



## ***Pennsylvanian stratigraphy in the northern Oscura Mountains, Socorro County, New Mexico***

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# PENNSYLVANIAN STRATIGRAPHY IN THE NORTHERN OSCURA MOUNTAINS, SOCORRO COUNTY, NEW MEXICO

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**ABSTRACT**—The Pennsylvanian strata exposed in the northern Oscura Mountains are a classic section because M. L. Thompson used it as a key reference section in his 1942 monographic synthesis of the Pennsylvanian in New Mexico. This section is ~ 334 m thick, and we assign it to the Sandia, Gray Mesa, Atrasado and Bursum formations. The Sandia Formation is thin (~ 13 m), overlies Precambrian granite and is mostly shale and sandy limestone. The lowest cherty limestone ledge marks the base of the overlying Gray Mesa Formation, which is ~ 162 m thick. Most of the Gray Mesa is limestone (63% of the section), the remainder is covered slopes (shale?). Most of the limestones are cherty, and numerous fusulinid packstones are present. In the northern Oscura Mountains, we are not able to subdivide the Gray Mesa Formation into members, and we abandon Thompson's Coane Formation as an unrecognizable unit that is part of the upper Gray Mesa Formation.

The Atrasado Formation is ~ 121 m thick and includes (in ascending order) the type sections of the Veredas, Hansonburg and Keller groups of Thompson, names that should be abandoned as chronostratigraphic, not lithostratigraphic units. The facies ranges from siliciclastic sandstone and fine-grained conglomerate to bedded fossiliferous limestone of an open marine shelf to massive algal limestone of a mound facies formed just below wave base in quiet water in the photic zone. We recognize six formations named by Thompson as members of the Atrasado Formation (in ascending order), the Adobe, Council Spring, Burrego, Story, Del Cuerto and Moya members. The Bursum Formation overlies the Atrasado Formation and is 35 m of marine limestone and red-bed clastics. Abo Formation red-bed siliciclastics overlie the Bursum Formation and are of presumed earliest Permian age.

Fusulinids indicate that the Desmoinesian-Missourian boundary is in the upper Gray Mesa Formation, the Missourian-Virgilian boundary is ~ the base of Del Cuerto Member and the Wolfcampian (Newwellian) base is in the Bursum Formation. The Pennsylvanian succession in the northern Oscura Mountains is a relatively thin section largely because the Atrasado Formation is unusually thin. The Atrasado Formation represents most of Missourian-Virgilian time but encompasses no more than eight transgressive-regressive cycles of deposition. Clearly, Atrasado deposition in the northern Oscura Mountains was heavily influenced by tectonic activity in the ancestral Rocky Mountain foreland, particularly of the nearby Pedernal uplift.

## INTRODUCTION

The eminent paleontologist and stratigrapher M.L. Thompson (1942) published "Pennsylvanian System in New Mexico," a monograph that presented the first detailed and formal lithostratigraphy of the Pennsylvanian strata that crop out in central and southern New Mexico. Prior to Thompson (1942), these rocks had been mapped and described only in reconnaissance. Early lithostratigraphic names applied to these strata include Sandia Formation, Madera Limestone and Magdalena Limestone or Group (e.g., Herrick, 1900; Keyes, 1903; Gordon, 1907; Darton, 1922, 1928). What Thompson (1942) proposed for the Pennsylvanian lithostratigraphy in central and southern New Mexico was a succession of 15 formations organized into 8 groups. Thompson's Pennsylvanian lithostratigraphy was based on detailed stratigraphic sections and fusulinid biostratigraphy in the Derry Hills and the Mud Springs Mountains of Sierra County, the northern Oscura Mountains of Socorro County and the northern Sacramento Mountains of Otero County.

Most subsequent workers did not adopt Thompson's (1942) lithostratigraphic nomenclature, though some have noted that it merits re-examination and that many of the formation names he proposed may be useful lithostratigraphic units of member rank in the Pennsylvanian section. Thompson's nomenclature was applied in the Socorro area in several graduate theses from New Mexico Tech (see Lucas et al., this volume). Here, we re-examine Thompson's (1942) Pennsylvanian lithostratigraphy in the northern Oscura Mountains (Fig. 1) and also describe the older part of that section, which he did not explicitly study. Our

lithostratigraphic conclusion is that most of Thompson's (1942) formation names proposed for Pennsylvanian strata in the northern Oscura Mountains are useful as member-rank units in central New Mexico.

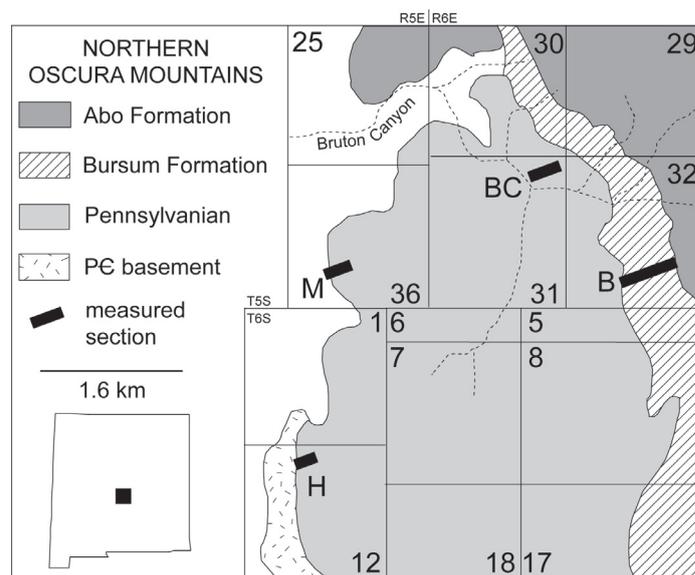


FIGURE 1. Simplified geologic map of part of the northern Oscura Mountains (after Wilpolt and Wanek, 1951) showing locations of measured sections. Measured sections are: B = type Bruton (Fig. 8), BC = Bruton Canyon (Fig. 7), H = Hansonburg (Fig. 4) and M = Mex Tex Mine (Fig. 5).

**PREVIOUS STUDIES**

Darton (1928, p. 193-195, figs. 77-78, pl. 42) published the first information on the geology of the northern Oscura Mountains in the form of text, structural cross sections and a reconnaissance geologic map. He assigned the Pennsylvanian strata in the range to the Magdalena Group, above Precambrian granite and overlain by the Abo Formation (Fig. 2).

As already stated, Thompson (1942) provided the first detailed lithostratigraphy of the Upper Pennsylvanian strata in the northern Oscura Mountains (Fig. 3). Indeed, Thompson's (1942) stratigraphic sections provide a level of lithologic detail rarely seen at that time in the literature of the geology of New Mexico (some of the beds discriminated and described are less than 0.3 m thick). However, Thompson did not clearly designate lithologic breaks between his formations that might serve as mappable boundaries. Indeed, many of his formations are very thin units (some as thin as 6 m thick) that would be nearly impossible to map, and many lack a lithologic unity that would allow the field geologist to recognize them as distinct formations. A good example is the ~20-m-thick Story Formation, which consists of two contrasting halves, a lower clastic and an upper carbonate interval (Fig. 3). Furthermore, a careful reading of Thompson (1942) indicates that many of his formations equate to fusulinid assemblage zones, so they are biostratigraphic, not lithostratigraphic units. As Kottowski (1960, p. 21) stated: "to date most field geologists have not had the time nor the paleontologic data to map such detailed units as Thompson's formations...whereas some of the formations can be recognized in much of south-central New Mexico,

others change markedly in lithology away from the type localities, so that their equivalents can be correlated only by detailed fusulinid studies."

Indeed, subsequent geologic mappers, especially those of the U. S. Geological Survey, did not use Thompson's lithostratigraphic nomenclature. Thus, Wilpolt and Wanek (1951) published mapping that includes the Pennsylvanian outcrops in the northern Oscura Mountains. They used a nomenclature for these rocks (Fig. 2) that had largely been developed by workers of the U. S. Geological Survey, from Gordon (1907) to Read and Wood (1947), and assigned the entire Pennsylvanian section to the Magdalena Group divided into the Sandia Formation, Madera Limestone and Bursum Formation (the latter considered by them to be of Permian age). They further divided the Madera informally into a lower gray limestone member and an upper arkosic limestone member.

Kottowski (1960) used Thompson's (1942) lithostratigraphic nomenclature for the Pennsylvanian strata in the northern Oscura Mountains, but no other worker did. For example, Siemers (1978, 1983), in a comprehensive study of Pennsylvanian strata in Socorro County, used the U. S. Geological Survey nomenclature employed by Wilpolt and Wanek (1951). Thus, despite the fact that Thompson (1942) provided the first detailed lithostratigraphy and biostratigraphy of the Pennsylvanian strata of central and southern New Mexico, that stratigraphy was largely ignored and forgotten.

Kues (2001) recommended that the names Gray Mesa Limestone (Formation) and Atrasado Formation (of Kelley and Wood, 1946; cf. Krainer and Lucas, 2004) be used in the northern Oscura

Darton (1928)	Thompson (1942)		Wilpolt & Wanek (1951)		Kues (2001)	this paper			
<b>Magdalena Group</b>	Fresnal Group	Bruton Formation	Bursum Formation		Bursum Formation	Bursum Formation			
	Keller Group	Moya Formation	Magdalena group	Madera limestone	Arkosic limestone member	Atrasado Formation	Moya Member		
		Del Cuerto Formation					Del Cuerto Member		
	Hansonburg Group	Story Formation					Story Member		
		Burrego Formation					Burrego Member		
	Veredas Group	Council Spring Member					Council Spring Member		
		Adobe Formation					Adobe Member		
		Coane Formation							
		not explicitly studied					Lower gray limestone member	Gray Mesa Formation	Gray Mesa Formation
							Sandia formation (upper clastic member)	Sandia Formation	Sandia Formation

FIGURE 2. Comparison of previously used Pennsylvanian lithostratigraphic nomenclature in the northern Oscura Mountains and the nomenclature advocated in this article.

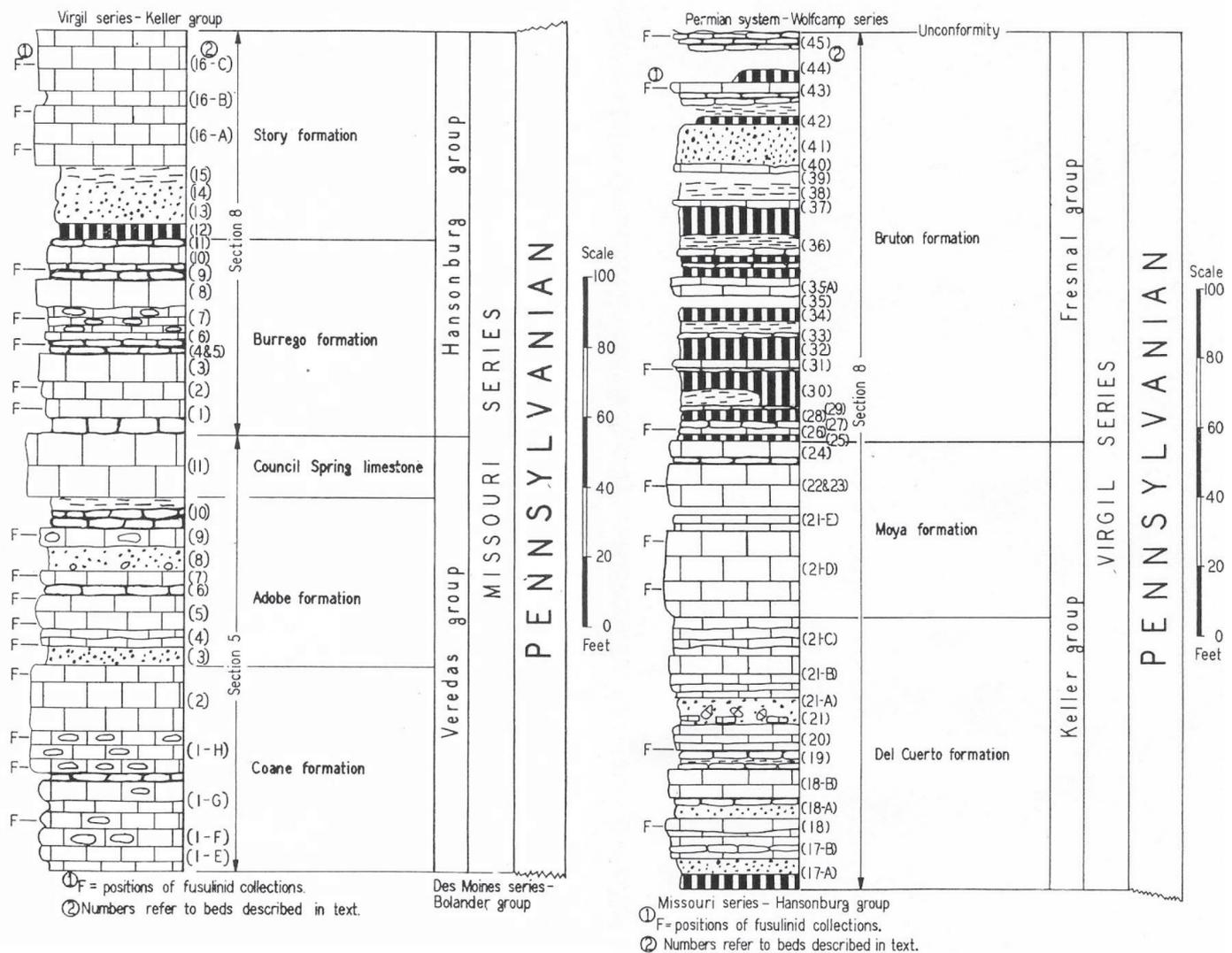


FIGURE 3. Thompson's (1942, fig. 6) type sections of the Veredas, Hansonburg and Keller groups and section of the Fresnal Group, and their included formations, measured in the northern Oscura Mountains of Socorro County.

Mountains, as they are the oldest formal names proposed for what the U. S. Geological Survey informally termed the gray limestone member (=Gray Mesa Formation) and the arkosic limestone member (=Atrasado Formation) of the Madera Limestone (Fig. 2). He included these units in a Madera Group, overlying the Sandia Formation and overlain by the Bursum Formation. Kues (2001; also see Lucas, 2002) also suggested that Thompson's (1942) Pennsylvanian formation names proposed in the northern Oscura Mountains may prove useful as member-level units in the local Pennsylvanian lithostratigraphy.

We follow Kues (2001) in applying the names Gray Mesa and Atrasado formations to the Pennsylvanian strata in the northern Oscura Mountains between the Sandia and the Bursum formations (Fig. 2). We do not use the term Madera Group, which we regard as imprecise and unnecessary (Krainer and Lucas, 2004). We also agree with Kues (2001) and Lucas (2002) that Thompson's (1942) lithostratigraphic nomenclature in the northern Oscura Mountains is of local value, though all of his formations should

be reduced in rank to member-level units (Lucas et al., 2008), and we here abandon one of his formations as unrecognizable (Fig. 2). Thus, Thompson's (1942) work provides a useful local lithostratigraphy for some of the Pennsylvanian strata exposed in the northern Oscura Mountains.

**LITHOSTRATIGRAPHY**

**Sandia Formation**

We measured one stratigraphic section of the basal portion of the Pennsylvanian section on the northern flank of the Oscura Mountains, which we term the Hansonburg section, in the NE ¼ sec. 12. T6S, R 5E (Fig. 4). We assign the lower 12.5 m of this section to the Sandia Formation, which nonconformably overlies red Proterozoic granite and a 0.8-m-thick layer of granitic gneiss. Wilpolt and Wanek (1951) mapped these strata as Sandia Formation, and in the southern Oscura Mountains and northern

San Andres Mountains, Bachman (1968) and Bachman and Harbour (1970) assigned equivalent strata to the Sandia Formation. Nevertheless, the Sandia Formation section we measured is very thin relative to sections to the south, such as at Mockingbird Gap, where the Sandia Formation is more than 80 m thick (Bachman, 1968) and the Socorro area (Lucas et al., this volume), where the Sandia measures about 162 m thick. In most areas where the Sandia Formation is thick, it contains a substantial amount of sandstone.

At the Hansonburg section (Fig. 4), the lower 8.5 m of the Sandia Formation (units 3-11) consist of brown, sandy shale intercalated with three thin, sandy bioclastic limestone beds. The upper 4 m (units 12-18) are composed of thin-bedded nodular limestone (0.8 to 1.1 m thick), thin, sandy bioclastic limestone beds, shale with limestone nodules, gray shale and a thin covered interval. We draw the boundary between the Sandia Formation and the overlying Gray Mesa Formation at the base of the first cherty limestone bed (Fig. 4, unit 19).

### Gray Mesa Formation

In the northern Oscura Mountains, as elsewhere in central New Mexico, the Gray Mesa Formation is about 150 m thick and consists of cherty, fossiliferous limestone with interbeds of shale, eroding to a step-and-ledge topography. At the Hansonburg section (Fig. 4), the basal 36 m of the Gray Mesa Formation is composed of different kinds of thin- to medium-bedded limestone and covered intervals. Most limestone beds contain black chert nodules, chert lenses and thin, irregular layers of chert. Fossils observed in the field are crinoids, fusulinids, brachiopods and algae, which are abundant in some limestone beds. The lower part of the section includes chert-free algal limestone beds and thin-bedded algal limestone with fusulinid packstone on bed tops. In the upper part of the section, a distinct horizon with numerous silicified *Chaetetes* is present (Fig. 4, unit 37), overlain by bioturbated, cherty micritic limestone. Fusulinid limestone (wackestone-packstone) occurs at several levels in the section. In the middle part, black shale is exposed above a covered slope.

We measured a nearly complete section of the Gray Mesa Formation at the Mex Tex Mine in the SE ¼ sec. 36, T5S, R5E. At the Mex Tex Mine section (Figs. 5-6A), the exposed section of the Gray Mesa Formation is 150 m thick. The lowermost 12 m are missing (exposed at the Hansonburg section: Mex Tex Mine unit 12 corresponds to Hansonburg unit 40 and Mex Tex Mine unit 16 corresponds to Hansonburg unit 42: Figs 4-5). Therefore, the total thickness of the Gray Mesa Formation in the northern Oscura Mountains is about 162 m. Most of the Gray Mesa Formation is ledge- and cliff-forming limestone (about 63% of the measured section), and the remainder is covered slopes presumably underlain by shale or it is slope-forming shale (Figs. 5, 6A)

Thus, the Gray Mesa Formation at the Mex Tex Mine section consists of different kinds of cherty limestone and less abundant beds of non-cherty limestone, alternating with covered intervals 0.2 to 2.4 m thick. The limestone is thin to thick bedded, and the bedding is mostly wavy. In the middle of the section, thick bedded

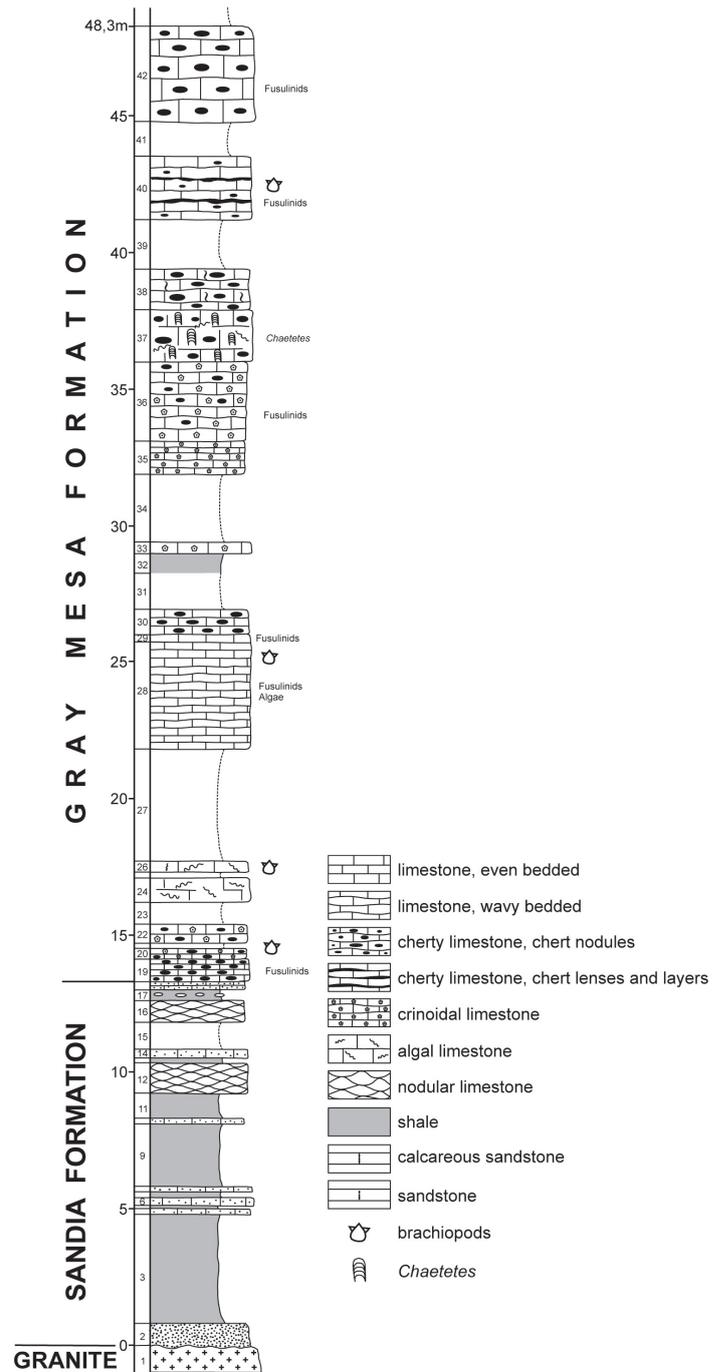


FIGURE 4. Hansonburg section of the Sandia Formation and lower part of the Gray Mesa Formation.

to massive algal limestone beds (algal mound facies) are present. All limestone beds are fossiliferous, and they contain crinoids (locally forming crinoidal packstone), fusulinids (commonly fusulinid wackestone and packstone), brachiopods (frequently silicified), rugose corals (frequently silicified), gastropods and/or algae (all observed in the field). Micritic limestone types of a low-energy environment dominate, and crinoidal packstone is

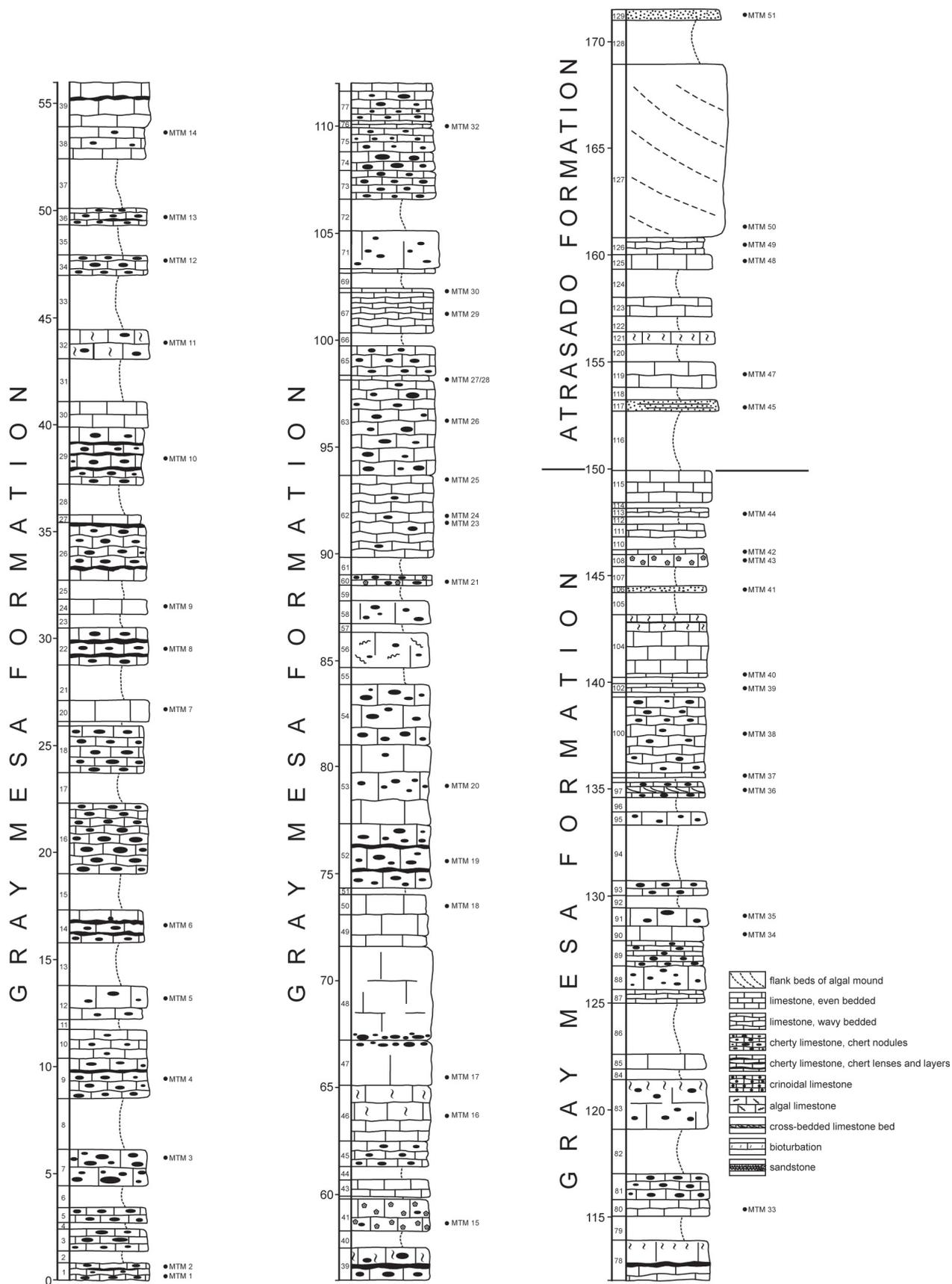


FIGURE 5. Mex Tex Mine section of the Gray Mesa Formation and the lower part of the Atrasado Formation.

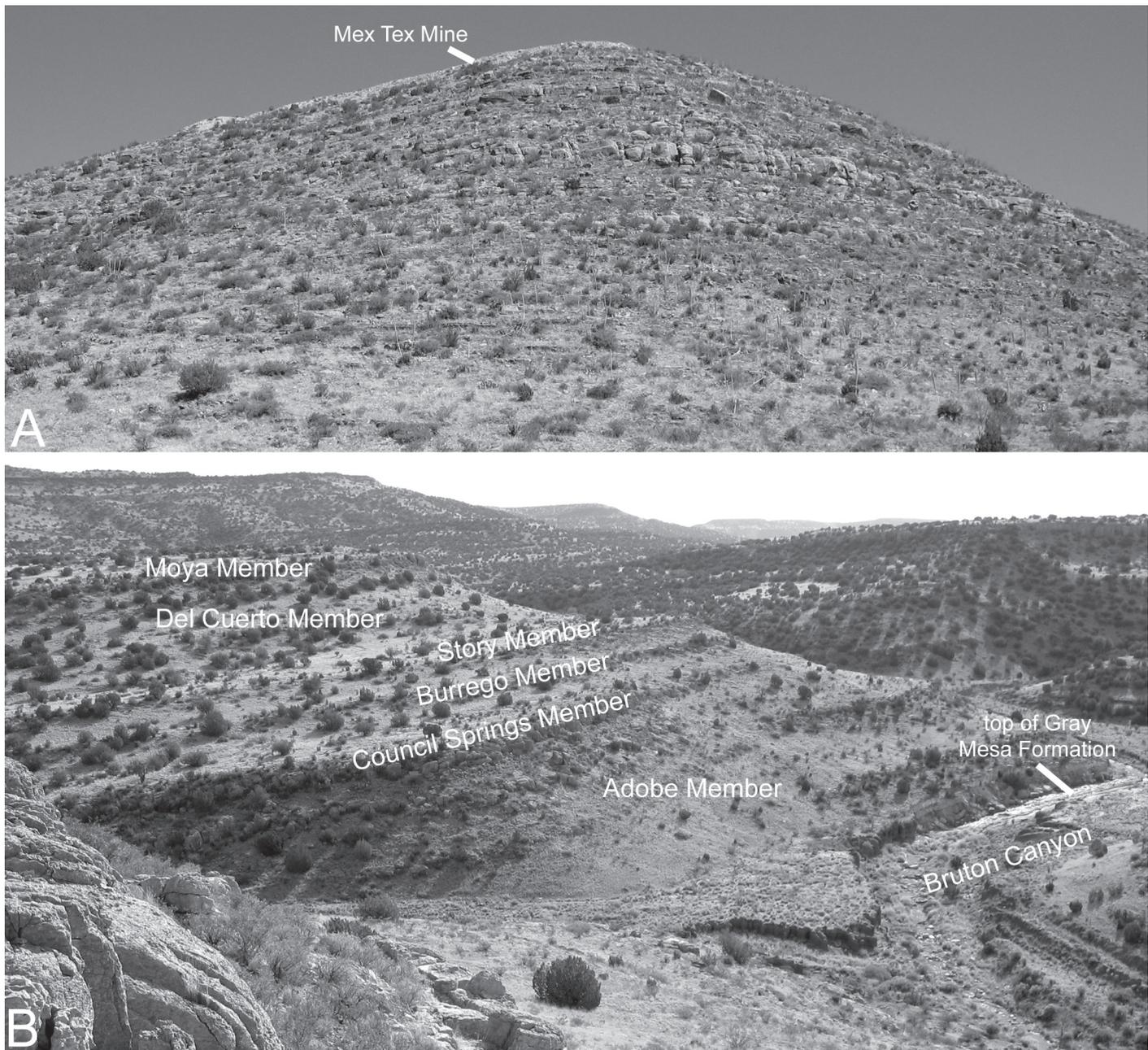


FIGURE 6. Photographs of the Mex Tex Mine (A) and Bruton Canyon (B) sections.

rare. Some grainstone indicative of a high-energy setting is present. Massive algal limestone in the middle part of the section represents algal mounds (biostromes). Chert occurs as nodules, irregular lenses and thin layers. Individual chert nodules measure up to about 25 cm in diameter.

Thompson (1942) proposed five formation rank units in three groups for strata that we assign to the Gray Mesa Formation (in ascending order): Elephant Butte, Whiskey Canyon, Garcia and Coane formations, with the undivided Bolander Group between the Garcia and the Coane formations. Only one of these units—the Coane Formation—has its type section in the northern Oscura Mountains. The others were based on type sections in the Mud

Springs Mountains of Sierra County (Thompson, 1942). Thompson's (1942, p. 59-60, fig. 6) type section of the Coane Formation was measured in the SE ¼, sec. 36, T5S, R5E, which is where our Mex Tex Mine section was measured. Thompson (1942) described the type section of the Coane Formation as 18 m thick and mostly cherty limestone in the lower half and non-cherty limestone in the upper half (Fig. 3). Furthermore, Thompson (1942, p. 60) reported the stratigraphically lowest record of *Triticites* in the northern Oscura Mountains in his bed 1-G of the Coane Formation. We believe this corresponds to our bed 102 near the top of the Gray Mesa Formation in the Mex Tex Mine section (Fig. 5), because this is where we encountered the stratigraphically lowest

*Triticites*. Therefore, Thompson's (1942) Coane Formation type section corresponds to beds 95 to 115 of our Mex Tex Mine section.

Our Mex Tex Mine section indicates that there is no strong lithostratigraphic basis for drawing a local base to a Coane Formation. Limestones lower in the section (for example, units 87-93) differ little from limestones in the Coane interval. Instead, it seems clear that the base of Thompson's Coane Formation is a biostratigraphic boundary that corresponded to where he put the base of the Missourian, indicated by the presence of the fusulinid *Wedekindellina ultimata* and by the lowest occurrence of *Triticites* (Thompson, 1942; Thompson and Kottlowski, 1955; Thompson et al., 1956). Therefore, we abandon the term Coane Formation, and we do not recognize it as a member of the Gray Mesa Formation in the northern Oscura Mountains.

Of the other names Thompson (1942) proposed for the Gray Mesa Formation interval, the most distinctive is the Whiskey Canyon Limestone, a very cherty limestone-dominated interval. It may be that the Whiskey Canyon Limestone corresponds to units 14-29 of our Mex Tex Mine section, as this is the most cherty part of the Gray Mesa Formation section. However, strata above and below this interval bear no close resemblance to the Elephant Butte Formation (below, which at its type section has little chert) or the Garcia Formation (above, which has significant siliciclastic sandstone/conglomerate beds at its base). Furthermore, we are also unable to distinguish Thompson's Bolander Group (a mixture of cherty limestone, non-cherty limestone and clastics, including red beds) in the Mex Tex Mine section. Therefore, we do not subdivide the Gray Mesa Formation in the northern Oscura Mountains into members. Instead, the formation appears to us to be a mappable unit of mostly cliff- and ledge-forming cherty limestone not readily subdivided (Figs. 5, 6A). The Elephant Butte, Whiskey Canyon, and Garcia members are recognizable in other areas of central New Mexico, including the hills east of Socorro (Lucas et al., this volume).

Strata we assign to the Gray Mesa Formation in the northern Oscura Mountains are the same lithosome that Bachman (1968) termed the "lower member of the Madera Formation" in the southern Oscura Mountains and at Mockingbird Gap, where it is about 124 m thick and dominantly cherty limestone. Immediately to the south, in the northern San Andres Mountains, Bachman and Harbour (1970) mapped this same unit as the Lead Camp Limestone, a name Bachman and Myers (1969) had introduced for a stratigraphic interval of "massive cliff-forming cherty limestone beds" in the southern San Andres Mountains. Clearly, the Lead Camp Limestone is the same unit we are assigning to the Gray Mesa Formation in the northern Oscura Mountains. Thus, we favor abandoning the superfluous junior synonym (Lead Camp Limestone of Bachman and Myers, 1969) and replacing it with the older name Gray Mesa Formation (of Kelley and Wood, 1946). Note also that fusulinids indicate that this cherty limestone lithosome in both the Oscura and the San Andres Mountains is mostly of Desmoinesian age (see below and Bachman, 1968; Bachman and Myers, 1969).

We pick the contact of the Gray Mesa Formation with the overlying Atrasado Formation at the top of the highest ledge-forming

limestone, which is overlain by a 2.8-m-thick covered interval (shale?) topped by a 0.5-m-thick bed of arkosic, crossbedded sandstone (Fig. 5, units 116-117). This contact corresponds to the base of the Adobe Formation of Thompson (1942).

### ATRASADO FORMATION

We use the term Atrasado Formation in the northern Oscura Mountains to refer to the ~ 121 m thick section of mixed siliciclastic and carbonate strata between the underlying Gray Mesa Formation and the overlying Bursum Formation (Figs. 6B, 7). As noted above, we pick the base of the Atrasado Formation at the first relatively thick siliciclastic beds (a covered slope) above the limestone-dominated Gray Mesa Formation, and this is also the base of Thompson's (1942) Adobe Formation. Our concept of the Atrasado Formation encompasses six formations named by Thompson (1942), in ascending order, the Adobe, Council Spring, Burrego, Story, Del Cuerto and Moya formations. However, we regard these formations as member-rank units recognizable on a lithostratigraphic basis in the northern Oscura Mountains.

At the Mex Tex Mine section (Fig. 5), only the lower part of the Atrasado Formation is exposed. The Atrasado Formation starts with a shale slope followed by a 0.5-m-thick arkosic and micaceous sandstone, overlain by 8 m of thin- to thick-bedded, partially bioturbated fossiliferous limestone (crinoids, brachiopods, fusulinids, algae) separated by covered intervals and an 8.1-m-thick massive algal limestone with inclined flanking facies overlain by a covered slope and a thin sandstone. Note that Mex Tex Mine section unit 115 is the same as Bruton Canyon section unit 1, Mex Tex 117 = Bruton Canyon 3 and Mex Tex 127 = Bruton Canyon 11 (Figs. 5, 7).

The section of the Atrasado Formation we measured at Bruton Canyon (NE ¼ sec. 31, T5S, R6E) is 121 m thick and includes the uppermost 4 m of the Gray Mesa Formation and the Atrasado Formation divided into the Adobe, Council Spring, Burrego, Story, Del Cuerto and Moya members (Figs. 6B, 7).

#### Adobe Member

The base of the Bruton Canyon section is the top of the Gray Mesa Formation, 3.7 m of thick, nodular to wavy bedded, gray limestone containing algae (Figs. 6B, 7). Thompson's type section of his Adobe Formation (Fig. 3) was measured near our Mex Tex Mine section and is 14 m of mixed siliciclastic and carbonate strata (Adobe is a now defunct settlement just north of the Oscura Mountains). Our section of the Adobe Member at Bruton Canyon is a little more than twice as thick but similar to Thompson's in its lithologic succession—both are two cycles of clastics overlain by carbonates. In the northern Oscura Mountains, the Adobe Member is recognizable as a slope-forming unit with significant siliciclastic content at the base of the Atrasado section above the underlying, cliff-forming limestone of the Gray Mesa Formation and below the ledge-forming algal limestone of the Council Spring Member (Fig. 6B).

The Adobe Member of the Atrasado Formation is 30.4 m thick at our Bruton Canyon section and displays two transgressive

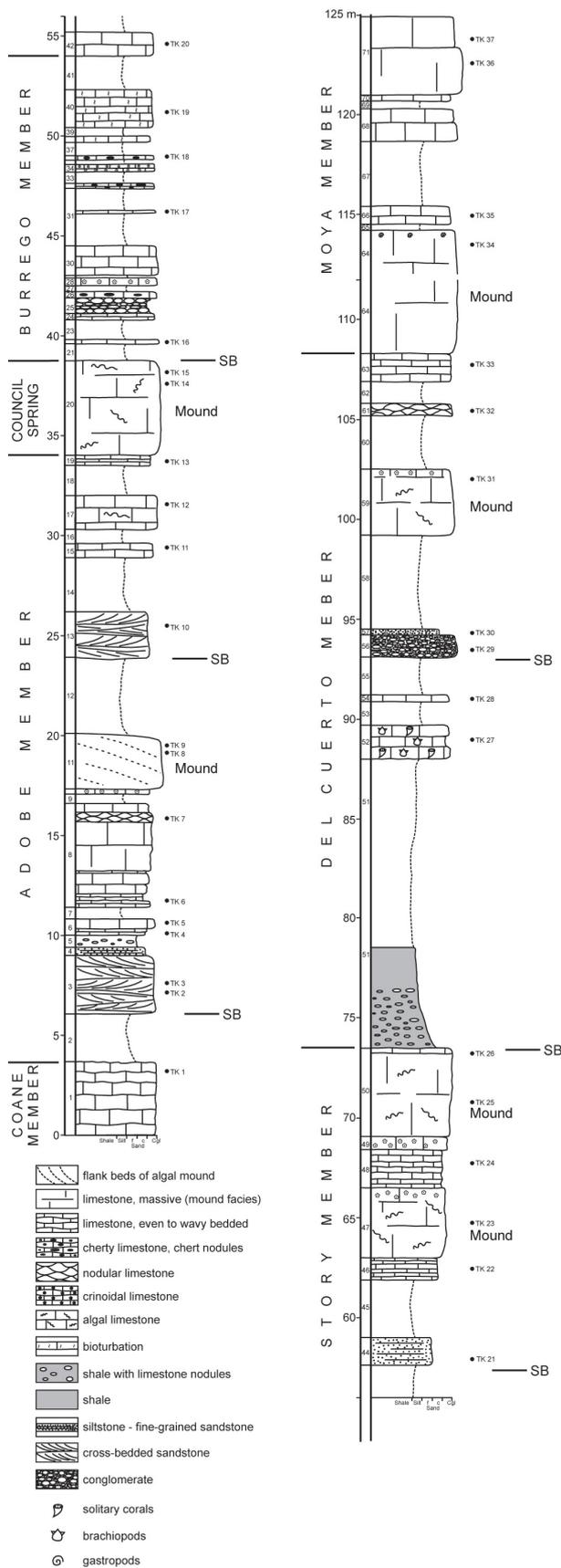


FIGURE 7. Bruton Canyon section of the top of the Gray Mesa Formation and of the Atrasado Formation.

cycles. At the base of the lower cycle there is a covered interval, which probably represents shale. Above follows a 2.9-m-thick interval of reddish to brownish, micaceous sandstone with small-scale crossbedding and syndepositional deformation structures of a ?fluvio-deltaic environment. The base of this sandstone interval (unit 3) represents a sequence boundary. The covered shale interval below probably formed during the initial regression of the late highstand. The overlying sandstone is interpreted to have formed during a lowstand. On top of the sandstone interval rests a 0.4-m-thick reddish siltstone to fine-grained sandstone, overlain by 0.6 m of greenish siltstone-mudstone with reworked limestone clasts. We interpret this horizon as a transgressive surface. Above follow thin-to-thick, wavy, bedded fossiliferous limestone containing algae and brachiopods and forming two thickening-upward successions, separated by a thin covered interval (shale?). The top of the lower cycle consists of a thin crinoidal limestone bed, overlain by a massive algal limestone (unit 11) that forms a cliff and extends laterally over several tens of meters. This massive algal limestone represents an algal mound (biostrome) with lateral thickness variations. Locally clinofolds are developed (slope of the mound). The mound is overlain by a covered interval (shale?).

Cycle 2 begins with reddish-brown sandstone with small-scale crossbedding (unit 13). We draw the sequence boundary at the base of this sandstone. The sandstone is overlain by a covered interval (shale?), two gray limestone beds containing fusulinids (this is bed 9 of Thompson, 1942, fig. 6), another covered interval and indistinctly thick-bedded algal limestone (biostrome), a third covered interval and an indistinctly bedded limestone.

**Council Spring Member**

The Adobe Member is overlain by a 4.8-m-thick, massive, light gray algal limestone that forms a prominent cliff that extends laterally for kilometers. This massive algal limestone represents a mound facies (biostrome) and is the Council Spring Formation of Thompson (1942), named for a spring at the northern end of the Oscura Mountains. Thompson's (1942) type section of his Council Spring Formation is 5.5 m thick (Fig. 3). We recognize it as the Council Spring Member (it can also be treated as a unit of bed-level rank), and it is one of the most readily recognized and laterally traceable parts of the Atrasado Formation in the northern Oscura Mountains. This member is also readily identified in the hills east of Socorro (Lucas et al., this volume).

**Burrego Member**

Overlying the Council Spring Member is another slope-forming unit, the Burrego Member. Thompson's (1942) type section of the Burrego and Story formations (his Hansonburg Group) is in the SE ¼ sec. 31, T5S, R6E, just across Bruton Canyon from our section. His type section of the Burrego Formation is 16 m thick (Fig. 3), whereas our section of the Burrego Member is 16.7 m thick. Thompson (1942) derived the name Burrego from Borrego Spring in the northern Oscura Mountains, so his spelling "Burrego" clearly is a corruption of "Borrego" (a Spanish sur-

name). Given that the name Burrego has been often used in the technical literature, even appearing in stratigraphic lexicons (e.g., Jicha and Lochman-Balk, 1958), we do not correct the spelling.

In the Bruton Canyon section, the Burrego Member consists of thin- (0.1-0.2 m) to thick-bedded (0.5 m) limestone and intercalated covered intervals 0.2 to 2.9 m thick. Limestone intervals are 0.2 to 1.9 m thick and encompass fossiliferous limestone containing crinoid fragments, bryozoans and algae, bioturbated micritic limestone and cherty limestone. The Burrego Formation does not show any obvious cyclic trend.

### Story Member

The Story Member is a bipartite lithostratigraphic unit—a lower, clastic interval capped by an algal mound lithofacies. Thompson's (1942) Story Formation type section is 17.5 m thick (Fig. 3), whereas our section of the Story Member is 18.3 m thick. The name comes from Story Tank, a watering hole west of the Oscura Mountains. The lower part of the Story Member is a slope former, whereas the upper part forms a ledge or cliff. On a purely lithostratigraphic basis, the name Story Member could be confined to the upper algal mound facies, but the arkosic sandstone/red mudstone units at its base are distinctive marker beds readily recognized in the field, so we retain the bipartite unit named by Thompson (1942) as the entire Story Member.

The Story Member represents a transgressive sequence. The base is formed by reddish-brown, fine-grained arkosic and micaceous sandstone, followed by a covered interval (shale?), thin-bedded algal limestone and a massive to indistinctly-bedded algal limestone (algal mound/biostrome). On top of the mound a crinoidal limestone is present ("capping bed"). The massive mound (unit 47) and its capping bed are overlain by wavy bedded limestone containing abundant brachiopods, and a thick crinoidal packstone bed followed by another massive algal mound, which is 4.4 m thick (unit 50). The massive algal limestone is overlain by a thin fossiliferous limestone bed, which forms the topmost bed of the Story Member.

### Del Cuerto Member

Thompson's (1942) type section of his Keller Group (Del Cuerto and Moya formations) was measured in the NE ¼ sec. 31, T5S, R6E and into the west-central part of sec. 32, so it is very close to our Bruton Canyon section. At his type section, the Del Cuerto Formation is ~ 25 m thick (Fig. 3), whereas in our Bruton Canyon section the Del Cuerto Member is ~ 35 m thick. The name is from a spring on the eastern flank of the Oscura Mountains. The Del Cuerto Member of the Atrasado Formation is a relatively thick, slope-forming unit between the cliff-forming algal limestones at the top of the Story Member (below) and at the base of the Moya Member (above).

The Del Cuerto Member at the Bruton Canyon section (Fig. 7) is 34.8 m thick and is composed of two transgressive cycles. The lower cycle starts with a 14.5-m-thick interval, which, in the lower 5 m, consists of pale calcareous shale with limestone nodules (base of unit 51, pedogenic?). The upper part of this interval

is covered and probably also consists of shale. The sharp boundary between the uppermost Story limestone bed and overlying shale again represents a sequence boundary.

Above this shale interval, indistinctly-bedded limestone is exposed containing brachiopods and solitary corals (Kues and Lucas, 2001). This limestone is followed by two covered intervals separated by a thin limestone bed. A fine-grained conglomerate with erosive base (sequence boundary) forms the base of the upper cycle (unit 56). The conglomerate is overlain by thin arkosic sandstone with carbonate matrix/cement, followed by a covered interval (shale?) and a massive algal limestone (mound facies) containing abundant crinoids and brachiopods on top ("capping bed") (unit 59). This capping bed forms the top of the upper cycle. The capping bed of the upper cycle is followed by a covered slope, greenish-gray mudstone with gray limestone nodules, a covered interval and bedded limestone containing algae, brachiopods and locally abundant gastropods. These strata comprise another cycle up through the overlying massive algal limestone that forms the base of the Moya Member.

### Moya Member

The Moya Member is a ledge- and cliff-forming limestone unit at the top of the Atrasado Formation in the northern Oscura Mountains. It has a distinctive topographic expression—two cliffs of algal limestone with a notch/slope in between. At Thompson's (1942) type section of his Moya Formation it is 15.5 m thick (Fig. 3), whereas our section of the Moya Member is 16.5 m thick. The name is taken from a spring on the eastern slope of the Oscura Mountains.

The Moya Member in the Bruton Canyon section is composed of a lower, 5.9-m-thick massive algal limestone forming a prominent cliff (unit 64), a medium- to thick-bedded limestone interval (forms a notch) containing algae and brachiopods, with covered intervals between, and an upper massive algal limestone (mound facies) (unit 71). The overlying base of the Bursum Formation is marked by red-bed mudstone.

## BURSUM FORMATION

Thompson (1942) named the Bruton Formation in the northern Oscura Mountains for a 35-m-thick type section in the SE1/4 sec. 32, T5S, R6E that is a mixture of nonmarine and marine strata between Virgilian limestones and Wolfcampian limestone and overlying Abo Formation red beds (Fig. 8). Four years later, on a map legend, Wilpolt et al. (1946) renamed essentially the same unit the Bursum Formation, with a type section in the Hansonburg Hills, only 15 km from Thompson's type section of the Bruton Formation (Lucas et al., 2000, 2002). Thompson (1942) placed the top of the Bruton Formation at the base of a marine limestone with the fusulinid *Schwagerina*. This limestone, and overlying intercalated marine and nonmarine strata (an interval about 40 m thick: Fig. 8), were assigned to no formation by Thompson (1942).

Thompson (1954, p. 18) subsequently used the term Bursum Formation and made it clear that his concept of the Bursum was

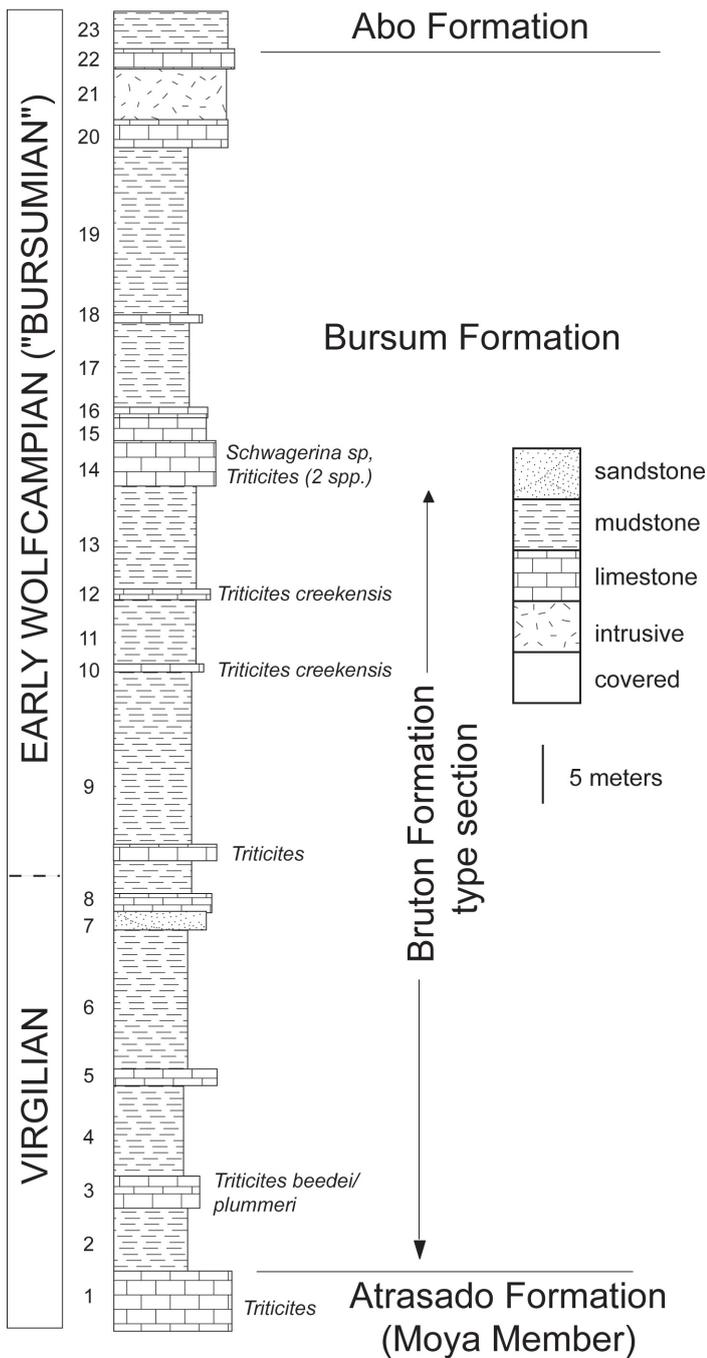


FIGURE 8. Type section of the Bruton Formation of Thompson (1942), including top of the Atrasado Formation (Moya Member), Bursum Formation and the base of the Abo Formation.

biostratigraphic/chronostratigraphic when he stated that “the term Bursum should be redefined so as to apply only to pre-Abo Wolfcampian rocks of New Mexico.” Thompson therefore reassigned the upper 40 m of strata above his Bruton type section and below the Abo to the Bursum Formation (Fig. 8, units 14-22), but he also stated that “a lower part of the Bursum as defined by Wilpolt et al. here is retained in the Bruton formation.”

After Wilpolt et al. (1946), Bursum came to be widely used as a formation name in central New Mexico, but no new data

were presented on its type section. Lucas et al. (2000, 2002) described in detail the type section of the Bursum Formation and documented its fusulinid assemblages (also see Lucas and Wilde, 2000). Also, redefinition of the Carboniferous-Permian boundary based on conodonts (Davydov et al., 1998) moved that boundary to a younger level so that the Bursum Formation, long considered earliest Permian, is now considered to be of latest Pennsylvanian age (Lucas et al., 2000, 2002).

We remeasured the Bruton Formation type section as a representative section of the Bursum Formation in the northern Oscura Mountains (Fig. 8). At that section, the Bursum Formation is ~ 101 m thick, mostly red-bed mudstone (83% of the measured section thickness), lesser amounts of limestone (16%) and a single bed of sandstone (1%). The base of the Bursum Formation is a 6-m-thick, slope-forming red mudstone with some purple color mottling. This unit is at the base of a slope of similar mudstone units broken by thin fossiliferous limestone and by one bed of arkosic, trough-crossbedded sandstone. The limestones are thin fusulinid packstones or wackestones that yield fusulinids, algae, gastropods and/or brachiopods. About two-thirds up the section, a ledge of light gray/white limestone (unit 14) contains numerous fusulinids, and is the highest bed in the section to yield fusulinids. Overlying Bursum strata are red-bed mudstones and thin beds of algal wackestone or grainstone. The contact of the Bursum Formation with the overlying Abo Formation is placed at the highest marine limestone bed of the Bursum Formation beneath red-bed mudstones and other siliciclastic beds of the Abo Formation (cf. Lucas and Krainer, 2004).

### BIOSTRATIGRAPHY

No age-diagnostic fossils are known from the Sandia Formation in the northern Oscura Mountains, so our assignment of Atokan age is based primarily on fusulinid biostratigraphy from other areas (e.g., Kues, 2001; Kues and Giles, 2004). Indeed, at Mockingbird Gap at the southern end of the Oscura Mountains, Bachman (1968) assigned an Atokan age (“Zone of *Fusulinella*”) to the Sandia Formation because Atokan fusulinids are present at the base of the overlying Gray Mesa Formation (his “lower member of Madera Formation”).

The Gray Mesa Formation contains numerous fusulinid-bearing beds (mostly *Beedeina* and/or *Wedekindellina*) in the Mex Tex Mine section. These are under study and indicate most of the formation is of Desmoinesian age. As mentioned above, the fusulinids *Wedekindellina ultimata* and the lowest *Triticites* are stratigraphically high in the Gray Mesa Formation. This means that the Desmoinesian-Missourian boundary is in the upper part of the Gray Mesa Formation (e.g., Thompson, 1942; Thompson et al., 1956).

Thompson’s (1942) fusulinid data indicate that the Atrasado Formation in the northern Oscura Mountains is of Missourian-Virgilian age. According to Thompson (1942), the base of the Virgilian is close to the base of the Del Cuerto Member.

Fusulinids from the type section of the Bruton Formation indicate that in the northern Oscura Mountains the Bursum Formation is of late Virgilian and early Wolfcampian age. Identifications by

the late Garner L. Wilde (personal commun., 2000) indicate that the stratigraphically lowest fusulinids in the Bursum Formation are late Virgilian (below unit 9, Fig. 8), whereas those higher in the section are early Wolfcampian (Newwellian = Bursumian) in age. This is slightly different from Thompson (1942), who placed the base of the Wolfcampian at unit 14. Given that the Bursum Formation is overlain by nonmarine Abo Formation red beds, the exact position of the base of the Permian is not certain in the northern Oscura Mountains, but we place it at the Abo base.

**LATE PENNSYLVANIAN TECTONICS AND DEPOSITIONAL CYCLES**

The Pennsylvanian section exposed in the northern Oscura Mountains is one of the thinnest Pennsylvanian sections exposed in central New Mexico (e.g., Kottlowski, 1963; Siemers, 1983; Broadhead and Jones, 2004). Thus, it is an unusually thin Pennsylvanian section between the Lucero basin to the northwest, San Mateo basin to the west and the Orogrande basin to the south, sitting on a prong or ramp of the western edge of the Pedernal uplift (e.g., Kottlowski, 1963; Siemers, 1983). The Sandia Formation is very thin—about 20% of its regional thickness. The Gray Mesa Formation, however, at ~ 162 m thick, is of average thickness for central New Mexico. It is the Atrasado Formation, at a mere 124 m thick, that accounts for much of the lack of thickness of this section.

The Atrasado Formation in the northern Oscura Mountains represents most of Missourian-Virgilian time and is mostly marine limestone and shale, but also contains some arkosic sandstones and conglomerates as well as red-bed mudstones of near-shore or nonmarine origin. The lithofacies range from siliciclastic sandstone and fine-grained conglomerate to bedded, fossiliferous limestone of an open marine shelf environment to massive algal mound facies formed just below the wave base under quiet water conditions within the photic zone. Within the Atrasado Formation, some well-developed transgressive cycles are present, most beginning with a siliciclastic interval, grading into bedded limestone and ending with a massive algal mound facies on top.

Some of these siliciclastic beds form evident sequence boundaries at the bases of transgressive cycles of deposition (see above). However, by our estimation, there are no more than eight such transgressive cycles (depositional sequences) in the Atrasado Formation, four in the Missourian strata and four in the Virgilian strata (Fig. 9).

Thus, sequence boundaries at the base of intercalated siliciclastic intervals allow a subdivision of the Atrasado succession into mixed siliciclastic-carbonate depositional cycles (Fig. 9). Each cycle starts with a siliciclastic unit at the base, grading into bedded limestone and finally into massive algal mound facies. We assume that the siliciclastic sediments were deposited in a nearshore to nonmarine environment during periods of low relative sea-level with high siliciclastic influx. Algal mounds formed in the photic zone below the wave base in quiet water as much as 25-30 m deep.

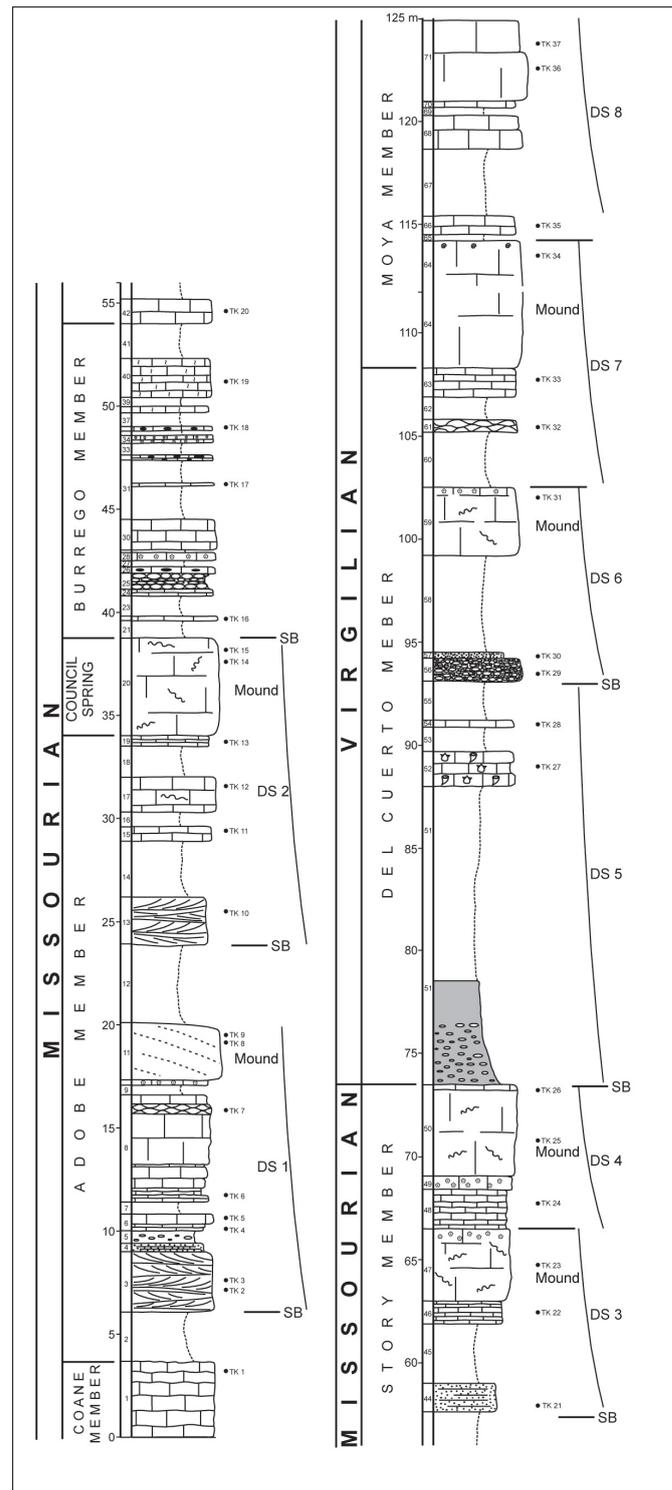


FIGURE 9. Interpretation of depositional cycles (DS) and sequence boundaries (SB) in the Atrasado Formation in the Bruton Canyon section.

The Adobe and Council Spring members display two well-developed transgressive cycles, and the Story Member represents another transgressive cycle, all ending with an algal mound facies on top. The lower cycle of the Del Cuerto Member probably starts with nonmarine shale and ends with bedded marine

limestone and shale; an algal mound facies is absent. The upper part of the Del Cuerto displays two cycles; the top of the upper cycle is formed by the basal algal mound of the Moya. The upper part of the Moya represents another cycle composed of a transgressive systems tract represented by bedded limestone and a highstand systems tract represented by the topmost massive algal limestone.

In the northern Oscura Mountains, the Atrasado Formation is approximately 124 m thick and encompasses almost the entire Missourian and Virgilian. The Desmoinesian-Missourian boundary lies approximately 10 m below the base of the Atrasado Formation, and the Virgilian-Wolfcampian boundary lies within the Bursum Formation, approximately 10 to 15 m above its base (see above). Heckel (2003) estimated a timespan of 3 Ma for the Missourian and 4 Ma for the Virgilian, indicating that the Atrasado Formation was deposited during at least 6 Ma (resulting in an average sedimentation rate of 20m/Ma). Whereas 50 glacioeustatic cycles are listed for the Virgilian and 24 for the Missourian (e.g., Rasbury et al., 1998; Boardman, 1999; Heckel, 2003), only eight cycles are recognizable within the Atrasado Formation in the northern Oscura Mountains (Fig. 9). This indicates that the cycles of the Atrasado Formation do not simply represent glacioeustatic high-frequency cycles. Indeed, the fact that only about 10% of the inferred glacioeustatic cycles are present in the Missourian-Virgilian section in the northern Oscura Mountains suggests the presence of considerable gaps at the erosional bases (sequence boundaries) of each Atrasado depositional sequence, caused by syndimentary tectonic movements related to ancestral Rocky Mountain deformation.

Tectonic processes related to ancestral Rocky Mountain deformation thus were a significant controlling factor on Atrasado Formation sedimentation in the northern Oscura Mountains.

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#### REFERENCES

- Bachman, G. O., 1968, Geology of the Mockingbird Gap quadrangle, Lincoln and Socorro Counties, New Mexico: U. S. Geological Survey, Professional Paper 594-J, 43 p.
- Bachman, G. O. and Harbour, R. L., 1970, Geologic map of the northern part of the San Andres Mountains, central New Mexico: U. S. Geological Survey, Miscellaneous Geologic Investigations Map I-600, scale 1: 62,500.
- Bachman, G. O. and Myers, D. A., 1969, Geology of the Bear Peak area Dona Ana County New Mexico: U. S. Geological Survey, Bulletin 1271-C, 46 p.
- Boardman, D.R., 1999, Virgilian and lowermost Permian sea-level curve and cyclothem; in Heckel, P.H., ed., Field trip #8: Middle and Upper Pennsylvanian (Upper Carboniferous) cyclothem succession in midcontinent basin, U.S.A.: Kansas Geological Survey, Open-File Report 99-27, p. 103-118.
- Broadhead, R. F. and Jones, G., 2004, Oil, natural gas and helium potential of the Chupadera Mesa area, Lincoln and Socorro Counties, New Mexico: New Mexico Bureau of Geology and Mineral Resources, Open-file Report 478, 95 p.
- Darton, N. H., 1922, Geologic structure of parts of New Mexico: U. S. Geological Survey, Bulletin 726, p. 173-275.
- Darton, N. H., 1928, "Redbeds" and associated formations in New Mexico: U. S. Geological Survey, Bulletin 794, 356 p.
- Davydov, V. I., Glenister, B. F., Spinosa, C., Ritter, S. M., Chernykh, V. V., Wardlaw, B. R. and Snyder, W. S., 1998, Proposal of Aidalash as global stratotype section and point (GSSP) for the base of the Permian System: Episodes, v. 21, p. 11-18.
- Gordon, C. H., 1907, Notes on the Pennsylvanian formations in the Rio Grande Valley, New Mexico: Journal of Geology, v. 15, p. 805-816.
- Heckel, P. H., 2003, Updated cyclothem constraints on radiometric dating of the Pennsylvanian succession in North America and its correlation with dates from Europe: Newsletter on carboniferous Stratigraphy, v. 21, p. 12-20.
- Herrick, C. L., 1900, The geology of the White Sands of New Mexico: Journal of Geology, v. 8, p. 112-128 [also published in 1900 in New Mexico University Bulletin, v. 2, 17 p.].
- Jicha, H. L., Jr. and Lochman-Balk, C., 1958, Lexicon of New Mexico geologic names: Precambrian through Paleozoic: New Mexico Bureau of Mines and Mineral Resources, Bulletin 61, 137 p.
- Kelley, V. C. and Wood, G. H., Jr., 1946, Lucero uplift, Valencia, Socorro and Bernalillo Counties, New Mexico: U. S. Geological Survey, Oil and Gas Investigations Preliminary Map 47, scale 1:63,360.
- Keyes, C. R., 1903, Geological sketch of New Mexico: Ores and Metals, v. 12, p. 48.
- Kottowski, F. E., 1960, Summary of Pennsylvanian sections in southwestern New Mexico and southeastern Arizona: New Mexico Bureau of Mines and Mineral Resources, Bulletin 66, 187 p.
- Kottowski, F. E., 1963, Paleozoic and Mesozoic strata of southwestern and south-central New Mexico: New Mexico Bureau of Mines and Mineral Resources, Bulletin 79, 100 p.
- Krainer, K. and Lucas, S. G., 2004, Type sections of the Pennsylvanian Gray Mesa and Atrasado formations, Lucero uplift, central New Mexico: New Mexico Museum of Natural History and Science, Bulletin 25, p. 7-30.
- Kues, B. S., 2001, The Pennsylvanian System in New Mexico—overview with suggestions for revisions of stratigraphic nomenclature: New Mexico Geology, v. 23, p. 103-122.
- Kues, B.S. and Giles, K.A., 2004, The late Paleozoic ancestral Rocky Mountains system in New Mexico; in Mack, G.H. and Giles, K.A., eds., The geology of New Mexico: A geological history: Socorro, New Mexico Geological Society, p. 95-136.
- Kues, B. S. and Lucas, S. G., 2001, An unusual Virgilian marine assemblage dominated by the brachiopods *Composita* and *Enteleles* in the northern Sierra Oscura, Socorro County, New Mexico: New Mexico Geology, v. 23, p. 55-56.
- Lucas, S. G., 2002, M. L. Thompson's Pennsylvanian stratigraphy in the Oscura Mountains, New Mexico: New Mexico Geological Society, 53<sup>rd</sup> Fall Field Conference Guidebook, p. 15-16.
- Lucas, S. G. and Krainer, K., 2004, The Red Tanks Member of the Bursum Formation in the Lucero uplift and regional stratigraphy of the Bursum Formation in New Mexico: New Mexico Museum of Natural History and Science, Bulletin 25, p. 43-52.
- Lucas, S. G. and Wilde, G. L., 2000, The Bursum Formation stratotype, Upper Carboniferous of New Mexico, and the Bursumian Stage: Permophiles, no. 36, p. 7-10.
- Lucas, S. G., Krainer, K. and Barrick, J. E., 2009, Pennsylvanian stratigraphy and conodont biostratigraphy in the Cerros de Amado, Socorro County, New Mexico: New Mexico Geological Society, 60<sup>th</sup> Fall Field Conference Guidebook, p.183-212.
- Lucas, S. G., Krainer, K. and Kues, B. S., 2002, Type section of the Upper Carboniferous Bursum Formation, south-central New Mexico, and the Bursumian Stage: New Mexico Geological Society, 53<sup>rd</sup> Fall Field Conference Guidebook, p. 179-192.
- Lucas, S. G., Krainer, K., Rinehart, L. F. and Spielmann, J. A., 2008, Pennsylvanian stratigraphy on the northern flank of the Oscura Mountains, Socorro County, New Mexico: New Mexico Geology, v. 30, p. 61-62.
- Lucas, S. G., Wilde, G. L., Robbins, S. and Estep, J. W., 2000, Lithostratigraphy and fusulinaceans of the type section of the Bursum Formation, Upper Car-

- boniferous of south-central New Mexico: New Mexico Museum of Natural History and Science Bulletin 16, p. 1-13.
- Rasbury, E. T., Hanson, G. N., Meyers, W. J., Holt, W. E., Goldstein, R. H. and Sailer, A. H., 1998: U-Pb dates of paleosols: Constraints on the Late Paleozoic cycle durations and boundary ages: *Geology*, v. 26, p. 403-406.
- Read, C. B. and Wood, G. H., 1947, Distribution and correlation of Pennsylvanian rocks in late Paleozoic sedimentary basins of northern New Mexico: *Journal of Geology*, v. 55, p. 220-236.
- Siemers, W. T., 1978, Stratigraphy, petrology, and paleoenvironments of the Pennsylvanian System of the Socorro region, west-central New Mexico [Ph. D. dissertation]: Socorro, New Mexico Institute of Mining and Technology, 275 p.
- Siemers, W. T., 1983, The Pennsylvanian System, Socorro region, New Mexico: Stratigraphy, petrology, depositional environments: *New Mexico Geological Society*, 34<sup>th</sup> Fall Field Conference Guidebook, p. 147-155.
- Thompson, M. L., 1942, Pennsylvanian System in New Mexico: New Mexico School of Mines, State Bureau of Mines and Mineral Resources, Bulletin 17, 92 p.
- Thompson, M. L., 1954, American Wolfcampian fusulinaceans: *University Kansas Paleontological Contributions*, Protozoa, Article 5, p. 1-226.
- Thompson, M. L. and Kottowski, F. E., 1955, Pennsylvanian and lower marine Permian stratigraphy of south-central New Mexico: *New Mexico Geological Society*, 6<sup>th</sup> Fall Field Conference Guidebook, p. 71- 76.
- Thompson, M. L., Verville, G. J. and Lokke, D. H., 1956, Fusulinids of the Desmoinesian-Missourian contact: *Journal of Paleontology*, v. 30, p. 793-810.
- Wilpolt, R. H. and Wanek, A. A., 1951, Geology of the region from Socorro and San Antonio east to Chupadera Mesa, Socorro County, New Mexico: U. S. Geological Survey, Oil and Gas Investigations Map OM-121, scale 1:63,360.
- Wilpolt, R. H., MacAlpin, A. J., Bates, R. L. and Vorbe, G., 1946, Geologic map and stratigraphic sections of Paleozoic rocks of Joyita Hills, Los Pinos Mountains, and northern Chupadera Mesa, Valencia, Torrance, and Socorro Counties, New Mexico: U. S. Geological Survey, Oil and Gas Investigations Preliminary Map 61.