

The Pennsylvanian section at Cedro Peak: A local Pennsylvanian reference section in the Manzanita Mountains, central New Mexico (USA)

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The Pennsylvanian section at Cedro Peak: a reference section in the Manzanita Mountains, central New Mexico

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Abstract

At Cedro Peak in the Manzanita Mountains of Bernalillo County, New Mexico, a nearly complete, structurally uncomplicated, fossiliferous and characteristic local Pennsylvanian section is exposed. Approximately 340 m thick, we assign this section to the (in ascending order) Sandia, Gray Mesa (= Los Moyos), Atrasado (= Wild Cow), and Bursum Formations. We divide the Gray Mesa Formation into the (in ascending order) Elephant Butte, Whiskey Canyon, and Garcia Members, and we divide the Atrasado Formation into the (in ascending order) Bartolo, Amado, Tinajas, Council Spring, Burrego, Story, Del Cuerto, and Moya Members. We thus reject the names Sol se Mete, Pine Shadow, and La Casa for member-level subdivisions of the Atrasado Formation.

We describe the lithostratigraphy, microfacies, and paleontology of the Pennsylvanian strata at Cedro Peak to interpret their depositional environments and age. The approximately 14-m-thick Sandia Formation is almost entirely of nonmarine origin and is assigned an Atokan age based on regional correlations. The approximately 119-m-thick Gray Mesa Formation records normal marine deposition. It contains fusulinids from latest Atokan? to middle Desmoinesian age. The approximately 200-m-thick Atrasado Formation is a complex succession of marine and nonmarine (mostly fluvial-deltaic) strata. It contains fusulinids of Missourian and middle Virgilian age. Only the lowermost 6 m of the Bursum Formation are exposed at Cedro Peak, but nearby sections indicate a Bursum thickness of approximately 90 m and yield Virgilian-age fusulinids. The continuity of the stratigraphic architecture of the Gray Mesa and Atrasado Formations from the Oscura Mountains in Socorro County to Cedro Peak, a distance of approximately 150 km, suggests that Middle–Late Pennsylvanian sedimentation was driven by the same underlying forces over much of central New Mexico. We posit these forces as a series of tectonic events overprinted at a few points by eustatic cycles.

Introduction

The Manzano Mountains are a fault block uplift of late Cenozoic age that forms the eastern border of the Rio Grande rift from Tijeras Canyon (at the approximate latitude of Albuquerque) on the north to Abo Pass (at the approximate latitude of Bernardo) on the south, a distance of approximately 75 km (Fig. 1). Above the Proterozoic basement core of the range, a relatively thick and stratigraphically complex Pennsylvanian section is exposed, mostly on the eastern

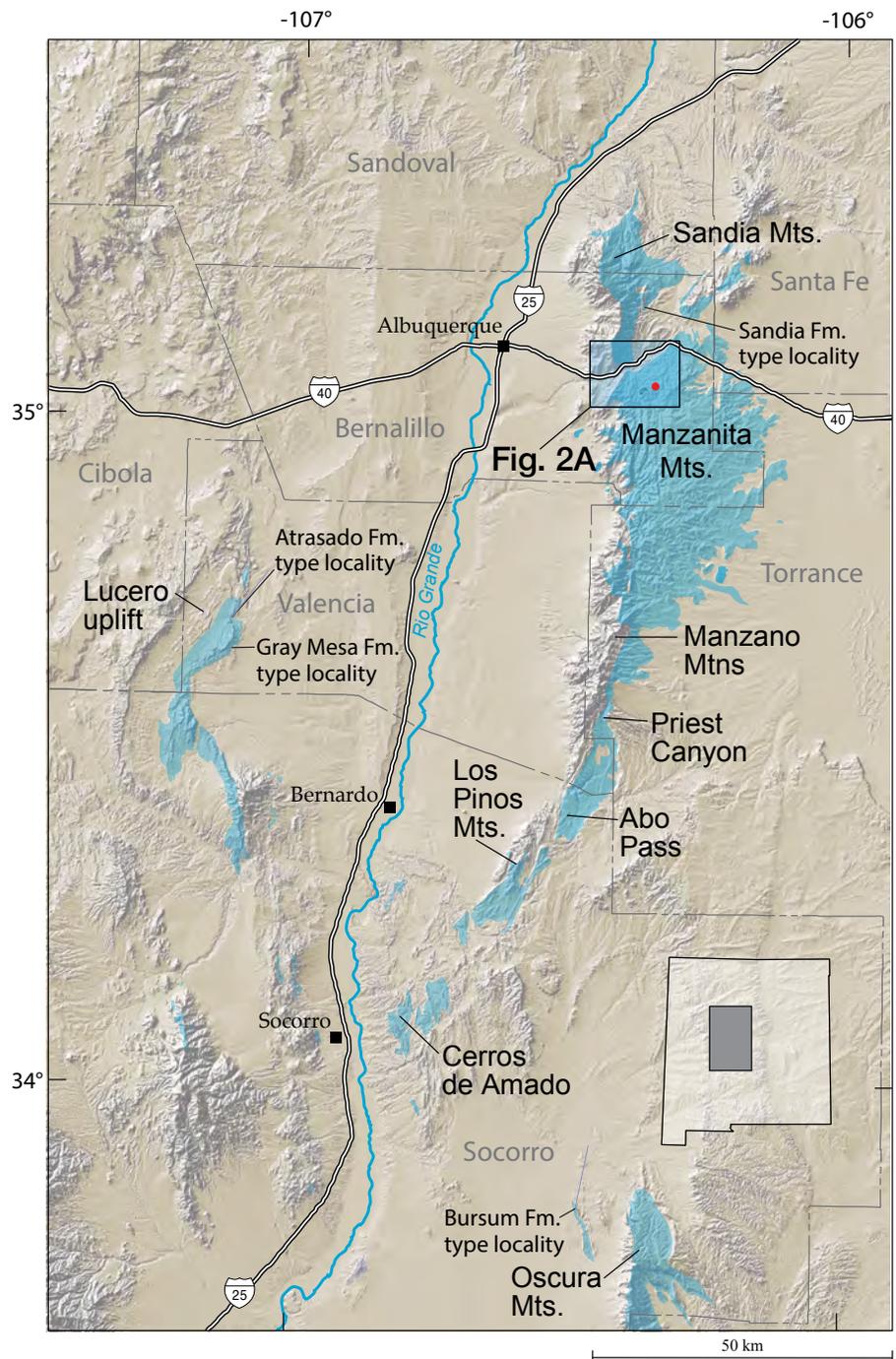


FIGURE 1—Regional location map of the Manzanita Mountains and the Cedro Peak area, central New Mexico. Surface extent of Carboniferous rocks is indicated by blue shading. Red dot indicates location of Cedro Peak.

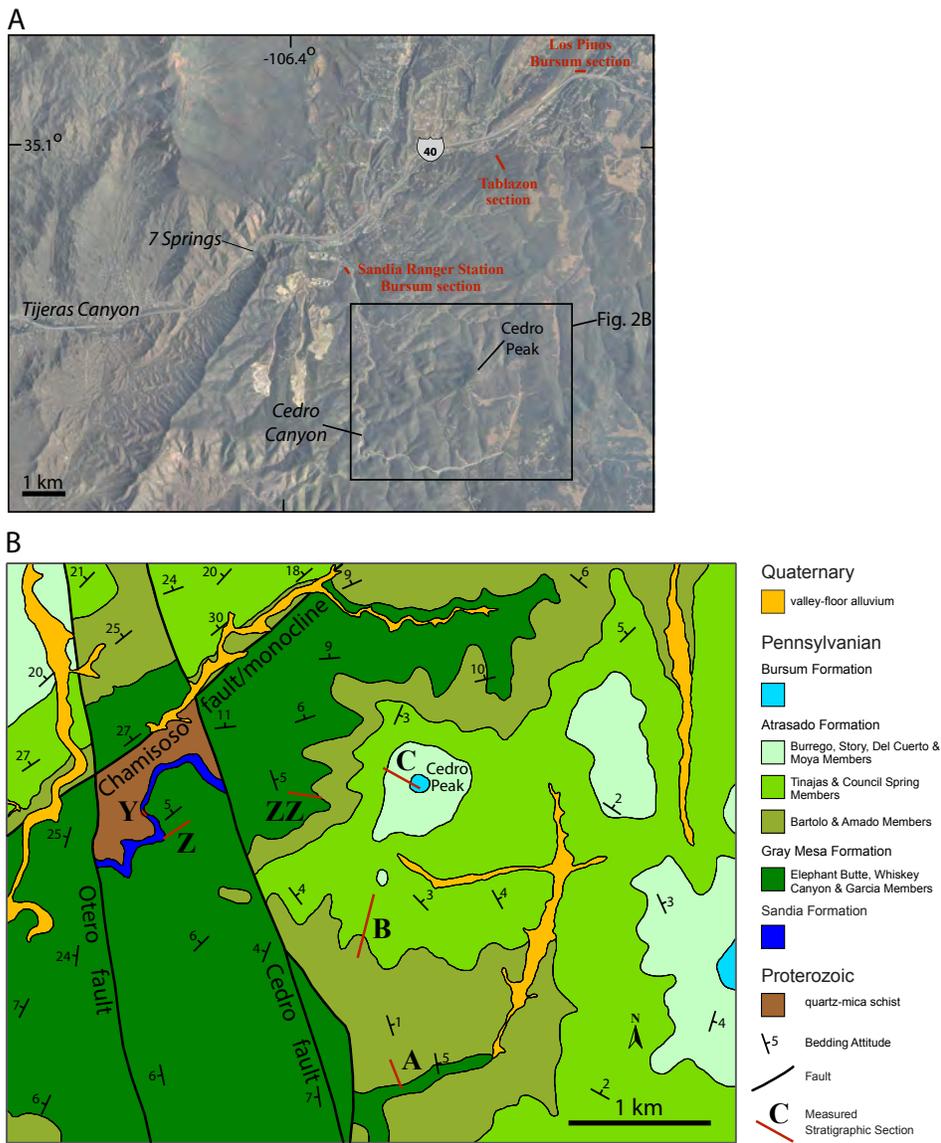


FIGURE 2—Aerial photograph locality map (A) and generalized geologic map of the Cedro Peak area (B), showing locations of measured stratigraphic sections described in this paper.

dip slope of the Manzanos (e.g., Myers 1973, 1982).

However, in the Manzano Mountains, because of structural complications and forested cover, only in a few local areas can the entire Pennsylvanian section be examined (Myers 1973). One such area is Cedro Peak, a conical mountain near the northern end of the Manzano uplift, in the part of the range usually termed the Manzanita Mountains (Figs. 1–2). Here, a Pennsylvanian section approximately 340 m thick is preserved with only minor structural complications, and this section is relatively well exposed along the steep flanks of Cedro Peak. In this article, we describe this Pennsylvanian section in detail for the first time. We regard it as a reference section of the Pennsylvanian in central New Mexico, one critical to the interpretation and correlation of the Pennsylvanian stratigraphy in the Manzano and Sandia Mountains.

Previous studies

Early work

The Pennsylvanian section exposed in the Manzano and Sandia uplifts is classic in the history of New Mexico geology. Thus, these were the first Carboniferous rocks identified in New Mexico, in 1853, when Jules Marcou traveled through Tijeras Canyon at the northern end of the Manzanita Mountains and examined the geology of the Sandia Mountains (Marcou 1858; Kelley and Northrop 1975; Lucas 2001). Furthermore, Herrick (1900a) and subsequent publications by Keyes (1903, 1904, 1906) and Gordon (1907) established the first Pennsylvanian stratigraphic nomenclature used in New Mexico, based largely on outcrops in the Sandia and Manzano uplifts (Fig. 3).

Herrick (1900a, pp. 115–116), in discussing the geology of the Sandia, Manzano,

Oscura, San Andres, and Organ Mountains, identified [Precambrian] granite overlain by quartzite followed by “a siliceous [sic] series with a few limestone bands whose fossils seem to be of undoubted Coal Measure age... [that] we have called the Sandia series from the place where best seen,” which he indicated is in the southern Sandia Mountains. Herrick (1900a, p. 114) described strata above the “Sandia series” as “a dark conchoidal limestone with shales having a fauna similar to that of the Upper Coal Measures in Ohio....” Above that limestone is a sandstone/conglomerate unit that Herrick (1900a, p. 115) named the Coyote Sandstone. In subsequent articles, Herrick (1900b; Herrick and Bendrat, 1900) made it clear that he considered the “Sandia series” to be approximately 150 ft (46 m) thick and to consist of shale, sandstone, conglomerate, and a few beds of sandy limestone. Keyes (1903, 1904, 1906) and Gordon (1907) subsequently referred to the unit Herrick named as the “Sandia Formation” and revised its thickness upward to as much as 700 ft (213 m).

Keyes (1903) used the name Madera limestone to refer to some of the Pennsylvanian section above Herrick’s Coyote Sandstone. He also introduced other terms for the Carboniferous strata (Keyes 1904, 1906), but Madera is the only term that Gordon (1907) and subsequent workers have used, as Madera Formation, to refer to all of the Pennsylvanian section above the Sandia Formation. Gordon (1907) united the Sandia and Madera formations in the Magdalena Group (Fig. 3).

Read and collaborator’s stratigraphy

Read et al. (1944; also see Wilpolt et al. 1946; Read and Wood 1947) divided the Sandia Formation into two members, a lower limestone member and an upper clastic member. However, Armstrong (1955) demonstrated that the lower limestone member is of Mississippian age and renamed it the Arroyo Peñasco Formation (later elevated to a group). Read and collaborators also divided the Madera limestone into a lower, gray limestone member and an upper, arkosic limestone member, and they brought the term Bursum Formation into use in Bernalillo County (Fig. 3). Read and Wood (1947, fig. 5) thus diagrammed a Pennsylvanian section at Cedro Canyon (secs. 26 and 35 T10N R5E) that consisted of the upper clastic member of the Sandia Formation (approximately 33 m thick) resting on basement, a gray limestone member (approximately 130 m thick), and an arkosic limestone member (approximately 244 m thick) of the Madera capped by Abo Formation. Incidentally, Read and Wood (1947, fig. 1) made it clear that their informal divisions of the Madera limestone were equivalent to the Gray Mesa Member (= gray limestone member) and Atrasado Member (= arkosic limestone member) of the Madera limestone named by Kelley and

Marcou (1858)	Herrick (1900)	Gordon (1907)	Read et al. (1944)		Myers & McKay (1976)		this paper																			
Mountain Limestone	Coal Measures	Manzano Group	Abo Formation	Permian	Abo Formation		Wolfcampian	Permian	Abo Formation		Wolfcampian	Perm														
					Bursum Formation				Bursum Formation																	
					Madera Limestone	Magdalena Group	Madera Formation	arkosic limestone member	Pennsylvanian	Wild Cow Formation	Virgilian	Missourian	Pennsylvanian	Atrasado Formation		Pennsylvanian										
														gray limestone member	La Casa Member		Moya Member									
															Pine Shadow Member		Del Cuerto Member	Story Member								
																	Sol Se Mete Member	Burrego Member	Council Spring Member							
														Sandia Formation	Sandia Fm.		Sandia Formation	upper clastic member lower limestone member	Atokan	Los Moyos Limestone	Desmoinesian	Atokan	Pennsylvanian	Gray Mesa Formation		Desmoinesian
																								Garcia Member	Whiskey Canyon Member	
					Sandia Formation	Sandia Fm.	Sandia Formation	upper clastic member lower limestone member	Atokan	Los Moyos Limestone	Desmoinesian	Atokan	Pennsylvanian	Sandia Formation		Atokan										
														Bartolo Member	Elephant Butte Member											
									Coyote Ss.Bed																	

FIGURE 3—Development of lithostratigraphic nomenclature of Pennsylvanian strata at Cedro Peak.

Wood (1946) in the Lucero uplift of Valencia County (Fig. 1).

The nomenclature of Read and collaborators, as the official nomenclature of the U.S. Geological Survey, found subsequent application across much of northern and central New Mexico, especially in the regional stratigraphic studies and mapping of the U.S. Geological Survey. In the Sandia Mountains and vicinity, a series of master's theses undertaken at the University of New Mexico (Albuquerque) provided detailed data on the Pennsylvanian strata. Kelley and Northrop (1975) published an overview of the Pennsylvanian strata in the Sandia Mountains and vicinity, based primarily on those theses.

Most relevant to the Pennsylvanian strata at Cedro Peak is the thesis of Szabo (1953), who described the Pennsylvanian strata along NM-337 near Cedro Peak and along the cuesta near Seven Springs in Tijeras Canyon, just south of I-40, approximately 5 km west of Cedro Peak (Fig. 2A). He used the regional stratigraphic nomenclature of Read et al. (1944), assigning the Pennsylvanian strata to the Sandia Formation (approximately 35 m thick) and overlying Madera limestone, divided into the lower gray (approximately 113 m thick) and upper arkosic (approximately 200 m thick) members. Szabo (1953) explicitly

rejected the Pennsylvanian stratigraphic nomenclature proposed by Thompson (1942) in southern New Mexico because it relied heavily on fusulinid biostratigraphy. Note that he also identified some of the clastic-dominated strata between the Sandia Formation (of his usage) and the Proterozoic basement as "pre-Pennsylvanian strata," although he lacked age data from these rocks. We follow subsequent workers who have identified this stratigraphic interval as the lower part of the Sandia Formation.

Myers' stratigraphy

During the 1960s and 1970s, in the Manzano and Manzanita Mountains an ambitious field program of lithostratigraphy, fusulinid biostratigraphy, and geologic quadrangle mapping, led by Donald Myers of the U.S. Geological Survey, created a new lithostratigraphic nomenclature and correlation of the Pennsylvanian strata. Thus, Myers (1966, 1967, 1969, 1973, 1977, 1982, 1988a, b; Myers and McKay 1970, 1971, 1972, 1974, 1976; Myers et al. 1986) assigned the Pennsylvanian section in this area to the (in ascending order) Sandia, Los Moyos, and Wild Cow Formations. Los Moyos Limestone was a new, formal lithostratigraphic name for the gray limestone member of the Madera Formation of prior

usage, and Wild Cow Formation was a formal name for the arkosic limestone member (Fig. 3). Myers also divided the Wild Cow Formation into new formal members, the Sol se Mete (lower), Pine Shadow, and La Casa (upper) Members (Fig. 3).

Myers' new lithostratigraphy was published with fusulinid biostratigraphy that indicated the Sandia Formation is Atokan, the "Los Moyos Limestone" is Desmoinesian, and the "Wild Cow Formation" is Missourian-Virgilian. Myers and McKay (1976) also mapped the Pennsylvanian strata at Cedro Peak and published a Pennsylvanian stratigraphic section there at a scale of 1 inch = 100 ft (approximately 2.5 cm = 30 m).

Quadrangle mapping (STATEMAP)

Renewed mapping in the Manzanita Mountains beginning in the 1990s as part of the U.S. STATEMAP Program necessitated a reevaluation of Myers' work. Most of the geologists involved in this mapping effort (e.g., Karlstrom et al. 1994; Chamberlin et al. 1997; Read et al. 1998), working in areas previously mapped by Myers and McKay, found it difficult to apply Myers' stratigraphic nomenclature, especially with respect to Myers' member-level units of the Atrasado Formation (Sol se Mete, Pine Shadow, and La Casa Members of Myers'



FIGURE 4—Photographs of selected Pennsylvanian outcrops at Cedro Peak. A—Overview of Cedro Peak, looking toward the east. B—Cherty limestone of Whiskey Canyon Member of Gray Mesa Formation. C—Sandstone of Coyote Sandstone Bed at base of Bartolo Member of Atrasado Formation. D—Overview of bedded limestones of the Amado Member of Atrasado Formation. E—Sandstone of Tinajas Member of Atrasado Formation.

Wild Cow Formation). Further confusion arose from Myers' (1988b) statement that the Bursum Formation was not present in the Manzanita Mountains, despite the fact that the Bursum lithosome is well exposed in outcrops near I-40 east of Albuquerque (see our Los Pinos section, discussed below). Myers and McKay (1976) included these strata in the La Casa Member of the Wild Cow Formation in their map of the area. STATEMAP mappers placed these strata in the Permian Abo Formation, but they are readily assigned to the Bursum Formation based on lithology (see below). The result of this renewed mapping effort was that, for the most part, Myers' formal stratigraphic divisions were abandoned, and map-unit designations used by most STATEMAP mappers reverted to the mid-20th century

nomenclature of the U.S. Geological Survey. Indeed, Myers' maps are, in many places, incompatible with his own stratigraphy. A good example is on Cedro Peak, where Myers and McKay (1976) placed the contact between the Gray Mesa and Atrasado Formations (their Los Moyos and Wild Cow Formations) far up in the Atrasado Formation (near the top of the Amado Member of our usage). The reason for this may be that the Amado is a relatively thick, cherty, cliff-forming limestone, similar to the underlying Gray Mesa Formation in many respects. Nonetheless, our reexamination of Cedro Peak shows that the stratigraphic sequence there, despite subtle structural modifications (faults and landslides), is rather clear and incompatible with the mapping of Myers and McKay (1976).

In addition, Myers and McKay (1976) did not map the same units that Myers (1973) defined. Thus, the mapped "Pine Shadow Member" of Myers and McKay (1976) in the Cedro Peak area is not the same unit as the type section of Myers (1973) Pine Shadow Member at Priest Canyon in the southern Manzano Mountains. It seems clear that the disconnect between Myers' fusulinid-based, biostratigraphic units, actual mappable lithostratigraphic units, and what he and his colleagues mapped on the ground is so great that Myers' member-rank nomenclature for the Atrasado Formation has to be abandoned (and much of the mapping redone). This is unfortunate, considering the large amount of good work that was done during Myers' nearly two-decade long efforts in the Manzanos.

Current stratigraphy

At present, all workers apply the term Sandia Formation to the lowest Pennsylvanian formation-rank stratigraphic unit in the Manzano-Manzanita Mountains—a succession of siliciclastic (notably quartz sandstone and conglomerate) and carbonate (especially coarse-grained bioclastic wackestone) rocks that generally yield fusulinids of Atokan age (e.g., Myers 1988a; Krainer et al. 2011; Krainer and Lucas 2013a). We use the term Bursum Formation for the stratigraphically highest Pennsylvanian strata in the local section—a mixed succession of red-bed clastics and marine limestones (the Bursum was long regarded to be of earliest Permian age but is now assigned to the latest Pennsylvanian, e.g., Lucas and Krainer 2004; Krainer and Lucas 2009, 2013b). Note that Myers (see especially Myers and McKay 1976) assigned these Bursum strata to the La Casa Member of the Wild Cow Formation, largely because the Bursum Formation in the Manzanita Mountains yields fusulinids of Virgilian age, which means it is older than Bursum Formation strata in the southern Manzano Mountains (see later discussion).

During the last decade, the terms Gray Mesa and Atrasado Formations have been used for the strata in central New Mexico that had previously been termed Madera limestone (Formation or Group) by many workers (Kues 2001; Krainer and Lucas 2004; Lucas et al. 2009; Nelson et al. 2013a, b). Gray Mesa and Atrasado are the oldest mappable, formation-rank unit names formally proposed for these units (Kelley and Wood 1946; Krainer and Lucas 2004) and apply to mappable lithosomes across much of central New Mexico, from the Oscura Mountains through the Cerros de Amado, the Los Pinos, Manzano, Manzanita, and Sandia Mountains and Mesa Lucero (Kues 2001; Krainer and Lucas 2004; Lucas and Krainer 2009; Lucas et al. 2009). They are formal terms for the lower gray limestone and upper arkosic limestone members, respectively, of the Madera limestone mapped by Read et al. (1944), Wilpolt et al. (1946),

and Wilpolt and Wanek (1951), among others. The formation names Myers (1973) introduced for what he termed the Madera Group in the Manzano Mountains—Los Moyos and Wild Cow Formations—are, as Kues (2001) first noted, obviously synonyms of the Gray Mesa and Atrasado Formations of Kelley and Wood (1946). The names Los Moyos Formation and Wild Cow Formation thus have been abandoned and replaced by Gray Mesa Formation and Atrasado Formation, respectively (Fig. 3).

Thompson (1942) proposed a very detailed lithostratigraphic nomenclature for Pennsylvanian strata in southern New Mexico, and much of it has been used by those who have subsequently studied and/or mapped the Pennsylvanian rocks in Socorro and Valencia Counties, just to the south of the Manzano–Manzanita Mountains (e.g., Hambleton 1959, 1962; Kottowski 1960; Rejas 1965; Maulsby 1981; Bauch 1982; Brown 1987; Cather and Colpitts 2005; Lucas and Krainer 2009; Lucas et al. 2009; Barrick et al. 2013). Our recent work indicates that much of this nomenclature can be applied to the Pennsylvanian section in the Manzano–Manzanita Mountains (Lucas and Krainer 2010; Lucas et al. 2011, 2013), so that an older, member-level nomenclature exists that predates the terminology introduced by Myers (1973). Here, we employ the member-level nomenclature of Thompson (1942) and Rejas (1965), as modified and used by Lucas et al. (2009) in the Cerros de Amado of Socorro County, and correlate it with the member-level nomenclature of Myers (1973; Fig. 3).

Working independently, as part of the STATEMAP effort in the Manzanita Mountains, one of us (BDA) attempted to retain Myers' formation- and member-rank nomenclature (e.g., Allen 2002), recognizing that it was indeed possible to divide the Atrasado Formation consistently into three map-scale units based on the presence of two, relatively thick and laterally extensive limestone beds separated by siliciclastic (abundant shale and sandstone) intervals. We now assign these two limestone beds to the Amado and overlying Council Spring Members of the Atrasado Formation (Figs. 3, 4A; these units are discussed below). Thus, we equate the Bartolo, Amado, and lower part of the Tinajas Members of the Atrasado Formation to Myers' Sol se Mete Member of the Wild Cow Formation, the overlying upper part of the Tinajas, Council Spring, and lower part of the Burrego Members to Myers' Pine Shadow Member, and all the overlying strata between the upper part of the Burrego Member and the Bursum Formation to Myers' La Casa Member (Fig. 3).

Base of the Pennsylvanian section in the Manzano and Sandia uplifts

At Cedro Peak the base of the Pennsylvanian section is a sandstone at the base of the

Sandia Formation that rests directly on metamorphic rocks of the Proterozoic basement (Fig. 5). This contact is characteristic of the base of the Pennsylvanian section throughout the Manzano, Manzanita, and Sandia Mountains, where Sandia Formation strata rest in depositional contact directly on metamorphic or granitic basement (e.g., Kelley and Northrop 1975; Myers 1982; Krainer et al. 2011; Krainer and Lucas 2013a). Only on the northern end of the Sandia uplift, at Placitas, are Mississippian strata definitely present between the Proterozoic basement and the Pennsylvanian Sandia Formation (Armstrong and Mamet 1974; Kelley and Northrop 1975; Armstrong et al. 1979). A possible Mississippian outlier was documented by Read et al. (1999) at Balsam Glade in the northern Sandia Mountains, and Read et al. (1998) also mapped small areas of thin Mississippian strata near Cedro Peak. In general, however, the base of the Pennsylvanian section in the Sandia–Manzano uplifts is the “great unconformity” at which Pennsylvanian strata directly overlie Proterozoic basement. This contact is well exposed at Cedro Peak at the base of our section Y (Fig. 5) and is described below.

Sandia Formation

Lithostratigraphy

At Cedro Peak we measured a complete section of the Sandia Formation at section Y (Fig. 5), and the upper part of the formation at section Z (Fig. 6). At section Y, the Sandia Formation is 13.6 m thick. The underlying Proterozoic basement rock, which is composed of phyllitic schist, is well exposed, contains shear bands, and consists of chlorite, fine-grained muscovite (sericite), fine-grained quartz, and opaque minerals. The base of the Sandia Formation at Cedro Peak is a 0.9-m-thick interval of massive greenish sandstone (Fig 5, units 2–4) containing quartz pebbles as much as 1–2 cm in diameter in its upper part. This sandstone rests with depositional contact on the basement, and the contact is one of erosional relief. The sandstone unit is followed by a partly covered interval of gray shale. The next unit is a 2.2-m-thick interval of red mudstone to siltstone with small pebbles as large as 1 cm floating in it. The uppermost unit is again a partly covered interval (gray shale), overlain by cherty limestone at the base of the Gray Mesa Formation (Fig. 5).

Microfacies

The sandstone near the base of the Sandia Formation (Fig. 7A) is nonlaminated, moderately to poorly sorted, and medium grained (mostly 0.2–0.5 mm, maximum 3 mm). Most grains are subrounded, monocrystalline quartz; polycrystalline quartz (stretched metamorphic and granitic) is subordinate, and fine-grained

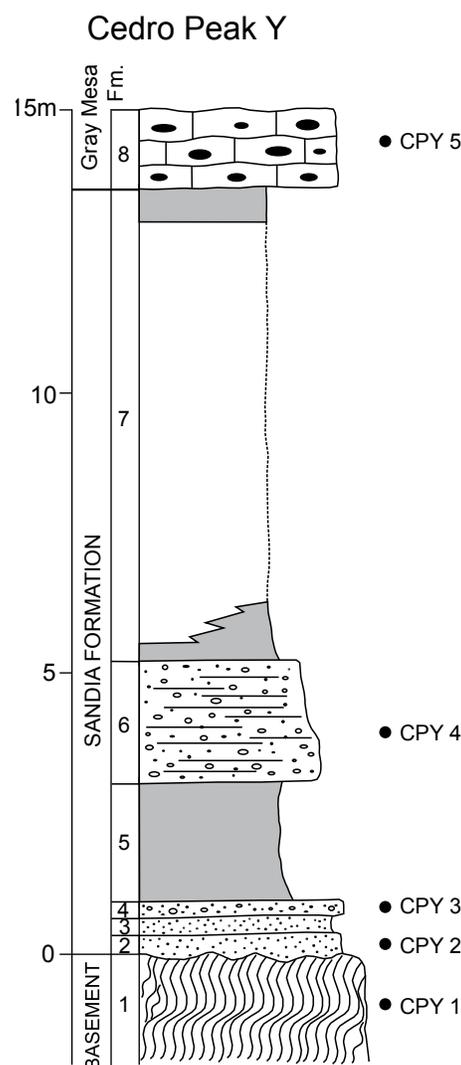


FIGURE 5—Measured stratigraphic section of the Sandia Formation at Cedro Peak (section Y). See Appendix for map coordinates of measured sections.

(phyllitic) metamorphic rock fragments are very rare. The sandstone contains many carbonate grains that probably replaced feldspars (in rare cases remnants of feldspar are still visible). Detrital micas (muscovite) are extremely rare, as are opaque grains. The sandstone is calcite cemented (coarse, poikilotopic), and locally some matrix is present. In the overlying sandstone bed (Fig. 7B), the matrix contains diagenetically formed chlorite.

The quartzose, coarse-grained pebbly sandstone at the base of section Z (unit 1) and the thick-bedded gray limestone (unit 3) represent the uppermost Sandia Formation (Fig. 6). The sandstone is coarse-grained (mostly 0.5–1.5 mm, maximum 5 mm), indistinctly laminated, and moderately to poorly sorted. It is composed mostly of quartz (granitic and schistose metamorphic), and rare, small phyllitic rock fragments are present. Detrital micas and detrital feldspars are absent. Many quartz grains display authigenic overgrowths. Locally, pore space is filled with

fine-grained quartz cement (chert). Rarely, some calcite cement is present.

Limestone of the topmost Sandia Formation (unit 3 of section Z, Fig. 6) is floatstone that is indistinctly laminated, nodular, bioturbated, and recrystallized. The fine-grained silty matrix contains a few small skeletons and peloids, and locally abundant, densely packed spicules (Fig. 7C). In the matrix, a few large brachiopod shells float, partly with both valves preserved and the interior filled with pelmicritic matrix. Smaller skeletons include bryozoans, echinoderms, gastropods(?), bivalves, rare ostracods, brachiopod spines, foraminifers (*Bradyina* sp.), and (locally) fecal pellets as much as 1 mm in diameter.

Paleontology

In contrast to the very fossiliferous lectostratotype section (Krainer et al. 2011), the Sandia Formation at Cedro Peak lacks fossils other than those seen in the limestone of section Z (Figs. 6, 7C), just listed above.

Depositional environments

The Sandia Formation at the lectostratotype section in the Sandia Mountains, approximately 13 km north of Cedro Peak, is 124 m thick and composed of alternating shale, sandstone, pebbly sandstone, fossiliferous limestone, and covered intervals (Krainer et al. 2011). The sediments were deposited in environments ranging from low-energy shelf to high-energy shoreface and nearshore settings (Krainer et al. 2011; Krainer and Lucas 2013a). At Cedro Peak, the Sandia Formation is much thinner, almost entirely siliciclastic and most likely nearly totally nonmarine. The immature sandstone overlying the basement and lacking sedimentary structures probably represents debris-flow or sheetflood deposits. The mud-supported pebbly sandstone of section Y (Fig. 5, unit 6) is interpreted as a debris-flow deposit intercalated in fine-grained sediments of a floodplain environment. The limestone bed in section Z (Fig. 6) is the only evidence of shallow marine deposition. The dramatic thickness changes of the Sandia Formation over short distances are indicative of its deposition on a highly irregular surface, thinning over buried hills and thickening into paleovalleys and/or they reflect syndepositional tectonism (Krainer and Lucas 2013a).

Gray Mesa Formation

The Gray Mesa Formation contrasts with the underlying Sandia Formation and overlying Atrasado Formation in containing a much higher proportion of limestone, a modest amount of shale, and very little sandstone (Nelson et al. 2013a). The limestone beds are characteristically fossiliferous, commonly cherty, and form bold ledges separated by poorly exposed intervals of shale or thin-bedded and nodular limestone. We

measured two sections at Cedro Peak (Z and ZZ, Fig. 6) to encompass the entire section of the Gray Mesa Formation. At Cedro Peak the Gray Mesa Formation is approximately 119 m thick and can be assigned to three members (in ascending order), Elephant Butte Member (units 5–41 of section Z), 47 m thick; Whiskey Canyon Member (units 42–62 of section Z), 30 m thick; and Garcia Member (units 63–76 of section Z and units 1–33 of section ZZ), 42 m thick (Fig. 6).

Elephant Butte Member

Lithostratigraphy—At Cedro Peak the Elephant Butte Member is the lowest stratigraphic interval of the Gray Mesa Formation. It is 47 m thick and conformably overlies the Sandia Formation. The Whiskey Canyon Member conformably overlies the Elephant Butte Member. To the south (e.g., Lucas et al. 2009, 2012a, b), we identify the Elephant Butte Member by its relatively large number of shale interbeds and relatively chert-free limestone beds, in contrast to the overlying Whiskey Canyon Member.

Exposed beds of the Elephant Butte Member are primarily different types of noncherty and cherty limestone. Individual limestone intervals are as much as 4.9 m thick and separated by covered intervals as thick as 4.3 m. Noncherty limestone consists of thin, wavy-bedded, crinoidal limestone beds as much as 0.7 m thick and an algal limestone bed 0.5 m thick in the upper part. Cherty limestone beds are either massive to indistinctly bedded, with chert nodules and thin chert bands, or medium- to thick-bedded, wavy-bedded and nodular limestone. In the upper part of the Elephant Butte Member, 1.2 m of greenish shale is exposed (Fig. 6, section Z, unit 33) containing a few small limestone nodules, brachiopods, bryozoans, and crinoidal debris.

Microfacies—In the Elephant Butte Member the most common limestone microfacies are bioclastic wackestone, packstone, and floatstone (Fig. 7D–H). The matrix is micrite and peloidal micrite. A few bioclasts in wackestone to packstone are encrusted by cyanobacteria, and rarely by *Tubiphytes*-like palaeonubeculariid foraminifers and bryozoans. Locally, this microfacies is bioturbated. Grainstone to packstone, mostly crinoidal grainstone to packstone, and rare foraminiferal grainstone to packstone composed of abundant calcivertellid foraminifers and crinoid fragments, are subordinate microfacies. The grainstone to packstone is microsparite cemented, and locally some micrite is present. The grainstone to packstone locally grades into bioclastic wackestone with micritic matrix.

The cherty nodular limestone at the base of the Elephant Butte Member is composed of cherty limestone rich in sponge spicules and bioclastic wackestone/packstone. The nodules consist of spicule-rich chert, and bioclastic wackestone/packstone is between

the nodules. The spicules are unoriented and calcified in a micritic matrix with a few other floating skeletons. In the upper part of the Elephant Butte Member, algal wackestone containing abundant large fragments of completely recrystallized “phyloid algae” and thin shells is present. This microfacies also contains many spherical grains that have been traditionally interpreted as algal spores (e.g., Flügel 2004).

Paleontology—Fossils in the Elephant Butte Member observed on outcrop are crinoidal debris, brachiopods (throughout the section), fusulinids in distinct horizons, rare *Chaetetes* sp., solitary corals, bryozoans, and calcareous algae. All Elephant Butte Member microfacies contain a diverse fossil assemblage (Vachard et al. 2012, 2013). The most abundant fossils recognized in thin sections are fragments of echinoderms (crinoids), brachiopod and bivalve shells, and bryozoans in various amounts. Subordinate are smaller foraminifers and microproblematica:

Calcisphaera laevis Williamson
Eotuberitina reitlingerae Miklukho-Maklay
Tuberitina bulbacea Galloway and Harlton
Insolentitheca horrida (Brazhnikova) (very rare;

Earlandia ex gr. *elegans* (Rauzer-Chernousova and Reitlinger)
Spireitlina conspecta (Reitlinger)
Endothyra whitesidei Galloway and Rynicker

E. sp.; *Endothyranella recta* (Brady)
E. stormi (Cushman and Waters)
Bradyina cf. *lucida* Morozova
B. sp.;

Tetrataxis sp.
Polytaxis laheei Cushman and Waters
Palaeotextularia angusta (Reitlinger)
Climacammina moelleri Reitlinger
Globivalvulina bulloides (Brady)
G. moderata Reitlinger
G. ex gr. mosquensis (Reitlinger)
G. sp.

Calcivertella cf. *fortis* (Reitlinger)

C. sp.;

Calcitornella heathi Cushman and Waters

Hedraites? sp.

Palaeonubecularia cf. *rustica* Reitlinger

P. sp.

Glomospiroides sp.

Hemigordiellina sp.

Cornuspira multivoluta (Reitlinger)

Syzrania confusa Reitlinger

fusulinids:

(Pseudonovella marshalli Vachard, Krainer, and Lucas

Pseudoacutella grozdilovae (Maslo and Vachard) emend. Vachard, Krainer, and Lucas

Pseudostaffella sp.

Staffella? sp

Schubertellina bluensis (Ross and Sabins)

S. sp.;

Profusulinella fittsi (Thompson)

Dagmarella iowensis (Thompson)

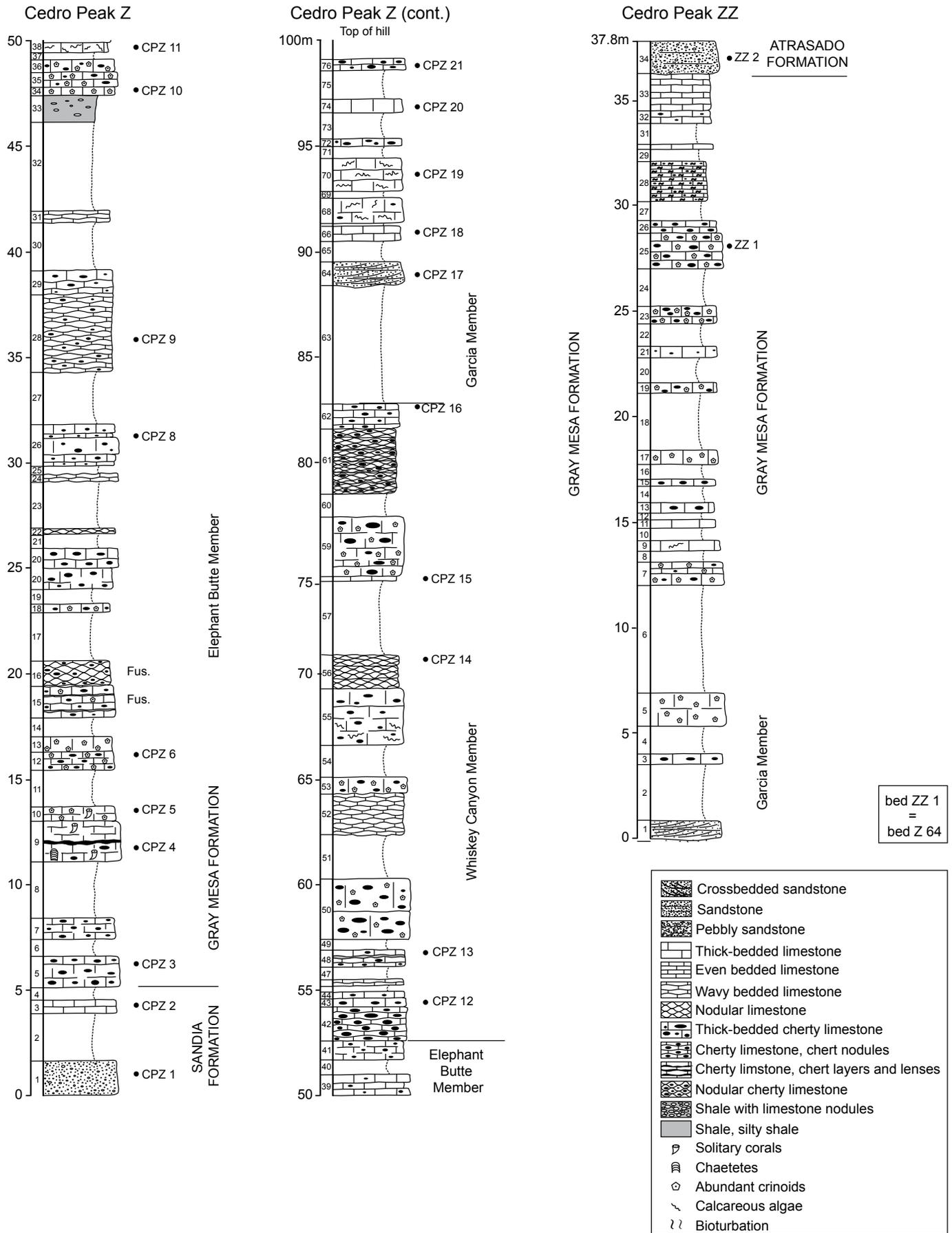
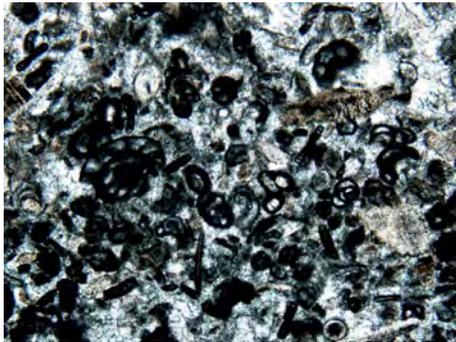
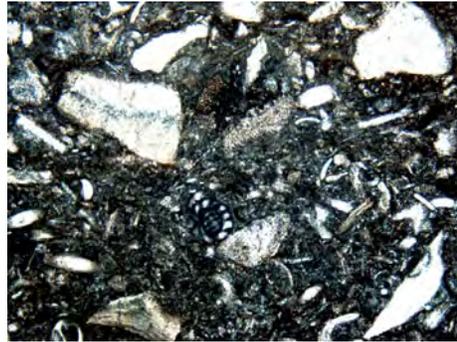
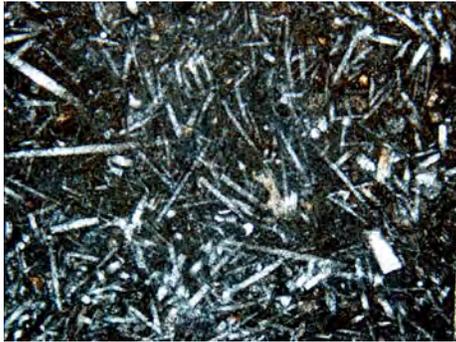
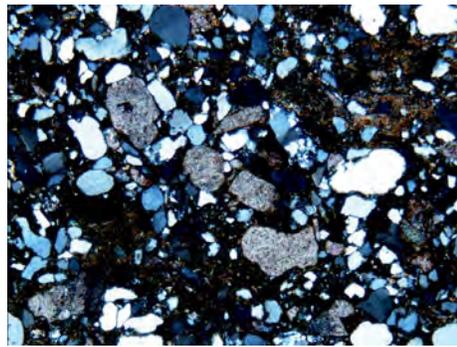
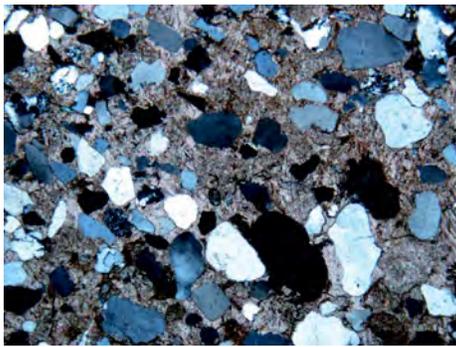


FIGURE 6—Measured stratigraphic sections of the uppermost Sandia Formation at Cedro Peak and most of the Gray Mesa Formation (section Z) and the upper part of the Gray Mesa Formation and base of the Atrasado Formation (section ZZ). See Appendix for map coordinates of measured sections.



A

B

C

D

E

F

G

H

FIGURE 7—Thin section photographs of sandstone from the Sandia Formation (A–B) and of limestone from the Elephant Butte Member of the Gray Mesa Formation (C–H). A—Medium-grained sandstone composed of abundant monocrystalline quartz and high amounts of calcite cement. Detrital feldspars are almost completely replaced by calcite; rarely, remnants of feldspars are visible. Polarized light, width of photograph is 3.2 mm, sample CPY 2. B—Poorly sorted sandstone composed of abundant monocrystalline and a few polycrystalline quartz grains and many carbonate grains that represent detrital feldspars replaced by calcite. The sandstone contains matrix (dark) and some calcite cement. Polarized light, width of photograph is 3.2 mm, sample CPY 3. C—Spiculite composed of abundant calcified, mostly monaxone sponge spicules and a few other skeletons embedded in micrite. Plane light, width of photograph is 3.2 mm, sample CPZ 3. D—Bioclastic wackestone to packstone containing a diverse fossil assemblage of echinoderms, brachiopods, bryozoans, smaller foraminifers, fusulinids, and ostracods embedded in micrite. Plane light,

width of photograph is 3.2 mm, sample CPZ 6. E—Foraminiferal grainstone to packstone containing abundant calcivertellids and a few other foraminifers, as well as a few other skeletons cemented by calcite. Plane light, width of photograph is 3.2 mm, sample CPZ 5. F—Bioclastic grainstone, poorly sorted, containing abundant crinoidal fragments and a few other skeletons derived from bryozoans, brachiopods, smaller foraminifers, and brachiopod spines cemented by coarse calcite. Plane light, width of photograph is 6.3 mm, sample CPZ 10. G—Algal wackestone to floatstone containing large, recrystallized, broken fragments of “phylloid algae” and a few other fossil fragments floating in micrite. Plane light, width of photograph is 6.3 mm, sample CPZ 7. H—Algal wackestone to floatstone containing recrystallized fragments of “phylloid algae” and a few other skeletons floating in micrite. Plane light, width of photograph is 6.3 mm, sample CPZ 11. For sample numbers, see Figures 5–6.

Plectofusulina manzanensis n. sp.
Wedekindellina cf. *excentrica* Roth and Skinner;
W. pseudomatura Ross and Tyrrell
Beedeina cf. *novomexicana* (Needham)
B. cf. leei (Skinner)
B. sp.,
 calcareous algae, mostly “phylloid algae”:
Epimastopora? sp.
Asphaltina cordillerensis Mamet (very rare)
Anthracoporellopsis novamexicana Vachard, Krainer, and Lucas;
Dvinella sp.;
Fourstonella? (= *Efluegelia*) *johnsoni* (Flügel) Vachard and Cózar
Komia eganensis Wilson et al.),
 ostracods, small gastropods, brachiopod spines, and sponge spicules (Vachard et al. 2012, 2013). Rare fossils include trilobite fragments, echinoid spines, and calcisponges.

Whiskey Canyon Member

Lithostratigraphy—The Whiskey Canyon Member is the medial, chert-rich interval of the Gray Mesa Formation (Thompson 1942; Rejas 1965; Lucas et al. 2009, 2012a, b). At Cedro Peak it is 30 m thick and mainly composed of cherty limestone that is massive to thick-bedded, wavy-bedded, and nodular limestone (Figs. 4B, 6). Individual cherty limestone intervals are as much as 4.3 m thick. Noncherty limestone beds are 0.2–0.8 m thick and composed of crinoidal limestone, wavy-bedded limestone, and algal limestone. Another lithofacies is thin-bedded nodular limestone composed of gray limestone nodules embedded in greenish-gray, cherty matrix, containing many brachiopods and crinoidal debris. Covered intervals, which probably consist mostly of shale, thin-bedded limestone, and/or nodular limestone, are as much as 3.5 m thick.

Microfacies—As in the Elephant Butte Member, the most common limestone microfacies of the Whiskey Canyon Member are bioclastic wackestone, packstone, and floatstone (Fig. 8A–C). Locally, the wackestone consists of fine bioclastic micrite containing abundant small, calcified spicules and a few other fossil fragments. Wackestone, packstone, and floatstone are common, locally containing abundant crinoid fragments

(crinoidal wackestone). Algal wackestone to floatstone is rare and composed of large, recrystallized, and broken fragments of the “phylloid alga” *Ivanovia tenuissima* and subordinate fossil fragments.

A rare microfacies is *Komia* wackestone to floatstone containing abundant, partly fragmented as well as scattered fusulinids, bryozoans, echinoderms, brachiopods, and ostracods. Rarely, these bioclasts are encrusted by calcivertellid foraminifers, and very rarely by bryozoans.

Paleontology—The diverse fossil assemblage of the Whiskey Canyon Member is similar to that of the Elephant Butte Member and includes echinoderms (crinoids), brachiopod and bivalve shells, bryozoans, fusulinids, and rare calcareous algae (Vachard et al. 2012, 2013).

Smaller foraminifers:

Tuberitina bulbacea,
Earlandia ex gr. *elegans*,
Spireitlina conspecta,
Endothyra whitesidei,
Endothyranella recta,
Bradyina cf. *lucida*,
Tetrataxis sp.,
Polytaxis laheei,
Palaeotextularia angusta,
Climacammina moelleri,
Globivalvulina spp.,
Calcivertella cf. *fortis*,
Calcitornella heathi,
Palaeonubecularia cf. *rustica*,
Hemigordiellina sp.,
Cornuspira multivoluta,
Syzrania confusa,

fusulinids:

Pseudoacutella grozdilovae,
Schubertellina bluensis,
Plectofusulina manzanensis,
Wedekindellina spp.,
Beedeina spp.

calcareous algae:

mostly “phylloid algae,” very rare
Anthracoporellopsis novamexicana,
Fourstonella (*Efluegelia*) *johnsoni*, and
locally abundant
Komia eganensis

ostracods, small gastropods, brachiopod spines, and sponge spicules are less common. Rare, larger fossils are represented by trilobite fragments, echinoid spines, and corals.

Garcia Member

Lithostratigraphy—The Garcia Member is the upper, relatively clastic (shale beds and sandstone) interval of the Gray Mesa Formation with relatively few cherty limestone beds (Thompson 1942; Rejas 1965; Lucas et al. 2009, 2012a, b). At Cedro Peak the Garcia Member is 42 m thick (Fig. 6). Its base is covered (shale?) followed by a bed of coarse-grained, pebbly, crossbedded sandstone, 1.1 m thick. The limestone facies include thick-bedded to massive algal limestone containing a few small chert nodules; coarse, crinoidal limestone;

thin- to thick-bedded limestone with rare chert nodules; thin-bedded cherty limestone; and thin-bedded shaly limestone. Individual limestone intervals are 0.2–2.4 m thick and separated by covered intervals as much as 5.1 m thick.

Microfacies—The sandstone near the base of the Garcia Member is moderately to poorly sorted, nonlaminated, grain-supported, and calcite cemented (Fig. 8D). It contains a few granitic rock fragments of quartz and feldspar, and abundant detrital feldspars (mostly potassium feldspar) that are slightly altered and mostly untwinned. Smaller grains are dominantly subangular, and larger grains are mostly subrounded. The most common grain type is monocrystalline quartz and less common polycrystalline quartz (mostly derived from granitic rocks). Many perthitic feldspars are present. Polysynthetic feldspars and feldspars displaying Karlsbad twins are rare. Microcline is absent, and detrital mica (muscovite, some are large) and phylitic metamorphic rock fragments are rare. Accessory bluish tourmaline is present. Many quartz grains display authigenic overgrowths. The rock contains abundant coarse, brownish calcite cement, randomly replacing feldspars and quartz.

Limestone of the lower part of the Garcia Member in section Z is bioclastic wackestone to packstone and “phylloid algal” wackestone to floatstone. The bioclastic wackestone/packstone contains abundant echinoderms, shell debris, bryozoans, some spicules, and rare trilobite fragments. The bioclastic wackestone is locally silicified (chert nodules) and contains abundant recrystallized skeletons (mollusk fragments, calcareous algae), subordinate echinoderms, bryozoans, ostracods, a few smaller foraminifers (*Globivalvulina* sp., *Palaeonubecularia* sp., and other calcivertellids), rare echinoid spines, and brachiopods.

“Phylloid algal” wackestone to floatstone contains abundant recrystallized, mostly fragmented, “phylloid algae” and bryozoans. Subordinate bioclasts are shell fragments (bivalves, brachiopods), a few ostracods, echinoderms, very rare calcivertellid foraminifers, and *Tuberitina* sp. The matrix is rarely pelmicritic, and in situ brecciation is observed.

Paleontology—The fossil assemblage of the Garcia Member is diverse and similar at higher taxonomic levels to that of the underlying Whiskey Canyon Member (Vachard et al. 2012, 2013). The most abundant fossils are crinoid fragments and calcareous algae; brachiopods and bryozoans are rare.

Comparison with the Gray Mesa type section

Compared to the type section of the Gray Mesa Formation in the Lucero uplift (Krainer and Lucas 2004), where it is 388 m thick, the Gray Mesa Formation at Cedro Peak is much thinner (119 m). It is also thicker toward the south of Cedro

Peak: at Priest Canyon in the southernmost Manzano Mountains it is 190 m thick (Lucas and Krainer 2010), in the Cerros de Amado of Socorro County it is 185 m thick (Lucas et al. 2009), and in the northern Oscura Mountains of southern Socorro County it is 162 m thick (Lucas and Krainer 2009). There are also differences in the facies: *Chaetetes* is common in the lower part (Elephant Butte and Whiskey Canyon Members) in the Lucero uplift (Krainer and Lucas 2004) but very rare in the lower part of the Elephant Butte Member and absent in the Whiskey Canyon Member at Cedro Peak. Calcareous algae also are less common at Cedro Peak.

Depositional environments and cycles

The dominant limestone microfacies types of the Gray Mesa Formation, particularly wackestone, indicate deposition in a low-energy setting. The diverse fossil assemblage of all microfacies types suggests open, normal marine conditions. The presence of calcareous algae, mostly “phylloid algae,” in distinct beds points to deposition in shallower water within the photic zone. High-energy deposits such as crinoidal grainstone are rare.

Wiberg (1993) and Wiberg and Smith (1994) correlated sections of the “lower Madera Limestone” in the Sandia Mountains with the lower part of the Desmoinesian Los Moyos Limestone of Myers (= Gray Mesa Formation) at Cedro Peak. They saw a cyclic succession in the measured section of the Gray Mesa Formation at Cedro Peak of Myers and McKay (1976) and provided a cycle-to-cycle correlation to the sections in the Sandia Mountains. According to Wiberg (1993) and Wiberg and Smith (1994), the “Madera Limestone” in the Sandia Mountains is characterized by 4th-order transgressive-regressive cycles. They correlated the cycles with those in other regions and concluded that cycle formation was mainly controlled by eustatic sea-level changes and less by tectonic movements of the Ancestral Rocky Mountain deformation. However, there is no age control of their measured sections (they did not identify any fusulinids), and it is also unclear how Wiberg (1993) and Wiberg and Smith (1994) correlated their sections to the Cedro Peak section of Myers and McKay (1976), which lacks detail as it only displays the Gray Mesa Formation section at a scale of 100 ft per inch (approximately 30 m per 2.5 cm).

Within the Gray Mesa Formation at Cedro Peak (Fig. 6), an alternation of lithofacies is observed, and shallowing-upward sequences are developed, particularly within the Whiskey Canyon Member (shale-wackestone-crinoidal packstone). But, the entire Gray Mesa Formation is not composed of well-developed shallowing-upward cycles as described by Wiberg (1993) and Wiberg and Smith (1994) from the Sandia Mountains and by Scott and Elrick (2004; Elrick and Scott 2010) from the

Lucero uplift. Whereas cherty limestone is very common at Cedro Peak, particularly in the Whiskey Canyon Member, it is absent in the sections studied by Wiberg (1993) and Wiberg and Smith (1994). On the other hand, subaerial exposure surfaces, grainstone and coarse siliciclastic sediments (subarkosic sandstone) are common in the sections in the Sandia Mountains, but rare to absent at Cedro Peak.

This indicates that the depositional environment at Cedro Peak was in deeper water compared to the Sandia Mountains and Lucero uplift—open marine shelf mostly below wave base, but still within the photic zone, probably some tens of meters deep. The shallowing-upward cycles of the Gray Mesa Formation identified in the Sandia Mountains and in the Lucero uplift are not clearly correlateable to Cedro Peak, indicating that tectonics, differential subsidence, and/or the buried paleotopography under the Sandia Formation may have influenced local deposition of the Gray Mesa Formation more intensively than suggested by Wiberg (1993), Wiberg and Smith (1994), and Scott and Elrick (2004; Elrick and Scott 2010).

Atrasado Formation

At Cedro Peak a complete section of the Atrasado Formation is exposed between the Gray Mesa Formation (below) and the Bursum Formation (above; Fig. 9). Our measured section of the Atrasado Formation at Cedro Peak consists of three overlapping segments that indicate total Atrasado thickness is approximately 200 m, and we can divide this Atrasado Formation section into eight members (Fig. 9; also see Lucas et al. 2011).

Our Cedro Peak A section is 48.4 m thick and includes the topmost Gray Mesa Formation and overlying Bartolo and Amado Members of the Atrasado Formation. Cedro Peak B section is 82.5 m thick and includes the Amado, Tinajas, and Council Spring Members. The Cedro Peak C section is 81.3 m thick and contains the Council Spring, Burrego, Story, Del Cuerto, and Moya Members and lower part of the Bursum Formation.

Bartolo Member

Lithostratigraphy—At Cedro Peak the top of the Gray Mesa Formation is a cherty limestone (bioclastic wackestone) containing brachiopods. The overlying, lower 40 m of the Atrasado Formation consists of olive-gray micaceous sandy shale or sandstone at the base, various limestones, and a quartz-rich crossbedded pebbly sandstone near the middle (Fig. 9). Limestone ledges are 0.2–1.9 m thick and include thin- to thick-bedded, locally cherty lime mudstone, crinoidal packstone, and thin-bedded algal limestone near the top. Covered slopes, presumably shale, are as much as 13.3 m thick. Such a slope-forming, clastic interval at the base of the Atrasado Formation is the

Bartolo Member of Rejas (1965) and Lucas et al. (2009). The thickness of 40 m at Cedro Peak compares to 67 m at the type locality.

The base of the Bartolo Member at Cedro Peak section ZZ (Figs. 4C, 6) is a sandstone interval that is the “Coyote Sandstone” of Herrick (1900a). We refer to this unit as the Coyote Bed of the Bartolo Member (Fig. 3) and note its presence at many outcrops in the Manzano Mountains (e.g., Myers 1973). However, note that this unit is not present at Cedro Peak section A, where silty shale at the base of the Bartolo Member rests directly on the Gray Mesa Formation (Fig. 9).

Microfacies—The dominant limestone microfacies of the Bartolo Member is bioclastic wackestone, locally grading to packstone with intercalated thin grainstone layers. Wackestone–packstone locally contains abundant spicules (“spiculite,” see Fig. 10A). Rarely, grainstone–rudstone is present (Fig. 10B). All studied limestone samples contain a diverse fossil assemblage. Sandstone is arkosic in composition.

Paleontology—Limestones of the Bartolo Member contain a diverse fossil assemblage dominated by echinoderms, bryozoans, and brachiopod fragments. Smaller foraminifers (*Bradyina* sp., *Globivalvulina* sp., *Syzrania* sp., tubular forms), ostracods, gastropods, locally abundant spicules, rare echinoid spines, and trilobites are evident in thin section. Fusulinids are rare.

Amado Member

Lithostratigraphy—The distinctive, cherty limestone interval between the clastic Bartolo Member (below) and Tinajas Member (above) is the Amado Member of Rejas (1965) and Lucas et al. (2009). At Cedro Peak the Amado Member is 14 m thick and composed of limestone intervals 0.3–2.1 m thick separated by shale (0.1-m-thick) or thicker covered intervals as much as 0.8 m thick (Figs. 4D, 9). The limestone types are mostly thin- to thick-bedded lime mudstone that locally contains large chert nodules, cherty bioclastic wackestone containing brachiopods, and algal wackestone.

Microfacies—Limestone of the Amado Member is mainly composed of bioclastic wackestone to packstone with a diverse fossil assemblage (Figs. 10C, E). Locally, bindstone is present in which skeletons are bound by cyanobacteria and tubular foraminifers.

Paleontology—The fossil assemblage of the Amado Member is similar to that of the Bartolo Member (echinoderms, bryozoans, brachiopods, smaller foraminifers including *Earlandia* sp., *Bradyina* sp., *Climacammina* sp., *Globivalvulina* sp., *Palaeonubecularia* sp., and other calcivertellid forms, ostracods, gastropods, rare trilobites, and fusulinids). Locally spicules and smaller foraminifers are abundant, and skeletons are encrusted

by cyanobacteria.

Tinajas Member

Lithostratigraphy—A relatively thick, clastic-dominated interval above the Amado Member is the Tinajas Member of Lucas et al. (2009). At Cedro Peak the Tinajas Member is 61 m thick (Fig. 9) and begins with olive-gray, sandy micaceous shale, overlain by coarse-grained, crossbedded arkosic sandstone (Fig. 4E), followed by 0.2–0.4-m-thick limestone beds (calcarenite and fusulinid wackestone). The thin limestone beds are separated by 1–5-m-thick covered intervals. In the middle of the section, green, laminated micaceous sandstone 0.2–2.1 m thick alternates with mostly covered shale. Where exposed, shale is generally yellowish brown and calcareous. The upper part of the Tinajas Member consists of limestone ledges 0.3–1.9 m thick and three sandstone horizons 0.4–1.1 m thick. The limestone ledges are lime mudstone and thin- to medium-bedded algal wackestone with brachiopods, locally containing some chert. The lowermost sandstone is massive, coarse-grained, and arkosic in composition. The middle sandstone is red, laminated, and very micaceous. The uppermost sandstone is a massive, coarse-grained carbonate (both grains and cement) sandstone.

Microfacies—In the Tinajas Member at Cedro Peak, bioclastic wackestone containing a diverse fossil assemblage is the dominant limestone microfacies (Fig. 10G). Rarely fusulinid wackestone containing abundant *Triticites* is present (Fig. 10H). Wackestone locally grades into packstone and floatstone, which contain abundant recrystallized skeletons of “phylloid algae” (“phylloid algal floatstone,” Fig. 10D) and brachiopods. Sandstone is fine-grained and composed dominantly of monocrystalline quartz and detrital feldspars, a few polycrystalline quartz grains, detrital mica, and rare granitic and fine-grained metamorphic rock fragments. The sandstone is cemented by authigenic quartz overgrowths and coarse, blocky carbonate cement.

Paleontology—The fossil assemblage of limestones of the Tinajas Member is similar to that of the Bartolo Member. Locally, recrystallized skeletons of “phylloid algae” are present.

Approximately 6 km to the south of Cedro Peak, the Kinney Brick Quarry (a commercial clay pit) is developed in the Tinajas Member (Lucas et al. 2011). As a classic Konservat Lagerstätte, Kinney preserves soft tissues and other delicate structures of plants and animals unknown from correlative deposits. Fossils documented from the Kinney Brick Quarry are palynomorphs; a diverse, conifer-rich megafloora; a shelly marine invertebrate assemblage that includes a few ammonoids but is dominated by brachiopods and the pectinacean bivalve *Dunbarella*; syncarid and hoplocarid

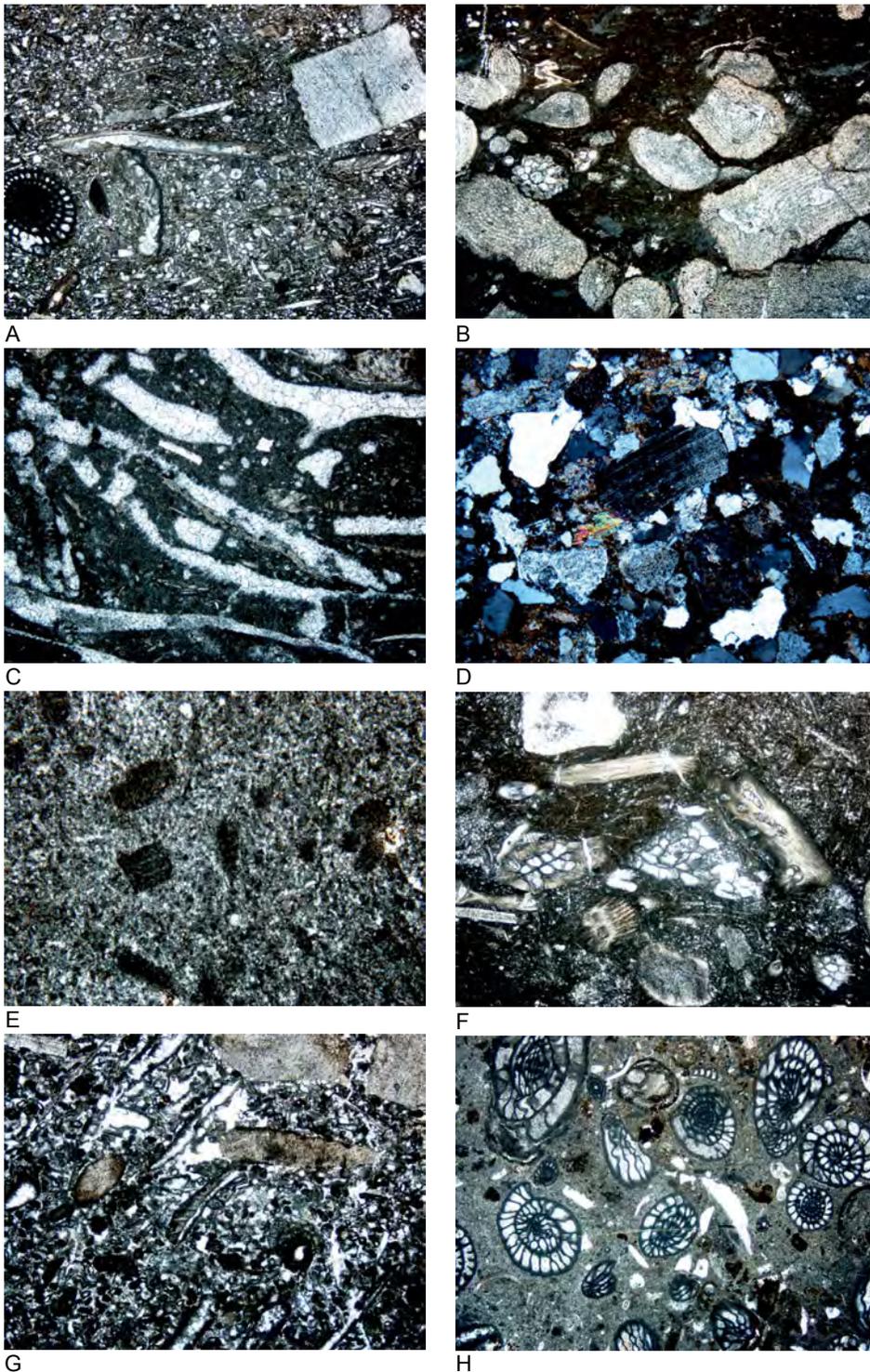


FIGURE 8—Thin section photographs of sandstone and limestone of the Gray Mesa Formation (A–D) and Atrasado Formation (E–H). A—Bioclastic wackestone containing large skeletons of crinoids, brachiopods, and fusulinids (*Wedekindellina* sp.) floating in fine-grained bioclastic matrix with abundant spicules and some other fossils. Plane light, width of photograph is 6.3 mm, sample CPZ 13 (Whiskey Canyon Member). B—*Komia* wackestone to floatstone composed of well-preserved, partly fragmented *Komia eganensis* and subordinately of other skeletons such as bryozoans, fusulinids, and echinoderms floating in micrite. Plane light, width of photograph is 6.3 mm, sample CPZ 16 (Whiskey Canyon Member). C—Algal wackestone containing fragments of recrystallized “phyllloid algae” *Ivanovia tenuissima* and a few other skeletons floating in micrite. Plane light, width of photograph is 6.3 mm, sample CPZ 7 (Whiskey Canyon Member). D—Medium-grained, arkosic sandstone containing abundant quartz and slightly altered detrital feldspars (mostly

potassium feldspars), rare granitic rock fragments, and detrital muscovite. Detrital grains are cemented by brownish carbonate. Polarized light, width of photograph is 3.2 mm, sample CPZ 17 (Garcia Member). E—Peloidal mudstone containing fecal pellets (dark gray). Plain light, width of photograph is 3.2 mm, sample CP 1 (Council Spring Member). F—Bioclastic wackestone composed of larger and many small skeletons of bryozoans, echinoderms, brachiopods, and smaller foraminifers floating in silty micrite. Plane light, width of photograph is 6.3 mm, sample CP 13 (Burrego Member). G—Bioclastic packstone composed of a few larger skeletons (bivalve shell fragments, crinoids) and abundant small skeletons of various fossils cemented by calcite. Plane light, width of photograph is 6.3 mm, sample CP 4 (Council Spring Member). H—Fusulinid wackestone containing abundant tests of *Triticites* sp. and other skeletal grains embedded in micrite. Plane light, width of photograph is 6.3 mm, sample CP-C 31 (Story Member). For sample numbers, see Figures 6 and 9.

crustaceans; eurypterids; conchostracans; ostracods; terrestrial arthropods, mostly diplopods and insects; conodonts; a diverse assemblage of fishes, mostly acanthodians and palaeoniscoids; amphibians; as well as coprolites and “fish eggs” (e.g., Zidek 1992; Lucas et al. 2011). A fusulinid-bearing limestone bed below the Kinney Quarry can be traced to Cedro Peak, where it is stratigraphically low in the Tinajas Member (Fig. 9, section B, unit 18).

Council Spring Member

Lithostratigraphy—The relatively thin but persistent limestone (mostly algal limestone) interval above the Tinajas Member is the Council Spring Member (Thompson 1942; Rejas 1965; Lucas et al. 2009; Vachard et al. 2012, 2013). At Cedro Peak the Council Spring Member is approximately 7 m thick and at its base is algal limestone (wackestone) that is locally bioturbated and contains brachiopods and fusulinids near the base (Fig. 9). This basal limestone is overlain by a 3-m-thick covered interval, followed by two limestone ledges, 1.8 and 0.6 m thick. Both ledges are composed of algal wackestone and separated by a thin shale notch.

Microfacies—In thin section, limestone of the Council Spring Member appears as wackestone with a diverse fossil assemblage, including recrystallized fragments of “phyllloid algae” (Fig. 8G). Locally, the wackestone grades into floatstone. Rarely, limestone is composed of peloidal mudstone (Fig. 8E).

Paleontology—Limestones of the Council Spring Member contain a fossil assemblage similar to that of the underlying Atrasado Formation members, and contain a characteristic abundance of “phyllloid algae.”

Burrego Member

Lithostratigraphy—The clastic-dominated interval above the Council Spring Member is the Burrego Member (Thompson 1942; Rejas 1965; Lucas et al. 2009; Vachard et al. 2012, 2013). Compared to outcrops to the south, the Burrego Member at Cedro Peak is sandstone dominated. At Cedro Peak the Burrego Member is 47 m thick

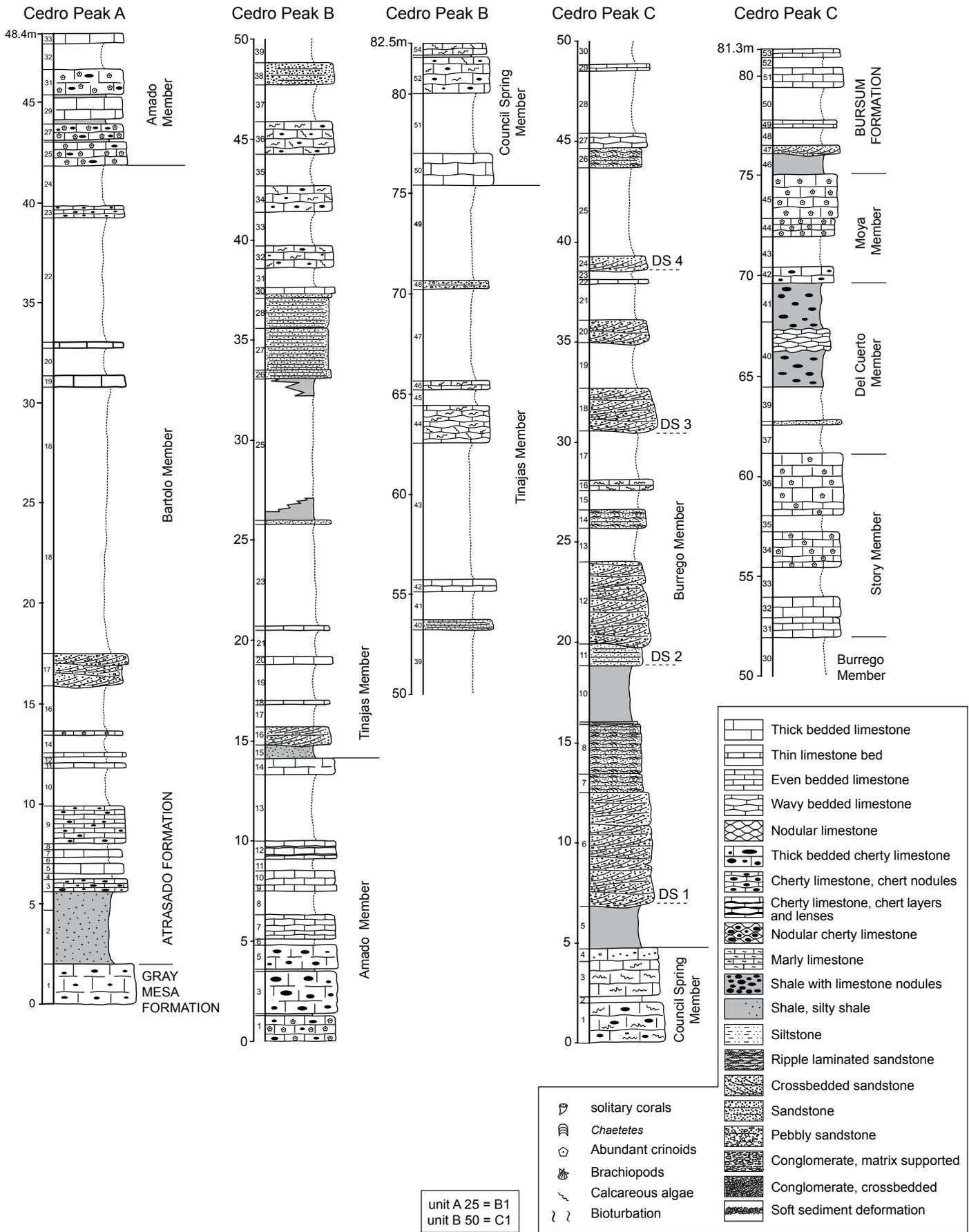


FIGURE 9—Measured stratigraphic sections of the uppermost Gray Mesa Formation (section A), the Atrasado Formation (sections A-C) and the Bursum Formation (section C). See Appendix for map coordinates of measured sections. Columns read from lower left (base) to upper right (top).

and composed of four fining-upward cycles (DS 1 through DS 4 in Fig. 9). The basal 2.1 m is not exposed and is overlain by cycle 1, which begins with 5.7 m of pebbly, crossbedded sandstone containing hematized plant stems, overlain by fine-grained, micaceous sandstone with horizontal lamination and ripple lamination, followed by siltstone and olive-green shale. Cycle 2 starts with horizontal laminated and crossbedded sandstone, overlain by a covered (shale) interval and green, thin-bedded micaceous sandstone with ripple lamination, followed by a thin algal limestone bed and a covered interval. Cycle 3 starts with a coarse-grained, pebbly arkosic sandstone, followed by a covered slope and a thin limestone bed (algal wackestone with brachiopods). Cycle 4 has a coarse, crossbedded arkosic sandstone at the base, overlain by a covered slope and fine-grained micaceous sandstone with ripple lamination, followed by crinoidal and algal limestone with covered intervals.

Microfacies—Limestone of the Burrego Member is mainly composed of bioclastic wackestone, including fusulinid wackestone, subordinate mudstone and bioclastic mudstone, floatstone containing large fragments of bryozoans and “phylloid algae” (algal floatstone), and rare grainstone (Figs. 8F, 11B). Wackestone, floatstone, and grainstone contain a diverse fossil assemblage. Sandstone is coarse grained, moderately to poorly sorted, and arkosic in composition, containing abundant monocrystalline quartz grains and detrital feldspars (Fig. 11E–G).

Paleontology—Other than oxidized plant stem fragments in sandstone and crinoidal and algal debris in limestone, we saw few fossils on outcrop in the Burrego Member. In thin section the fossil assemblage of the limestones includes skeletons of echinoderms, bryozoans, brachiopods, smaller foraminifers and microproblematica

Bradyina cf. *lucida*, *B.* cf. *compressa*
Morozova,
Pseudojanischewskina? sp.
Tetrataxis corona Cushman and Waters
T. aff. *paraconica* Reitlinger
Climacamma aff. *fragilis* Reitlinger
Palaeonubecularia rustica
Latitubiphytes rauzeriae Vachard and Moix
Syzrania confuse,
fusulinids *Reitlingerina* ex gr. *plummeri*
(Thompson)
Schubertellina bluensis (Ross and Sabins)
S. texana (Thompson)
Triticites turgidus Dunbar and Henbest
T. cf. *bungerensis* Kauffman and Roth
T. sp.

ostracods, sponge spicules, rare calcisponges and trilobites, “phylloid algae” (e.g., *Ivanovia tenuissima* Khvorova), epimastoporean dasycladales [*Epimastopora* ex gr. *alpina* Kochansky-Devidé and Herak, *E.* ex gr. *likana* Kochansky-Devidé and

Herak *Paraepimastopora kansasensis* (Johnson) Roux], and algae incertae sedis [*Fourstonella* (*Efluegelia*) *johnsoni*].

Story Member

Lithostratigraphy—Above the Burrego Member is a limestone interval termed the Story Member (Thompson 1942; Rejas 1965; Lucas et al. 2009; Vachard et al. 2012, 2013). At Cedro Peak the Story Member is 10.2 m thick and consists of lower (2 m), middle (1.8 m), and upper (3.1 m) limestone intervals separated by covered intervals (1.5 and 1.8 m thick; Fig. 9). The lower limestone is a fusulinid packstone at the base overlain by bioclastic wackestone containing bryozoans, fusulinids, brachiopods, and oncolids. The middle limestone is cherty, bedded, and contains crinoidal debris and brachiopods. The upper limestone is thick-bedded crinoidal wackestone containing brachiopods and algae.

Microfacies—Limestone microfacies types recognized in the Story Member are diverse wackestone, algal floatstone, and bryozoan floatstone. Fusulinid wackestone contains abundant *Triticites* (Fig. 8H), and bryozoan wackestone contains many fragments of fistuliporid and trepostome bryozoans (Fig. 11A). Another microfacies type is foraminiferal packstone (Fig. 11D) with abundant tubular foraminiferans (mostly *Calcivertella*).

Paleontology—In general, at higher taxonomic levels the fossil assemblage of the Story Member does not differ from that of the underlying Atrasado members. However, locally, recrystallized skeletons of “phylloid algae” and bryozoans are abundant, forming floatstone.

Del Cuerto Member

Lithostratigraphy—The slope-forming shaley interval above the Story Member is the Del Cuerto Member (Thompson 1942; Rejas 1965; Lucas et al. 2009; Vachard et al. 2012, 2013). At Cedro Peak the thickness of the Del Cuerto Member is 8.8 m (Fig. 9). In the lower part, a thin, fine-grained sandstone is exposed, within a covered slope, and is overlain by shale with limestone nodules and nodular limestone containing brachiopods.

Microfacies—Limestone of the Del Cuerto Member is composed dominantly of diverse bioclastic wackestone. Grainstone to packstone composed of abundant echinoderm fragments is also present (Fig. 11C). Sandstone is arkosic in composition with abundant detrital potassium feldspar grains (Fig. 11H). Sandstone is cemented by quartz overgrowths on detrital quartz grains.

Paleontology—In thin section, limestones of the Del Cuerto Member contain a diverse fossil assemblage similar at higher taxonomic levels to that of the other Atrasado members.

Moya Member

Lithostratigraphy—The uppermost limestone interval of the Atrasado Formation is the Moya Member (Thompson 1942; Rejas 1965; Lucas et al. 2009; Vachard et al. 2012, 2013). Note, though, that given the unconformity at the base of the Bursum Formation, that unit may rest locally on stratigraphically lower units of the Atrasado Formation. At Cedro Peak the Moya Member is approximately 4.9 m of limestone ledges that are 0.3–1 m thick, separated by covered intervals (Fig. 9). Limestones consist of crinoidal wackestone and algal limestone containing relatively large specimens of the fusulinid *Triticites*.

Microfacies—Limestone of the Moya Member is composed of diverse wackestone to packstone like those seen in underlying limestones of the Atrasado Formation (Fig. 10F). Locally, fecal pellets are present.

Paleontology—Limestones of the Moya Member contain a diverse biota, mainly skeletons of echinoderms, bryozoans, and brachiopods. Subordinate are smaller foraminifers (*Eotuberitina* sp., *Spireitlina* sp., *Endothyra* sp., *Bradyina* sp., *Climacamma* sp., *Tetrataxis* sp., *Globivalvulina* sp., *Palaeonubecularia* sp., and other calcivertellids forms, and *Syzrania* sp.), fusulinids, ostracods, spicules, trilobites, gastropods, and recrystallized skeletons. A few skeletons are encrusted by cyanobacteria.

Depositional environments

The microfacies of the limestones of the Atrasado Formation at Cedro Peak are very similar to those of the type section of the Atrasado Formation near Major Ranch in the Lucero uplift of Valencia County, with muddy microfacies, particularly wackestone, dominant (Krainer and Lucas 2004). The microfacies and fossil assemblage indicate that the limestones were deposited in a shallow marine shelf environment with open circulation and water depth of a few tens of meters, mostly below the wave base. “Phylloid algal” limestone, which is common in the lower part of the type section (Amado Member), is much less common at Cedro Peak. Whereas the limestone-dominated members (Amado, Council Spring, Story, and Moya) are of similar thickness to their type sections in Socorro County (Thompson 1942; Lucas and Krainer 2009), members containing siliciclastic sediments (Bartolo, Tinajas, and Burrego Members) are either thinner (Bartolo, Tinajas) or much thicker (Burrego) at Cedro Peak, with sandstone being much more abundant. In the Bartolo and Tinajas Members, siliciclastic facies are dominated by siltstone and shale. The siliciclastic sediments of these members are interpreted as nonmarine to marginal marine (e.g., Lorenz et al. 1992). The thick, crossbedded sandstone intervals in the Burrego Member are interpreted

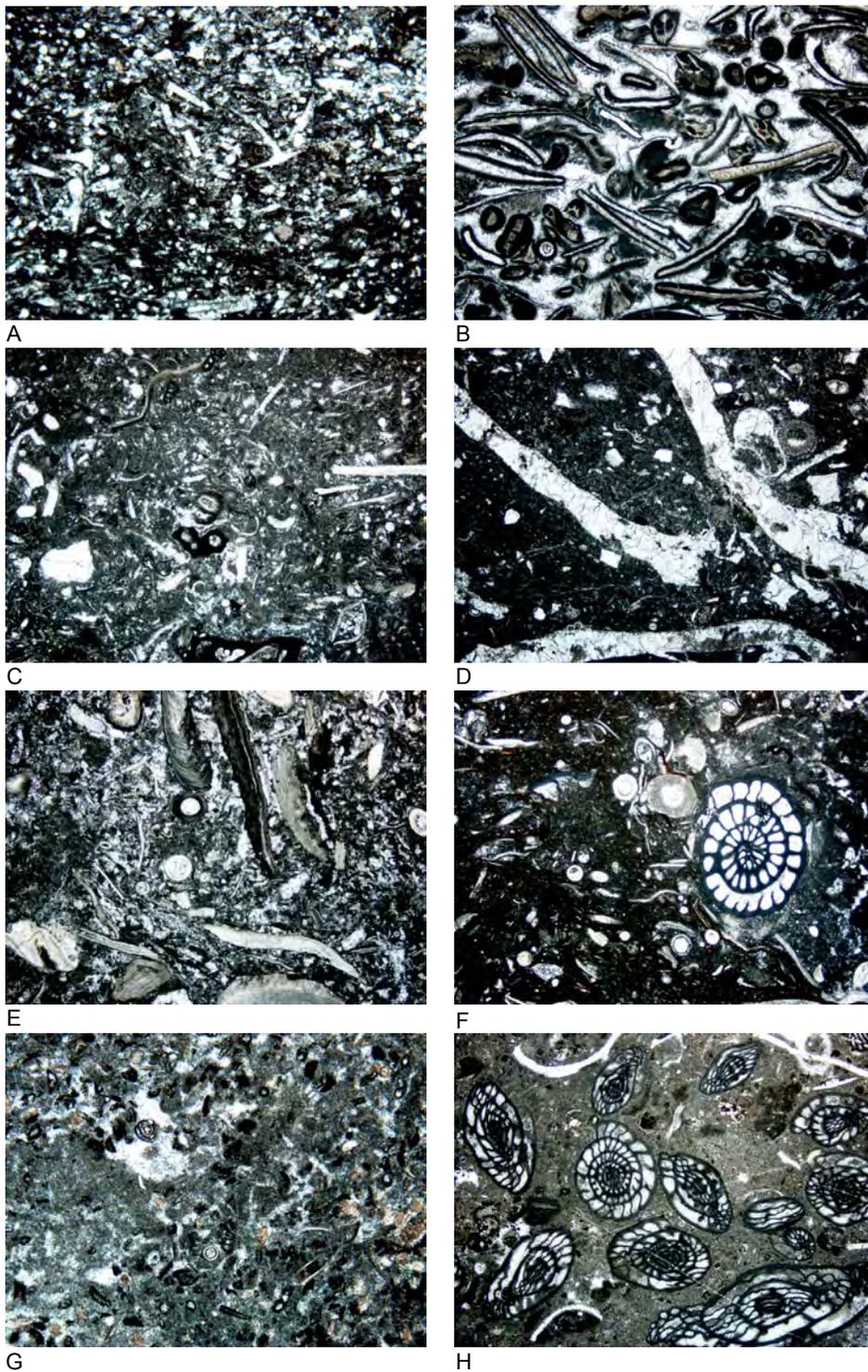


FIGURE 10—Thin section photographs of microfacies of the Atrasado Formation: Bartolo Member (A, B), Amado Member (C, E), Tinajas Member (D, G, H), and Moya Member (F). Width of photographs: A and G = 3.2 mm, all others = 6.3 mm. A—Fine-grained wackestone–packstone containing abundant spicules (“spiculite”) and subordinately other skeletons such as ostracods and echinoderms (sample CP-A3). B—Grainstone–rudstone containing shell fragments, bryozoans, echinoderms, and gastropods. Skeletons commonly display micritic envelopes (“coated grains”; sample CP-A15). C—Wackestone containing a diverse fossil assemblage of echinoderms, bryozoans, smaller foraminiferans, ostracods, spicules, and some other skeletons embedded in micritic matrix (sample CP-B5). D—Phylloid algal floatstone composed of completely recrystallized skeletons of phylloid algae embedded in micrite that contains a few smaller fossil fragments of brachiopods,

bryozoans, echinoderms, smaller foraminiferans, and ostracods (sample CP-B44). E—Wackestone–packstone containing a diverse assemblage of brachiopods and brachiopod spines, bryozoans, echinoderms, ostracods, and foraminifers embedded in micrite (sample CP-B14). F—Wackestone containing skeletons of brachiopods, bryozoans, echinoderms, fusulinid tests, smaller foraminiferans, and ostracods (sample CP-B52). G—Fine-grained wackestone containing small echinoderm fragments, ostracods, and many tubular foraminiferans embedded in micrite (sample TAB8). H—Fusulinid wackestone containing abundant fusulinid tests (*Triticites*) and subordinately smaller foraminiferans, brachiopods, bryozoans, echinoderms, and ostracods floating in micritic matrix (sample TAB14). For sample numbers, see Figures 6, 9, and 12.

as fluvial-deltaic deposits, representing channel fill on a delta plain, grading into fine-grained, ripple-laminated sandstone and siltstone, probably of a prodelta environment.

Correlation with the Atrasado type section near Major Ranch

The lectostratotype section of the Atrasado Formation near Major Ranch (Krainer and Lucas 2004) is much thinner (approximately 100 m) compared to the Atrasado Formation section at Cedro Peak. At the lectostratotype section, Krainer and Lucas (2004) divided the Atrasado Formation into five informal units, A through E. The Bartolo Member of Cedro Peak correlates with unit A, the Amado Member with most of unit B, the Tinajas Member with the upper part of unit B and lower part of unit C, Council Spring Member with upper part of unit C, the Burrego Member correlates with unit D, the Story Member with the lower part of unit E, the Del Cuerto Member with the middle part of unit E, and the Moya Member with the upper part of unit E. Limestone-dominated members are of similar thickness and facies at both sections, except for the Amado Member, in which “phylloid algal” limestone is common at the type section and rare at Cedro Peak. Siliciclastic sediments are rare and thin at the type section and more abundant and thicker at Cedro Peak.

Bursum Formation

Lithostratigraphy

In central New Mexico the Bursum Formation is an interval of marine limestone/shale intercalated with nonmarine red beds that represents a transition from the underlying, mostly marine Atrasado Formation to the overlying, nonmarine Abo Formation (Krainer and Lucas 2013b). At Cedro Peak only approximately 6 m of the lower part of the Bursum Formation is preserved (Figs. 9, 12). Therefore, we discuss other nearby Bursum Formation sections that we have measured to gain a complete understanding of Bursum lithostratigraphy in the Manzanita Mountains.

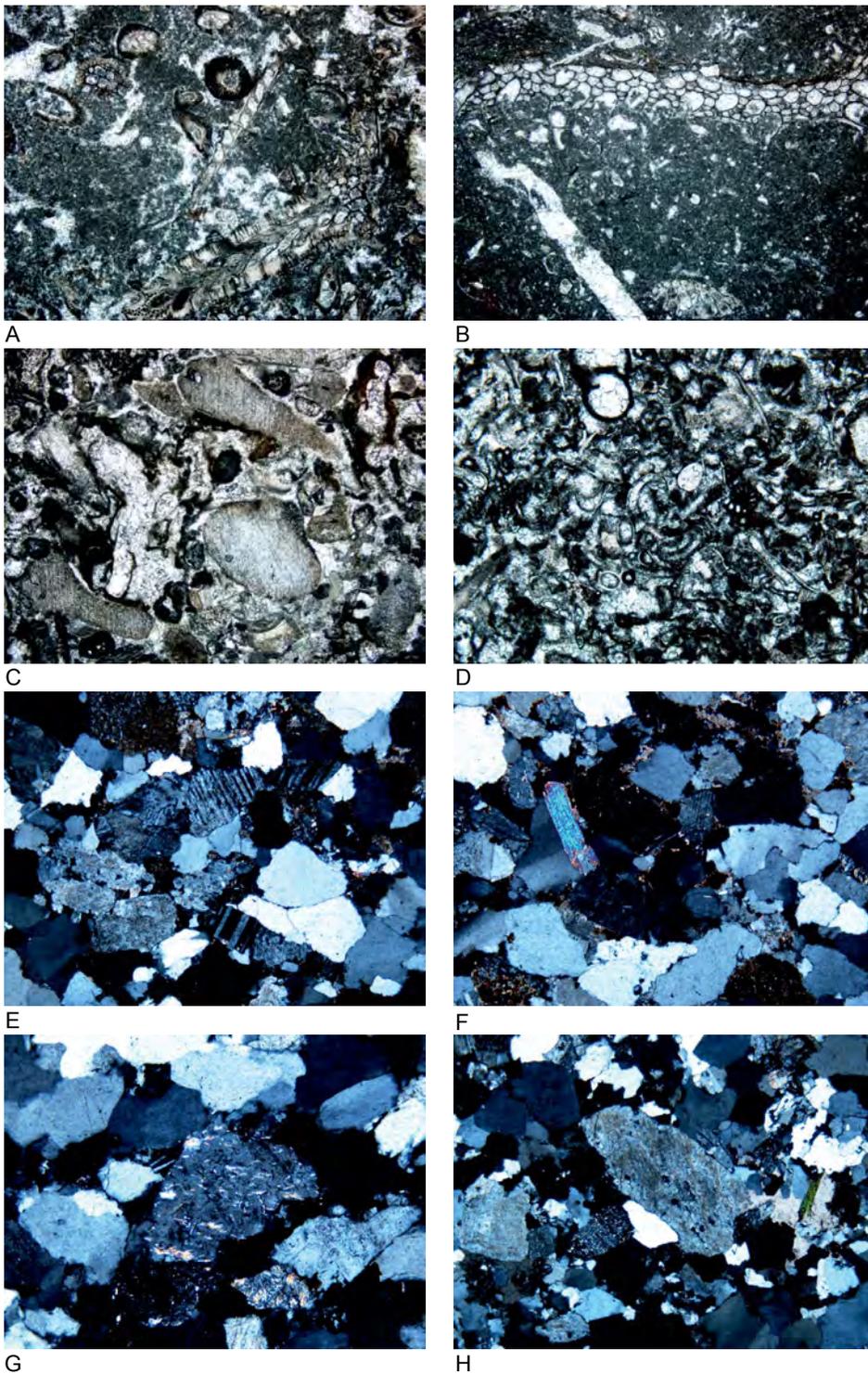


FIGURE 11—Thin section photographs of limestone (A–D) and sandstone (E–H) of the Atrasado Formation. A—Bryozoan wackestone containing mostly fistuliporid and subordinate trepostome skeletons of bryozoans, as well as subordinate other skeletons embedded in peloidal micrite. Plane light, width of photograph is 6.3 mm, sample CP 17 (Story Member). B—Floatstone composed of a few larger skeletons (bryozoans, recrystallized shells) and small skeletons in micritic matrix. Plane light, width of photograph is 6.3 mm, sample CP 14 (Burrego Member). C—Grainstone to packstone composed of abundant echinoderm fragments and a few other skeletons, and rare micritic intraclasts and peloids, cemented by calcite. Plane light, width of photograph is 6.3 mm, sample CP 20 (Del Cuerto Member). D—Foraminiferal packstone composed of abundant tubular foraminiferans (mostly *Calcivertella*), rare other smaller foraminiferans, and fragments of other fossils that are cemented by calcite. A small amount of micrite is present, too. Plane light, width of photograph is 3.2 mm, sample CP 18 (Story Member). E—Medium-grained, arkosic sandstone containing abundant monocrystalline quartz and slightly altered detrital feldspar grains. Polycrystalline quartz grains and rock

fragments are rare. The detrital grains are cemented by authigenic quartz overgrowths and some calcite cement. Polarized light, width of photograph is 3.2 mm, sample CP 5 (Burrego Member). F—Medium-grained, arkosic sandstone composed of monocrystalline and rare polycrystalline quartz and many detrital feldspar grains (mostly potassium feldspar). Detrital micas (muscovite) are rare. The sandstone is cemented by authigenic quartz overgrowths and calcite cement. Polarized light, width of photograph is 3.2 mm, sample CP 6 (Burrego Member). G—Medium-grained, arkosic sandstone containing abundant detrital feldspar grains. The potassium feldspar in the center is altered and contains small needles of clay minerals. Polarized light, width of photograph is 1.2 mm, sample CP 8 (Burrego Member). H—Arkosic sandstone composed of mono- and polycrystalline quartz and abundant detrital feldspars (dominantly potassium feldspar), cemented by authigenic quartz overgrowths. Polarized light, width of photograph is 3.2 mm, sample CP 21 (Del Cuerto Member). For sample numbers, see Figures 6 and 9.

At our Los Pinos section, a 90-m-thick, complete Bursum section is well exposed along the frontage road to I-40, with two covered intervals, one near the base (13.2 m) and one near the top (13.0 m), probably representing shale units (Fig. 12). The Bursum Formation rests on bedded limestone of the Atrasado Formation and is overlain by sandy red beds of the Abo Formation. The dominant lithofacies is mudstone–siltstone, in which thin conglomerate beds, sandstone units as much as 7 m thick, and a few thin limestone beds are intercalated. Mudstone–siltstone is micaceous, mostly red, subordinately greenish-gray, laminated, and nonfissile. Small (mostly 1–2 cm) carbonate nodules float in the mudstone–siltstone, particularly in the middle part, as distinct horizons. Two thin, fine-grained conglomerate beds (0.3 m thick in the lower part and 0.1 m thick in the upper part) are composed of carbonate clasts.

Sandstone is a common lithofacies and occurs as 0.3–7-m-thick intervals. Thicker sandstone intervals form fining-upward sequences starting with coarse, partly pebbly sandstone that erosively overlies mudstone–siltstone, displays large-scale trough crossbedding and grades upward into fine-grained sandstone with small-scale trough or planar crossbedding, horizontally laminated sandstone, and (rarely) ripple-laminated sandstone on top. A few syndepositional deformation structures are observed in fine-grained sandstone.

Limestone is rare, constituting only about 2% of the entire section. Limestone occurs in a 0.7-m-thick interval in the lower part, composed of 0.1-m-thick limestone beds and intercalated greenish marly shale, in a 1.1-m-thick interval in the middle composed of cm-thick limestone beds and lenses alternating with greenish mudstone and containing crinoids and brachiopods, and in two 0.1-m-thick gray limestone beds intercalated in red siltstone near the top. Additionally, one 0.1-m-thick limestone bed, in the lower part, is intercalated in greenish shale.

At Tijeras Ranger Station an incomplete 27-m-thick section of the lower part of the Bursum Formation is exposed, resting on bedded lime mudstone of the Atrasado Formation, which near the top seems to be pedogenically overprinted (Fig. 12). Here, the Bursum Formation is composed of

shale-siltstone intervals as much as 4.7 m thick with intercalated conglomerate, sandstone, and limestone. Shale to siltstone is micaceous, red, purple, and greenish-gray and locally contains limestone nodules. The shale interval of unit 11 contains crinoidal debris and brachiopods. The conglomerate bed of unit 19 is 0.6 m thick, partly mud supported, poorly sorted, and is composed of limestone clasts. Sandstone intervals are as much as 2.3 m thick and composed of individual sandstone beds as thick as 0.6 m, which commonly display trough crossbedding. Thin sandstone beds appear massive. Thin shale intercalations occur between individual sandstone beds. Limestone intervals are 0.3–0.9 m thick and composed of gray micritic limestone beds (0.1–0.5 m thick) and two nodular limestone beds with purple matrix (0.3 and 0.4 m thick). Brachiopods occur in unit 12, and fusulinids (*Triticites* sp.) in unit 13. Bryozoans and crinoidal debris are found in the nodular limestone of unit 15.

At Cedro Peak only the lowermost 6 m of the Bursum Formation is preserved (Figs. 9, 12). The base of the formation is red shale overlain by crossbedded, arkosic sandstone. Overlying beds are limestone between covered slopes (shale?). The nearby Tablazon section is similar, with only the lower 5 m of the Bursum Formation exposed (Fig. 12). Here, the base of the Bursum Formation is a relatively thick (approximately 2.5 m) arkosic sandstone with crossbeds and an erosional base. An overlying limestone bed contains abundant large fusulinids (*Triticites* sp.).

Sedimentary petrography and microfacies

The Bursum Formation conglomerate at the Tijeras section is composed of mostly subrounded micritic carbonate clasts, some of them displaying shrinkage fissures indicating reworking of caliche carbonates. The conglomerate contains as much as about 10% subangular detrital quartz grains as large as 4 mm in diameter and a few fossil fragments (bryozoans, echinoderms, and shell debris). The clasts are embedded in micritic matrix; locally, some calcite cement is present.

At the Bursum sections in the Manzanita Mountains (Fig. 12), sandstone is arkosic, composed of abundant monocrystalline and subordinate polycrystalline quartz grains, abundant detrital feldspars, rare granitic and metamorphic rock fragments, rare chert grains, and mica (Fig. 13A–B). Detrital feldspars are dominantly untwinned potassium feldspars; subordinate feldspar grains with polysynthetic twins are also present. Most feldspars are altered or partly replaced by calcite. Granitic rock fragments are composed of large quartz and feldspar grains. Micas are mostly muscovite and subordinate biotite. The sandstones are cemented, either by authigenic quartz overgrowths on detrital quartz grains or by coarse, blocky calcite

cement that partly replaces detrital quartz and feldspar grains. Locally, both quartz and calcite cement are present, and some sandstone beds contain small amounts of fine-grained matrix.

At the Tijeras section the dominant microfacies of limestone is wackestone to packstone that contains a diverse fossil assemblage and locally is bioturbated (Fig. 13C, E). Packstone to rudstone, locally containing many intraclasts (reworked wackestone), is subordinate. Common fossil fragments are echinoderms, recrystallized skeletons, brachiopod shell and spine fragments, bryozoans, fusulinids, smaller foraminifers (*Endothyra* sp., *Bradyina* sp., *Climacamina* sp., *Tetrataxis* sp., and undetermined tubular forms), trilobite fragments, ostracods, and rare sponge spicules. The nodular limestone of unit 15 is fossiliferous, mixed siliciclastic-carbonate siltstone composed of abundant small angular quartz grains and a few micas embedded in micrite. The siltstone contains a few fossil fragments, including echinoderms, bryozoans, and recrystallized skeletons, and rare oncolids as large as 9 mm in diameter.

At the Los Pinos section, wackestone with a diverse fossil assemblage is the most abundant limestone microfacies (Fig. 13D, F–H). Some wackestones contain abundant tubular foraminifers and locally abundant bivalve shell fragments. Recrystallized algal fragments are present, too. Wackestone may grade into packstone, rarely into rudstone. The two thin limestone beds in the uppermost part are composed of two types of wackestone: (1) ostracodal wackestone with abundant ostracod shells, many of them with both valves preserved; bivalve shells, recrystallized skeletons, and rare echinoderms embedded in micritic matrix that also contains abundant small quartz grains, a few detrital feldspars, and rare mica are subordinate; and (2) wackestone to floatstone composed of micritic to pelmicritic matrix in which gastropods and bivalve shells are floating; shelter porosity is filled with coarse calcite.

Paleontology

Fossil content of the Bursum Formation in the Manzanita Mountains is very similar at higher taxonomic levels to that of parts of the underlying Atrasado Formation. On outcrop, brachiopods, crinoid debris, and, locally, bivalves are common. Thin sections of limestone reveal abundant algae and smaller foraminifers, and, locally, ostracods and fusulinids are abundant.

Depositional environments

The Bursum Formation is the transitional facies between the dominantly shallow marine Upper Pennsylvanian carbonate deposits of the Atrasado Formation and the nonmarine red beds of the Abo Formation (Krainer and Lucas 2004, 2009, 2013b; Lucas and Krainer 2004). The Tijeras and Los

Pinos sections can be assigned to the Red Tanks Member of the Bursum Formation, which is a moderately thick unit of mostly nonmarine mudstone present in the Lucero uplift; Sandia, Manzano, and Los Pinos Mountains; and locally, in the Joyita Hills east of Socorro (Lucas and Krainer 2004; Krainer and Lucas 2009).

Compared to the Bursum sections in the Lucero uplift (Red Tanks Arroyo, Coyote Draw: Lucas and Krainer 2004; Carrizo Arroyo: Krainer and Lucas 2004) the Red Tanks Member at Tijeras and Los Pinos is of similar thickness but contains much higher amounts of sandstone (21% of the total section) and less limestone and limestone conglomerate. The dominant lithofacies at Tijeras and Los Pinos is mudstone–siltstone.

We interpret the red mudstone–siltstone of the Bursum Formation that locally contains pedogenic nodules as nonmarine deposits of distal alluvial plains. Greenish mudstone–siltstone associated with marine limestone formed in a brackish to shallow marine environment. Thicker sandstone units composed of grouped sets of trough crossbedded sandstone are interpreted as fluvial channel-fill deposits that formed in broad and shallow channels. Thin, intercalated massive to horizontally laminated sandstone beds probably represent sheet splay deposits. The thin carbonate conglomerates, which also contain a few marine fossils, may have formed in a high-energy, nearshore environment, although the fossils are likely reworked from older (Mississippian or Pennsylvanian) carbonate rocks. Limestone containing a high taxonomic diversity of fossils and muddy texture indicates deposition in a low- to moderate-energy shallow marine environment with normal salinity. The uppermost two thin limestone beds with a low-diversity fossil assemblage indicate formation in a restricted, shallow marine setting.

The Los Pinos section can be divided into six depositional sequences that range in thickness from 5 to 30 m (Fig. 12). Each depositional sequence (except DS 1) starts with a pebbly sandstone or sandstone that overlies mudstone–siltstone with an erosional contact. Sandstone units display a fining-upward trend, are overlain by mudstone–siltstone, and, near the top of DS 1, 2, 3, and 6, thin marine limestone beds are intercalated in mudstone–siltstone.

Similar depositional sequences have been described from Bursum sections in the Lucero uplift (Krainer and Lucas 2004; Lucas and Krainer 2004) and from the Joyita Hills and Cerros de Amado area east of Socorro (Krainer and Lucas 2009). According to Krainer and Lucas (2004, 2009), the cyclic deposition of nonmarine and marine sediments of the Bursum Formation was influenced by both glacial-eustatic sea-level fluctuations and tectonic movements of the Ancestral Rocky Mountain orogeny, the latter indicated by the strong lateral variations in thickness and facies. The large

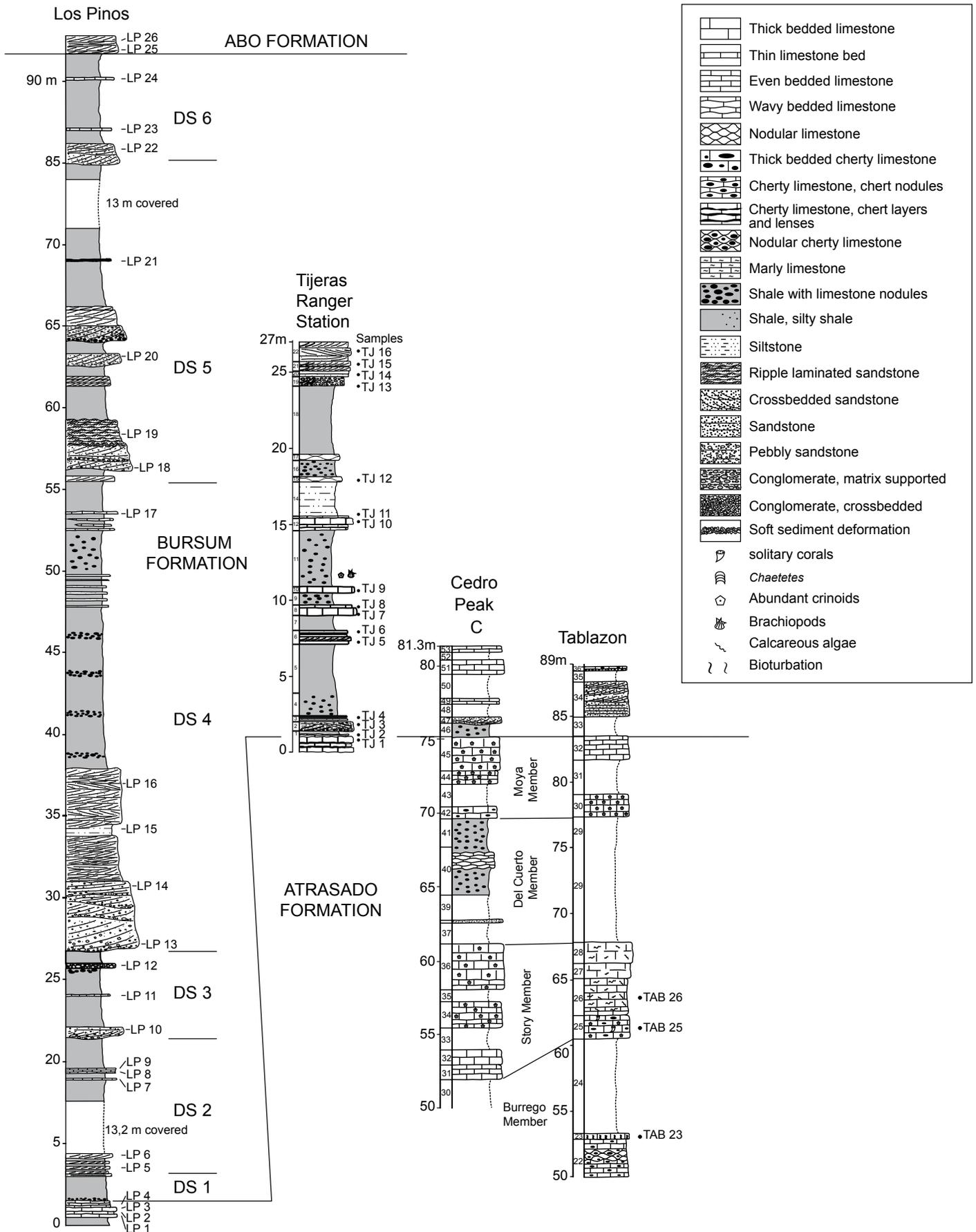


FIGURE 12—Measured stratigraphic sections of the Bursum Formation in the Manzanita Mountains. See Appendix for map coordinates of measured sections.

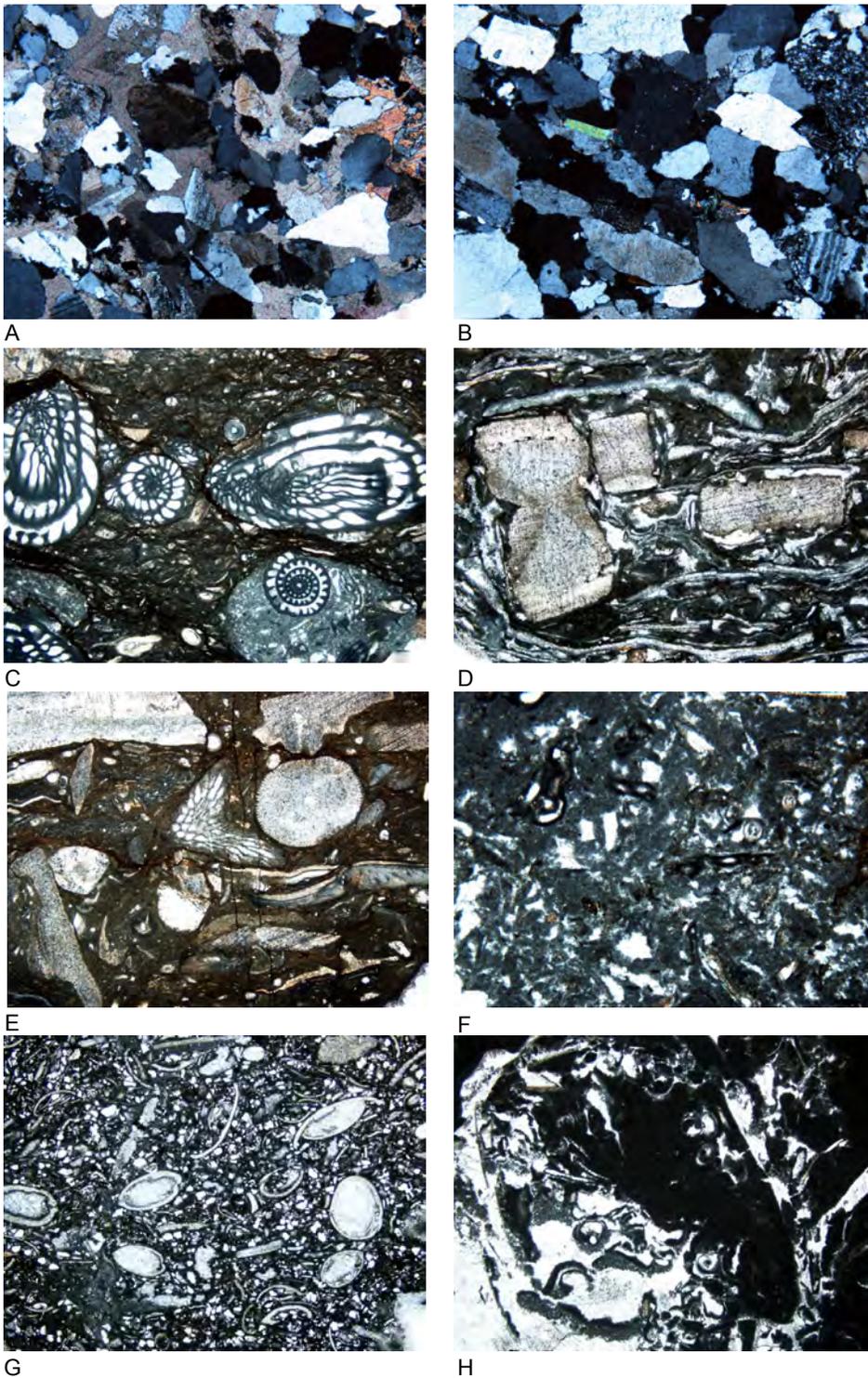


FIGURE 13—Thin section photographs of sandstone and limestone of the Bursum Formation at Tijeras and Los Pinos. A—Arkosic sandstone cemented by coarse blocky calcite cement that randomly replaces feldspars and quartz. Sample TJ 7 (Tijeras), plane light, width of photograph is 6.3 mm. B—Arkosic sandstone cemented by quartz that occurs as authigenic overgrowths. Sample LP 14 (Los Pinos), polarized light, width of photograph is 3.2 mm. C—Diverse wackestone containing many fusulinids and some intraclasts (reworked wackestone that also contains fusulinids: *Triticites* sp.). Sample TJ 10 (Tijeras), plane light, width of photograph is 6.3 mm. D—Packstone containing abundant recrystallized bivalve shells and crinoid fragments, some calcite cement, and micritic matrix. Sample LP 17 (Los Pinos), plane light, width of photograph is 6.3 mm. E—Packstone—rudstone

containing a diverse fossil assemblage including large fragments of crinoids, bryozoans, and brachiopods. Sample TJ 7 (Tijeras), plane light, width of photograph is 6.3 mm. F—Wackestone containing abundant tubular foraminifers and small, mostly recrystallized skeletons embedded in micrite. Sample LP 9 (Los Pinos), plane light, width of photograph is 3.2 mm. G—Wackestone containing abundant ostracod shells embedded in micrite that contains abundant small angular quartz grains, few feldspars, and mica. Sample LP 23 (Los Pinos), plane light, width of photograph is 6.3 mm. H—Low diverse wackestone—floatstone composed of recrystallized bivalve and gastropod shells floating in micrite. Sample LP 24 (Los Pinos), plane light, width of photograph is 6.3 mm.

amounts of coarse siliciclastic sediment in the Bursum Formation sections we measured in the Manzanita Mountains indicate deposition in a more proximal environment compared to the sections in the Lucero uplift. Sandstone composition suggests the reworking of mainly granitic bedrock, most likely derived from the Pederal uplift to the east.

Biostratigraphy and age

Biostratigraphy of the Pennsylvanian section at Cedro Peak is based on fusulinids (Fig. 14). Myers and McKay (1976) showed eight fusulinid levels in the Cedro Peak section (also see Myers 1988a, b). Lucas et al. (2011) documented some Missourian fusulinids from the Tinajas Member at Cedro Peak, and Vachard et al. (2012, 2013) documented extensive microfossil assemblages that include fusulinids from throughout the Pennsylvanian section at Cedro Peak. Lucas et al. (2013) recently provided a summary of the fusulinid biostratigraphy at Cedro Peak and clearly correlated the work of Myers to our recent work.

Atokan

We recognized no age-diagnostic fusulinids in the Sandia Formation section at Cedro Peak (see above). Fusulinids from the Sandia Formation at the lectostratotype section in the Sandia Mountains, 13 km north of Cedro Peak, are of late Morrowan? to early Atokan age (Krainer et al. 2011). Myers (1988a) documented Atokan fusulinids (his zone of *Fusulinella*) from the Sandia Formation at Sol se Mete Peak, approximately 9 km southwest of Cedro Peak. At Cedro Peak, the limestone of the basal Gray Mesa Formation immediately above the Sandia Formation contains fusulinids that indicate a latest Atokan? to early Desmoinesian age (Vachard et al. 2012, 2013). Therefore, at Cedro Peak, we assign an Atokan age to the Sandia Formation (Fig. 14).

Latest Atokan?—early Desmoinesian

In the lower part of the Elephant Butte Member of the Gray Mesa Formation at Cedro Peak, Vachard et al. (2013) documented a fusulinid assemblage that

consists of *Pseudostaffella* sp., *Profusulinella fittsi* (Thompson), *Schubertellina* sp., and *Dagmarella iowensis* (Thompson). They considered this assemblage to be late or latest Atokan?–early Desmoinesian because of the association of *Dagmarella iowensis* and *Profusulinella fittsi* (cf. Wilde 1990, 2006).

Myers and McKay (1976) listed *Beedeina* aff. *B. arizonensis* (Ross and Sabins) and *Plectofusulina?* sp. from approximately 7 m above the base of the Elephant Butte Member of the Gray Mesa Formation (USGS locality f1087). Myers (1988a, pl. 3) later illustrated these fusulinids, identifying them as *Beedeina insolita* (Thompson) and *Plectofusulina* sp. He considered them to be of early Desmoinesian age, assigning them to his subzone of *Beedeina insolita*.

Early Desmoinesian

In the middle to upper part of the Elephant Butte Member and overlying Whiskey Canyon Member of the Gray Mesa Formation, Vachard et al. (2013) documented a fusulinid assemblage that consists of *Pseudostaffella* sp.; *Schubertellina bluensis* (Ross and Sabins); *Plectofusulina manzanensis* Vachard, Krainer, and Lucas; *Wedekindellina* cf. *W. excentrica* Roth and Skinner; *W. pseudomatura* Ross and Tyrrell; *Beedeina* cf. *B. novamexicana* (Needham); *B. cf. B. leei* (Skinner); and *B. sp.* Vachard et al. (2013) correlated this assemblage to the second biozone of the early Desmoinesian, DS2 of Wilde (e.g., Myers 1988a; Wilde 1990, 2006; Groves and Reisdorph 2009) because of the presence of *Beedeina novamexicana*, a species relatively advanced of the first lineage of *Beedeina*.

Myers and McKay (1976) also reported *B. novamexicana* from this stratigraphic interval (USGS locality f10188). Myers (1988a, pl. 3) illustrated *Wedekindellina* cf. *W. euthysepta* (Henbest) and *Beedeina* aff. *B. novamexicana* (Needham) from this locality, assigning it to his *Beedeina novamexicana* subzone of early Desmoinesian age.

We did not recognize any fusulinids in our samples from the Garcia Member of the Gray Mesa Formation at Cedro Peak. However, Myers and McKay (1976) reported *Beedeina* aff. *B. sulphurensis* (Ross and Sabins) from a horizon 113 m above the base of the Gray Mesa Formation at Cedro Peak, which is a level in the Garcia Member (USGS locality f10189). Myers (1988a, pl. 5) illustrated *Beedeina rockymontana* (Roth and Skinner) from this locality and assigned it to his *Beedeina rockymontana* subzone of middle Desmoinesian age. The fusulinids thus suggest that the entire Gray Mesa Formation is of Desmoinesian age at Cedro Peak.

However, there is a large stratigraphic gap in fusulinid age control in the Cedro Peak section that spans much of the Garcia Member of the Gray Mesa Formation and the Bartolo and Amado Members of the Atrasado Formation (Fig. 14). Based on conodont biostratigraphy in the Cerros de Amado of Socorro County, approximately 110 km to the south, the Desmoinesian–Missourian

boundary is close to the base of the Amado Member (Lucas et al. 2009). However, direct dating of this interval at Cedro Peak will require additional data.

Missourian

At Cedro Peak Myers and McKay (1976) reported *Triticites* sp. from strata near the base of the Tinajas Member of our stratigraphy. Myers (1988b, pl. 3) later illustrated *Triticites nebraskensis* Thompson from this locality (USGS locality f10258). This indicates an early Missourian age for a horizon near the base of the Tinajas Member.

Myers and McKay (1976) reported *Triticites* sp. from a horizon 44 m above the base of the Tinajas Member at Cedro Peak. Myers (1988b, pl. 3) illustrated *Triticites ohioensis* Thompson from this locality (USGS locality f10259), which indicates an early-middle Missourian age.

The laterally extensive, fusulinid-bearing limestone of the Tinajas Member at Cedro Peak (which is also a few meters below the level of the Kinney Brick Quarry to the south) yields an early-middle Missourian fusulinid assemblage consisting of *Tumulotriticites* cf. *T. tumidus* Wilde and species of *Triticites*: *T. cf. T. planus* Thompson and Thomas, *T. cf. T. myersi* Wilde, and *T. ex gr. T. ohioensis* Thompson (Lucas et al. 2011). At the Kinney Brick Quarry a conodont fauna in the Tinajas Member (a few meters above the fusulinid bed) is characterized by *Idiognathodus corrugatus* Gunnell and *I. cherryvalensi* Gunnell, which suggest an assignment to the *Idiognathodus confragus* Zone of the North America midcontinent region (Dennis cyclothem; middle Missourian; Lucas et al. 2011).

Virgilian

At Cedro Peak from limestones of the Council Spring, Burrego, Story, Del Cuerto, and Moya Members, Vachard et al. (2013) and Lucas et al. (2013) documented a fusulinid assemblage that includes the following taxa: *Triticites turgidus* Dunbar and Henbest in Dunbar et al. and *T. cf. T. bungerensis* Kauffman and Roth and *T. sp.* This assemblage was dated as middle Virgilian (VC2) by Vachard et al. (2012, 2013) and Lucas et al. (2013) because of the presence of two characteristic species of *Triticites*: *T. turgidus* and *T. cf. bungerensis* (Myers 1988b; Wilde 1990, 2006; Sanderson et al. 2001). This suggests the top of the Atrasado Formation at Cedro Peak is of middle Virgilian age (Fig. 14).

At Cedro Peak Myers and McKay (1976) identified the fusulinids *Oketaella* sp. and *Triticites* sp. from horizons in the Burrego Member of the Atrasado Formation. Myers (1988b, pl. 6) illustrated *Oketaella?* sp. from the lower horizon (USGS locality f10260) and (pl. 7) illustrated *Triticites* cf. *T. turgidus* Dunbar and Henbest from the upper horizon (USGS locality 10261). He considered the sites to straddle his *Triticites bensonensis* and overlying *Triticites cullomensis* zones of early-middle Virgilian age.

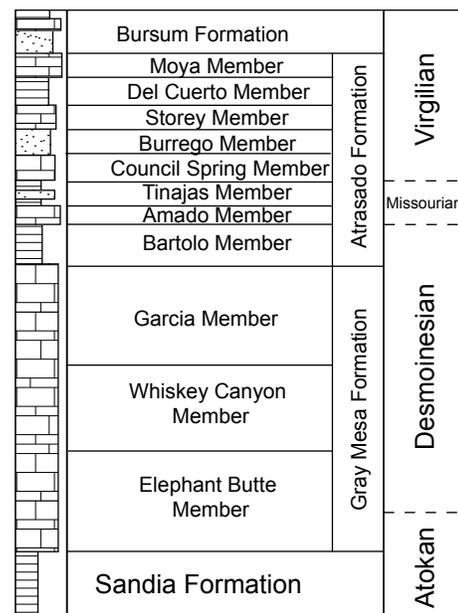


FIGURE 14—Summary of lithostratigraphy and age assignments of the Pennsylvanian section at Cedro Peak. Dashed lines indicate some uncertainty with regard to precise placement of chronostratigraphic boundaries (see text for discussion).

Bursum Formation fusulinids

Myers and McKay (1976) considered the stratigraphically highest bedrock at Cedro Peak to belong to the La Casa Member of the Wild Cow Formation. Yet, these rocks can be correlated to more complete sections nearby (Fig. 12) that indicate they are the mixed siliciclastic-carbonate strata of the Bursum Formation. In the southern Manzano Mountains, the Bursum Formation yields fusulinids of early Wolfcampian age, as it does to the south in Socorro and Sierra Counties (e.g., Myers 1988b; Lucas and Krainer 2004). However, at Cedro Peak and in other sections in the Manzanita Mountains, the Bursum Formation yields Virgilian fusulinids (this apparent north-south Bursum diachroneity was discussed by Lucas and Krainer 2004).

Myers (1988b, Myers and McKay 1976) recognized the Virgilian fusulinids in the Manzanita Mountains as the stratigraphically highest fusulinids in the section, occurring just below nonmarine siliciclastic red beds of the Abo Formation. We believe Myers used biostratigraphy, not lithostratigraphy, to assign the strata to his La Casa Member of the Wild Cow Formation, which is of Virgilian age, but does not lithologically resemble the strata in the Manzanita Mountains that yielded this stratigraphically highest fusulinid assemblage. Instead, we assign these Virgilian strata to the Bursum Formation because of their lithology and stratigraphic position (note, for example, the Los Pinos section, where they are directly overlain by the Abo Formation; Fig. 12), not because of their age. Myers evidently was not aware that the Bursum Formation is time transgressive from north to south in the Manzano uplift.

Myers and McKay (1976) reported the fusulinids *Triticites* aff. *T. rhodesi* Needham, *Dunbarinella* sp., and *Ozawainella* sp. from the stratigraphically highest limestone beds at Cedro Peak, which they termed La Casa, but we term Bursum (Fig. 9). Myers (1988b, pl. 7) illustrated *Triticites* cf. *T. beedei* Dunbar and Condra, *Dunbarinella* sp., and *Ozawainella?* sp. from these strata (USGS localities f10262 and 10263). He assigned these fusulinids to his *Triticites beedei* subzone of late Virgilian age.

Discussion: tectonics vs. eustasy

The Pennsylvanian section at Cedro Peak well reflects the basic Pennsylvanian stratigraphic succession present throughout the Manzano and Sandia uplifts—basal, clastic-dominated Sandia Formation, limestone-dominated Gray Mesa Formation and mixed clastic-carbonate Atrasado and Bursum formations. This succession extends from Abo Pass at the southern tip of the Manzano Mountains to Placitas at the northern tip of the Sandia Mountains (e.g., Kelley and Northrop, 1975; Myers, 1973, 1982; Lucas et al., 1999; Lucas and Krainer, 2010; Krainer et al., 2011). The only unusual aspect of the Cedro Peak section is the relatively thin section of the Sandia Formation at measured section Y (Fig. 5). This unit is as much as 124 m thick at the lectostratotype section of the Sandia Formation described by Krainer et al. (2011), which is only 13 km north of Cedro Peak. We believe lateral thickness changes of the Sandia Formation are primarily a reflection of the irregular paleotopography associated with the unconformity at its base.

The general continuity of the stratigraphic architecture of the Gray Mesa and Atrasado formations from the Oscura Mountains in Socorro County to Cedro Peak, a distance of approximately 150 km (Fig. 1), suggests that Middle-Late Pennsylvanian sedimentation was driven by the same underlying forces over much of central New Mexico. We posit these forces as a series of tectonic events overprinted occasionally by eustatic cycles. We do so, in part, because we cannot identify sufficient eustatic cycles per time interval at Cedro Peak to match what are perceived to be complete records of eustatic cycles in relatively tectonically passive settings, such as the midcontinent region of Kansas-Illinois (Heckel, 2003). Another factor influencing our decision is the fact that many of the depositional cycles we can recognize at Cedro Peak cannot be correlated regionally; for example, those in the Gray Mesa Formation at Cedro Peak are not readily correlated to those in the Sandia and Lucero uplifts (see discussion above).

A third and important factor in choosing tectonics vs. eustasy as the primary driver of Pennsylvanian sedimentation at Cedro Peak is the evident diachroneity of some of the major facies (sequence) boundaries in the Pennsylvanian section.

Thus, biostratigraphy indicates that the Desmoinesian-Missourian boundary in the northern Oscura Mountains of Socorro County is in the upper part of the Gray Mesa Formation (Thompson, 1942; Lucas and Krainer, 2009), whereas it is in the lower part of the Atrasado Formation (near the base of the Amado Member) in the Cerros de Amado of Socorro County (Lucas et al., 2009) and probably at approximately the same level at Cedro Peak. The Bursum Formation at Cedro Peak is older (late Virgilian) than it is in the southern Manzano Mountains and Cerros de Amado (where it is Wolfcampian) but straddles the Virgilian-Wolfcampian boundary in the northern Oscura Mountains. These diachroneities are readily understood to indicate that some of the major unconformities and facies changes in the Pennsylvanian section from Socorro through Bernalillo Counties are not explicable as having been driven by a relatively synchronous, eustatic mechanism. Instead, they are most readily explained as resulting from detectably diachronous local tectonic events, which were only occasionally overprinted by obvious eustatic cycles.

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Appendix—Map coordinates of measured stratigraphic sections.

All coordinates are UTM meters in zone 13 using NAD 83 datum.

Cedro Peak sections

- Cedro Peak A:** Base at 376567E, 3877651N and top at 376487E, 3877855N.
- Cedro Peak B:** Base at 376260E, 3878570N; top at 376372E, 3879018N.
- Cedro Peak C:** Base at 376452E, 3879901N; top at 376697E, 3879763N.
- Cedro Peak Y:** Measured at 374755E, 3879582N.
- Cedro Peak Z:** Base at 374891E, 3879410N; top at 375081E, 3879532N.
- Cedro Peak ZZ:** Base at 375772E, 3879735N; top at 376008E, 3879696N.

Bursum sections

- Los Pinos:** Base at 379236E, 3886735N; top at 378987E, 3886735N.
- Sandia Ranger Station:** Base at 373764E, 3882042N; top at 373665E, 3882191N.
- Tablazon:** Base at 377354E, 3884457N; top at 377165E, 3884787N.