilla east of Socorro and much thicker than at Priest Canyon in the southern Manzano Mountains (70 m). South of Arroyo de la Presilla in the Cerros de Amado, the Sandia Formation interfingers and grades into the Red House Formation (Lucas et al., 2012). In the Little San Pascual Mountains, the lower part of the Pennsylvanian succession is represented by the Red House Formation, which differs from the Sandia in containing little or no sandstone.

At Sepultura Canyon the lower part (18.4 m) of the Sandia Formation is developed as fluvial, quartz-rich conglomerate and sandstone with some covered (shale) intervals. The first marine facies, composed of dominantly mudstone intercalated with thin limestone, probably correlates with the first thin marine limestone at Arroyo de la Presilla, exposed approximately 24 m above the base (Lucas et al., 2009a).

The facies of the overlying succession (~ 143 m thick) of the Sandia Formation differs from all other sections. This thick succession is dominantly clastic and entirely marine. The main lithology is fossiliferous, mixed siliciclastic-carbonate sandstone and rudstone with minor arkosic sandstone, some mudstone intercalations and a few thin limestone horizons. This facies of mixed siliciclastic-carbonate sandstone and rudstone, which form units up to 13 m thick, is rare in other sections of the Sandia Formation, where it occurs as thin intercalations (see Krainer and Lucas, 2013). At Arroyo de la Presilla, fluvial conglomerate and sandstone are present in the middle part of the Sandia Formation (Lucas and Krainer, 2009; Lucas et al., 2009a; Krainer and Lucas, 2013). Such fluvial deposits are absent above the first marine facies at Sepultura Canyon.

Sandstone of the fluvial facies at the base of the Sandia Formation at Sepultura Canyon is composed of quartz arenite. Detrital feldspars are rare to absent due to intense chemical weathering. A significant change in sandstone petrography occurs approximately 43 m above the base from quartzarenite to subarkose and arkose.

At Sepultura Canyon, the Gray Mesa Formation is very thin compared to sections farther north (Cedro Peak: 119 m, Lucas et al. 2014; Vachard et al. 2012, 2013; Priest Canyon: 192 m, Lucas et al. 2016a) and south (Cerros de Amado: 233 m, Lucas et al., 2009a; Krainer et al., 2017) (Fig. 20). However, the limestone facies (microfacies and fossil assemblage) do not differ from the other sections. Coarse siliciclastic intercalations, which are locally present in the Elephant Butte and Garcia members elsewhere (see Nelson et al. 2013b for a discussion of the three members of the Gray Mesa Formation), are absent at Sepultura Canyon. Mudstone-siltstone (covered) intervals are less abundant. This indicates that the depositional environment of the limestone facies was very uniform over large areas (at least from Cedro Peak/Manzanita Mountains in the north to the Cerros de Amado region and Fra Cristobal Mountains in the south) with only minor changes in water depth. Limestone was dominantly deposited in a low-energy, normal, open marine shelf environment. Subsidence rates varied locally, and local intercalations of conglomerate and sandstone in the Elephant Butte Member, and particularly in the Garcia Member, are expressions of slight local tectonic activity related to the ARM orogeny. The Whiskey Canyon Member is free of coarse siliciclastics and almost free of fine-grained siliciclastic sediment, indicating that deposition took place during a tectonically stable period.

The Atrasado Formation is characterized by the alternation of siliciclastic-dominated and limestone-dominated units, allowing subdivision into eight members. These members can be traced from Cedro Peak in the Manzanita Mountains to the Cerros de Amado area east of Socorro and to Bruton Canyon in the Oscura Mountains. The limestone-dominated members (Amado, Council Spring, Story and Moya members) display a quite uniform facies and only minor changes in thickness, whereas the clastic-dominated members (Bartolo, Tinajas, Burrego and Del Cuerto members) are generally thicker and characterized by distinct lateral facies changes and more pronounced variations in thickness. Sandstone of all clastic-dominated members contains high amounts of detrital feldspars, classifying them as subarkose to arkose.

In a classic paper, Krynine (1948) pointed out that sandstones of the "arkose series" (subarkose and arkose) are composed of detrital grains derived from the rapid erosion of granitic, subordinately metamorphic rocks, thus indicating large-scale block faulting. Folk (1974) distinguished three types of arkosic sandstones: (1) tectonic arkose, (2) climatic arkose and (3) volcanic arkose. Tectonic arkose is deposited when the source area is uplifted and eroded so rapidly that there is not enough time for chemical weathering of feldspars. Climatic arkose forms when the climatic conditions are too dry to allow intense chemical weathering of feldspars. Volcanic arkose is formed by the rapid erosion and deposition of volcanic feldspars, mainly plagioclase, from volcanic rocks.

A lycopsid flora near the base of the Sandia Formation (Atokan) northeast of Socorro indicates a wetland swamp flora and perhumid climatic conditions (Lucas et al., 2009b). Conifer trees are described from the Late Pennsylvanian Atrasado Formation from a semiarid sabkha environment, although the stumps indicate more sub-humid tropical conditions (Falcon-Lang et al., 2016). The Tinajas shale flora of the Atrasado Formation contains elements of a wetland flora, but also elements indicating seasonality with alternating dry and wet periods (Lerner et al., 2009). This indicates that the climate during the Pennsylvanian in central New Mexido was not dry (arid) but sub-humid. Dry and wet periods alternated during sedimentation of the Atrasado Formation.

Therefore, we interpret the arkosic sandstones of the Sandia and Atrasado formations as "tectonic arkoses" (subarkose, arkose; also sublitharenite and lithic arenite) that were deposited as the result of rapid uplift of Proterozoic basement rocks, dominantly of granitic composition (providing most of the mono- and polycrystalline quartz, feldspars such as orthoclase, microcline and perthite, and granitic rock

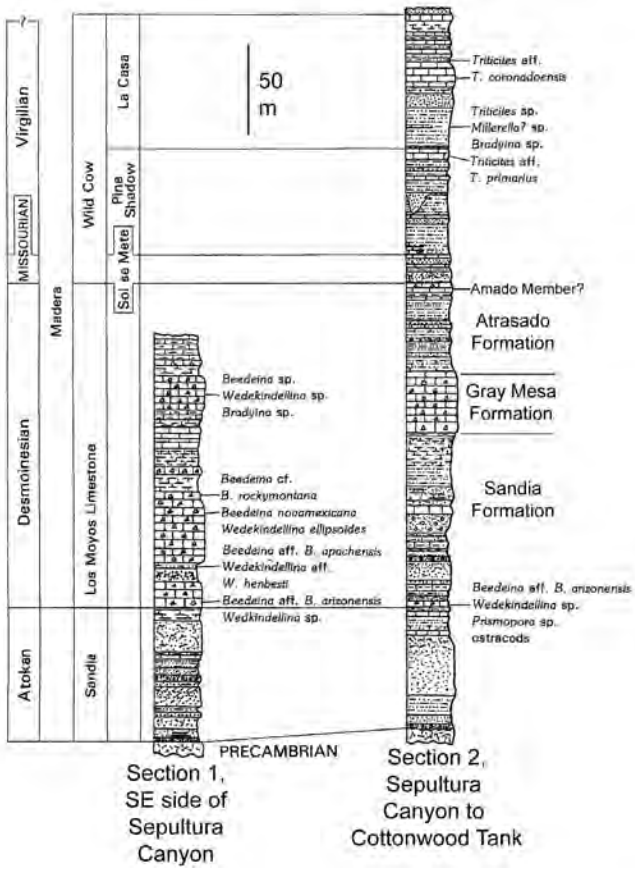

FIGURE 19. Measured sections from Myers et al. (1986) showing distribution of fusulinid taxa and demonstrating the lateral facies change between upper Sandia and lower Gray Mesa Formation. On the right, some of our lithostratigraphic assignments are indicated.

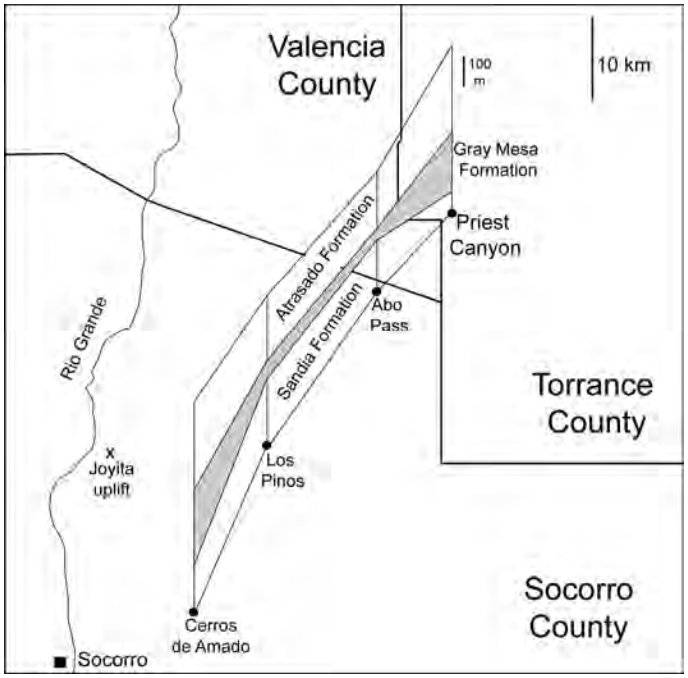

FIGURE 20. Fence diagram depicting unusually thick Sandia Formation in the vicinity of the Los Pinos Mountains relative to areas to the northeast and southwest. Possible source areas for siliclastic sediment are the Joyita uplift to the west, and the much larger Pedernal landmass off the map area to the east.

fragments). Subordinately metamorphic basement rocks were eroded, too, providing some of the detrtial quartz grains (schistose metamorphic quartz) and metamorphic rock fragments (Fig. 14).

Limestone-dominated members of the Atrasado Formation reflect periods of relative tectonic quiescence. The limestone members that can be traced across all sections thus represent "marker beds" of the same age between Cedro Peak and the Cerros de Amado. The clastic-dominated members represent tectonically active periods during which rapid uplift of basement blocks occurred. Four tectonically active phases occurred during deposition of the Atrasado Formation. The Tinajas Member marks the strongest, and the Del Cuerto Member, which contains only small amounts of siliciclastic sediments, represents the weakest tectonic phase.

South of the Cerros de Amado and Bruton Canyon the Atrasado Formation grades/interfingers with the Bar B Formation (in the Little San Pascual Mountains, San Mateo Mountains, Fra Cristobal Mountains, Caballo Mountains, Mud Springs Mountains) (Nelson et al., 2013a). The Bar B Formation is a succession of alternating limestone and partly thick mudstone units not readily subdivided into members. The thicker mudstone units likely represent the distal facies of the clastic-dominated members of the Atrasado Formation.

Siliciclastic-dominated units of the Pennsylvanian-lower Permian succession in northern and central New Mexico reflect periods of tectonic activity related to the ARM orogeny. In general, the timing of ARM uplifts and peak basin subsidence varies from basin to basin (Kluth, 1986; Ye et al., 1996; Dickinson and Lawton, 2003; Kues and Giles, 2004). Basins in northeastern and eastern New Mexico began to subside during the latest Mississippian to Early Pennslyvanian, whereas basins to the south and west started subsiding later in the Pennsylvanian, and their subsidence peaked during the early Permian (Wolfcampian) (Kluth, 1986; Ye et al., 1998; Dickinson and Lawton, 2003; Kues and Giles, 2004).

Several tectonic phases of the ARM can be distinguished in central New Mexico (between Cedro Peak and the Cerros de Amado). The main source was the Pedernal uplift, subordinately the Joyita uplift (Fig. 20). The biostratigraphy of the Pennsylvanian succession in central New Mexico (e. g., Krainer and Lucas, 2013, Nelson et al., 2013a, b; Lucas et al., 2016a, b) indicates the following timing of ARM tectonic phases:

1. The Sandia Formation represents the first tectonic phase of the ARM orogeny during the Atokan, starting locally during the latest Morrowan. At Sepultura Canyon the first tectonic phase lasted until the early Desmoinesian, documented by the Sandia sandstone facies, which continues into the early Desmoinesian.

2. The Gray Mesa Formation was deposited during a period of little tectonic activity, although local intercalation of sandstone and conglomerate in the lower (Elephant Butte) and upper (Garcia) members suggest some tectonic activity. This period of relative tectonic quiescence lasted for much of the Desmoinesian in most areas.

3. Four tectonic phases of rapid uplift of basement blocks are recorded by the clastic-dominated members of the Atrasado Formation. These tectonic phases are separated by periods of tectonic quiescence during which limestone was deposited. The first tectonic phase, represented by the Bartolo Member, occurred during the latest Desmoinesian/earliest Missourian. The second phase (Tinajas Member) was the strongest and can be dated as Missourian. The third phase (Burrego Member) occured during the early Virgilian, and the last tectonic phase was the weakest (Del Cuerto) and occurred during late Virgilian time.

4. Tectonic activity continued during sedimentation of the Bursum Formation (lower Wolfcampian), which contains substantial amounts of siliciclastic sediments, including nonmarine conglomerate and arkosic sandstone.

5. The onset of deposition of the overlying Abo Formation (and Cutler Group in northwestern New Mexico) marks the last and strongest tectonic phase, causing rapid uplift of basement blocks, erosion and sedimentation of huge masses of siliciclastic sediments that were deposited as nonmarine red beds during the middle and upper Wolfcampian, covering large areas of northern and central New Mexico.

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APPENDIX-GPS COORDINATES OF MEASURED STRATIGRAPHIC SECTIONS

We measured two sections. Sepultura Canyon is Sandia Formation through Amado Member of Atrasado Formation, in two segments (Fig. 7). Cottonwood Well is Amado Member through Bursum Formation base in three segments (Fig. 8). Coordinates are UTM meters, NAD 83, zone 13.

Sepultura Canyon:

Segment A

Base 350324E, 3796569N

Top 350036E, 3795999N

Segment B

Base 349904E, 3794743N

Top 349821E, 3794637N

Cottonwood Well:

Segment A

Base 348116E, 3793411N

Top 348228E, 3793228N

Segment B

Base 347516E, 3792428N

Top 347485E, 3792140N

Segment C

Base 347245E, 3791723N

Top 347135E, 3790764N