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THE PERMIAN SYSTEM AT ABO PASS, CENTRAL NEW MEXICO (USA)

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ABSTRACT—The Permian stratigraphic section at Abo Pass at the southern tip of the Manzano Mountains (Torrance, Valencia and Socorro Counties, New Mexico) is ~800 m thick and is assigned to the (ascending order): Bursum Formation (Red Tanks Member), Abo Formation (Scholle and Cañon de Espinoso members), Yeso Group (Arroyo del Alamillo Formation and overlying Los Vallos Formation divided into Torres, Cañas and Joyita members), Glorieta Sandstone and San Andres Formation. The Bursum Formation is ~35-40 m thick and consists of interbedded red-bed siliciclastics (mudstone, sandstone and conglomerate) and marine limestones. The Abo Formation is ~310 m thick and consists of siliciclastic red beds divided into the Scholle Member (~140 m of mudstone with channelized beds of crossbedded sandstone and conglomerate) overlain by the Cañon de Espinoso Member (~170 m of mudstone, siltstone and many thin beds of sandstone that display climbing ripple lamination). The lower formation of the Yeso Group, the Arroyo de Alamillo Formation, consisting of ~80 m of red-bed sandstone (mostly ripple and laminar with some gypsiferous beds) and very minor dolomite. The overlying Torres Member of the Los Vallos Formation is ~180 m thick and consists of mostly gypsiferous siltstone, claystone, gypsum and a few prominent beds of dolomite and gypsiferous sandstone. The overlying Cañas Member is 16-52 m thick, consisting mostly of gypsum and includes a few beds of gypsiferous siltstone and dolomite. The Joyita Member is ~21 m thick and consists of red-bed sandstone that is crossbedded, ripple laminated and, in some beds, gypsiferous. The Glorieta Sandstone is ~78 m thick and consists of crossbedded, laminar and ripple laminar quartzose sandstone. In the Abo Pass area, the upper part of the San Andres Formation has been eroded, leaving up to 91 m of mostly limestone (lime mudstone). It is overlain by Triassic strata east of the Abo Pass area.

Bursum deposition took place in a mixture of nonmarine fluvial and shallow marine depositional environments in a tectonically active, mostly coastal setting. Rivers that deposited the Abo Formation formed extensive muddy floodplains traversed by incised rivers early in Abo deposition that later gave way to extensive sheetflooding. Yeso sedimentation began with dominantly eolian deposition on an arid coastal plain (Arroyo de Alamillo Formation) followed by deposits of coastal sabkhas, dunes and restricted marine embayments (Torres and Cañas members of Los Vallos Formation). Yeso sedimentation ended with the Joyita Member of the Los Vallos Formation, which formed by eolian and fluvial processes during lowered sea level. The Glorieta Sandstone is mostly of eolian origin, and the San Andres Formation represents shallow marine deposits.

Fusulinids from the Bursum Formation at Abo Pass indicate it is early Wolfcampian in age. The Abo Formation at Abo Pass yields fossil plants, tetrapod tracks and other trace fossils, as well as vertebrate fossils of Coyotean age. Microfossils from the Yeso Group, Glorieta Sandstone and San Andres Formation encompass two new species named here, *Velebitella americana* and *Calcitornella interpsammica*. Local paleontological data coupled with regional correlations indicate that the Abo Formation is middle Wolfcampian to early Leonardian and the Glorieta and San Andres formations are late Leonardian in age.

INTRODUCTION

Abo Pass is the topographically low area between the southern end of the Manzano Mountains and the northern end of the Los Pinos Mountains that encompasses parts of Valencia, Torrance and Socorro Counties, New Mexico (Fig. 1). For our purposes, it extends from Mountainair southwest to the northern end of the Los Pinos Mountains, and from the southern tip of the Manzano Mountains eastward to Chupadera Mesa. The Permian section at Abo Pass is important to New Mexico geology for several reasons, including work by Lee (1909), who named the Abo Formation for some of the oldest Permian strata exposed there. The Abo Formation is a distinctive stratigraphic unit long recognized across much of New Mexico (Lucas et al., 2013c).

Here, we present a comprehensive review of the Permian strata exposed at Abo Pass (Figs. 2-3) aimed at elucidating their lithostratigraphy, petrography, depositional environments, paleontology, age and correlation. This review is based in part on work previously published on the Abo Pass Permian section (e.g., Berman, 1976, 1979, 1993; Lucas et al., 2005, 2009, 2013c; Krainer et al., 2009; Oviatt, 2010, 2011) and new data not previously published.

DATA

At Abo Pass, Permian strata form a homoclinal section that generally dips eastward from the southern tip of the Manzano Mountains to Chupadera Mesa (Figs. 1, 3). Our stratigraphic and petrographic data are derived primarily from seven measured stratigraphic sections (Fig. 1) and thin sections prepared from selected rock samples (Figs. 4-15):

1. Priest Canyon, where we measured an almost complete section of the Bursum Formation (Fig. 4).

2. Highway 60 roadcut, an essentially complete Bursum Formation section earlier described by Krainer et al. (2009) (Fig. 4).

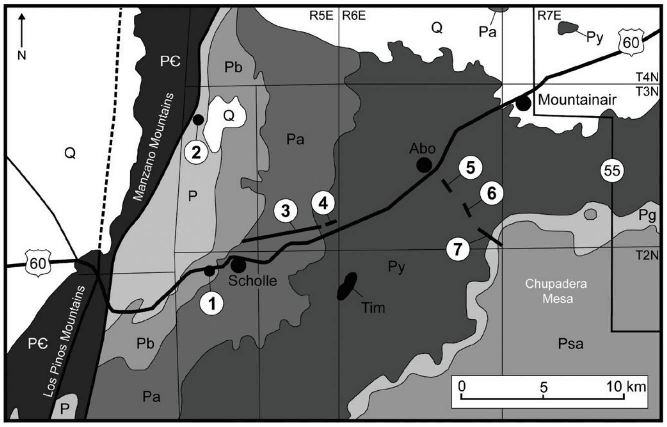


FIGURE 1. Generalized geologic map of the Abo Pass area showing locations of measured stratigraphic sections discussed in the text. Geology modified from NMBGMR (2003). Map units are: PC = Precambrian, P = Pennsylvanian, Pb = Bursum Formation, Pa = Abo Formation, Py = Yeso Group, Pg = Glorieta Sandstone, Psa = San Andres Formation and Q = Quaternary. Measured stratigraphic sections are: 1= Highway 60 Bursum; 2 = Priest Canyon Bursum; 3 = Abo type section; 4 = Abo Ruins, 5 = Abo Cemetary; 6 = Red Canyon trail; 7 = Deer Canyon Preserve.

3. The type section of the Abo Formation, originally described by Needham and Bates (1943) and later by Hatchell et al. (1982) and Lucas et al. (2005) (Fig. 7).

4. Abo Ruins, a complete section of the Arroyo de Alamillo Formation of the Yeso Group (Fig. 10).

5. Abo Cemetery, a section of most of the lower part of the Los Vallos Formation of the Yeso Group (Fig. 13).

6. Red Canyon Trail, a section of much of the upper part of the Los Vallos Formation (Fig. 13).

7. Deer Canyon Preserve, a section of the uppermost Los Vallos Formation, the entire Glorieta Sandstone and the lower part of the San Andres Formation (Fig. 14). Lucas et al. (2013a) previously described the Glorieta Sandstone at this section.

Taken together, these sections mostly overlap and present essentially complete coverage of the Permian section exposed at Abo Pass. From the measured sections, we selected rock samples for thin section preparation to analyze their petrography and/or microfossil content (Figs. 5, 8-9, 11-12, 15, 18-19**).** Collection of macrofossils (principally tetrapod footprints and bones; Figs. 21-22) has been undertaken sporadically since the 1970s.

PREVIOUS STUDIES

Herrick (1900) first recognized the presence of Permian strata at Abo Pass. He coined the name Manzano series for these strata, which he divided into a lower or red-bed division (essentially the Abo Formation of Lee, 1909), middle or chocolate-colored series, and upper or vermillion marls and clays (Lee, 1909, combined these middle and upper parts into his Yeso Formation) (Fig. 2). Herrick (1900) considered the lower part of his Manzano series to be Permian based on brachiopod and bivalve fossils, the middle part Triassic and the upper part Jurassic, but lacked any fossil evidence to support these latter two age assignments.

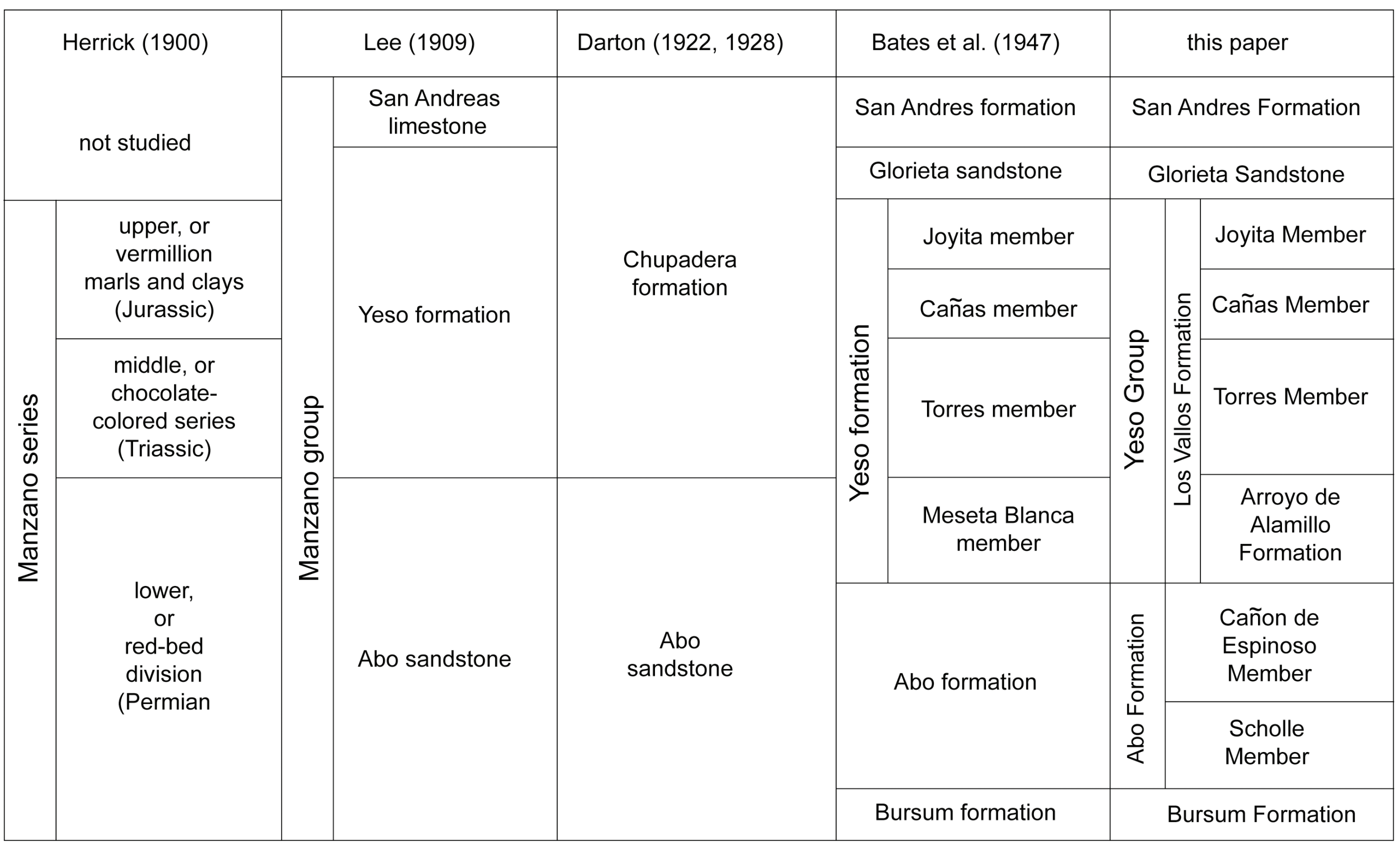


FIGURE 2. Evolution of Permian lithostratigraphic nomenclature in the Abo Pass area.

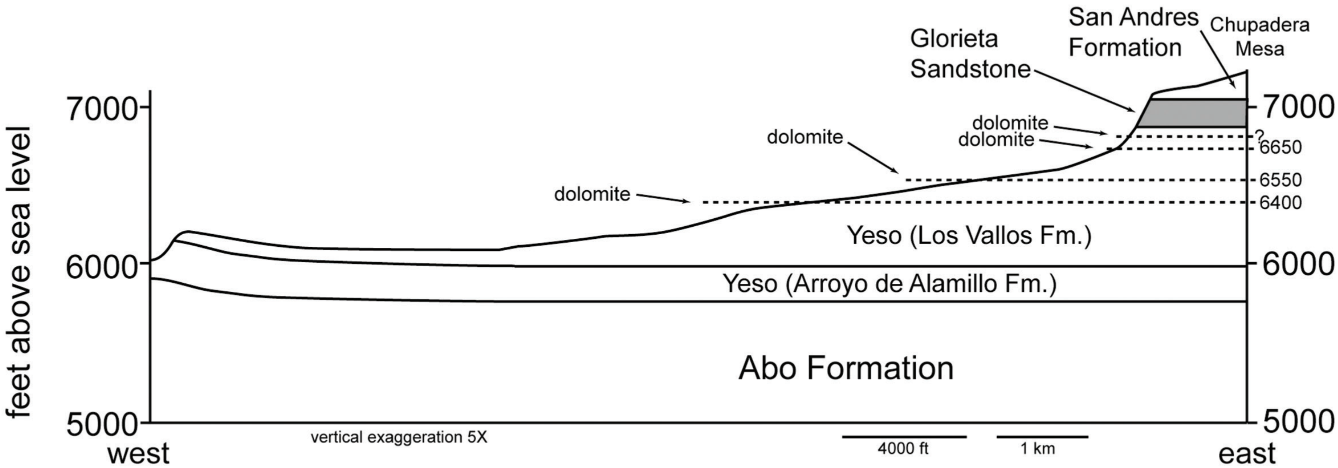


FIGURE 3. West-east cross section across the Abo quadrangle showing Permian strata (modified from Oviatt, 2010). Cross section line is about at the T3N/T2N boundary in Figure 1.

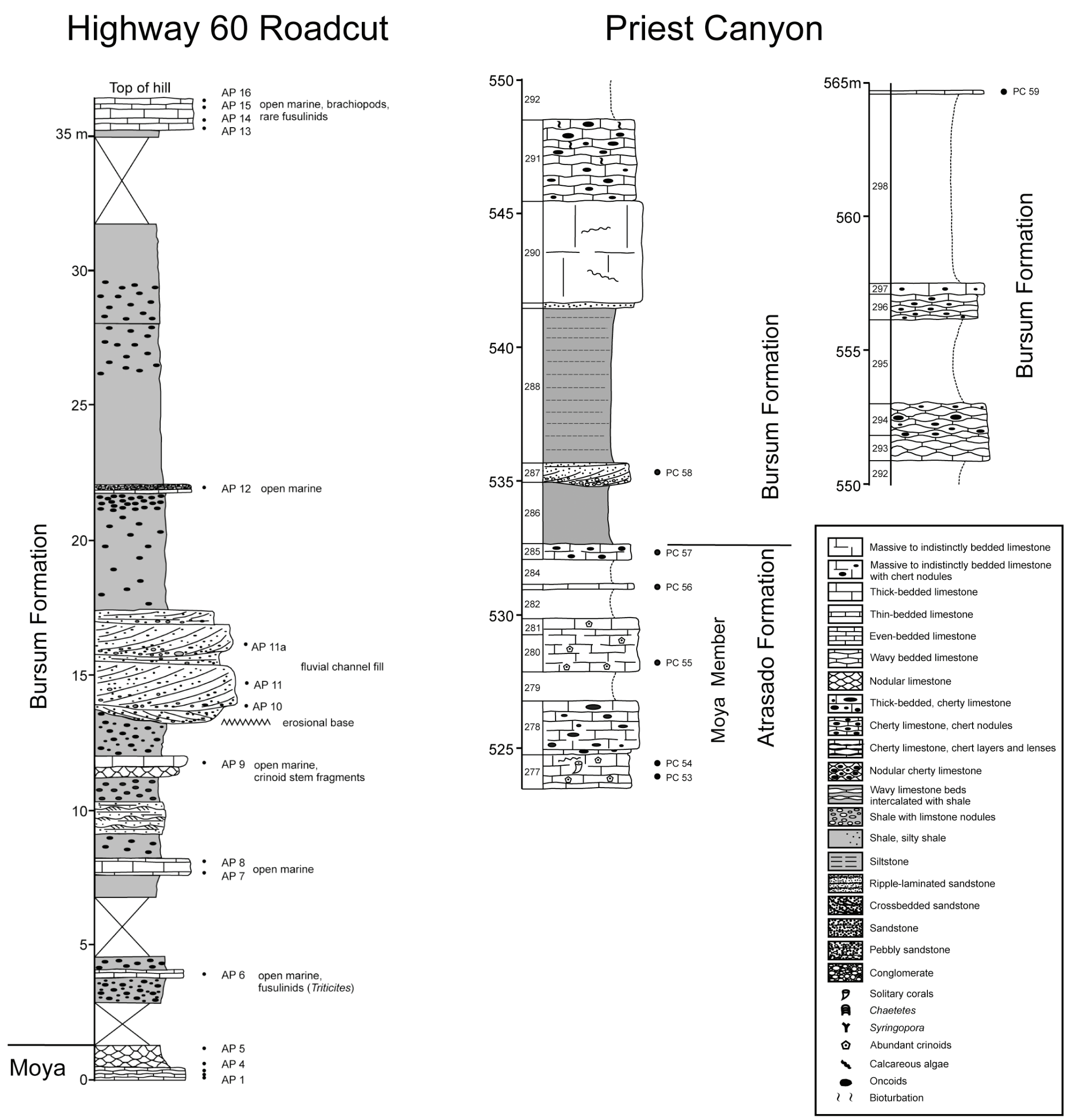


FIGURE 4. Measured stratigraphic sections of the Bursum Formation in the Abo Pass area. Thin section sample numbers (AP6, etc.) to right of section.

Lee (1909) applied the name Manzano Group to three formations he named, the Abo sandstone, the overlying Yeso formation and the San Andreas (sic) limestone (soon corrected to San Andres limestone by Darton, 1922, 1928). The name Abo sandstone was coined for Abo Canyon, where Lee (1909) assigned to it 650 ft (198 m) of "sandstone-dominated" strata with a basal conglomerate eroded into limestone that he assigned to the Magdalena Group. Lee (1909, p. 20) noted "several thin layers of earthy limestone 30 to 50 feet above the base" of the Abo sandstone. He listed a marine invertebrate fossil assemblage from these limestone beds, mostly brachiopods, bivalves and gastropods, and assigned them a Late Carboniferous age (see Girty, 1909). Clearly, these are strata of the Bursum Formation (no marine limestones are present in the Abo Formation) (also see Needham and Bates, 1943).

Lee's (1909) Abo, Yeso and San Andres formations and Keyes' (1915a, b) Glorieta Sandstone (between the Yeso and San Andres) have long been accepted as the standard Permian section in central New Mexico. An exception was Darton (1922, 1928), who combined the Yeso, Glorieta and San Andres formations into his Chupadera Formation, a term abandoned in the 1940s (Lucas, 2009).

Darton (1922, pl. 38; 1928, pl. 17) thus mapped the Permian strata at Abo Pass as Abo and Chupadera formations (Fig. 2). Bates et al. (1947) presented the most extensive study of the Lower Permian strata at Abo Pass prior to our work. In their regional mapping of the Gran Quivira Quadrangle (which encompasses the Abo Pass area of our study), they mapped and described the Permian strata, assigning them to the Bursum, Abo, Yeso, Glorieta and San Andres formations (Fig. 2). Following Wood and Northrop (1946), Wilpolt et al. (1946) and Wilpolt and Wanek (1951), Bates et al. (1947) divided the Yeso Formation into the (ascending) Meseta Blanca, Torres, Cañas and Joyita members (Fig. 2).

Myers (1977) mapped the Scholle 7.5-minute quadrangle, which includes the type section of the Abo Formation. He assigned the Permian strata to the Bursum, Abo and Yeso formations, dividing the Yeso into the Meseta Blanca and overlying Torres members. Hatchell et al. (1982) provided a detailed redescription of the Abo type section. They also reported fossil plants and tetrapod footprints from this section. Scott et al. (2005) remapped the Scholle quadrangle, but simply repeated the mapping of the Permian units as done by Myers (1977).

Lucas et al. (2005) modified the Lower Permian stratigraphic nomenclature in central New Mexico. Thus, they divided the Abo Formation into two members, Scholle and overlying Cañon de Espinoso members (Fig. 2). Both members have type sections that are part of the Abo Formation type section. Lucas et al. (2005) also raised the Yeso Formation to group rank and abandoned the name Meseta Blanca for its lower interval in central New Mexico (also see Baars, 1962). Instead, they named this interval the Arroyo de Alamillo Formation. They applied the name Los Vallos Formation to the remainder of the Yeso Group, dividing it into the Torres, Cañas and Joyita members. We employ this lithostratigraphic nomenclature of the Abo and Yeso strata here (Fig. 2).

Oviatt (2010, 2011) mapped the Abo and Punta de Agua quadrangle maps in the Abo Pass area. He used the Permian lithostratigraphy of Lucas et al. (2005). Lucas et al. (2013a) described the section of the Glorieta Sandstone along the flank of Chupadera Mesa at Deer Canyon Preserve.

The history of paleontological studies of the Permian strata at Abo Pass parallels the stratigraphic studies just listed. Thus, Lee (1909), Bates et al. (1947) and Myers (1988) reported marine macrofossils and/or fusulinids from strata of the Bursum Formation (also see Krainer et al., 2009). Hatchell et al. (1982) is the only published record of fossil plants from the Abo Formation at Abo Pass. Hatchell et al. (1982) also first illustrated tetrapod footprints, and Lucas et al. (2001, 2009) described an extensive footprint assemblage from a single locality in the Abo Formation. Berman (1976, 1979, 1993) described tetrapod body fossils, which were recently reviewed by Berman et al. (2015).

STRATIGRAPHY AND PETROGRAPHY

Bursum Formation

At Abo Pass, an excellent section of the Red Tanks Member of the Bursum Formation is exposed along and adjacent to a roadcut of US Highway 60 near the boundary between Sections 11 and 14, T2N, R4E (Fig. 4). Although Bursum Formation is shown on bedrock maps of the Abo Pass area (e.g., Myers, 1977; Fig. 1), the section along the highway is probably the best exposed Bursum section at the southern tip of the Manzanos. A good section of much of the Bursum Formation is also present at Priest Canyon (Fig. 4), but its uppermost strata and upper contact with the Abo Formation are not exposed. Bates et al. (1947) reported a range in thickness of the Bursum Formation in the Abo Pass area of 39-67 m, with the unit generally thickening southward. Given that the Bursum Formation is unconformity-bounded, its thickness varies markedly over short distances (Krainer and Lucas, 2009).

The exposed Bursum Formation along Highway 60 (Fig. 4) is 35 m thick, where it rests on the Moya Member of the Atrasado Formation (= La Casa Member of Wild Cow Formation of Myers, 1973). The uppermost bed of the Bursum here is a stripped limestone surface that is very close to the base of the overlying Abo Formation. The underlying, uppermost Moya Member consists of thinly bedded, nodular gray limestone.

Along Highway 60, the Bursum Formation (Fig. 4) can be divided into three lithologic units: (1) lower part composed of shale with thin intercalated limestone beds and a siltstone to fine-grained sandstone horizon; (2) conglomerate and sandstone horizon; and (3) upper part composed mainly of shale with a thin limestone bed intercalated, and a bedded limestone interval on top. The lower part is approximately 10 m thick and composed mainly of reddish, greenish-gray and purple shale with limestone nodules up to a few cm in diameter. Three limestone horizons are 0.3-0.75 m thick, and a 1.2-m-thick siltstone/fine-grained sandstone horizon is intercalated in the shale. The siltstone to fine-grained sandstone horizon is red, micaceous and contains small-scale current ripples and small carbonate nodules. The lowermost 0.3-m-thick limestone horizon is composed of bioclastic grainstone to packstone with a diverse microfossil assemblage (Fig. 5C). Laterally, this microfacies grades into a bioclastic wackestone (Fig. 5A) containing abundant fusulinids (see below).

The middle limestone horizon is 0.6 m thick. The lower part is composed of bioclastic wackestone, which locally grades upward into a grainstone (Fig. 5B, D). The upper 0.75-m-thick limestone interval is nodular in its lower part. The upper, massive part consists of wackestone (Fig. 5E) composed of bioturbated, inhomogeneous micrite containing relatively few bioclasts. The 4.2-m-thick conglomerate-sandstone horizon is erosively cut into the underlying mudstone and displays multistorey trough-crossbedding (Fig. 4). Near the base, reworked red mudstone clasts occur. The flow direction was towards the northeast. The horizon lenses out laterally over about 100 m. In the upper part, fossil plant stems are present.

Conglomerate and coarse-grained sandstone are poorly sorted and grain supported. The dominant grain type is mono- and polycrystalline quartz. Granitic rock fragments are composed of quartz and feldspar, and sedimentary rock fragments are minor constituents. Detrital feldspars are mostly altered or replaced by calcite. A few small detrital muscovite grains and rare large garnets are present. The grains are cemented by coarse calcite cement, which randomly replaces quartz. The sandstones to fine-grained conglomerates are classified as arkosic and lithic arenites (see details in Krainer et al., 2009).

The upper part of the Bursum Formation in the Highway 60 roadcut at Abo Pass is mainly composed of red mudstone and silty mudstone, which locally contain carbonate nodules (Fig. 4). The intercalated thin limestone bed is underlain by gray to greenish shale containing carbonate nodules, and overlain by nodular (pedogenic?) limestone. The limestone bed is 0.3 m thick and composed of bioturbated bioclastic wackestone (Fig. 5G). The topmost 1.25-m-thick limestone horizon is bedded and fossiliferous, containing brachiopods, bryozoans and rare fusulinids. The microfacies is bioclastic wackestone containing a diverse invertebrate fossil assemblage (Fig. 5H; see details in Krainer et al., 2009).

Due to the dominance of fine-grained siliciclastics, we assign the Bursum section at the Highway 60 roadcut to the Red Tanks Member, which represents a transitional facies from the underlying, predominantly calcareous, shallow marine Atrasado Formation to the overlying red beds of the Abo Formation (Lucas and Krainer, 2004; Krainer and Lucas, 2009, 2013). Bursum strata at Priest Canyon are also assigned to the Red Tanks Member (Fig. 4).

At Priest Canyon, the Bursum Formation is at least 35 m thick (Fig. 4). The unit is mostly covered/mudstone (64% of the section) and limestone (32%) with a bed of sandstone near its base. The lowermost 9 m consist of red siltstone with an intercalated red sandstone bed. This sandstone bed is 0.7 m thick and has a conglomeratic base. The top of this siliciclastic interval is represented by a thin, fine-grained sandstone bed (0.2 m), which is overlain by 3.8 m of indistinctly bedded to massive algal limestone, followed by 3 m of wavy bedded cherty limestone, which is bioturbated in the upper part. Above a covered (shale) interval, another limestone interval is exposed, which is 2.1 m thick, wavy bedded to nodular, bioturbated and contains chert nodules in the upper part. The next covered interval (3.2 m) is followed by wavy bedded, bioturbated cherty limestone that contains crinoidal debris and is overlain by an algal limestone bed (0.4 m) with chert nodules near the top. The topmost exposure is a thin (0.1 m) limestone bed that contains fusulinids and overlies a 7.1-m-thick covered interval (shale).

The crossbedded sandstone is moderately sorted and composed of subangular grains. Monocrystalline quartz is the dominant grain type. Polycrystalline quartz is rare. Some detrital feldspars are present (mostly potassium feldspars, rare plagioclase), which are slightly altered and partly replaced by calcite. Granitic and fine-grained schistose metamorphic rock fragments are rare. The sandstone contains a few opaque grains. The detrital grains are cemented by coarse, poikilotopic calcite. Locally, dark brownish cement (Fe-hydroxides) is present.

Limestone is mostly composed of bioclastic wackestone to floatstone with a diverse fossil assemblage, locally containing abundant fusulinids (fusulinid wackestone) or phylloid algal fragments (phylloid algal wackestone to floatstone).

Abo Formation

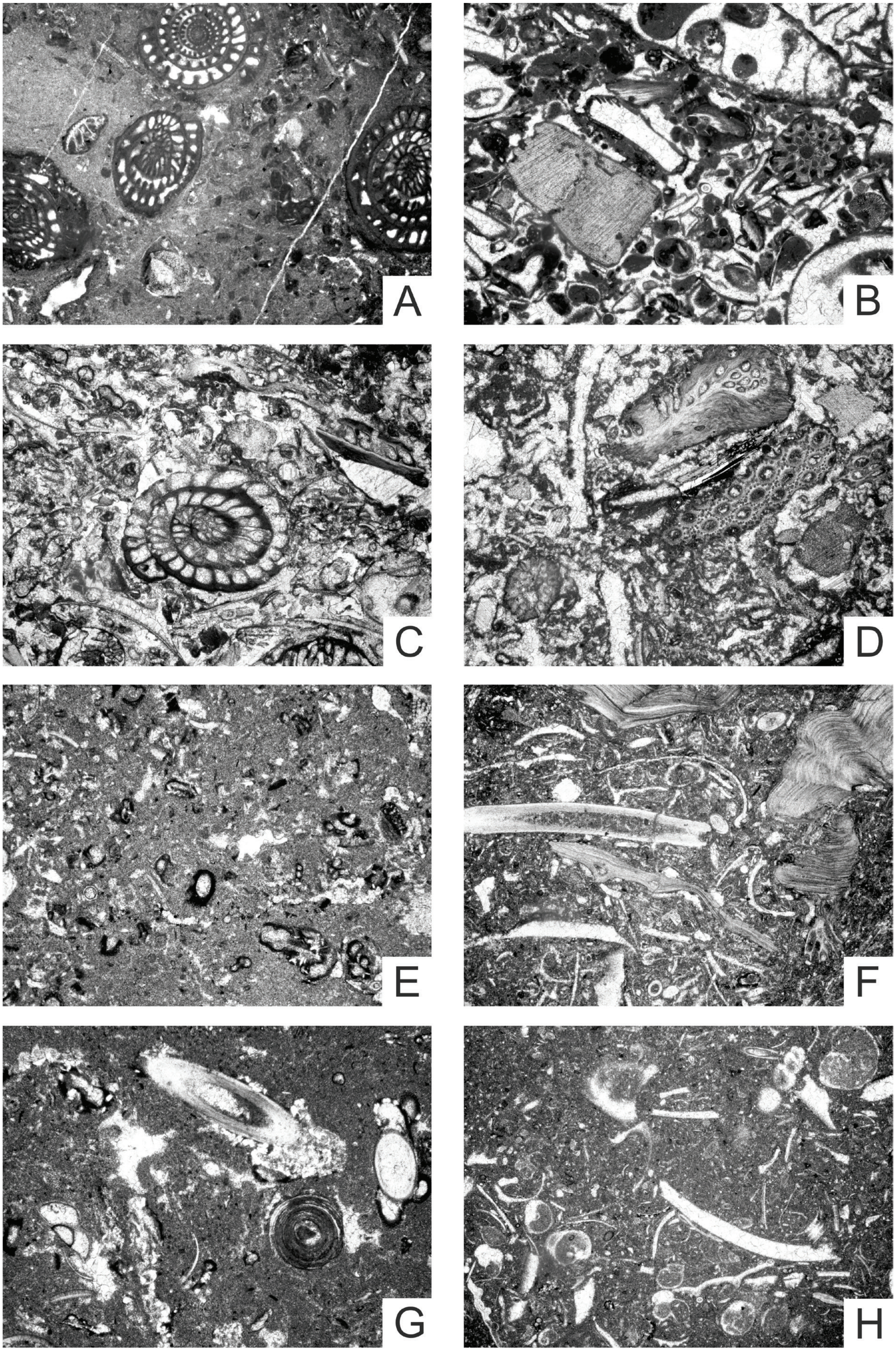
Lithostratigraphy

The Lower Permian red beds above the Bursum Formation across central New Mexico are the Abo Formation (Lucas et al., 2013c). Needham and Bates' (1943) Abo type section at Abo Pass is between Priest Canyon and the Abo Mission Ruins and was remeasured and redescribed by Hatchell et al. (1982) and by Lucas et al. (2005) (Figs. 6A-B, 7-9). Because of the low topography, the section traverse is relatively long and extends from Section 33 through Sections 34, 35 and 36, T3N, R5E (Fig. 1). The total Abo Formation thickness is approximately 300 m.

Lee (1909) claimed the Abo Formation at its type section is mostly sandstone, hence his name "Abo sandstone." Note, though, that this was in part based on including what are now lower, sandstone-dominated strata of the Yeso Group (Arroyo de Alamillo Formation) in the Abo. Nevertheless, Needham and Bates (1943) and Bates et al. (1947) corrected Lee (1909), noting that the formation is mostly mudrock in its type area (about 70%). Our data support that conclusion.

Several workers noted that the Abo Formation in central New Mexico can be divided into lower and upper intervals (e.g., Myers, 1977; Hatchell et al., 1982; Colpitts, 1986, 1989; Lucas et al., 1999; Seager and Mack, 2003; Lucas and Zeigler, 2004). The lower interval is mudstone dominated, and its sandstones are coarse grained and conglomeratic and are trough crossbedded, channelform (incised) deposits (Fig. 6A). In contrast, the upper interval, though it may also be mudstone dominated, has a significant component of siltstone, and its sandstones are sheet-like bodies with prominent ripple and climbing-ripple bedforms (Fig. 6B).

This distinction is well demonstrated at the Abo type section (Figs. 6A-B, 7), where the lower part of the formation (~140 m thick) forms thick mudstone slopes (87% of the mea-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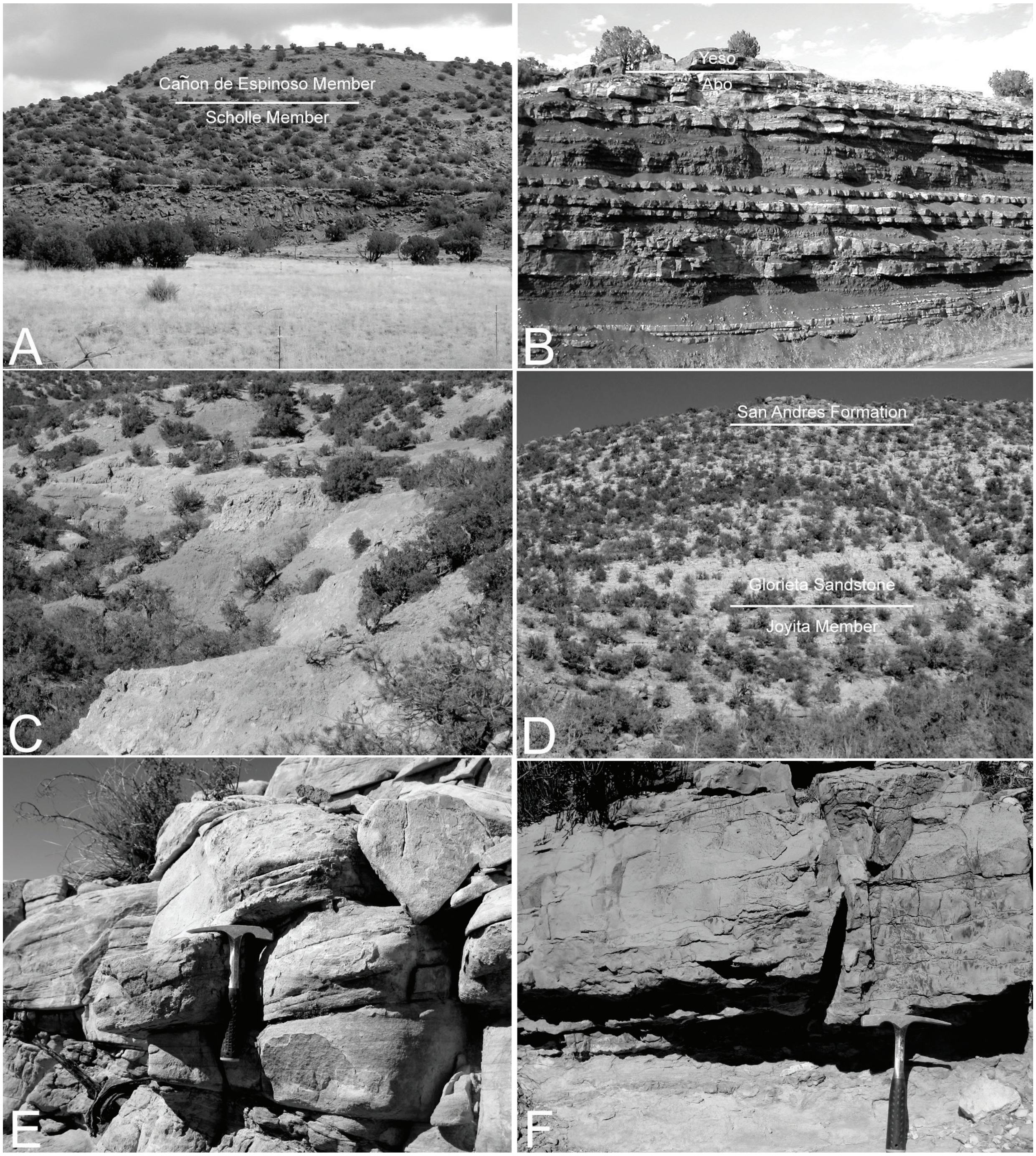


FIGURE 6. Selected outcrops of Permian strata in the Abo Pass area. **A-B**) Photographs of portions of the type section of the Abo Formation. **A**) Overview of lower part of section, which is type section of the Scholle Member. **B**) Overview of part of upper part of section, which is part of type section of Cañon de Espinoso Member. **C**) Outcrops of the Torres Member of the Los Vallos Formation in the Red Canyon Trail section. Darker slopes are siltstone broken by light-colored, ledge-forming gypsum and dolomite beds. **D**) Overview of upper part of Deer Canyon Preserve section. **E**) Cross-bedded sandstone of Glorieta Sandstone at Deer Canyon Preserve section. **F**) Limestone of San Andres Formation at Deer Canyon Preserve section.

FIGURE 5. Thin section photographs of limestones from the Bursum Formation at the Highway 60 roadcut (Fig. 4). Width of photographs is 6.3 mm. **A**) Bioclastic wackestone containing many fusulinids, subordinate echinoderms, bryozoans and peloids embedded in micrite. Sample AP 6**. B**) Bioclastic packstone containing abundant mollusk shell fragments, a few echinoderms, bryozoans, ostracodes and smaller foraminifers. Many bioclasts display micritic envelopes. Sample AP 7**. C**) Bioclastic grainstone/packstone composed of recrystallized mollusk shell fragments, subordinate echinoderms, bryozoans, fusulinids, ostracodes and smaller foraminifers. Sample AP 6. **D**) Poorly sorted bioclastic grainstone/wackestone with abundant shell fragments, bryozoans and echinoderms. Some bioclasts display micritic envelopes. Sample AP 8. **E**) Bioclastic wackestone composed of micritic matrix and small fossils, mostly calcivertellid foraminifers and ostracodes. Sample AP 9. **F**) Bioclastic wackestone, poorly sorted, containing abundant recrystallized mollusk shell fragments and subordinate ostracodes, bryozoans, brachiopod spines, echinoderms and smaller foraminifers. Sample AP 16. **G**) Bioclastic wackestone, bioturbated, composed of micritic matrix and some ostracodes, brachiopod spines, smaller foraminifers and shell fragments. Sample AP 12. **H**) Bioclastic wackestone composed of micritic matrix containing a few larger and many small bioclasts, mostly recrystallized mollusk shell fragments, and subordinate echinoderms, brachiopod spines and smaller foraminifers. Sample AP 13.

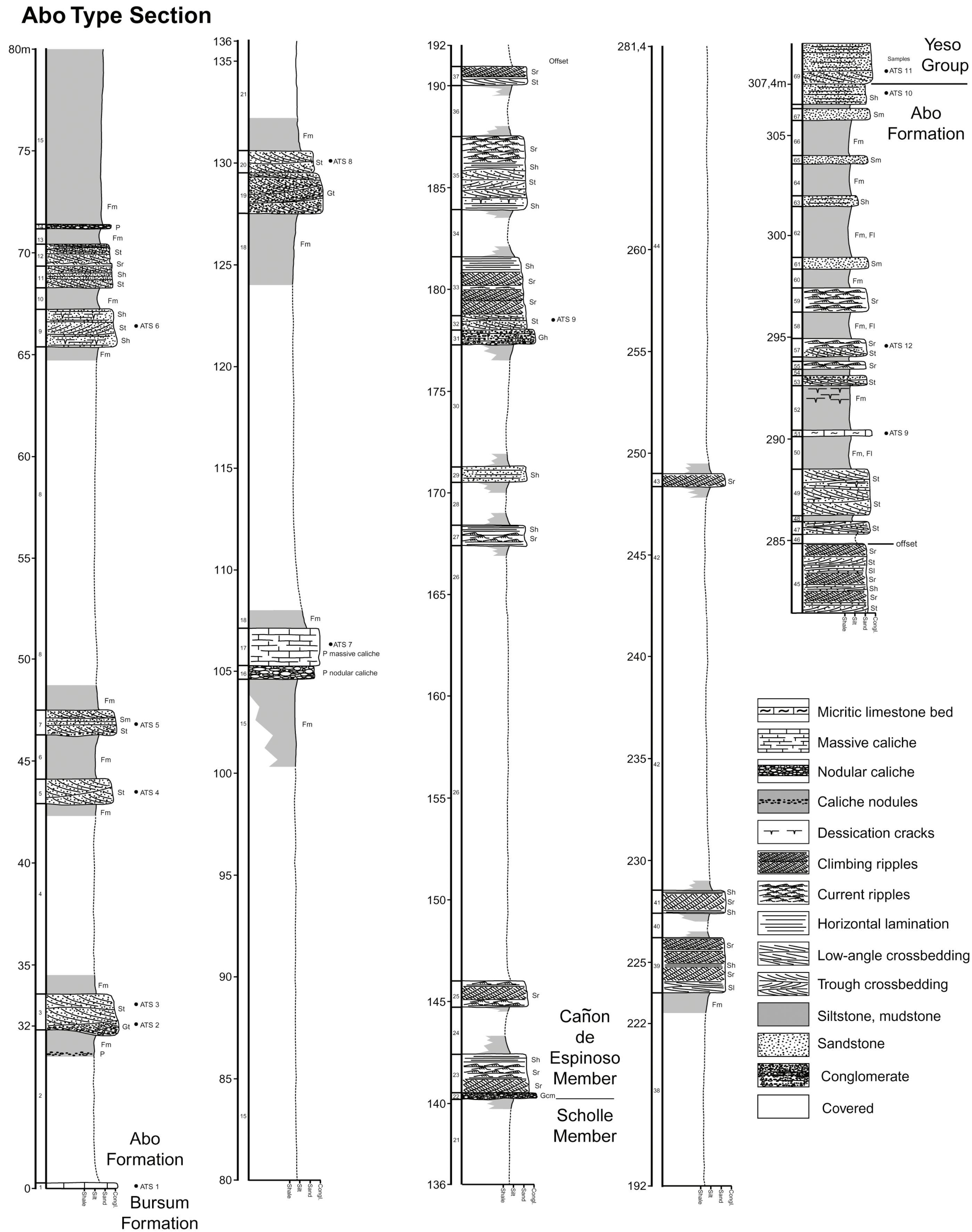


FIGURE 7. Type section of the Abo Formation (modified from Lucas et al., 2005). Thin section sample numbers (ATS7, etc.) to right of section.

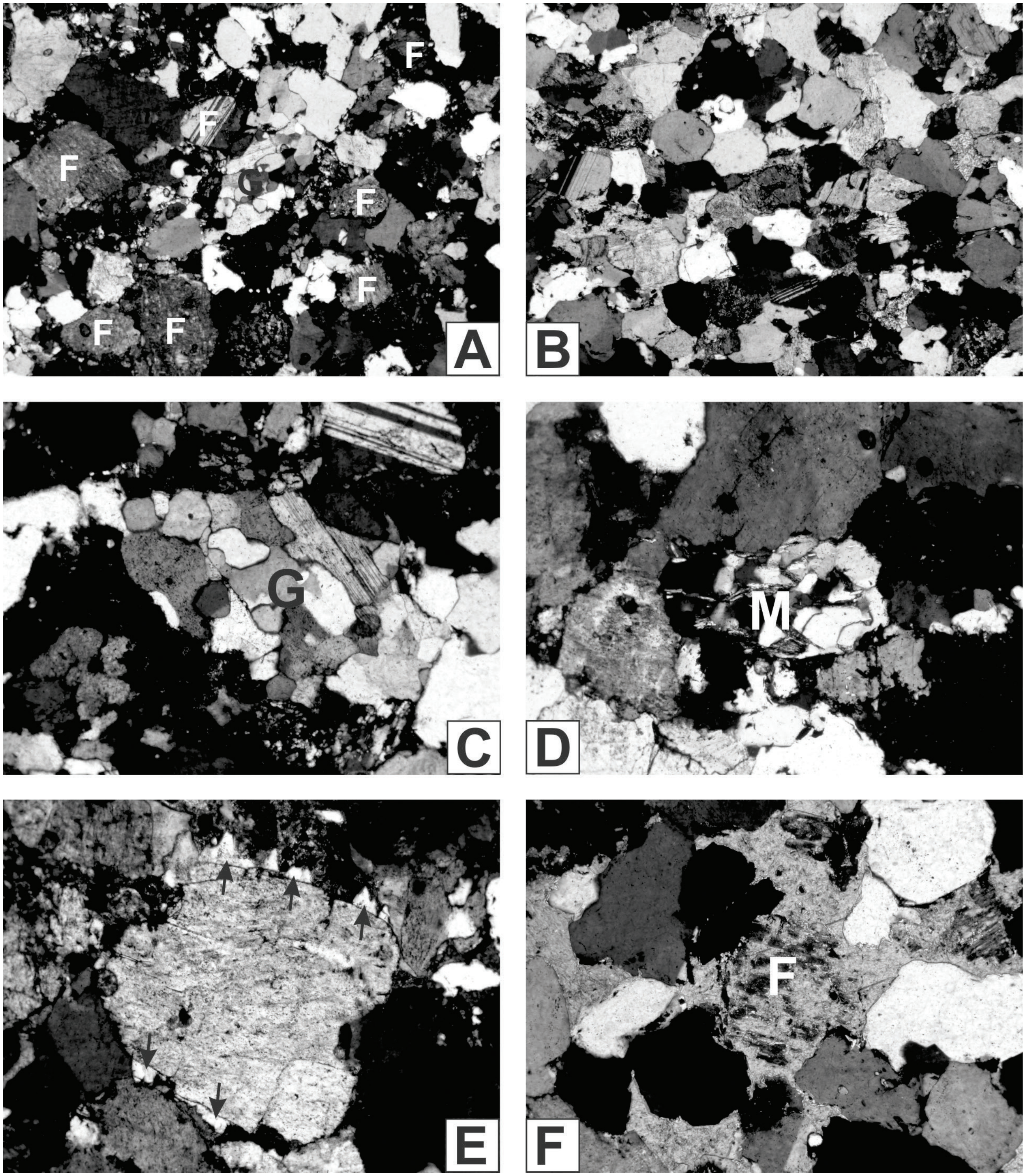


FIGURE 8. Thin section photographs of sandstone from the Abo Formation (Scholle Member) at the type section. All photographs under polarized light. Width of photos A and B is 3.2 mm, of photos C-F is 1.2 mm. **A**) Arkosic sandstone, moderately sorted, composed of mono- and polycrystalline quartz and detrital feldspars (F). The detrital grains are cemented by authigenic quartz overgrowths. Sample ATS 2. **B**) Arkosic sandstone, well sorted, containing mono- and polycrystalline quartz, detrital feldspars and rare detrital muscovite. The sandstone is cemented by quartz overgrowths and coarse blocky calcite. Some of the detrital feldspar grains also display authigenic overgrowths. Sample ATS 3. **C**) Arkosic sandstone with a granitic rock fragment composed of quartz and feldspar (G) in the center. Sample ATS 2. **D**) Arkosic sandstone with a metamorphic rock fragment composed of schistose mica and quartz (M) in the center. Sample ATS 2. **E**) Large detrital potassium feldspar grain that is slightly altered and displays authigenic overgrowths (arrows). Sample ATS 2. **F**) Arkosic sandstone cemented by coarse blocky calcite that partly replaces detrital feldspar grains (F, center). Sample ATS 3.

sured section) broken by thin ledges of trough-crossbedded sandstone and conglomerate (11% of the section) and minor calcrete ledges (2% of the section). In contrast, the upper (~170 m thick) of the section is mostly slope forming, largely covered intervals of mudstone (70% of the section) but includes significant siltstone beds (9% of the section) and many thin ledges of climbing-ripple laminated sandstone (21% of the section).

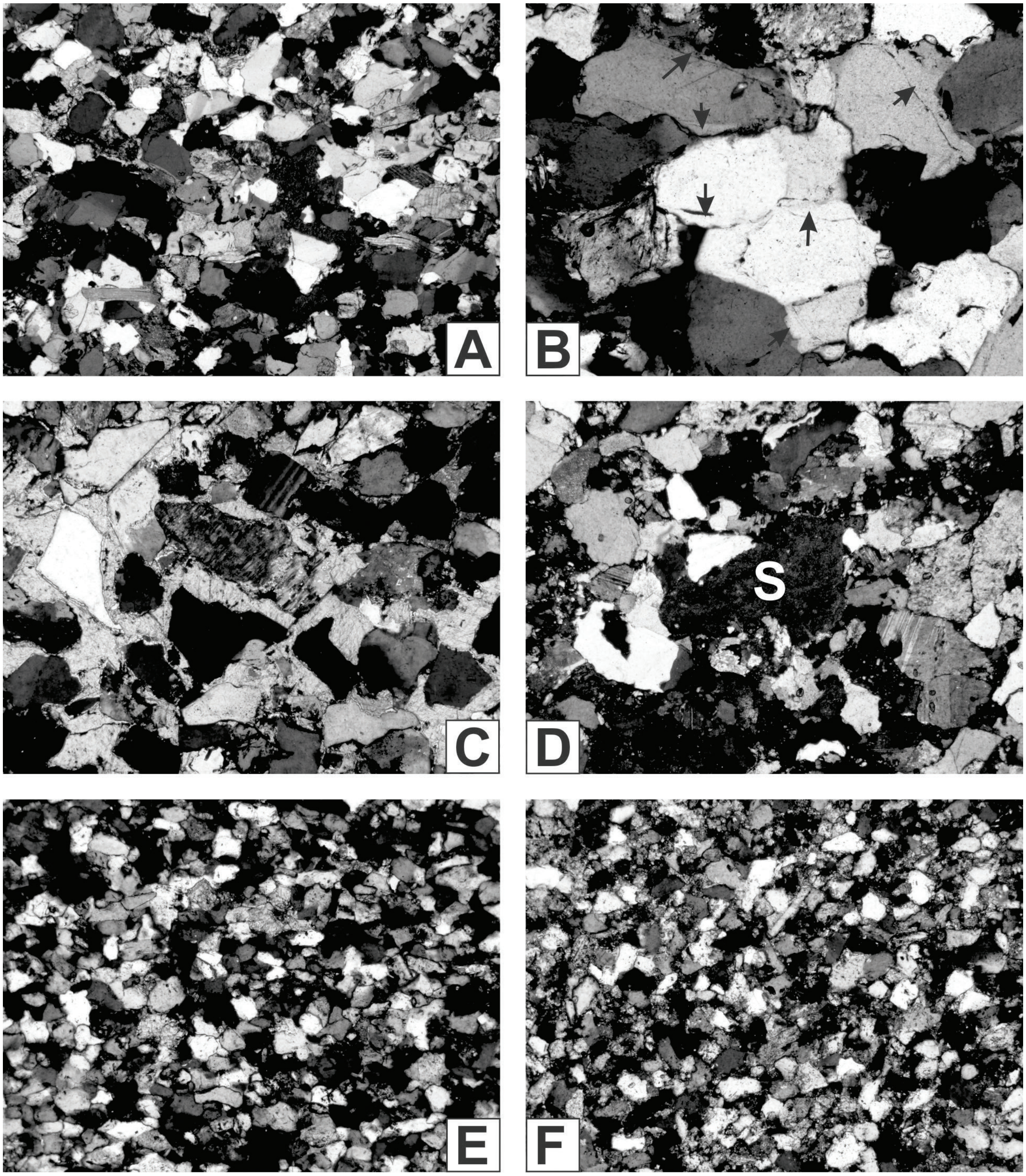


FIGURE 9. Thin section photographs of sandstone from the Abo Formation (Scholle Member, **A-D**; Cañon de Espinoso Member, **E**) and basal Yeso Group (Arroyo de Alamillo Formation, **F**). All under polarized light. Width of photos A and D is 3.2 mm, of photos B, C, E and F is 1.2 mm. **A**) Arkosic sandstone composed of mono- and polycrystalline quartz, abundant detrital feldspars (mostly untwinned potassium feldspars) and a few muscovite grains. Detrital grains are cemented by authigenic quartz overgrowths, rare feldspar overgrowths and by calcite cement. Sample ATS 4. **B**) Arkosic sandstone showing detrital quartz grains with well-developed authigenic overgrowths (arrows). Sample ATS 4. **C**) Fine-grained, well-sorted arkosic sandstone cemented by coarse blocky calcite. Sample ATS 6. **D**) Arkosic sandstone containing a large sedimentary rock fragment (micritic carbonate grain: S) probably derived from reworking of caliche carbonates. Sample ATS 8. **E**) Fine-grained, well-sorted sandstone containing abundant monocrystalline quartz grains and many detrital feldspar grains, cemented by quartz overgrowths and calcite. Sample ATS 9. **F**) Fine-grained, well-sorted sandstone composed mostly of monocrystalline quartz grains and subordinately of detrital feldspar grains, cemented by calcite. Sample ATS 11.

Therefore, Lucas et al. (2005) named two formal members of the Abo Formation to recognize these subdivisions. The lower member is the Scholle Member, and the upper member is the Cañon de Espinoso Member. The two members of the Abo Formation can be recognized at Rhodes Canyon in the northern San Andres Mountains of Sierra County, in the Caballo Mountains of Sierra County, at Red Gap in the Fra Cristobal Mountains of Sierra County, near Bingham in Socorro County, in the Cerros de Amado and the Cerrillos del Coyote in Socorro County, at Placitas in Sandoval County, at Carrizo Arroyo in Valencia County, at Jemez Springs in Sandoval County and at Gallinas Peak in the Zuni Mountains of Cibola County (Kottlowski et al., 1956; Colpitts, 1986, 1989; Lucas et al., 1999, 2012a, b, 2013c; Seager and Mack, 2003; Lucas and Zeigler, 2004).

The change in sandstone architecture evident between the two members of the Abo Formation reflects the difference between incised channel deposits (lower unit) and unchannelized sheetflood deposits (upper unit). Changes in subsidence rate (higher subsidence rate for lower unit, slower subsidence for the upper unit) and/or changes in climate (wetter lower unit, drier upper unit) are obvious underlying causes, and merit further investigation.

Petrography

Sandstone of the Scholle Member is mostly medium to coarse grained and moderately sorted. Most of the detrital grains are angular to subangular. The most common grain types are monocrystalline quartz and different types of polycrystalline quartz, including stretched metamorphic (Figs. 8A-B, 9A, 9C). Chert grains are very rare. Granitic rock fragments, composed of large, intergrown quartz and feldspar, are a common constituent (Fig. 8C). Very rarely present are rock fragments displaying a granophyric texture (but common in the Abo Formation of the northern Sacramento Mountains; Lucas et al., 2014).

Another rare grain type consists of metamorphic rock fragments composed of fine-grained mica and quartz displaying well-developed schistosity (Fig. 8D) and phyllitic rock fragments. Sedimentary rock fragments are locally present, such as reworked red siltstone clasts and less common micritic carbonate rock fragments, which are probably reworked caliche carbonates (Fig. 9D).

Detrital feldspars are a common constituent of all Abo sandstones (Fig. 8A-B). Most feldspar grains are slightly altered (Fig. 8E). Untwinned potassium feldspars are most abundant; subordinately, polysynthetic twinned feldspars (plagioclase) and perthitic feldspar grains are present. Microcline is very rare. A few detrital micas are present, mostly muscovite and rarely chlorite and biotite. Locally, muscovite grains are up to 1 mm in diameter and oriented parallel to the bedding plane.

Some of the sandstones contain small amounts of matrix that is commonly stained brownish-red by hematite and iron hydroxides. In most of the sandstones, the detrital quartz grains display authigenic quartz overgrowths (Fig. 9B). In some of the sandstones, authigenic overgrowths have been observed on detrital feldspar grains (Fig. 8E).

In many sandstones, besides quartz and feldspar cement, coarse blocky calcite cement also is present that, in places, randomly replaces detrital quartz and feldspar grains (Figs. 8F, 9C). Hematite cement is present in small amounts. Textural relationships indicate that quartz cement in the form of authigenic overgrowths formed first, followed by the formation of feldspar overgrowths, and, during the last phase, the remaining pore space was filled with coarse blocky calcite cement that started to replace detrital quartz and feldspar.

The composition and texture of Abo Formation sandstones at Abo Pass are very similar to sandstones of the Abo Formation and Cutler Group in northern New Mexico. There are only small differences, such as the content of microcline, which is common in northern New Mexico but is almost absent at the Abo type section. The amount of monocrystalline quartz and detrital feldspars is higher at the type section, whereas the amount of rock fragments, particularly granitic rock fragments, is lower (Lucas and Krainer, 2005; Krainer and Lucas, 2010; Lucas et al., 2013c).

As in northern New Mexico, sandstones of the Scholle Member at the Abo type section are classified dominantly as arkose, subordinately as subarkose (Fig. 16), and locally, where sandstone contains high amounts of reworked caliche carbonates and siltstone, as lithic arenite, using the classification scheme proposed by Pettijohn et al. (1987). Most of the detrital grains (including part of the mono- and polycrystalline quartz, most feldspar grains and granitic rock fragments) are derived from granitic basement rocks. Subordinately, detrital grains (part of the mono- and polycrystalline quartz, a few feldspars, metamorphic rock fragments and some of the micas) are derived from metamorphic basement rocks. Locally, sedimentary rock fragments are present that were derived from the reworking of siltstone and caliche carbonates.

In the Cañon de Espinoso Member, sandstone is fine grained and commonly well sorted. The detrital grains are mostly subangular. Due to the fine grain size, the amount of monocrystalline quartz is higher than in the Scholle Member, whereas polycrystalline quartz is rare, and rock fragments are almost completely absent. The amount of detrital feldspar is lower compared to the Scholle Member. Sandstone contains opaque grains and rarely greenish tourmaline and zircon. Matrix is rare. The detrital grains are cemented by quartz that occurs as authigenic overgrowths. Overgrowths on detrital feldspars are rarely observed. Many sandstones also contain calcite cement that locally replaces detrital quartz and feldspar grains. In some of the sandstones, calcite cement is absent. Sandstones of the Cañon de Espinoso Member plot into the field of subarkose (Figs. 9E, 16).

Yeso Group—Arroyo de Alamillo Formation

Introduction

As Bates et al. (1947) noted, at no place in the Abo Pass area is a single, complete section of the Yeso Group exposed. Therefore, we measured four sections that capture almost all of the thickness of the unit (Figs. 10, 13, 14). Bates et al. (1947) similarly measured several incomplete Yeso sections, concluding that the entire unit is about 207 m thick at Abo Pass but rapidly thickens to the south to ~481 m. Our composite Yeso section at Abo Pass is about 260 m thick.

Lee (1909) originally included the strata we assign to the Arroyo de Alamillo Formation (Meseta Blanca Member of previous workers) in the Abo Formation. Thus, his Yeso base was the first limestone/dolomite bed at the base of what we call the Torres Member of the Los Vallos Formation (Fig. 2).

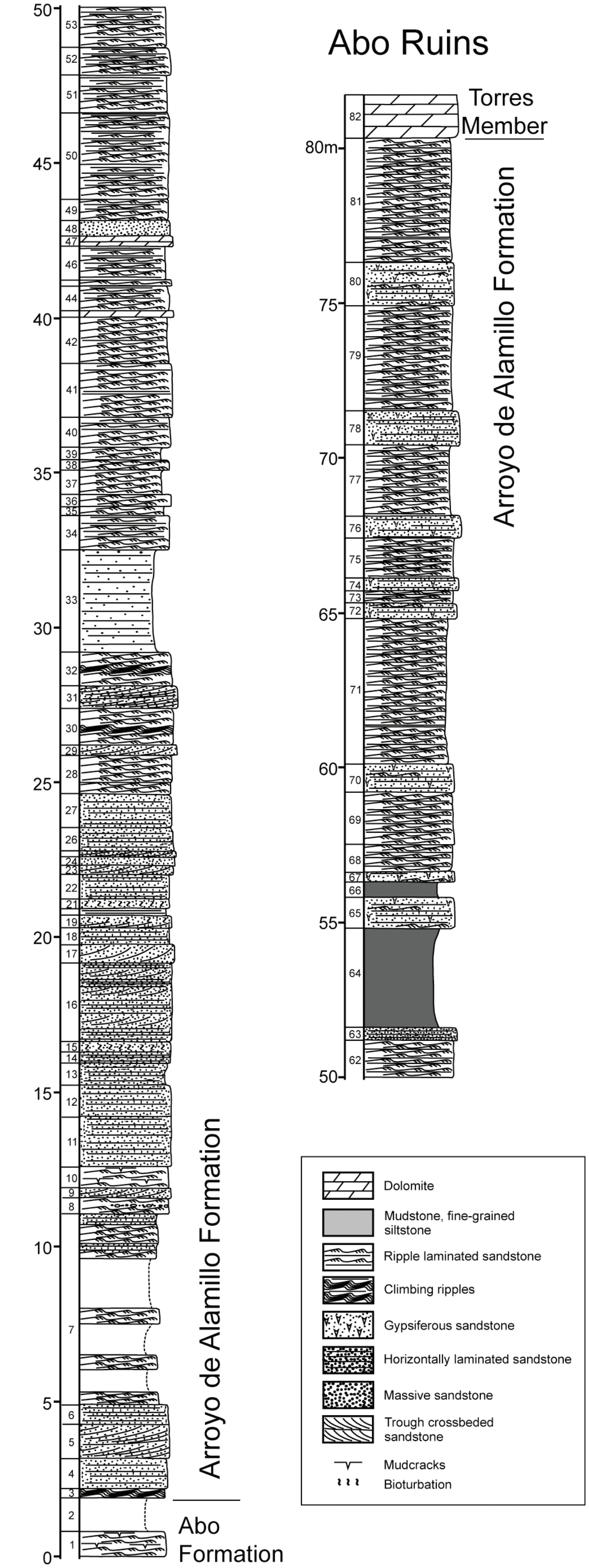


FIGURE 10. Section of Arroyo de Alamillo Formation at Abo Ruins. Base of section is at UTM 373305E, 3812557N and top is at 373711E, 3812516N (zone 13, datum NAD 83).

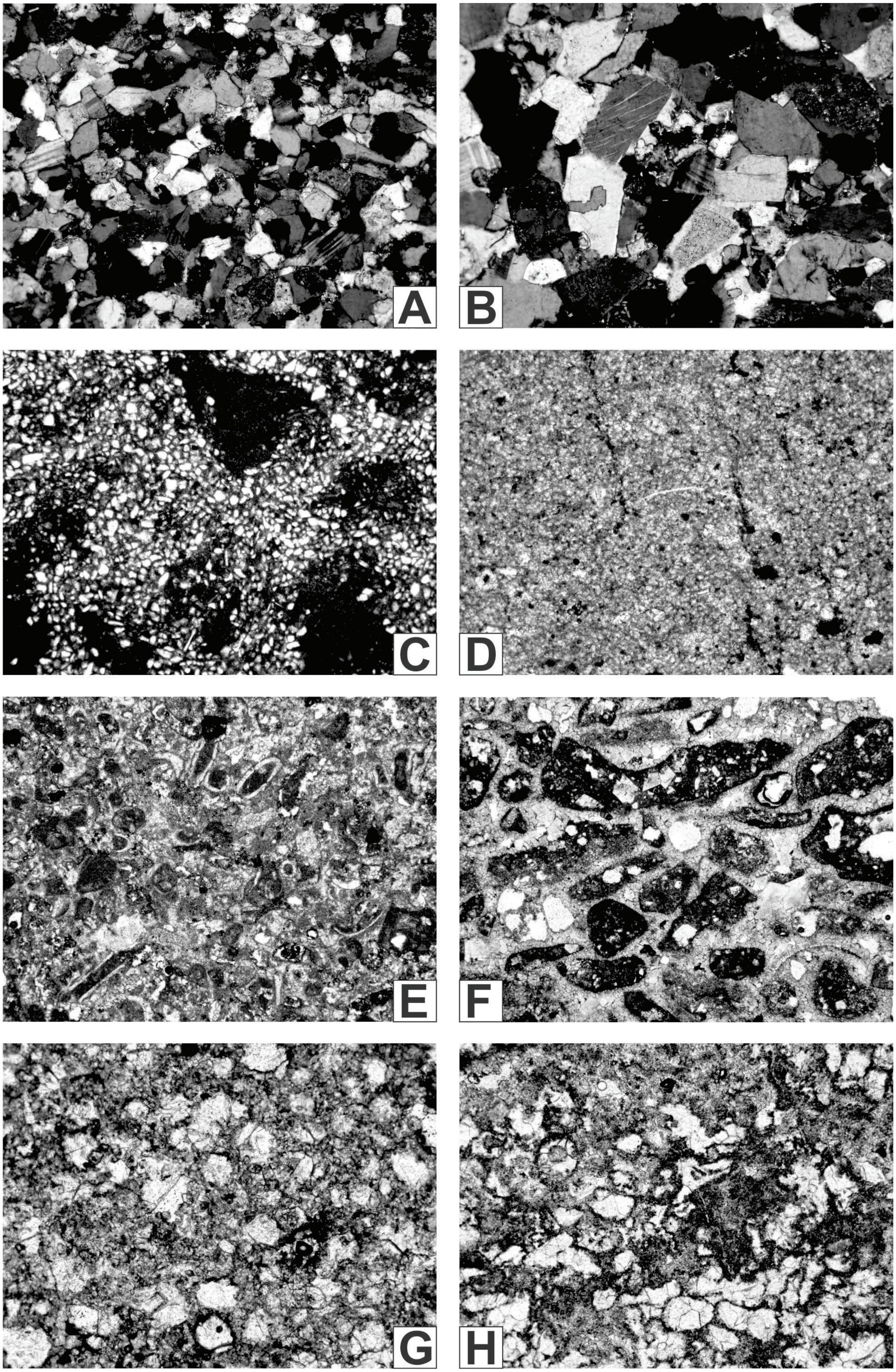
Needham and Bates (1943; also see Darton, 1922, 1928) drew the Abo-Yeso contact in the same way. However, following the work of Wood and Northrop (1946), Wilpolt et al. (1946) and Wilpolt and Wanek (1951) in the southern Manzano Mountains, Bates et al. (1947) removed the upper sandstone-dominated strata (they estimated this interval as 32 m thick) of the Abo Formation and reassigned it to the Meseta Blanca Member of the Yeso Formation. These are strata we assign to the Arroyo de Alamillo Formation at the base of the Yeso Group.

Cather et al. (2013) opposed raising Yeso Formation to group status, refused to recognize that Meseta Blanca is a synonym of DeChelly (Baars, 1962) and did not acknowledge the substantial facies change in that part of the section south of Albuquerque, which was the justification for recognizing a distinct Arroyo de Alamillo Formation (Lucas et al., 2005). In effect, Cather et al. (2013) advocate maintaining the 1940s lithostratigraphic nomenclature of the Yeso interval, despite subsequent work that justifies modifying that nomenclature to best reflect the stratigraphic architecture of the Yeso lithosome. We reject Cather et al.'s (2013) conclusions as a substantial step backward in understanding the Permian lithostratigraphy in New Mexico.

Lithostratigraphy

The base of the Yeso Group is the base of the Arroyo de Alamillo Formation. In the Abo Pass area, some workers have experienced difficulty identifying the base of the Arroyo de Alamillo Formation. Nevertheless, the lowest sandstone of the Arroyo de Alamillo Formation, as just noted, is readily identified as texturally and mineralogically more mature than any Abo sandstone stratigraphically below it (Lucas et al., 2005).

FIGURE 11. Thin section photographs of sedimentary rocks of the Yeso Group (Arroyo de Alamillo Formation and Torres Member: **A-G**) and basal San Andres Formation (**H**). Sample numbers refer to the unit numbers in the measured sections. **A**) Well-sorted, fine-grained sandstone composed of abundant monocrystalline quartz, rare polycrystalline quartz and some detrital feldspars (subarkose), cemented by authigenic quartz overgrowths and calcite cement. Sample ARU 24, Arroyo de Alamillo Formation, Abo Ruins, width of photograph is 3.2 mm (polarized light). **B**) Well-sorted sandstone containing many detrital feldspar grains (subarkose). The sandstone is cemented by authigenic quartz overgrowths, well-developed authigenic feldspar overgrowths on detrital feldspar grains, and rarely by calcite. Sample ARU 7, Arroyo de Alamillo Formation, Abo Ruins, width of photograph is 1.2 mm (polarized light). **C**) Siltstone to fine-grained sandstone composed of abundant detrital quartz and a few feldspar grains embedded in micritic matrix. The sandstone is strongly bioturbated. Sample ARU 45, Arroyo de Alamillo Formation, Abo Ruins, width of photograph is 3.2 mm (plane light). **D**) Carbonate mudstone containing a few ostracodes (center). Sample ACE 10, Torres Member, Abo Cemetery, width of photograph is 1.2 mm (plane light). **E**) Wackestone to grainstone containing abundant fragments of calcareous algae, a few other skeletal grains and abundant micritic intraclasts. Locally, micritic matrix is present. Sample ACE 17, Torres Member, Abo Cemetery, width of photograph is 3.2 mm (plane light). **F**) Intraclast-grainstone, moderately sorted and well washed, containing abundant micritic intraclasts that are partly recrystallized. Sample ACE 24, Torres Member, Abo Cemetery, width of photograph is 3.2 mm (plane light). **G**) Recrystallized wackestone containing abundant spherical grains (?algal fragments). Sample RCT 9, Torres Member, Red Canyon Trail, width of photograph is 1.2 mm (plane light). **H**) Recrystallized wackestone containing abundant skeletal grains, probably algal fragments. Sample DEC 87, basal San Andres Formation, Deer Canyon Preserve, width of photograph is 3.2 mm (plane light).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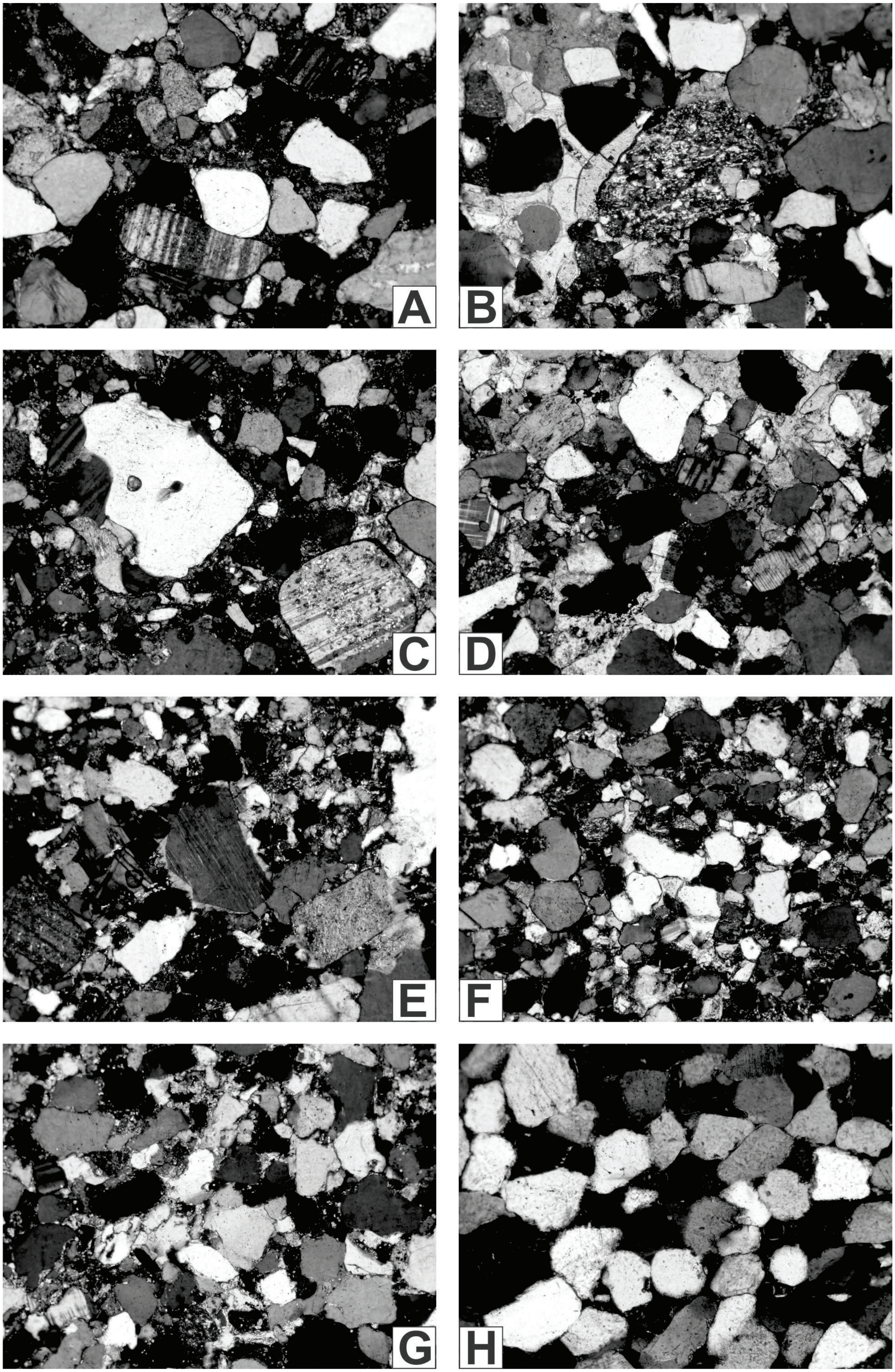
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Myers' (1977) mapping in the Scholle quadrangle drew the Abo Formation almost to the very eastern edge of the map (especially in Section 1, T2N, R5E and Section 36, T3N, R5E). However, most of these easternmost Abo outcrops are sandstones of the lower part of the Arroyo de Alamillo Formation. The Abo-Yeso contact here is close to the 6000-ft contour line, so it should be moved westward on Myers' (1977) map, into Section 2, T2N, R5E. Scott et al. (2005) merely repeated Myers' (1977) erroneous mapping of the Abo-Yeso contact.

A couple of years after Oviatt (2010) finished mapping the Abo quadrangle, at the request of the New Mexico Bureau of Geology, he worked along the common boundary between the Abo quadrangle and the Scholle quadrangle to align his mapping (on Abo) with that of Scott et al. (2005) (on Scholle). Oviatt thereby made a few changes on the Abo quadrangle and many changes on the Scholle quadrangle. On the Scholle quadrangle, he moved the contact at the base of the "Meseta Blanca" ("Pya" on the map – Arroyo de Alamillo Formation of the Yeso Group) to positions consistent with the lithologic change that marks the Abo-Yeso boundary.

In the same area, Hatchell et al.'s (1982, fig. 3) Cañon de Espinoso section (their section AMS 4) shows the Yeso base much higher than it actually is. That base is at the base of unit 15 of their section, not at the base of unit 35 as they indicate.

At Abo Ruins, a complete section through the Arroyo de Alamillo Formation is exposed and consists of 80 m of red beds (Fig. 10). The succession is composed of the following lithofacies types: (1) trough crossbedded sandstone, small-scale crossbedding, sets 0.2-0.3 m thick; crossbedded intervals are 0.2-1.1 m thick; (2) massive to crudely horizontally laminated sandstone (0.3-1.6 m thick); (3) horizontally laminated sandstone (0.2-1.1 m thick); (4) gypsiferous sandstone, horizontally and ripple laminated, two units (1 and 1.4 m thick) in the upper part; (5) gypsiferous massive sandstone (0.5 m thick), in the upper part of the section; (6) ripple-laminated sandstone, the most abundant lithotype, as 0.3-4.7 m thick intervals, with rare climbing ripples and rare mudcracks; (7) sandy siltstone (3.3 m thick); (8) blocky siltstone (0.5 and 3.2 m thick); (9) dolomite in two thin, partly laminated beds (0.2 and 0.3 m thick); and (10) covered intervals, which are rare in the lower part (Fig. 10, unit 7).

The topmost ripple-laminated sandstone of the Arroyo de Alamillo Formation is sharply overlain by gray dolomite at the base of the Torres Member of the Los Vallos Formation (Fig. 10). Trough crossbedded, horizontally laminated and massive sandstone are more abundant in the lower part of the Arroyo de Alamillo Formation, which is slightly coarser grained than the upper part. The upper part of the Arroyo de Alamillo Formation is dominated by ripple-laminated, fine-grained sandstone with intercalated massive and horizontally laminated sandstone. Gypsiferous sandstone also is present in the upper part. Two thin dolomite beds are intercalated in the middle of the section.

Petrography

The basal sandstone of the Arroyo de Alamillo Formation is well sorted and mainly composed of monocrystalline quartz with small amounts of polycrystalline quartz and detrital feldspars (subarkose: Figs. 9F, 16). Rock fragments and mica are almost completely absent. The detrital grains are cemented by calcite. Compared to the Abo Formation, the amount of monocrystalline quartz is higher and the amount of polycrystalline quartz, rock fragments and detrital feldspars is significantly lower.

Most of the sandstones of the Arroyo de Alamillo Formation (Figs. 9F, 11A-C, 12A-E) are fine grained (0.05-0.3 mm), and rarely medium grained (up to 0.7 mm). They are moderately to well sorted, and the detrital grains are mostly subangular to subrounded. The most abundant grain type is monocrystalline quartz. Other quartz grain types such as polycrystalline quartz (including stretched metamorphic quartz) and microcrystalline quartz (chert) are rare. Rock fragments composed of quartz and feldspar (granitic rock fragments) are very rare, as are fine-grained, schistose metamorphic rock fragments composed of mica and quartz (phyllitic rock fragments).

Detrital feldspars are abundant, particularly potassium feldspars, which are fresh to slightly altered. Feldspar grains are untwinned or twinned (microcline, rare polysynthetic twins, Carlsbad twins). A few perthitic feldspar grains are also present. Detrital micas are very rare and are represented by muscovite. Accessory grains include opaque grains, zircon, tourmaline, rutile and apatite.

The detrital grains are cemented by both quartz, which occurs as authigenic overgrowths, and by blocky calcite cement that randomly replaces quartz and feldspar locally. Rarely, dolomite rhombs are present, replacing detrital grains. In some of the sandstone beds, detrital feldspars display well-developed authigenic overgrowths. Rarely, sandstone is cemented just by coarse blocky calcite. In the classification diagram of Pettijohn et al. (1987), sandstones of the Arroyo de Alamillo Formation plot into the lower part of the field of subarkose (Fig. 16).

FIGURE 12. Thin section photographs of sandstones of the Yeso Group (Arroyo de Alamillo Formation and Joyita Member). All photos under polarized light, width of all photos is 1.2 mm. Sample numbers refer to the unit numbers in the measured sections. **A**) Moderately sorted sandstone composed of subangular to rounded grains of monocrystalline, rare polycrystalline quartz and many detrital feldspar grains (subarkose). The detrital grains are cemented by blocky calcite. Sample ARU 65, Arroyo de Alamillo Formation (Abo Ruins). **B**) Same as A, with large, fine-grained schistose metamorphic rock fragment in the center of the photograph. Sample ARU 65, Arroyo de Alamillo Formation (Abo Ruins). **C**) Same as A, with large granitic rock fragment composed of quartz and feldspar. Sample ARU 65, Arroyo de Alamillo Formation (Abo Ruins). **D**) Fine-grained, moderately to well-sorted sandstone (subarkose), composed of quartz and detrital feldspar grains cemented by blocky calcite. Sample ARU 76, Arroyo de Alamillo Formation (Abo Ruins). **E**) Sandstone containing many detrital feldspar grains (subarkose). Some of the detrital feldspar grains display well-developed authigenic overgrowths (e.g., large feldspar grain in the center). Sample ARU 9, Arroyo de Alamillo Formation (Abo Ruins). **F**) Fine-grained, moderately to well-sorted sandstone composed of mostly detrital quartz grains and a few feldspar grains. The detrital grains are cemented by blocky calcite. Sample DEC 13, Joyita Member (Deer Canyon Preserve). **G**) Moderately to well-sorted sandstone mostly composed of quartz and a few detrital feldspar grains. A few quartz grains display authigenic quartz overgrowths. The detrital grains are mainly cemented by blocky calcite. Sample DEC 11, Joyita Member (Deer Canyon Preserve). **H**) Very well-sorted sandstone composed almost entirely of detrital quartz grains (quartz arenite). The detrital quartz grains are cemented by authigenic quartz overgrowths. Sample DEC 15, Joyita Member (Deer Canyon Preserve).

Siltstone of unit 45 (Fig. 10) is siliciclastic-carbonate in composition, mostly abundant monocrystalline quartz, rare polycrystalline quartz, minor detrital feldspar and muscovite grains. The siltstone is mostly grain supported, locally matrix supported, nonlaminated and strongly bioturbated. The matrix is micrite.

At the type section of the Yeso Group east of Socorro (Lucas et al., 2005), the Arroyo de Alamillo Formation is thicker (107 m) than at Abo Ruins (Fig. 17). Also, the facies displays distinct differences between the type section and the section at Abo Ruins. At the type section, the succession is finer grained and contains much more mudstone-siltstone. Ripple-laminated sandstone is rare at the type section. Halite pseudomorphs are present at the type section, but absent to very rare (R. Colpitts, written commun., 2016) at Abo Ruins.

Yeso Group—Los Vallos Formation

Lithostratigraphy

The Los Vallos Formation consists of three members at Abo Pass (ascending): Torres, Cañas and Joyita (Fig. 2). The base of the Torres Member is gray dolomite at the top of the Arroyo de Alamillo Formation in the Abo Ruins section (Fig. 10). This gray dolomite at the base of the Torres Member is a prominent stratigraphic marker and is important in mapping. Indeed, this dolomite is also a regional-scale stratigraphic marker across central New Mexico (Lucas et al., 2005, 2013b; Lucas and Krainer, 2012). Nevertheless, it is difficult to measure sections in the Torres Member in the Abo Pass area because exposures are poor in most areas and because of the intra-formational deformation of the unit–numerous small-scale (100 m and less) folds and faults are probably caused by anhydrite dissolution in the subsurface as well as by Cretaceous-Tertiary tectonic deformation and Paleogene igneous intrusions (Bates et al., 1947).

Above the basal Torres Member dolomite there is a gap (no strata measured, but no more than 15-20 m) followed by a well-exposed succession at the Abo Cemetery section that represents the lower part of the Torres Member (Fig. 13). The upper part of the Torres Member is well exposed at the Red Canyon Trail section (Fig. 13).

The exposed thickness of the Torres Member at Abo Cemetery is 66 m. The succession is composed of the following lithotypes: (1) crossbedded sandstone, one bed (0.4 m thick) in the upper part; (2) massive sandstone, one bed (0.3 m thick) in the upper part; (3) ripple-laminated siltstone and sandstone intervals, partly gypsiferous (0.3-1.9 m thick); (4) gypsiferous siltstone (7.5-11 m thick); (5) gypsum, partly thinly laminated (0.5-0.9 m thick); (6) dolomite, massive, thick bedded, laminated, partly vuggy and interbedded with gypsum (0.2-1.3 m thick); and (7) laminated mudstone, intercalated in the lower part (0.3 m thick).

The dominant lithofacies of the Torres Member at the Abo Cemetery section is gypsiferous siltstone with intercalated thin intervals of mudstone and gypsum. Sandstone and dolomite are common lithofacies in the upper 10 m of the section. The top of the section (Fig. 13, unit 24) is a thick-bedded dolomite that we estimate is about 30-m stratigraphically lower than unit 9 of the Red Canyon Trail section. The relatively small stratigraphic gap at the base of the Abo Cemetery section is less than 20 m thick and likely encompasses gypsiferous siltstone and a dolomite interval, based on comparison to the Yeso type section east of Socorro (Lucas et al., 2005) (Fig. 17). These are the only stratigraphic gaps in our coverage of the Permian section at Abo Pass.

At Red Canyon Trail, the exposed section is approximately 79 m thick and encompasses the upper part of the Torres Member (Fig. 13). The lower 15 m (units 1-9) overlie the upper part of the section at Abo Cemetery and consist of gypsiferous siltstone and gypsum, overlain by crossbedded, horizontally laminated, massive and ripple laminated sandstone. We estimate the gap between the Abo Cemetary and Red Canyon Trail sections is about 15 m.

Above this basal unit, the upper part of the Torres Member (Fig. 6C) is exposed with a thickness of 63 m. The succession is composed of: (1) gypsiferous siltstone (4.2-11.9 m thick); (2) gypsum, partly laminated (3.3-10.8 m thick); (3) rare claystone, one bed (0.2 m thick); and (4) dolomite, bedded (0.9 and 2.1 m thick) in the upper part. Dolomite at the top of the Red Canyon Trail section corresponds to unit 2 of the Deer Canyon Preserve section (Fig. 14).

The lower 16 m of the Deer Canyon Preserve section are assigned to the Cañas Member of the Los Vallos Formation (Fig. 14). The succession is composed of: gypsum (0.4-3.3 m thick), alternating with gypsiferous siltstone (0.6-1.1 m thick); dolomite, which is thinly laminated and locally stromatolitic (2.2 m); and thin dolomite lenses intercalated in gypsum in the upper part. In their studies of the Permian strata in the Abo Pass area, Bates et al. (1947) reported a thickness range of 32-52 m for the Cañas Member. Our section of the Cañas Member at Deer Canyon Preserve is much thinner (16 m), but local thickness of the Cañas Member is perhaps highly variable due to dissolution and slippage of the gypsum beds.

At Deer Canyon Preserve (Figs. 6D, 14), the Joyita Member is 21 m thick and includes the following lithofacies: (1) crossbedded sandstone, two units (0.9 and 1.4 m thick); (2) massive sandstone (0.8 m thick, at the top of the section); (3) horizontally laminated siltstone to fine-grained sandstone (0.9-1.3 m thick); (4) ripple-laminated siltstone to fine-grained sandstone (0.1-2.1 m thick); (5) intercalated beds of gypsiferous sandstone that are massive (0.3 m), crossbedded (0.9 m), horizontally laminated (0.9 and 1.3 m) or partly ripple laminated (1.5 m); and (6) red siltstone intervals, which are rarely bioturbated (0.3-1.8 m thick). The most common lithofacies of the Joyita Member is ripple-laminated siltstone to fine-grained sandstone. In their studies of the Permian strata in the Abo Pass area, Bates et al. (1947) reported a thickness range of 9-28 m for the Joyita Member. The Glorieta Sandstone has a sharp contact on top of the Joyita Member at Deer Canyon Preserve (Figs. 6D, 14).

Petrography

At the Abo Cemetery section, gypsiferous siltstone of the Torres Member (Fig. 13, unit 8) is composed of mixed siliciclastic-carbonate siltstone with grain size mostly in the range

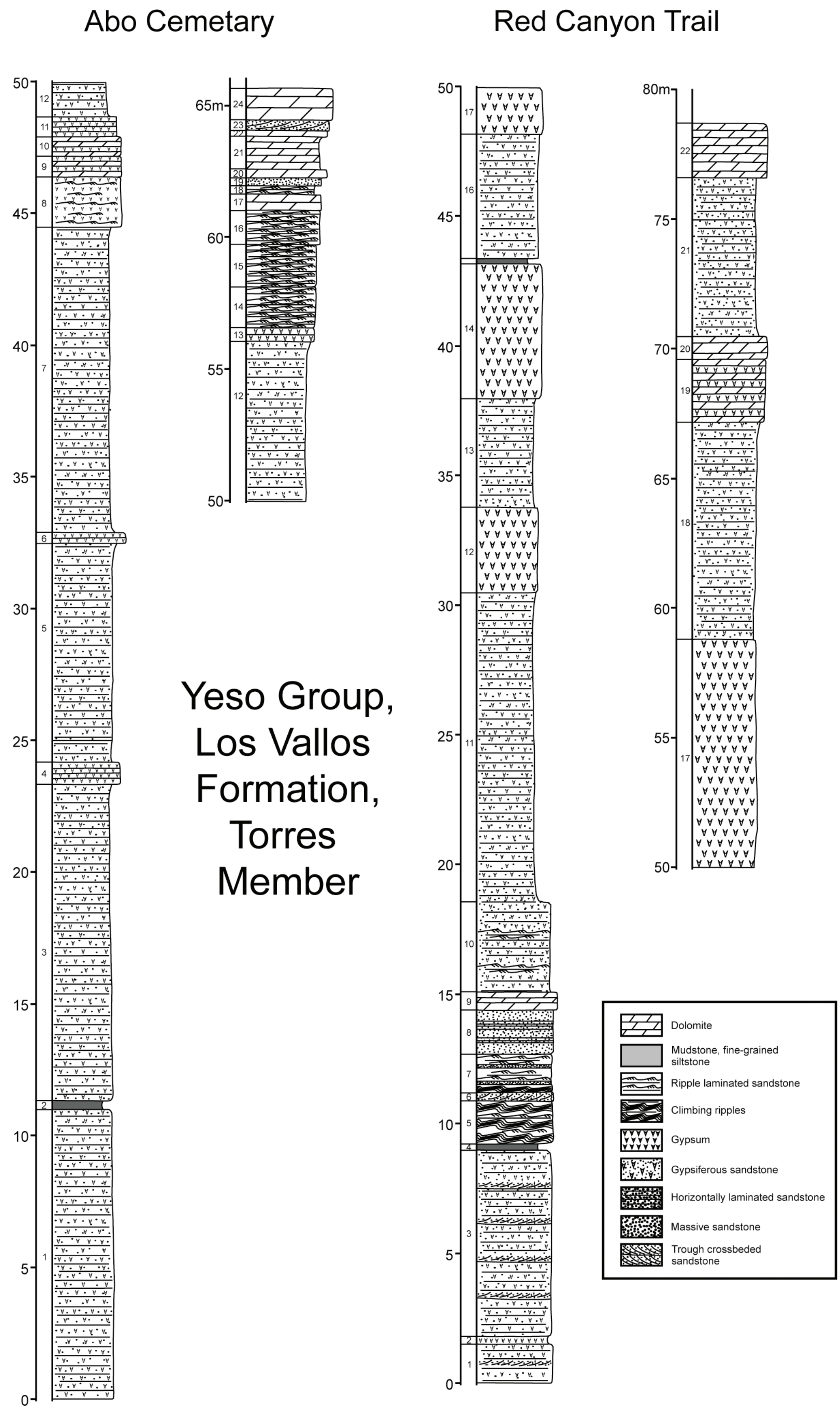


FIGURE 13. Measured sections of the Torres Member of the Los Vallos Formation (Yeso Group) at Abo Cemetery and Red Canyon Trail. Base of Abo Cemetery section at UTM 378385E, 3813195N and top at 378483E, 3813087N (zone 13, datum NAD 83). Base of Red Canyon Trail section at UTM 383196E, 3813684N and top is at 383900E, 3813251N (zone 13, datum NAD 83).

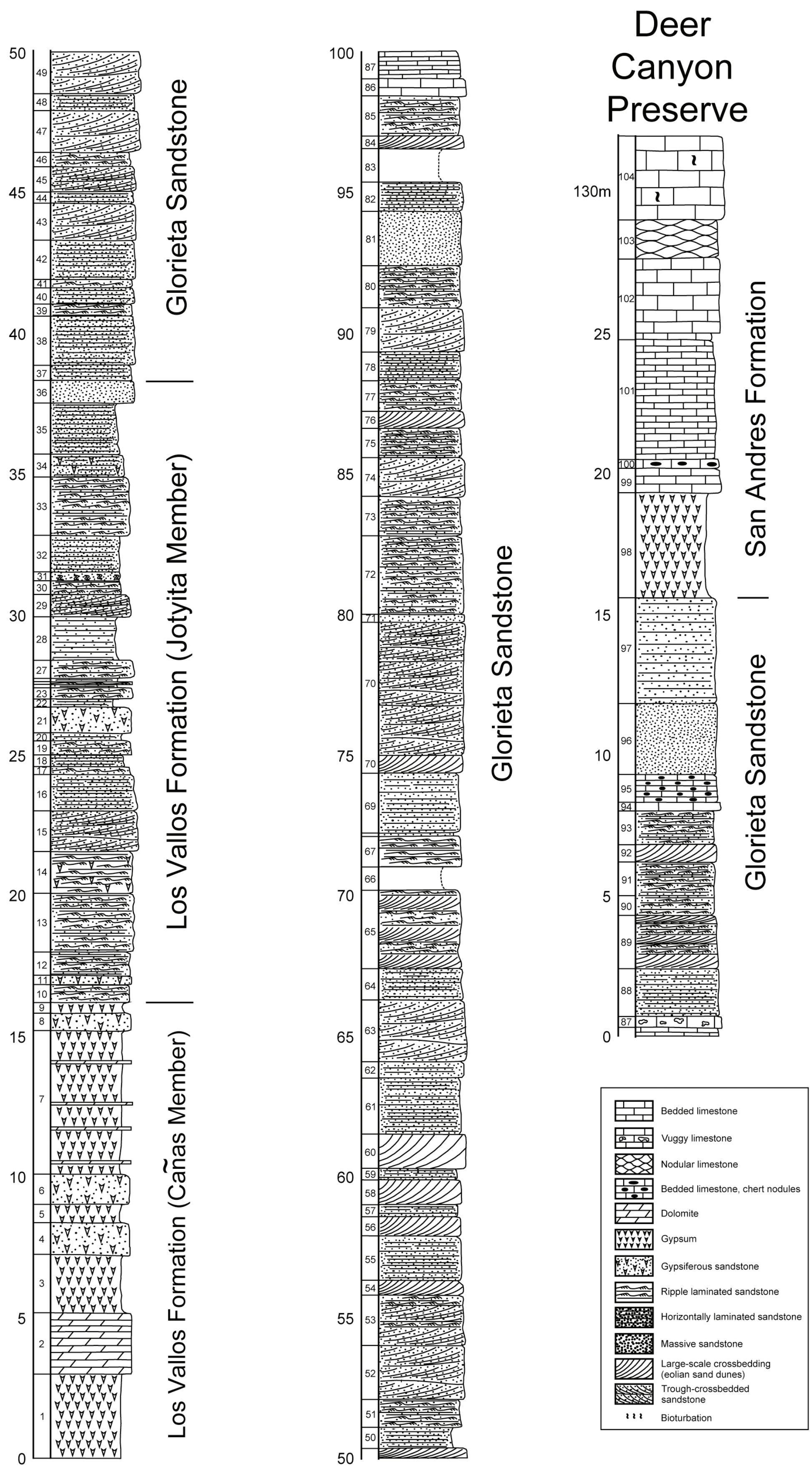


FIGURE 14. Measured section of the upper part of the Yeso Group, the Glorieta Sandstone and the lower part of the San Andres Formation at Deer Canyon Preserve. Base of the section is at UTM 382808E, 3811639N and top is at 383098E, 3811728N (zone 13, datum NAD 83).

of 0.05 mm, and rarely up to 0.1 mm. The siltstone is composed of quartz, carbonate (recrystallized) and a few detrital muscovite grains. It displays lamination–coarser grained layers contain more quartz than finer grained layers, which are dominantly carbonate mudstone.

The dolomite of unit 10 (Fig. 13) is composed of mudstone, which is indistinctly laminated, gray and contains a few ostracode shells and abundant small voids that probably were originally filled with evaporitic minerals (Fig. 11D). The mudstone contains a few small detrital quartz grains. The dolomite of unit 17 is recrystallized wackestone to grainstone composed of abundant dasycladacean algal fragments (Fig. 20C, I; including a new species of *Velebitella: V. americana*: see Appendix and Fig. 20D-N), subordinately of echinoderm fragments, foraminifers (mostly *Globivalvulina,* including *Globivalvulina* cf. *retroseptata* and *G*. cf. *novamexicana*; Fig. 20A, B), rare gastropods and other skeletal grains. Non-skeletal grains include abundant micritic intraclasts and, subordinately, small detrital quartz grains (Fig. 11E, F). Locally, micritic matrix (recrystallized to microsparite) is present, and the rock is washed and contains cement.

At the Red Canyon Trail section, the dolomite of unit 9 (Fig. 13) is a recrystallized wackestone composed of thin layers containing abundant, round carbonate grains (probably calcitarchans) that alternate with layers containing less abundant calcispheres (Fig. 11G). In the micritic matrix (recrystallized to microsparite), small detrital quartz grains and a few muscovite grains are present. The dolomite of unit 19 is a mudstone, which is nonlaminated and locally bioturbated. Silty layers contain abundant, small, detrital quartz grains.

Crossbedded sandstone of the Joyita Member is fine grained (mostly 0.1-0.2 mm), very well sorted and mostly composed of rounded detrital grains (Fig 15A). The sandstone contains abundant monocrystalline quartz, rare polycrystalline quartz (including stretched metamorphic) and chert. Metamorphic rock fragments composed of quartz and mica are very rare. Feldspars are rare and represented mainly by potassium feldspars, which are mostly untwinned, and rarely occur as microcline. Some of the detrital feldspar grains are obviously altered to clay minerals (forming pseudomatrix) and display thin authigenic overgrowths.

In the Joyita Member, horizontal- and ripple-laminated sandstone is fine grained (0.05-0.3 mm), moderately to well sorted and composed of subangular to subrounded grains, and locally of dominantly rounded grains. Monocrystalline quartz grains dominate, and polycrystalline quartz (including stretched metamorphic) and chert grains are rare. Detrital feldspar grains are present in small amounts and are represented mostly by untwinned grains, and subordinately by grains displaying microcline twinning. Some of the feldspar grains are strongly to almost completely altered to clay minerals or replaced by calcite. Rarely, metamorphic rock fragments composed of quartz and mica are present. Detrital mica (muscovite) is very rare. Accessory minerals include opaque grains, zircon, tourmaline and rutile.

Some sandstone beds of the Joyita Member contain small amounts of clayey matrix. And, some detrital quartz grains display authigenic overgrowths. More commonly the detrital grains are cemented by fine-grained, partly stained reddish brown, and coarser, blocky calcite, which locally replaces detrital grains.

Sandstones of the Joyita Member differ from those of the Arroyo de Alamillo Formation in their lower amounts of detrital feldspars and higher textural maturity. Following the classification scheme of Pettijohn et al. (1987), the Joyita Member sandstones still plot in the field of subarkose, but are close to the field of quartzarenite (Fig. 16).

Glorieta Sandstone

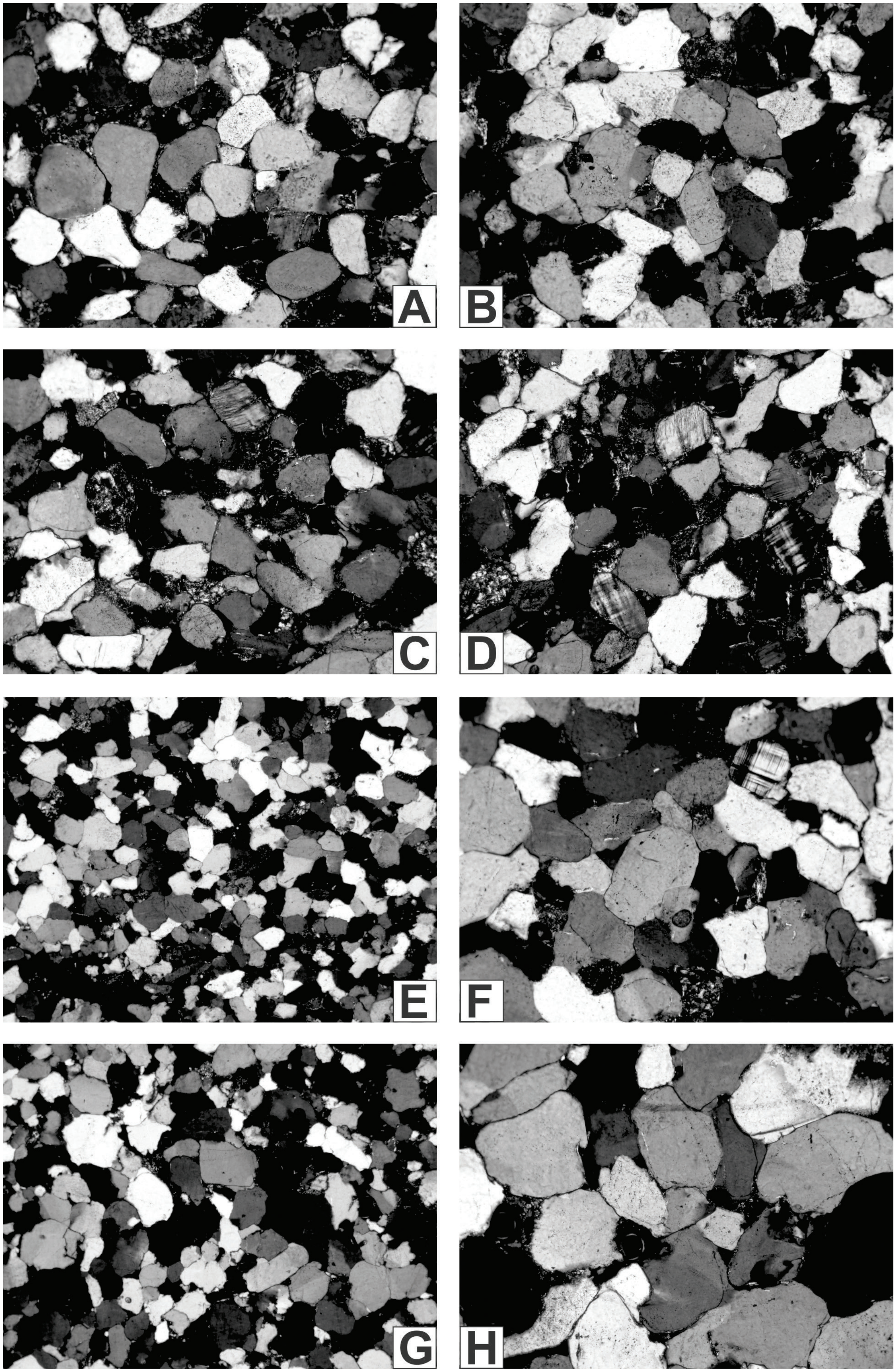
Lithostratigraphy

Although many workers during the 1940s-1970s considered the Glorieta Sandstone to be a member of the San Andres Formation, since the 1980s the trend has been to regard it as a separate formation (e.g., Woodward, 1987; Colpitts, 1986, 1989; Lucas et al., 1999; Lucas and Zeigler, 2004; Mack and Dinterman, 2002; Kues and Giles, 2004; Lucas et al., 2013a; Mack and Bauer, 2014; Krainer and Lucas, 2015). This has particularly been the case in quadrangle mapping by STATEMAP from the Jemez Mountains of Sandoval County through the Cerros de Amado of Socorro County. Connell (2008), who compiled all of the STATEMAP results from the Albuquerque area, is a good example of recent use of Glorieta Sandstone as a formation-rank unit. We also note that Bates et al. (1947), in their discussion of the Permian strata in the southern Manzano Mountains, were ahead of their time in regarding the Glorieta Sandstone as a formation-rank unit.

The Glorieta Sandstone is a lithologically distinctive unit almost always mappable at a scale of 1:24,000 (Oviatt, 2010, 2011). Therefore, the Glorieta Sandstone merits formation rank as either a sandstone sheet beneath the San Andres Formation or a basal sandstone sheet and stratigraphically higher sandstone bed(s) interbedded with carbonate/gypsum beds that are lithologies characteristic of the Yeso Group and/or the San Andres Formation (cf. Bates et al., 1947). Distinction of an upper sandstone of Glorieta lithology as the Hondo Sandstone Member of the San Andres Formation appears to have merit locally (Harbour, 1970). However, the regional interrelationships of Glorieta Sandstone bodies and lithologies characteristic of the San Andres Formation merit more study, along the lines of Milner (1978).

Baars (1961, 1962, 1974, 2000), Brose (2011, 2013) and Lucas et al. (2013a) provide strong evidence that the Glorieta Sandstone and the Coconino Sandstone are contemporaneous deposits representing a regional eolian system (erg) that extended from Arizona through New Mexico, and are inclusive of Harbour's (1970) Hondo Sandstone.

The Glorieta Sandstone is 78 m thick at the Deer Canyon Preserve section (Figs. 6D, 14), including two thin limestone intervals (2.3 and 1.3 m thick) of San Andres Formation lithology in its upper part. Bates et al. (1947) reported that Glorieta thickness is 46-84 m thick in the Abo Pass area. In the Glorieta Sandstone at Deer Canyon Preserve, the following lithofacies are observed: (1) crossbedded sandstone (Fig.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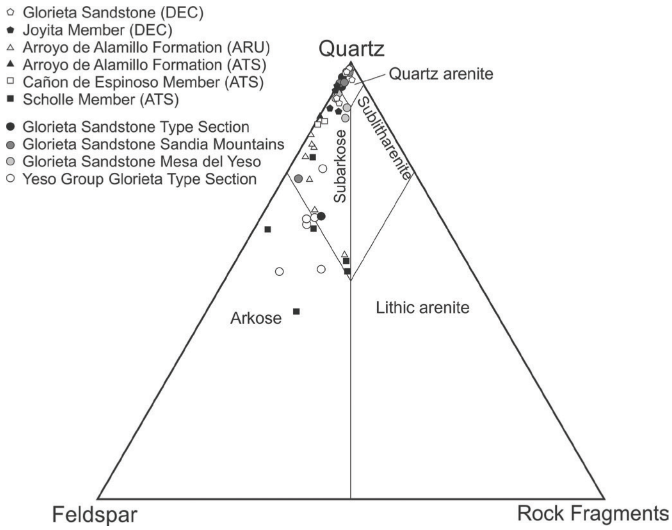

FIGURE 16. Ternary diagram of Permian sandstone compositions from the Abo Pass area and some other parts of New Mexico, using the classification scheme of Pettijohn et al. (1987).

6E); individual units display large-scale eolian crossbedding; trough-crossbedding is the dominant sedimentary structure, locally associated with ripple lamination, and crossbedded intervals are 0.5-5.4 m thick (mostly 0.6-2.2 m); (2) indistinctly horizontally laminated sandstone (with tabular beds) and rare, thinly laminated sandstone; individual units are 0.4-3.8 m thick; (3) ripple-laminated sandstone with mostly crudely developed ripples (0.3-2.9 m thick); (4) rare massive sandstone (0.3-2.5 m thick); (5) rare red siltstone, 0.8 m thick; and (6) rare covered intervals (0.8 and 1.2 m thick).

Petrography

Crossbedded sandstone of the Glorieta Sandstone at Deer Canyon Preserve is fine grained (mostly 0.1-0.3 mm), well sorted and contains subrounded to rounded grains (Fig. 15B-H). Detrital grains are dominantly monocrystalline quartz, rare polycrystalline quartz and chert. Detrital feldspar grains are common; they are mostly potassium feldspars (untwinned grains, microcline) that are fresh to altered grains. Indeed, some of the feldspar grains are almost completely altered to clay minerals. Rare schistose metamorphic rock fragments composed of fine-grained quartz and mica are present. Accessory grains are also rare and include opaque minerals, zircon and tourmaline. The sandstone is commonly well cemented by authigenic quartz overgrowths, and partly also by coarse, blocky calcite that locally replaces detrital grains. Rarely, authigenic overgrowths are observed on detrital feldspar grains (Fig. 15H). Small amounts of clayey matrix may be present, mostly formed diagenetically by the alteration of detrital feldspars ("pseudomatrix").

Horizontally and ripple-laminated sandstone is slightly finer grained (0.1-0.2 mm), well sorted and composed of mostly rounded grains, displaying the same mineralogical composition and diagenetic features as crossbedded sandstone. Due to their high compositional maturity, sandstones of the Glorieta Sandstone plot mostly into the field of quartzarenite (Fig. 16). Only a few samples contain higher amounts of detrital feldspars and therefore plot into the field of subarkose.

Near the top of the Glorieta Sandstone, detrital grains are mainly monocrystalline quartz, rare polycrystalline quartz (including stretched metamorphic) and rare detrital feldspar grains (potassium feldspar, including microcline and perthitic feldspar grains). The sandstone contains microfossils, including well-preserved foraminifers (including a new species of *Calcitornella: C. interpsammica:* see Appendix and Fig. 20Q-T) and, subordinately, recrystallized bivalve shells and other skeletons. Rarely, micritic intraclasts are present. The sandstone locally contains recrystallized micritic matrix (microsparite) and is cemented by coarse, blocky calcite cement.

San Andres Formation

Lithostratigraphy

The San Andres Formation is a Permian lithostratigraphic unit primarily composed of limestone that is exposed discontinuously across approximately two-thirds of New Mexico, with sparse outcrops in the central and western parts of the state (Brose et al., 2013). The formation thickens southward, from a minimum of 1-10 m in northern New Mexico, to as much as 181 m in south-central New Mexico. Most carbonate beds of the San Andres Formation have muddy textures and are either lime mudstone, muddy wackestone or dolostone; some gypsum and sandstone beds also are present, particularly in the lower part of the formation.

Across New Mexico, the San Andres Formation overlies the Glorieta Sandstone (Figs. 6F, 14) at most outcrops but locally overlies the older Yeso Group. Thus, the base of the San Andres Formation marks an event of regional extent that can be traced across much of New Mexico and into Texas as far east

FIGURE 15. Thin section photographs of sandstone of the Yeso Group (Joyita Member: **A**) and Glorieta Sandstone at Deer Canyon Preserve (B-H) (samples DEC; sample numbers refer to the unit numbers in the measured section.). All under polarized light, width of photographs E and G is 3.2 mm, and of all other photographs is 1.2 mm. **A**) Well-sorted sandstone composed of rounded to well-rounded quartz grains and rare detrital feldspar grains (quartz arenite). The detrital grains are cemented by authigenic quartz overgrowths. Sample DEC 33, Joyita Member. **B**) Well-sorted sandstone with rare detrital feldspar grains (quartz arenite), well cemented by quartz that occurs as authigenic overgrowths. Sample DEC 37, Glorieta Sandstone. **C**) Well-sorted sandstone composed of subrounded to rounded quartz grains and a few feldspar grains (subarkose). The detrital grains are cemented by quartz, and, rarely, by feldspar overgrowths. Sample DEC 65, Glorieta Sandstone. **D**) Same as C with several detrital feldspar grains including microcline (subarkose). Sample DEC 65, Glorieta Sandstone. **E**) Very well sorted, fine-grained sandstone composed of rounded grains, mainly quartz, and rare feldspar. The grains are cemented by quartz overgrowths. Sample DEC 90, Glorieta Sandstone. **F**) Same as E with rare feldspar (microcline, upper right). The detrital grains are well cemented by quartz overgrowths that are not easy to distinguish from the detrital grains. Sample DEC 90, Glorieta Sandstone. **G**) Well-sorted fine-grained sandstone composed of rounded quartz grains and very rare detrital feldspar grains (quartz arenite). The detrital grains are well cemented by quartz overgrowths. Sample DEC 97, Glorieta Sandstone. **H**) Detail of G with partly well developed authigenic quartz overgrowths on detrital quartz grains. Sample DEC 97, Glorieta Sandstone.

as the Midland basin, and into Oklahoma where the homotaxial equivalent of the San Andres Formation is the Blaine Formation. Recent work by Brose (2011) indicates that the regional event marking the basal portion of the San Andres is equivalent to a similar environment farther west into Arizona, where the Kaibab Formation caps the Permian Coconino Sandstone, and is present within and capping the San Andres Formation to the east across New Mexico.

The upper contact of the San Andres Formation in central New Mexico is also an unconformity overlain by younger Permian (Kaibab and Artesia formations) or Triassic (Moenkopi Formation, Chinle Group) strata. Locally, carbonate beds of the San Andres Formation yield a diverse marine microfauna (mostly algae and foraminifers; Vachard et al., 2015) and macrofauna (brachiopod-dominated, but including gastropods, bivalves and some cephalopods, among others). The age of the San Andres Formation has been mostly determined from fusulinid and conodont data obtained in southeastern New Mexico and West Texas that indicate it is of late Leonardian and early Guadalupian (primarily Roadian) age. In central and west-central New Mexico, however, all data suggest that only the Leonardian part of the formation is preserved (Brose et al., 2013).

In the Abo Pass area, Bates et al. (1947) noted that the San Andres Formation is exposed over a large area (it caps Chupadera Mesa; Fig. 1) but consists of incomplete sections about 61-91 m thick. In this area, Triassic strata overlie the San Andres Formation, but that contact is poorly exposed and crops out well east of the Abo Pass area.

At Deer Canyon Preserve, we measured a very incomplete section (only about 20 m thick) of the San Andres Formation (Fig. 14). Here, the San Andres Formation is interbedded with the underlying Glorieta Sandstone, which is documented by two thin limestone intervals of San Andres Formation lithology intercalated in the upper part of the Glorieta Sandstone. The lower 2.3-m-thick limestone interval is thick-bedded lime mudstone, overlain by thin-bedded limestone and laminated, vuggy limestone.

We chose to place the Glorieta-San Andres contact here at the top of the stratigraphically highest sandstone of Glorieta lithology overlain by gypsum or limestone at the base of the San Andres Formation. Thus, the base of the San Andres Formation at our Deer Canyon Preserve section (Fig. 14) is a 3.7-m-thick bed of massive gypsum. Overlying limestones are muddy wackestones that are either thin, thick or nodular bedded. One thin limestone bed (Fig. 14, unit 100) has chert nodules. The uppermost limestone bed of the San Andres Formation in our section is bioturbated, and it is locally eroded and overlain by Quaternary alluvium.

The thick-bedded lime mudstone of the San Andres Formation is a wackestone composed of peloidal micrite (recrystallized to microsparite) in which completely recrystallized skeletal grains (calcareous algae?), a few foraminifers and rare detrital quartz grains are floating. The thin-bedded limestone is strongly recrystallized, so the original microfacies is completely destroyed. The vuggy limestone under the microscope appears as strongly recrystallized wackestone to grainstone containing abundant recrystallized skeletons (probably calcareous algae), rare foraminifers (*Hemigordiellina* cf. *simplex*; Fig. 20O-P) and other fossils. In part, micritic matrix is present, and, in part, the rock is washed and cemented. The upper limestone unit is 1.3 m thick and composed of lime mudstone, overlain by thin-bedded, vuggy wackestone.

Petrography

Carbonate mudstone, indistinctly laminated to nodular and bioturbated, with a few detrital quartz grains and recystallized to microsparite forms the bedded limestone of unit 101 (Fig. 14). The nodular limestone of unit 103 (Fig. 14) is recrystallized and probably was a wackestone originally composed of abundant micritic grains (intraclasts, peloids). Detrital quartz grains up to 0.15 mm in diameter and completely recrystallized skeletal grains float in micrite. The limestone appears to be rich in hydrocarbons, as is the basal San Andres at some other locations (R. Brose, written communication, 2015)

The uppermost exposed limestone is a recrystallized peloidal mudstone to wackestone. Besides abundant peloids, some micritic intraclasts, recrystallized skeletons and a few detrital quartz grains are embedded in microsparitic matrix. Locally, the sediment is bioturbated.

DEPOSITIONAL ENVIRONMENTS

Bursum Formation

The Bursum Formation is a unit of mixed marine and nonmarine origin (e.g., Krainer and Lucas, 2004, 2009). At the Abo Pass outcrops of the Bursum Formation (Fig. 4), we interpret the red and purple and rare, greenish unfossiliferous mudstones that locally contain carbonate nodules as nonmarine deposits of a coastal plain environment. The carbonate nodules are interpreted as pedogenic (calcrete nodules). Such mudstones are common in many Bursum sections, for example, in the Lucero uplift, in the Los Pinos Mountains and in the Joyita Hills (Krainer and Lucas, 2009). The intercalated siltstone to fine-grained sandstone horizon with ripple cross lamination was probably deposited in broad, shallow channels of a low sinuosity stream system during periods of high influx of sand. The conglomerate and sandstone horizon represents incised fluvial channel deposits.

Periodically, the flat coastal plain was flooded for short periods, and shallow, open marine conditions prevailed under which thin limestone beds composed of bioclastic wackestone, packstone and grainstone with a diverse invertebrate fauna accumulated. Such limestones are common in the Red Tanks Member of the Bursum Formation in the Lucero uplift of Valencia County (Krainer and Lucas, 2004; Lucas and Krainer, 2004). Limestone of the Bursum Formation at the type section in the Oscura Mountains of Socorro County (Lucas et al., 2002) also consists of bioclastic wackestone and mudstone with a similar composition. This indicates that the depositional environment of the limestone facies of the Bursum Formation was very similar across central New Mexico, representing a restricted to open marine, dominantly low-energy, shallow-shelf environment.

Abo Formation

The overall, regional deposition of the Abo Formation is well understood as having taken place on a low-gradient alluvial plain in which rivers flowed primarily to the south toward the shoreline of the Hueco seaway in southern New Mexico (Kues and Giles, 2004; Lucas et al., 2013c). Thus, Seager and Mack (2003, p. 29) stated that "the Abo fluvial system was characterized by widely dispersed silt-bed or very fine sand-bed rivers, broad, well-oxidized floodplains, and evidence in both the channel and floodplain strata for marked seasonality of paleoclimate" and that deposition was "strongly influenced by the overall dry and megamonsoonal climate postulated for Pangea in Early Permian time." The Abo Formation thus well represents the concept of "wet red beds" deposited during the late Paleozoic across much of tropical Pangea (e.g., Schneider et al., 2010).

At Abo Pass, mudstones with calcrete paleosols represent extensive muddy floodplains subjected to seasonal aridity. The occurrence of two estivating vertebrate taxa, the lungfish *Gnathorhiza* and the amphibian *Diplocaulus*, in a freshwater limestone (see below) also indicate seasonal aridity. Lenticular intraformational conglomerate beds and crossbedded sandstone bodies are channel deposits that accumulated during times of relatively rapid base-level fall. These are strata of the Scholle Member. Sheet sandstones characteristic of the Cañon de Espinoso Member indicate times of base level stability or relatively slow fall when Abo channels avulsed and spread across the floodplain to form thin, laterally extensive, tabular sandstone bodies (cf. Blakey and Gubitosa, 1984).

Yeso Group

In general, Yeso Group deposits record a major northward transgression across Abo red beds, followed by a regression (Lucas et al., 2013b). According to Baars (1974), Stanesco (1991), Mack and Suguio (1991), Mack and Dinterman (2002) and Kues and Giles (2004), during sedimentation of the Arroyo de Alamillo Formation, marine carbonates of the Delaware Basin grade northward into shallow-marine siliciclastics, carbonate and evaporitic sediments with intercalated eolian deposits towards the northern and northwestern shelf, and into eolian sand sheets in west-central New Mexico, eolian dune fields (DeChelly Sandstone) to the northwest and deposits of ephemeral streams and eolian sediments in north-central New Mexico.

Compared to the type section at Mesa del Yeso and to the sections farther south, the Arroyo de Alamillo Formation at Abo Ruins is generally coarser grained and lacks an evaporitic facies. The lower part is slightly coarser than the upper part and consists of horizontally laminated, ripple-laminated and trough crossbedded, fine-grained sandstone. High textural and compositional maturity indicate that the trough crossbedded sandstones represent eolian sand dunes.

The upper part of the Arroyo de Alamillo Formation at Abo Ruins is dominated by ripple- and horizontally laminated fine-grained sandstone and rare massive sandstone (Fig. 10). As most of these sandstones are also well sorted and rounded, we interpret these sediments as eolian sand sheet deposits. Mudstone and some of the sandstone beds may also represent interdune deposits. The thin dolomite beds in the middle of the Arroyo de Alamillo Formation represent two short, transgressive marine events.

The facies of the Torres Member of the Los Vallos Formation at Abo Pass is very similar to that of the Yeso type section and at Massacre Gap (Fra Cristobal Mountains, Sierra County) with gypsiferous siltstone, gypsum and dolomite being the principal lithologies (Lucas et al., 2005; Lucas and Krainer, 2012). Dolomite horizons are much thinner at Abo Pass than at the Yeso type section and farther south (Fig. 17). Gypsiferous siltstone and gypsum are interpreted as deposits of a coastal sabkha environment. Intercalated sandstone beds are likely of eolian origin (Lucas and Krainer, 2012). Dolomite is mostly poorly preserved, and the original microfacies has been strongly overprinted during diagenesis, although rare lime mudstone with a low-diversity fossil assemblage (a few ostracodes) indicates very shallow, restricted marine conditions. Wackestone to grainstone with abundant dasycladacean algal fragments and a more diverse fossil assemblage, including foraminifers, echinoderms, gastropods and other fossils, point to a periodically shallow, more open marine depositional environment of normal salinity and moderate to high water energy.

These three principal lithologies can be arranged to form cycles similar to those at the Yeso type section and Massacre Gap section in the Fra Cristobal Mountains of Sierra County (Lucas et al., 2005, 2013b; Lucas and Krainer, 2012) (Fig. 17). But, as the basal part of the Torres Member is not exposed at Abo Pass, the number of cycles is unclear, though it seems that the cycles of the composite of the Abo Cemetery and Red Canyon Trail sections are correlatable with the cycles at the Yeso type section and at Massacre Gap (Fig. 17).

Compared to the Yeso type section and Massacre Gap section, the Cañas Member at Deer Canyon Preserve is developed in a similar evaporitic facies of gypsum, gypsiferous siltstone and rare dolomite, but is much thinner (66.4 m at the type section, 58 m at Massacre Gap, 99 m in the McLeod Hills, less than 20 m at Deer Canyon Preserve) (Fig. 17).

The Joyita Member at Deer Canyon Preserve is thicker (21 m) than at the Yeso type section (12.3 m) but thinner than at Massacre Gap (42 m) and in the Lucero uplift (65 m) (Lucas and Zeigler, 2004; Lucas et al., 2005, 2013b; Lucas and Krainer, 2012) (Fig. 17). Due to the high textural maturity, we interpret the horizontally and ripple laminated fine-grained sandstones of the Joyita Member as dominantly eolian sand sheet deposits. Intercalated crossbedded sandstone beds, composed of very well-sorted and well-rounded quartz grains, represent eolian sand dunes. Interbedded gypsiferous siltstones indicate periodic sabkha conditions. Individual beds of fine-grained sandstone and bioturbated siltstone represent interdune deposits. This facies is very similar to the Joyita Member at Mesa del Yeso and Massacre Gap.

The Joyita Member forms the top of the Yeso Group and represents a period of lowered sea level during which the shallow marine and evaporitic sediments of the underlying Torres and Cañas members are overlain by nonmarine redbeds of

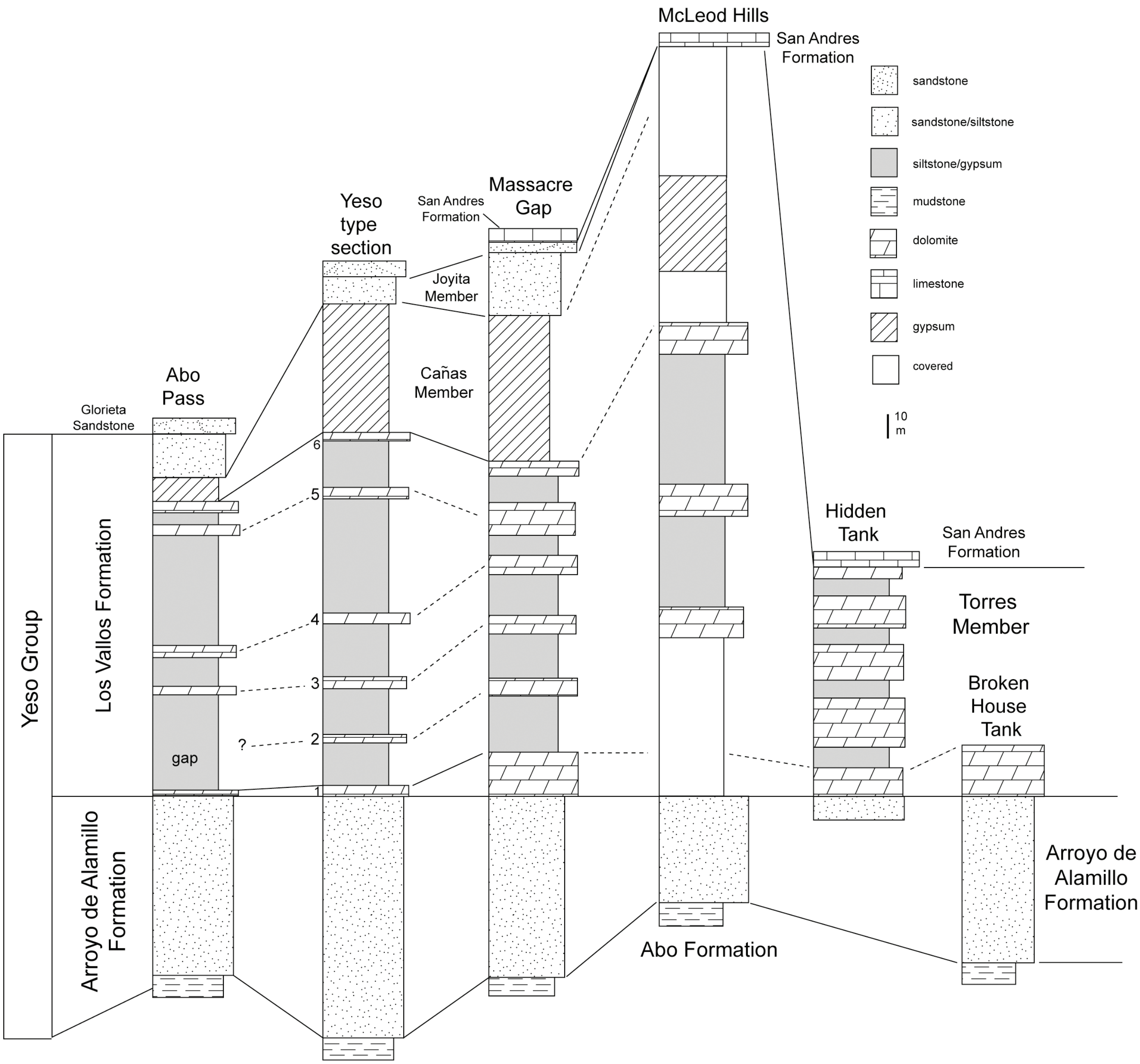

FIGURE 17. Correlation of Yeso Group sections, including the composite Yeso section at Abo Pass described here, the type Yeso section in Socorro County (Lucas et al., 2005) and Yeso Group sections in at Massacre Gap and the McLeod Hills of Sierra County (Lucas and Krainer, 2012).

mostly eolian, subordinately fluvial, origin. Thus, the Joyita Member represents an extensive eolian and fluvial sand sheet that prograded southward across shallow-marine and evaporitic deposits during a period of regionally low sea level (Mack and Dinterman, 2002; Lucas et al., 2013b).

Glorieta Sandstone

The Glorieta Sandstone is a relatively thin (<100 m) but widespread geologic unit in north-central New Mexico, which has been interpreted as either deposits of a dominantly shallow-marine environment (e.g., Baars, 1961, 1962, 2000; Kelley, 1971; Milner 1978; Dinterman, 2001) or as dominantly eolian deposits (e.g., Bauer, 2011; Bauer and Mack, 2011; Lucas et al., 2013a; Mack and Bauer, 2014; Krainer and Lucas, 2015).

Milner (1978) listed cross-stratification, ripples and parallel stratification as the common sedimentary structures of the Glorieta Sandstone in Lincoln County, eastern New Mexico. He interpreted the Glorieta Sandstone as sediments deposited along the coastline. Crossbedded sandstones formed in foreshore to upper shoreface, coastal dune and tidal channel environments. Sea-level rise caused deposition of carbonate sediments in tidal flat, restricted, open marine and evaporitic environments (see discussion in Brose et al., 2013 and Lucas et al., 2013a).

In contrast, Bauer (2011), Bauer and Mack (2011), Mack and Bauer (2014) and Krainer and Lucas (2015) interpreted sandstone with ripple lamination, large-scale planar crossbedded sandstone and massive sandstone of the Glorieta Sandstone to be of eolian origin, and small-scale trough-crossbedded sandstone as deposits of shallow interdunal streams.

The facies of the Glorieta Sandstone at Deer Canyon Preserve is very similar to the type section at Glorieta Mesa near Rowe (San Miguel County), where Krainer and Lucas (2015) interpreted the crossbedded sandstone intervals as eolian dune deposits that probably represent transverse or barchanoid dunes (cf. Ahlbrandt and Fryberger, 1982; Fryberger, 1990; Brookfield and Silvestro, 2010). The horizontally and ripple-laminated sandstones intercalated in the crossbedded sandstone in the lower part of the type section are interpreted as interdune deposits. Krainer and Lucas (2015) noted that ripples in the Glorieta Sandstone at the type section are poorly preserved, and the ripple foresets observed by Milner (1978) are absent. Shallow marine carbonate intercalations are absent at the type section but have been observed in the Sandia Mountains at Cedar Crest in Bernalillo County (Lucas et al., 2013a, 2015b) and are present at Deer Canyon Preserve.

According to Baars (1961, 1962, 1974, 2000), the Glorieta Sandstone is an eastward extension of the Coconino erg of northern Arizona (e.g., Kues and Giles, 2004). In the northwestern and western outcrops on the Colorado Plateau portion of New Mexico, and at the type section described by Krainer and Lucas (2015), as well as at Deer Canyon Preserve, the Glorieta Sandstone is mainly composed of eolian dune and interdune deposits and eolian sheet sands. To the southeast and east, the Glorieta Sandstone interfingers more extensively with shallow marine carbonates of the San Andres Formation, and parts of the Glorieta Sandstone were deposited in marginal marine settings (Krainer et al., 2012; Brose et al., 2013).

Textural and compositional maturity increase from the fluvial red beds of the Cutler Group and Abo Formation to the sandstones of the overlying Yeso Group and Glorieta Sandstone (Fig. 16). Sandstones of the Cutler Group and Abo Formation are classified as arkose to subarkose, and due to the locally higher amount of rock fragments also as lithic arenites, rarely as sublitharenites (Krainer and Lucas, 2010; Lucas and Krainer, 2005; Lucas et al., 2012a, b, 2013c). Sandstones of the mixed fluvial-eolian Arroyo de Alamillo Formation – the basal unit of the Yeso Group – display better sorting and rounding compared to the Abo Formation and are classified as subarkoses (Fig. 16). Sandstones of the Joyita Member – the top unit of the Yeso Group – are also mixed fluvial-eolian in origin and show textural maturity similar to those of the Arroyo de Alamillo Formation, and slightly higher compositional maturity, although Joyita Member sandstones are still classified as subarkoses (Fig. 16). The dominantly eolian Glorieta Sandstone is composed of sandstones with the highest textural and compositional maturity (quartzarenite).

Although textural and compositional maturity increase from the Cutler Group and Abo Formation to the Yeso Group (Arroyo de Alamillo Formation), there was no obvious change in the bedrock of the source areas. Sandstones are mainly derived from granitic source rocks throughout the succession, subordinately from metamorphic source rocks and locally from reworking of sedimentary rocks, particularly of paleocaliche.

The high compositional maturity of the Glorieta Sandstone – composed almost entirely of quartz grains – makes it difficult to reconstruct the source rocks. Foresets of eolian sand dunes dip mostly towards the southwest, indicating formation in a relatively unimodal wind regime (Lucas et al., 2013a). Orientation of the foresets of eolian sand dunes in the Glorieta Sandstone indicates transport and deposition of the sand grains by northeasterly trade winds (Mack and Bauer, 2014). From U-Pb dates of detrital zircons, Mack and Bauer (2014) concluded that the sediments are mainly derived from deflation of a transcontinental river system with its headwaters in the Appalachian-Ouachita Orogen and Canadian Shield, and subordinately from the Uncompahgre and Front Range uplifts of the Ancestral Rocky Mountains.

San Andres Formation

Carbonate sedimentary rocks of the San Andres Formation document the last major Paleozoic transgression onto the North American craton. Two intercalated thin limestone horizons within the upper part of the Glorieta Sandstone at Deer Canyon Preserve (Fig. 14) demonstrate that, as in the Sandia Mountains (Lucas et al. 2015b), the Glorieta Sandstone is interbedded with the San Andres Formation. These two intercalated limestone intervals indicate that two short marine transgressions occurred, followed by regressions and deposition of eolian sandstone, before the major transgression flooded eolian dune fields of the Glorieta Sandstone.

At the reference section of the San Andres Formation in the San Andres Mountains of Sierra County, microfacies types indicate that deposition of the San Andres Formation took place in a shallow, normal marine environment of low to medium water turbulence. Intercalated limestones with a less diverse fossil assemblage document short periods of shallow, restricted settings with increased salinity (Krainer et al., 2012; Brose et al., 2013). In the Sandia Mountains, the San Andres Formation is thinner and displays a more restricted shallow marine environment compared to the reference section in the San Andres Mountains (Lucas et al. 2015b).

At Deer Canyon Preserve, microfacies of the intercalated thin limestone intervals also indicate deposition in a dominantly restricted shallow marine environment with probable increased salinity. The San Andres Formation on top of the Glorieta Sandstone starts with gypsum, indicating deposition in a coastal sabkha environment, followed by marine transgression and deposition of limestone under shallow, restricted to open marine conditions.

PALEONTOLOGY

Introduction

From samples collected at Abo Pass, we identified microfossils in thin sections of the Bursum Formation, Yeso Group, Glorieta Sandstone and San Andres Formation. We have collected tetrapod footprints and other trace fossils from the Abo Formation. The Bursum and Abo formations also have yielded a vertebrate fossil assemblage. Here, we present/review some of these fossils and summarize what is known of the paleobotany of the Abo Formation at Abo Pass.

Microfossils

In thin section, we recovered microfossils from limestones of the Bursum Formation, as well as from the Yeso Group, Glorieta Sandstone and San Andres formation (Figs. 18-20).

Bursum Formation

Bates et al. (1947, p. 25) reported that the Bursum Formation in the southern Manzano Mountains yields the fusulinids "*Schwagerina* and advanced forms of *Triticites ventricosus*" indicative of a Wolfcampian age. Myers (1988) reported a succession of fusulinids from the Bursum Formation in the southern Manzano Mountains, beginning with *Triticites creekensis*, overlain by *Leptotriticites* sp. and culminated by *Schwagerina pinosensis* Thompson. He assigned these fusulinids to his "assemblage subzone of *Triticites creekensis*" and "zone of *Schwagerina*," both of early Wolfcampian age. Krainer et al. (2009) reported early Wolfcampian fusulinids and other microfossils from the Bursum Formation at the Highway 60 roadcut.

The microfossils from the Bursum Formation at the Highway 60 roadcut include fusulinids and smaller foraminifers: *Triticites pinguis* (Fig. 18A-B), *Triticites* aff. *T. creekensis* (Fig. 18C, E), *Triticites* aff. *T. parameeki* (Fig. 18F), *Spireitlina conspecta* (Fig. 18M-N), *Calcivertella* sp. (Fig. 18I), *Climacammina* sp., *Diplosphaerina* sp., *Hemigordius* ex gr. *harltoni* (Fig. 18P, R), *Tetrataxis* sp., *Earlandia* sp., *Globivalvulina mosquensis* (Fig. 18L), *Nodosinelloides pinardae* (Fig. 18J, K), *Pseudovidalina modificata* (Fig. 18H), *Syzrania* ex gr. *bella* (Fig. 18G) and *Syzranella* sp. (Fig. 18D). From Priest Canyon, we illustrate specimens of the fusulinids *Triticites* and *Leptotritictes* that indicate an early Wolfcampian age for the Bursum strata (Fig. 19).

Yeso Group

From Yeso Group thin sections, we recovered a foraminifer-dominated microfossil assemblage from the Torres Member in the Abo Cemetery section (Figs. 13, 20) that includes *Globivalvulina* cf. *retroseptata* Vachard, Krainer and Lucas, 2015 (Fig. 20A), *G.* cf. *novamexicana* Vachard, Krainer and Lucas, 2015 (Fig. 20B), undetermined Chlorophyta (Fig. 20C, I) and *Velebitella americana* n. sp. (Fig. 20D-H, J-N), described in the Appendix.

Glorieta Sandstone/San Andres Formation

From thin sections of the Glorieta Sandstone and San Andres Formation at the Deer Canyon Preserve section, we recovered a few microfossils. Unit 86 (limestone intercalated in the Glorieta Sandstone) contains *Hemigordiellina* aff. *simplex* (Harlton, 1928) (Fig. 20P). Unit 99 (lower San Andres Formation on top of the Glorieta Sandstone) contains *Calcitornella interpsammica* n. sp. (Fig. 20Q-T), described in the Appendix.

Fossil Plants

The only published fossil plants from the Permian strata at Abo Pass are from the Abo Formation (Hatchell et al., 1982). These are specimens of walchian conifers and the peltasperm *Supaia*. They represent a low diversity flora found throughout the Abo Formation of central New Mexico (DiMichele et al., 2007, 2013). Elsewhere in this volume, DiMichele et al. document unpublished Abo plants from the Priest Canyon area.

Tetrapod Footprints

Hatchell et al. (1982, fig. 7) illustrated a trackway (*Limnopus*?) from the Arroyo de Alamillo Formation near Abo Ruins, but we have not been able to relocate that site. Numerous tetrapod (amphibian and reptile) footprint localities are present in the Abo Formation in the Abo Pass area. The most prolific of these localities is the Abo Pass tracksite, first published by Lucas et al. (2001). Lucas et al. (2001) drew attention to and documented records of the ichnogenera *Amphisauropus* and *Varanopus* at the Abo Pass tracksite, and Lucas et al. (2009) provided more complete documentation of the footprint assemblage.

The tracksite is located ~140 m above the base of the Abo Formation in the Cañon de Espinoso Member. Indeed, the track-bearing bed is equivalent to unit 23 of the Abo type section (Fig. 7). Given that the Abo Formation is ~300 m thick at Abo Pass, the Abo Pass tracksite is approximately in the middle of the formation.

The locality is dominated by footprints of *Amphisauropus kablikae*, with far fewer numbers of *Dromopus lacertoides*, *Batrachichnus salamandroides, Varanopus cuvidactylus* and *Ichniotherium cottae* (Fig. 21). This tracksite exemplifies the concept of a Lower Permian *Amphisauropus* sub-ichnocoenosis of red-bed tetrapod tracksites from inland fluvial settings near uplifts (e.g., Hunt and Lucas, 2006). However, the abundance of *Amphisauropus* at the site could be anomalous, and this possibility highlights the need for additional data with which to fully evaluate proposed ichnofacies models of Early Permian red-bed tetrapod footprints.

Vertebrate Bones and Teeth

Permian vertebrate fossils in the Lower Permian of the Abo Pass area (the Los Pinos Mountains locality of Berman, 1993) have been described from three sites (Table 1). Assemblages from two of the sites in the Scholle Member on the eastern margin of the Los Pinos Mountains were listed by Berman (1993). One of the sites, a limestone layer as much as 16 cm thick and perhaps about 100 m in outcrop exposure that probably represents a freshwater pond or lake, is of particular importance in yielding several articulated specimens, including skulls, of the lungfish *Gnathorhiza* preserved in estivation burrow casts (Berman, 1976) (Fig. 22A-B). This is the only

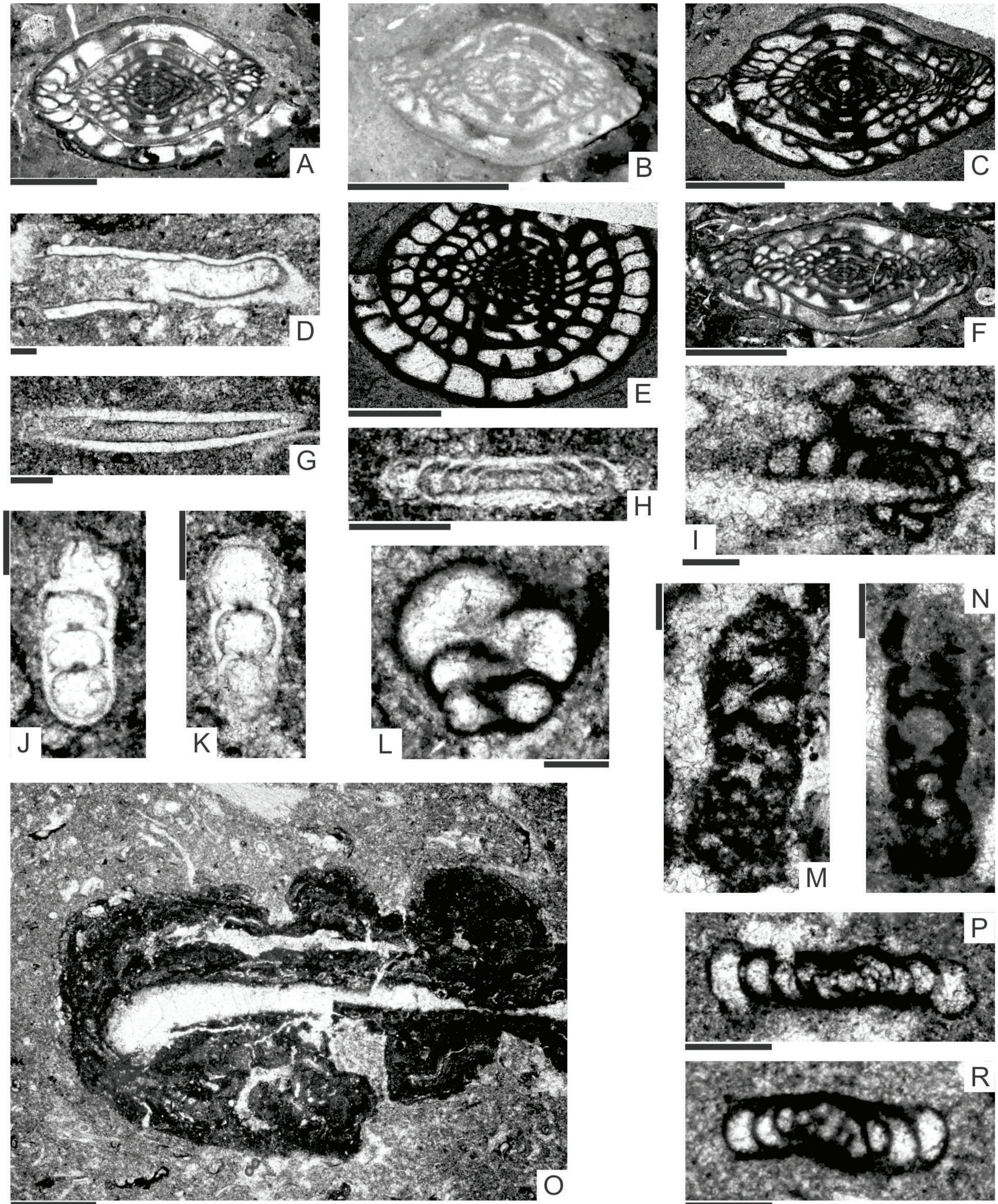

FIGURE 18. Foraminifers of the Bursum Formation at the Highway 60 roadcut (Fig. 4). **A, B**) *Triticites pinguis* Dunbar & Skinner, 1931 (sample AP 6). **C**) *Triticites* aff. *creekensis* Thompson, 1954 (sample AP 6). **D**) *Syzranella* sp. (sample AP 14). **E**) *Triticites* sp. (probably an oblique section of *T. creekensis*). **F**) *Triticites* aff. *parameeki* Wilde, 2006 (sample AP 6). **G**) *Syzrania* ex gr. *bella* Reitlinger, 1950 (sample AP 13). **H**) *Pseudovidalina (= Raphconilia) modificata* (Potievskaya, 1962) (sample AP 16). **I**) *Calcivertella* sp. (sample AP 8). **J, K**) *Nodosinelloides pinardae* Groves and Wahlman, 1997 (sample AP 15). **L**) *Globivalvulina mosquensis* Reitlinger, 1950 (sample AP 15). **M, N**) *Spireitlina conspecta* (Reitlinger, 1950) (M = sample AP 6, N = sample AP 7). **O**) Oncoid with cyanobacteria and *Palaeonubecularia* sp. (= "*Osagia*" of authors) (sample AP 14). **P, R)** *Hemigordius* ex gr. *harltoni* Cushman and Waters, 1928 (sample AP 12). A, B, C, E, F, O: scale bar = 1 mm; D, G-N, P, R: scale bar = 0.1 mm.

known locality in New Mexico preserving lungfish in their estivation burrows. These specimens formed the basis of a new species, *Gnathorhiza bothrotreta* (Berman, 1976), which was redescribed subsequently in greater detail with the discovery of additional specimens (Berman, 1979). The preservation of *Gnathorhiza* in estivation burrows has been considered irrefutable evidence of an ability to survive prolonged periods of severe drought and temporary loss of aquatic habitat (Romer

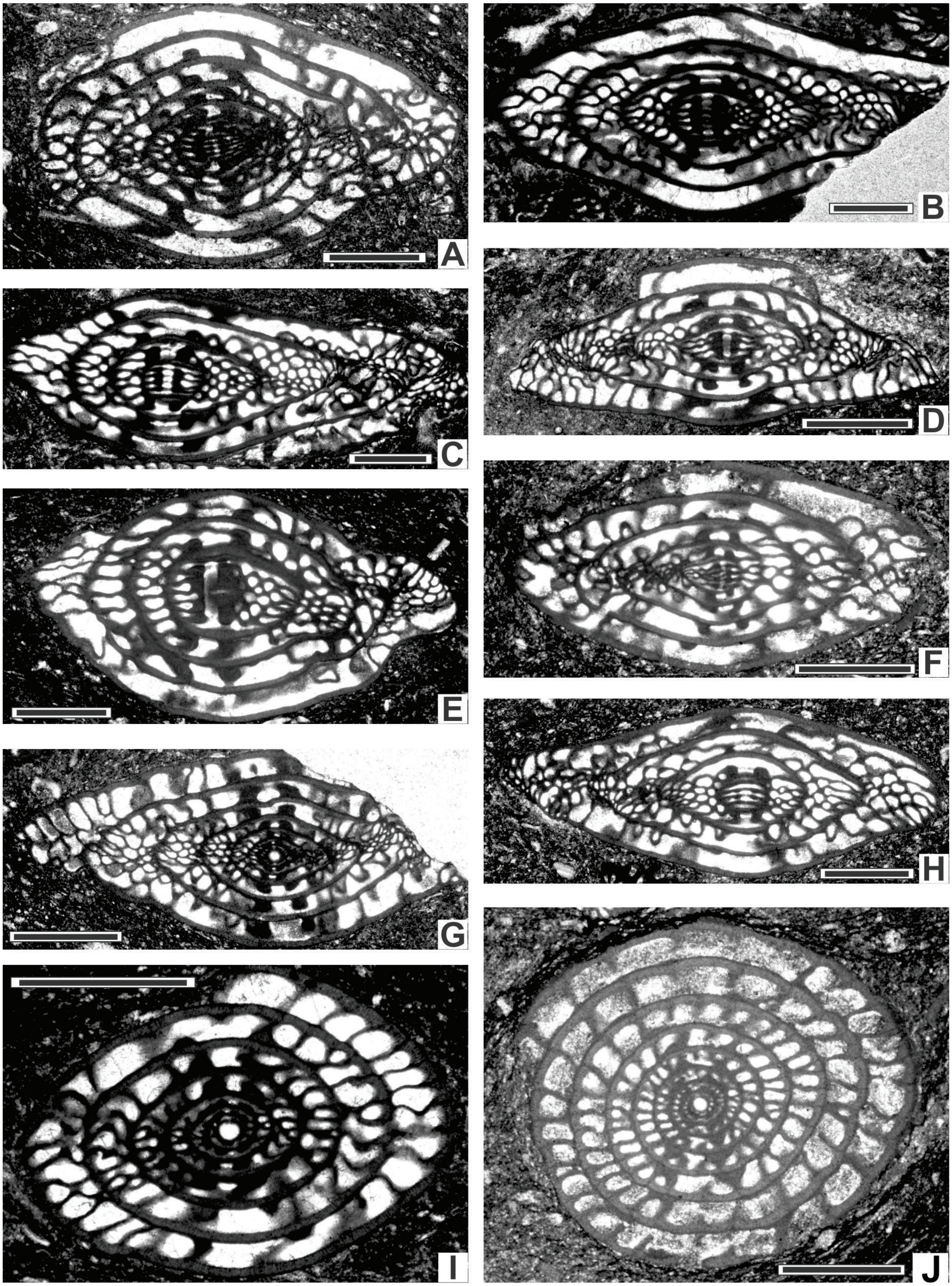

FIGURE 19. Selected fusulinids (triticitids) of the early Wolfcampian (Asselian) Bursum Formation of Priest Canyon (Fig. 4). Scale bars = 1 mm. **A, E, I**) *Triticites* cf. *cellamagnus* Dunbar and Condra, 1927. **A**) Subaxial section. Sample PC55-1. **E**) Subaxial section. Sample PC55b-2. **I**) Oblique subaxial section. Sample PC56a-1. **B-D**) *Leptotriticites* aff. *americanus* (Thompson, 1954). **B**) Subaxial section. Sample PC55-4. **C**) Subaxial section. Sample PC55b-1. **D**) Subaxial section. Sample PC55c-1a. **F-H**) *Leptotricites* aff. *hughesensis* (Thompson, 1954). **F**) Subaxial section. Sample PC55-2. **G**) Axial section. Sample PC56-2. **H**) Subaxial section. Sample PC55-3. **J**) *Triticites* or *Leptotriticites* sp. Transverse section. Sample PC56-1.

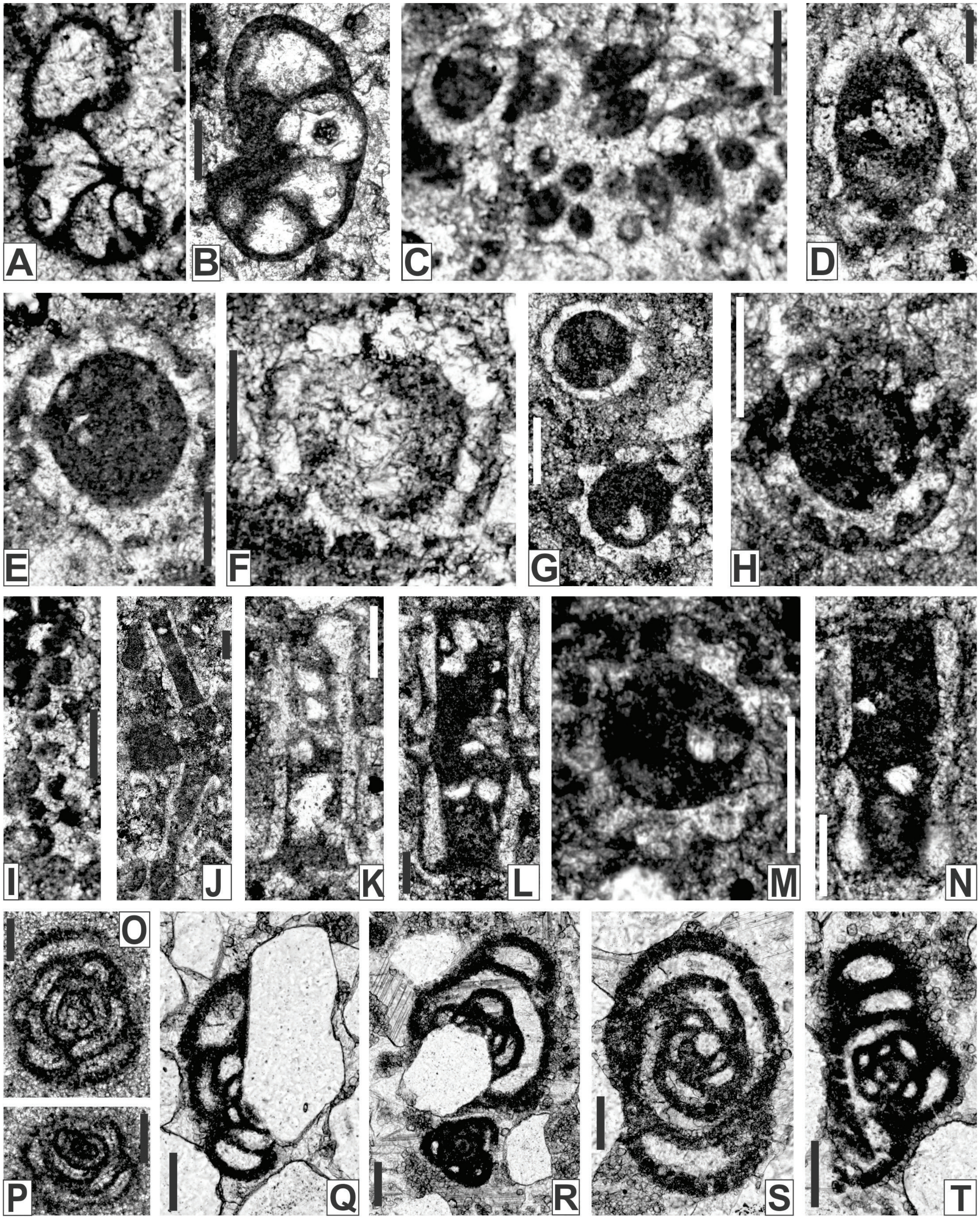

FIGURE 20. Thin section photographs of foraminifers and calcareous algae of the Torres Member, Los Vallos Formation, Yeso Group (samples ACE-Abo Cemetery) and basal San Andres Formation (samples DEC-Deer Canyon Preserve). Scale bars = 0.50 mm. **A**) *Globivalvulina* cf. *retroseptata* Vachard, Krainer and Lucas, 2015. Subtransverse section. Sample ACE 17-1. **B**) *Globivalvulina* cf. *praegraeca* Vachard, Krainer and Lucas, 2015. Subtransverse section. Sample ACE 17-2. **C, I**) Dasyclad indet. Tangential section. 3. Sample ACE 17-3. I, Sample ACE 17-13. **D-H, J-N**) *Velebitella americana* Vachard, Krainer and Lucas n. sp. **D**) Paratype. Oblique section. Sample ACE 17-7. **E**) Paratype. Transverse section. Sample ACE 17-5. **F**) Paratype. Transverse section. Sample ACE 17-6. **G**) Two paratypes. Transverse section. Sample ACE 17-9. **H**) Paratype. Transverse section. Sample ACE 17-12. **J**) Two paratypes. Subaxial sections. Sample ACE 17-15. **K**) Paratype. Subaxial section. Sample ACE 17-16. **L**) Holotype. Axial section. Sample ACE 17-17. **M**) Paratype. Transverse section. Sample ACE 17-18. **N**) Paratype. Axial section. Sample ACE 17-19. **O-P**) *Hemigordiellina* aff. *simplex* (Harlton, 1928) **O**) Sample DEC 86-2. **P**) DEC 86-5. **Q-T**) *Calcitornella interpsammica* Vachard, Krainer and Lucas n. sp. **Q**) Paratype. Sample DEC 99-2, 0.36mm. **R**) Top. Holotype; bottom paratype. Sample DEC 99-8. **S**) Paratype. DEC99-2. **T**) Paratype. Sample DEC99-1.

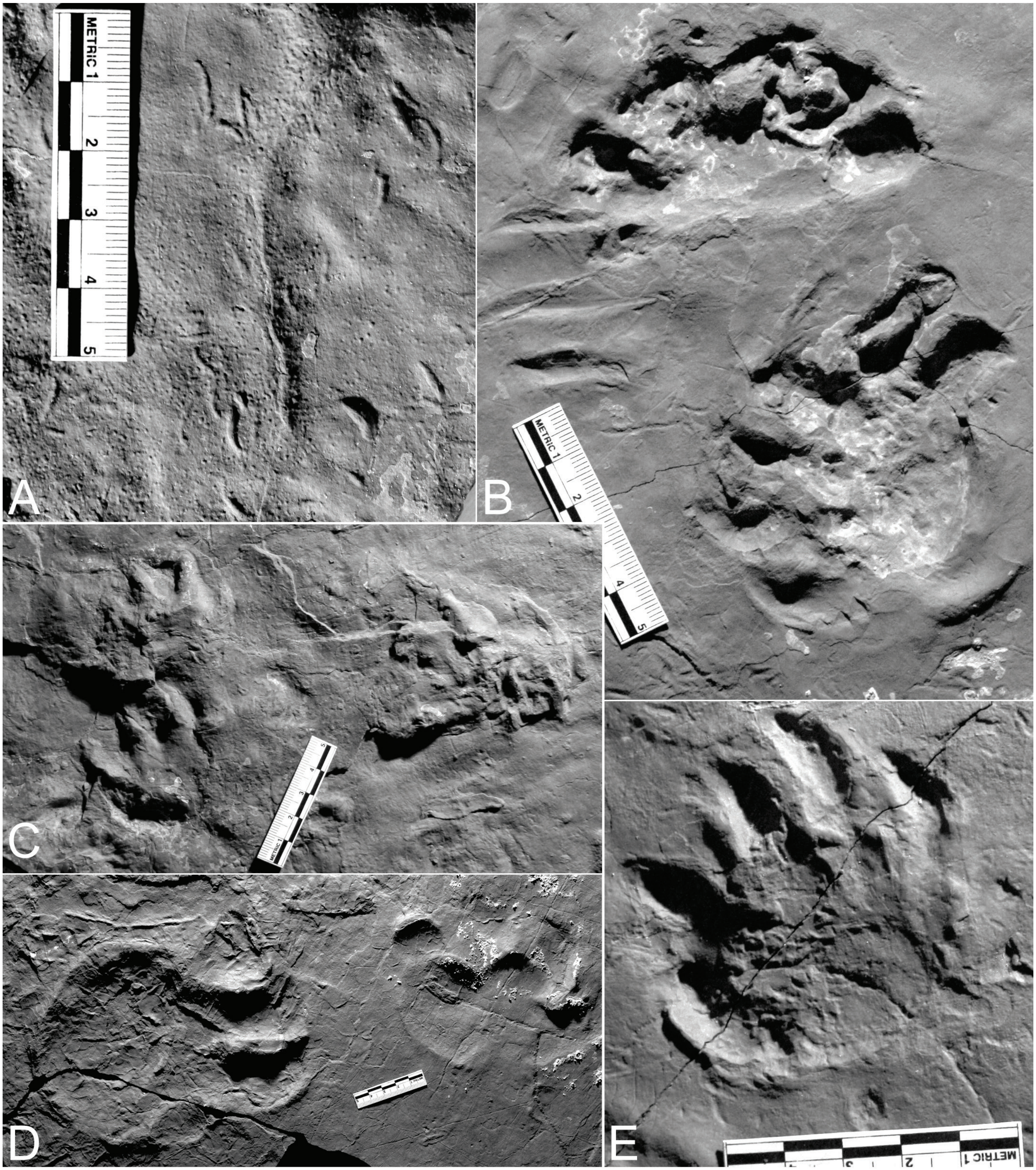

FIGURE 21. Selected tetrapod footprints from the Abo Formation at NMMNH locality 4510. **A**) *Dromopus lacertoides*, NMMNH P-31315. **B, C, E**) *Amphisauropus kablikae*, NMMNMH P-31343. **D**) *Ichniotherium cottae*, NMMNH P-51593.

and Olson, 1954). This interpretation is based on the estivation behavior of modern lungfish to survive conditions of extreme seasonal, summer drought.

From the same deposit, partial, articulated skulls of the amphibians *Trimerorhachis* and *Diplocaulus* were also reported (e.g., Fig. 22D). *Diplocaulus* has also been suspected of being capable of estivation, at least during early growth stages, but certainly capable of surviving severe drought conditions, even as adults (Olson, 1958, 1977). Although both genera were presumably aquatic-dependant, their presence in a freshwater

TABLE 1. Vertebrate fossil taxa from the Abo and Bursum formations in the Abo Pass area.

Dipnoi (lungfish)
Gnathorhiza bothrotreta Berman, 1976
Temnospondyli (amphibians)
Family Eryopidae
Eryops, species indet.
Family Dissorophidae
Indeterminate specimen
Family Trimerorhachidae
Trimerorhachis, species indet.
Lepospondyli (amphibians)
Family Diplocaulidae
Diplocaulus, species indet.
Family Phlegethontiidae
Phlegethonia, species indet.
Anthracosaurs (amphibians)
Subfamily Embolomeri
Synapsida ("pelycosaurs")
Family Ophiacodontidae
Ophiacodon, species indet.
Family Sphenacodontidae
Dimetrodon, species indet.
Indeterminate specimens

limestone layer suggests that this environment may have served as a temporary retreat from drier, surrounding conditions. Not previously reported from this site is the left half of the occipital margin of a skull table assignable to the amphibian family Dissorophidae (Fig. 22E) that was found on a weathered slope of red shale a few meters above the limestone layer. Specimens referable to several species within this family, although rarely encountered, have been described from widely scattered localities throughout the Permo-Carboniferous of New Mexico (Berman et al., 2015). Dissorophidae is only one of two Early Permian amphibian families considered to be highly terrestrial and adapted to a dry environment (DeMar, 1968). The other family, Trematopidae, has been reported from north-central New Mexico on the basis of a single occurrence of two closely associated skeletons from the Late Pennsylvanian, El Cobre Canyon Formation in El Cobre Canyon, Rio Arriba County, and assigned to a new genus and species, *Anconastes vesperus* Berman, Reisz and Eberth, 1987 (Berman et al., 1987).

The second site described by Berman (1993), about 0.8 km east of the first and at a slightly lower stratigraphic level, has yielded isolated, fragmentary elements preserved in a limestone-pebble conglomerate and included the amphibians *Platyhystrix* and *Phlegethontia*, and the basal synapsid ("pelycosaurs ") *Ophiacodon*. Both sites are very near the base of the Abo Formation.

From a third site in Torrance County, also near Abo Pass, a fragment of a *Dimetrodon* neural spine was identified and recorded by McKeighen et al. (2010) and subsequently described by Cantrell et al. (2011). This specimen is from the lower part of the Cañon de Espinoso Member of the Abo Formation.

Vertebrate remains were recovered from a fourth site (Table 1), reported here for the first time, in the Bursum Formation of Priest Canyon, Socorro County, about 2-km north of State Highway 60. In addition to an intercentrum and jaw fragment with empty alveoli most likely pertaining to *Eryops* and a centrum of an embolomere, identifiable, skeletal elements, predominately of the appendicular skeleton, appear to belong to two size classes of a small, basal synapsid (Fig. 22G-N). The bones were collected on a weathered slope over an area of a few square meters and are typically coated by a thin layer of an indurated, iron oxide with the superficial, laminar bone badly fractured. Only a single, articulated specimen was recovered – a string of five dorsal vertebrae (Fig. 22G-H). Whereas, typically synapsid vertebrae can be assigned with reasonable confidence to family and less often to genus, this specimen exhibits a combination of features attributed to the families Varanopseidae and Sphenacodontidae. All of the taxa described above from the Abo Pass area are either known to occur elsewhere in the Abo Formation or equivalent-aged deposits in New Mexico (Berman et al., 2015).

BIOSTRATIGRAPHY, AGE AND CORRELATION

Some of the paleontological data from Abo Pass, and regional correlations, indicate that all of the Permian strata exposed at Abo Pass are of Early Permian age (Fig. 23). The fusulinid assemblage of the Bursum section at Abo Pass points to a lower Wolfcampian (Newwellian) age (e.g., Wilde, 2006).

Compared with the biozonation of Lucas et al. (2015a) and Vachard et al. (2015), it is currently impossible to attribute the microfossil levels we recovered in the Yeso-Glorieta-San Andres at Abo Pass to a precise zone of the Yeso Group or San Andres Formation, which was dated as Leonardian (early Kungurian) by these authors. *G. retroseptata*, *G. novamexicana*, and undetermined Chlorophyta are known in the lower part of the Yeso Group but they re-appear in the entire San Andres Formation. *Velebitella americana* was not represented in the material of Vachard et al. (2015).

Hemigordiellina is especially abundant in the San Andres Formation, but this genus appears as early as the Late Mississippian (Serpukhovian) (Cózar et al., 2013) and is already abundant in the Late Pennsylvanian-earliest Permian. The *Calcitornella* documented here is a new species, but the similar species *Calcitornella elongata* was represented in both the Yeso Group and San Andres Formation.

Therefore, two local biozones might be defined at Abo Pass, a biozone with *Velebitella americana* n. sp. (Torres Member) and a zone with *Calcitornella interpsammica* n. sp. (uppermost Glorieta Sandstone). For correlation of the Yeso-San Andres interval at Abo Pass, we rely on the correlations of Vachard et al. (2015). We thus assign a middle-late Leonardian age to the Yeso-San Andres interval at Abo Pass (Fig. 23).

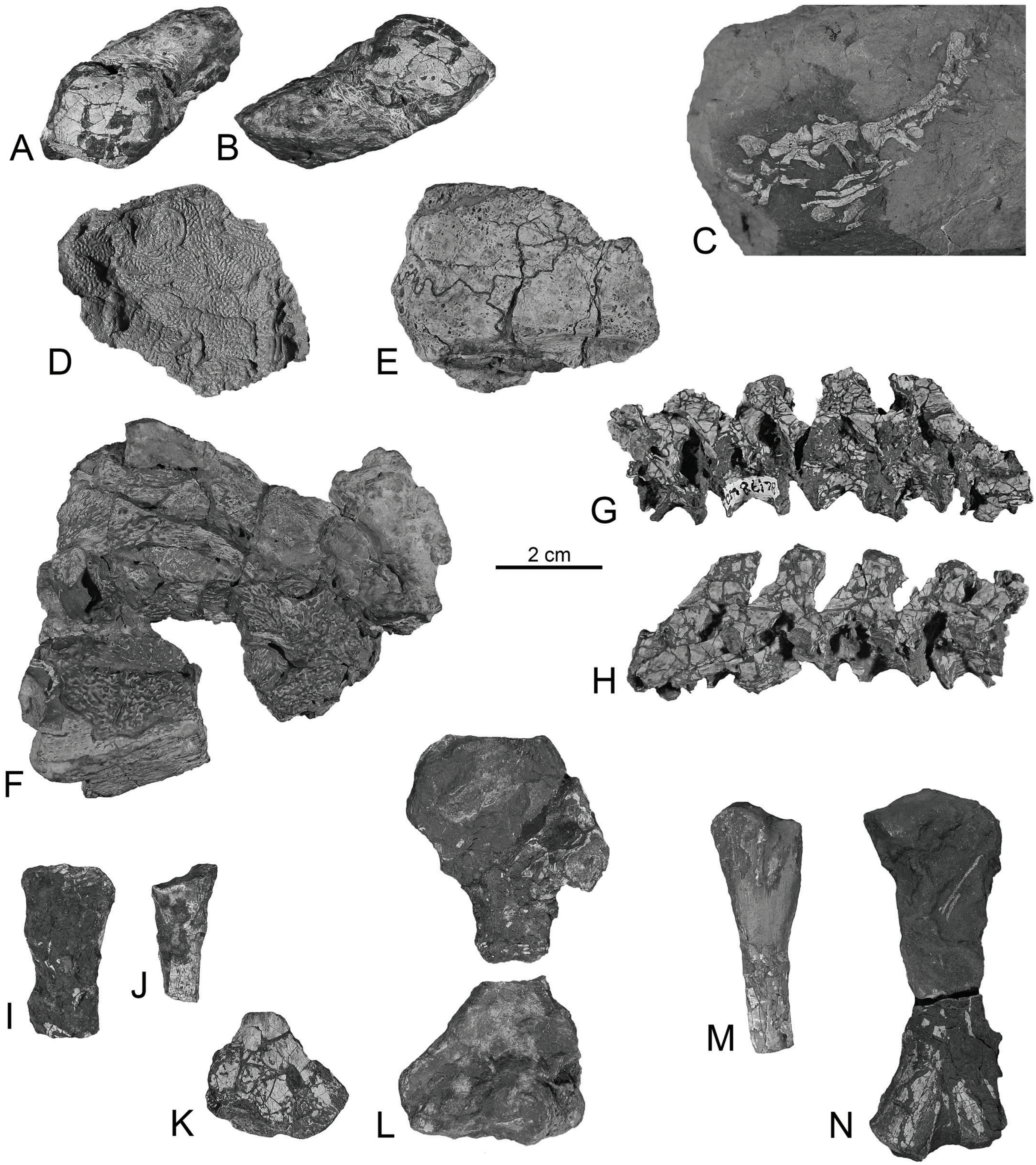

FIGURE 22. Selected fossil vertebrates of the Bursum and Abo formations. CM = Carnegie Museum of Natural History, Pittsburgh, Pennsylvania. **A-F**) from the Abo Formation at the Los Pinos locality of Berman (1993). **A**) *Gnathorhiza bothrotreta* Berman, 1976, CM 26558, skull in dorsal aspect, **B**) *Gnathorhiza bothrotreta* Berman, 1976, CM 26558, skull in right dorsolateral aspect, **C**) *Diplocaulus* sp., CM 26562, string of vertebrae, **D**) *Trimerorachis* sp., CM 38032, skull in dorsal aspect, anterior to left, **E**) dissorophid, CM 38038, left posterolateral corner of skull table, **F**) labyrinthodont, CM 26558, partial skull in dorsal aspect, **G-N**) basal (primitive) synapsid from the Bursum Formation at Priest Canyon. **G**) CM 86178, five articulated dorsal vertebrae in left lateral aspect, **H**) CM 86178, five articulated dorsal vertebrae in right lateral aspect, **I**) CM 89983, proximal end of radius of larger individual, **J**) CM 89982, proximal end of radius of smaller individual, **K**) CM 89981, distal end of humerus of smaller individual in dorsal aspect, **L**) CM 89980, humerus of larger individual in ventral aspect, **M**) CM 89985, proximal end of fibula, **N**) CM 89984, femur in dorsal aspect. All to the same scale.

CONCLUSIONS

The Permian stratigraphic section at Abo Pass is ~800 m thick and is assigned to the (ascending order): Bursum Formation (Red Tanks Member), Abo Formation (Scholle and Cañon de Espinoso Members), Yeso Group (Arroyo del Alamillo Formation and overlying Los Vallos Formation divided into Torres, Cañas and Joyita Members), Glorieta Sandstone and San Andres Formation.

The Bursum Formation is ~35-40 m thick and consists of interbedded red-bed siliciclastics (mudstone, sandstone and conglomerate) and marine limestones.

The Abo Formation is ~310 m thick and is siliciclastic red beds divided into the Scholle Member (~140 m of mudstone with channelized beds of crossbedded sandstone and conglomerate) overlain by the Cañon de Espinoso Member (~170 m of mudstone, siltstone and many thin beds of sandstone that display climbing ripple lamination).

The lower formation of the Yeso Group, the Arroyo de Alamillo Formation, is ~80 m of red-bed sandstone (mostly ripple and laminar with some gypsiferous beds) and very minor dolomite. The overlying Torres Member of the Los Vallos Formation is ~180 m thick and is mostly gypsiferous siltstone, claystone, gypsum and a few prominent beds of dolomite and gypsiferous sandstone. The overlying Cañas Member is 16-52 m thick, mostly gypsum and includes a few beds of gypsiferous siltstone and dolomite. The Joyita Member is ~21 m thick and is red-bed sandstone that is crossbedded, ripple laminated and, in some beds, gypsiferous.

The Glorieta Sandstone is ~78 m thick and consists of crossbedded, laminar and ripple quartzose sandstone.

In the Abo Pass area, the upper part of the San Andres Formation has been eroded, leaving up to 91 m of mostly limestone (lime mudstone).

Bursum deposition took place in a mixture of nonmarine fluvial and shallow marine environments in a tectonically active, mostly coastal setting.

Rivers that deposited the Abo Formation formed extensive muddy floodplains traversed by incised rivers early in Abo deposition that gave way to extensive sheetflooding later.

Yeso sedimentation began with dominantly eolian deposition on an arid coastal plain (Arroyo de Alamillo Formation) followed by deposits of coastal sabkhas, dunes and restricted marine embayments (Torres and Cañas Members of Los Vallos Formation). Yeso sedimentation ended with the Joyita Member of the Los Vallos Formation, which formed by eolian and fluvial processes during lowered sea level.

The Glorieta Sandstone is mostly of eolian origin, and the San Andres Formation represents shallow-marine deposits.

Fusulinids from the Bursum Formation at Abo Pass indicate it is early Wolfcampian in age. Microfossils from the Torres Member and Glorieta Sandstone document two new species named here, *Velebitella americana* and *Calcitornella interpsammica*.

The Abo Formation at Abo Pass yields fossil plants, tetrapod tracks and other trace fossils, as well as vertebrate fossils of Coyotean age.

FIGURE 23. Summary of the Permian section at Abo Pass showing lithostratigraphic nomenclature, approximate thickness of units and age assignments.

Local paleontological data coupled with regional correlations indicate that the Abo Formation is middle Wolfcampian-early Leonardian and the Yeso Group and Glorieta and San Andres formations are Leonardian in age.

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REFERENCES

Ahlbrandt, T.S., and Fryberger, S.G., 1982, Eolian deposits, *in* Scholle, P.A., and Spearing, S., eds., Sandstone Depositional Environments: Tulsa, American Association of Petroleum Geologists, Memoir 31, p. 11-47.

Baars, D.L., 1961, Permian strata of central New Mexico: New Mexico Geological Society, Guidebook 12, p. 113-120.

Baars, D.L., 1962, Permian System of Colorado Plateau: American Association of Petroleum Geologists Bulletin, v. 46, p. 149-218.

Baars, D.L., 1974, Permian rocks of north-central New Mexico: New Mexico Geological Society, Guidebook 25, p. 167-169.

Baars, D.L., 2000, The Colorado Plateau. A geologic history (revised and updated): Albuquerque, University of New Mexico Press, 254 p.

Bates, R.L., Wilpolt, R.H., MacAlpin, A.J., and Vorbe, G., 1947, Geology of the Gran Quivira quadrangle: New Mexico Bureau of Mines and Mineral Resources, Bulletin 26, 57 p.

Bauer, E.M., 2011, Depositional environments, sediment dispersal, and provenance of the lower Permian Glorieta Sandstone, central and northern New Mexico [M.S. thesis]: Las Cruces, New Mexico State University, 87 p.

Bauer, E.M., and Mack, G.H., 2011, Depositional environments, sediment dispersal, and provenance of the Lower Permian Glorieta Sandstone, central and northern New Mexico: New Mexico Geology, v. 33, p. 56.

Berman, D.S, 1976, Occurrence of *Gnathorhiza* (Osteichthyes: Dipnoi) in aestivation burrows in the Lower Permian of New Mexico with description of a new species: Journal of Paleontology, v. 50, p. 1034-1039.

Berman, D.S, 1979, *Gnathorhiza bothrotreta* (Osteichthyes: Dipnoi) from the Lower Permian Abo Formation of New Mexico: Annals of Carnegie Museum, v. 48, p. 211-230.

Berman, D.S, 1993, Lower Permian vertebrate localities of New Mexico and their assemblages: New Mexico Museum of Natural History and Science, Bulletin 2, p. 11-21.

Berman, D.S, Henrici, A.C., and Lucas, S.G., 2015, Pennsylvanian-Permian red bed localities of New Mexico and their assemblages: New Mexico Museum of Natural History and Science, Bulletin 68, p. 1-12.

Berman, D.S, Reisz, R.R., and Eberth, D.A., 1987, A new genus and species of trematopid amphibian from the Late Pennsylvanian of north-central New Mexico: Journal of Vertebrate Paleontology, v. 7, p. 252-269.

Blakey, R.C., and Gubitosa, R., 1984, Controls of sandstone body geometry and architecture in the Chinle Formation (Upper Triassic), Colorado Plateau: Sedimentary Geology, v. 38, p. 51-86.

Bogush, O.I., and Yuferev, O.V., 1966, Foraminifery karbona i permi Verkhoyanya [Carboniferous and Permian foraminifers from Verkhoiansk]: Akademiya Nauk SSSR, Sibirskoe Otdelenie, Institut Geologii i Geofiziki, p. 1-208 (in Russian).

Brookfield, M.E., and Silvestro, S., 2010, Eolian systems; *in* James, N.P., and Dalrymple, R.W., eds., Facies Models 4: GEOtext 6, Geological Association of Canada, p. 139-166.

Brose, R.J., 2011, The Permian Kaibab Formation of New Mexico: New Mexico Museum of Natural History and Science, Bulletin 53, p. 19-33.

Brose, R.J., Lucas, S.G., and Krainer, K., 2013, The Permian San Andres Formation in central and western New Mexico: New Mexico Museum of Natural History and Science, Bulletin 59, p. 213-226.

Cantrell, A.K., Suazo, T.L., McKeighen, K. L., Jr., McKeighen, H.W., Lucas, S.G., Harris, S.K., Spielmann, J.A., and Rinehart, L.F., 2011, *Dimetrodon* (Eupelycosauria: Sphenacodontidae) from the Lower Permian Abo Formation, Socorro and Torrance Counties, New Mexico: New Mexico Museum of Natural History and Science, Bulletin 53, p. 34-37.

Cather, S.M., Zeigler, K.E., Mack, G.H., and Kelley, S.A., 2013, Toward standardization of Phanerozoic stratigraphic nomenclature in New Mexico: Rocky Mountain Geology, v. 48, p. 101-124.

Chapman, F., and Howchin, W., 1905, A monograph of the Foraminifera of the Permo-Carboniferous of New South Wales: Proceedings of the Royal Society of Victoria, new series, v. 47, p. 175-189.

Colpitts, R.M., Jr., 1986, Geology of the Sierra de la Cruz area, Socorro County, New Mexico [M.S. thesis]: Socorro, New Mexico Institute of Mining and Technology, 166 p.

Colpitts, R.M., Jr., 1989, Permian reference section for southeastern Zuni Mountains, Cibola County, New Mexico: New Mexico Geological Society, Guidebook 40, p. 177-180.

Connell, S.D., 2008, Geologic map of the Albuquerque-Rio Rancho metropolitan area and vicinity, Bernalillo and Sandoval Counties, New Mexico: New Mexico Bureau of Geology and Mineral Resources, Geologic Map 78, scale 1:200,000.

Cózar, P., Vachard, D., Somerville, I.D., Medina-Varea, P., Rodríguez, S., and Said, I., 2013, The Tindouf Basin, a marine refuge during the Serpukhovian mass extinction (Carboniferous) in the northwestern Gondwana platform: Palaeogeography, Palaeoclimatology, Palaeoecology, v. 394, p. 12-28

Crespin, I., 1958, Permian Foraminifera of Australia: Commonwealth of Australia, Department of National Development, Bureau of Mineral Resources, Geology and Geophysics, v. 48, p. 1-207.

Cushman, J.A., and Waters, J.A., 1928, Some Foraminifera from the Pennsylvanian and Permian of Texas: Contributions from the Cushman Laboratory for Foraminiferal Research, v. 4, p. 31-55.

Dager, Z., 1978, Sur quelques Foraminifères nouveaux du Trias de Kocaeli, Turquie: Notes Laboratoire Paléontologique Université Genève, v. 4, p. 21-24.

Darton, N.H., 1922, Geologic structure of parts of New Mexico: U.S. Geological Survey, Bulletin 726-E, p. 173-275.

Darton, N.H., 1928, "Redbeds" and associated formations in New Mexico: U.S. Geological Survey, Bulletin 794, 356 p.

DeMar, R., 1968, The Permian labyrinthodont amphibian *Dissorophus multicinctus*, and adaptation and phylogeny of the family Dissorophidae: Journal of Paleontology, v. 42, p. 1211-1243.

DiMichele, W.A., Chaney, D.S., Nelson, W.J., Lucas, S.G., Looy, C.V., Quick, K., and Wang, J., 2007, A low diversity, seasonal tropical landscape dominated by conifers and peltasperms: Early Permian Abo Formation, New Mexico: Review of Palaeobotany and Palynology, v. 145, p. 249-273.

DiMichele, W.A., Chaney, D.S., Lucas, S.G., Kerp, H., and Voigt, S., 2013, Flora of the Lower Permian Abo Formation redbeds, western equatorial Pangea, New Mexico: New Mexico Museum of Natural History and Science, Bulletin 59, p. 265-288.

Dinterman, P.A., 2001, Regional analysis of the depositional environments of the Yeso and Glorieta formations (Leonardian), New Mexico [M.S. thesis]: Las Cruces, New Mexico State University, 165 p.

Dunbar, C.O., and Condra, G.E., 1927, The Fusulinidae of the Pennsylvanian System in Nebraska: Nebraska Geological Survey, second series, Bulletin 2, p. 1-135.

Dunbar, C.O., and Skinner, J.W., 1931, New fusulinid genera from the Permian of West Texas: American Journal of Science, v. 22, 5th series, p. 252-268.

Endo, R., 1969, Fossil algae from the Khao Phlong Phrab District in Thailand: Geology and Paleontology of Southeast Asia, v. 7, p. 33-85.

Fryberger, S.G., 1990, Eolian stratification, *in* Fryberger, S.G., Krystinik, L.F., and Schenk, C.J., eds., Modern and Ancient Eolian Deposits: Petroleum Exploration and Production: Denver, Rocky Mountain Section Society of Economic Paleontologists and Mineralogists, p. 4-1-4-12.

Gaillot, J., and Vachard, D., 2007, The Khuff Formation (Middle East) and time-equivalents in Turkey and South China: Biostratigraphy from Capitanian to Changhsingian times (Permian), new foraminiferal taxa, and palaeogeographical implications: Coloquios de Paleontología, v. 57, p. 37-223.

Girty, G.H., 1909, Paleontology of the Manzano Group: U.S. Geological Survey, Bulletin 380, p. 41-141.

Groves, J.R., and Wahlman, J.P., 1997, Biostratigraphy and evolution of Late Carboniferous and Early Permian smaller foraminifers from the Barents Sea (offshore Arctic Norway): Journal of Paleontology, v. 71, p. 758-779.

Harbour, R.L., 1970, The Hondo Sandstone Member of the San Andres Limestone of south-central New Mexico: U.S. Geological Survey, Professional Paper 700-C, p. C175-C182.

Harlton, B.H. 1928, Pennsylvanian Foraminifera of Oklahoma and Texas: Journal of Paleontology, v. 1, p. 305-311.

Hatchell, W.O., Blagbrough, J.W., and Hill, J.M., 1982, Stratigraphy and copper deposits of the Abo Formation, Abo Canyon area, central New Mexico: New Mexico Geological Society, Guidebook 33, p. 249-260.

Herrick, C.L., 1900, The geology of the White Sands of New Mexico: Journal of Geology, v. 8, p. 112–128.

Hunt, A.P., and Lucas, S.G., 2006, Permian tetrapod ichnofacies, *in* Lucas, S.G., Cassinis, G., and Schneider, J.W., eds., Non-marine Permian Biostratigraphy and Biochronology: London, Geological Society of London, Special Publication 265, p. 137-156.

Kelley, V.C., 1971, Geology of the Pecos country, southeastern New Mexico: New Mexico Bureau of Mines and Mineral Resources, Memoir 24, p. 7-13.

Keyes, C.R., 1915a, Conspectus of the geologic formations of New Mexico: Des Moines, privately published, 12 p.

Keyes, C.R., 1915b, Foundation of exact geological correlation: Iowa Academy of Science Proceedings, v. 22, p. 249-267.

Kochansky-Devidé, V., 1964, *Velebitella*, eine neue jungpaläzoische Diploporeengattung und ihre phylogenetischen Verhältnisse: Geoloski Vjesnik, v. 17, p. 135-142.

Kochansky-Devidé, V., and Gusic, I., 1971, Evolutions-Tendenzen der Dasycladaceen mit besonderer Berücksichtigung neuer Funde in Jugoslawien: Paläontologische Zeitschrift, v. 45, p. 82-91.

Kottlowski, F.E., Flower, R.H., Thompson, M.L., and Foster, R.W., 1956, Stratigraphic studies of the San Andres Mountains, New Mexico: New Mexico Bureau of Mines and Mineral Resources, Memoir 1, 132 p.

Krainer, K., and Lucas, S.G., 2004, The Upper Pennsylvanian Red Tanks Member of the Bursum Formation at Carrizo Arroyo, central New Mexico: Transition from shallow marine to nonmarine facies: New Mexico Museum of Natural History and Science, Bulletin 25, p. 53-70.

Krainer, K., and Lucas, S.G., 2009, Cyclic sedimentation of the Upper Pennsylvanian (lower Wolfcampian) Bursum Formation, central New Mexico: Tectonics versus glacioeustasy: New Mexico Geological Society, Guidebook 60, p. 167-182.

Krainer, K., and Lucas, S.G., 2013, The Pennsylvanian-Permian Bursum Formation in central New Mexico: New Mexico Museum of Natural History and Science, Bulletin 59, p. 143-160.

Krainer, K., and Lucas, S.G., 2010, Sedimentology of the Pennsylvanian-Permian Cutler Group and Lower Permian Abo Formation, northern New Mexico: New Mexico Museum of Natural History and Science, Bulletin 49, p. 25-36.

Krainer, K. and Lucas, S. G., 2015, Type section of the Lower Permian Glorieta Sandstone, San Miguel County, New Mexico: New Mexico Geological Society, Guidebook 66, p. 205-210.

Krainer, K., Lucas, S.G., and Brose, R.J., 2012, Reference section of the Lower Permian San Andres Formation, Sierra County, New Mexico: New Mexico Geological Society, Guidebook 63, p. 395-405.

Krainer, K., Lucas, S.G., and Vachard, D., 2009, The Upper Carboniferous Bursum Formation at Abo Pass, Socorro County, New Mexico: New Mexico Geological Society, Guidebook 60, p. 98-102.

Kues, B.S., and Giles, K.A., 2004, The late Paleozoic ancestral Rocky Mountains system in New Mexico, *in* Mack, G.H., and Giles, K.A., eds., The Geology of New Mexico: A Geologic History: New Mexico Geological Society, Special Publication 11 p. 95-136.

Kützing, F.T., 1843, Phycologia Generalis oder Anatomie, Physiologie und Systemkunde der Tange: Leipzig, F.A. Brockhaus, 458 p.

Lankester, E.R., 1885, Protozoa, *in* Traioll, T.S., ed., Encyclopedia Britannica 17 (ninth edition), p. 830-866.

Lee, W.T., 1909, The Manzano Group of the Rio Grande valley, New Mexico. Stratigraphy of the Manzano Group: U.S. Geologic Survey, Bulletin 389, p. 5-40.

Loeblich, A.R., and Tappan, H., 1964, Sarcodina, chiefly "Thecamoebians" and Foraminiferida, *in* Moore, R.C., ed., Treatise on Invertebrate Paleontology, Part C, Protista 2 : Geological Society of America and University of Kansas Press, 2 volumes, p. C1- C900.

Lucas, S.G., 2009, The Permian Chupadera Formation: New Mexico Geological Society, Guidebook 60, p. 38-39.

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

Lucas, S.G., and Krainer, K., 2005, Stratigraphy and correlation of the Permo-Carboniferous Cutler Group, Chama Basin, New Mexico: New Mexico Geological Society, Guidebook 56, p. 145-159.

Lucas, S.G., and Krainer, K., 2012, The Lower Permian Yeso Group in the Fra Cristobal and Caballo Mountains, Sierra County, New Mexico: New Mexico Geological Society, Guidebook 63, p. 377-394.

Lucas, S.G., and Zeigler, K.E., 2004, Permian stratigraphy in the Lucero uplift, central New Mexico: New Mexico Museum of Natural History and Science, Bulletin 25, p. 71-82.

Lucas, S.G., Krainer, K., and Brose, R.J., 2013a, The Lower Permian Glorieta Sandstone in central New Mexico: New Mexico Museum of Natural History and Science, Bulletin 59, p. 201-211.

Lucas, S.G., Krainer, K., and Colpitts, R.M., Jr., 2005, Abo-Yeso (Lower Permian) stratigraphy in central New Mexico: New Mexico Museum of Natural History and Science, Bulletin 31, p. 101-117.

Lucas, S.G., Krainer, K., and Vachard, D., 2015a, The Lower Permian Hueco Group, Robledo Mountains, New Mexico: New Mexico Museum of Natural History and Science, Bulletin 65, p. 43-96.

Lucas, S.G., Krainer, K., and Vachard, D., 2015b, The Permian-Triassic stratigraphic section at the Sandia Mountain Natural History Center, Bernalillo County, New Mexico: New Mexico Museum of Natural History and Science, Bulletin 67, p. 77-87.

Lucas, S.G., Krainer, K., and Voigt, S., 2013b, The Lower Permian Yeso Group in central New Mexico: New Mexico Museum of Natural History and Science, Bulletin 59, p. 181-199.

Lucas, S.G., Lerner, A. J., and Haubold, H., 2001, First record of *Amphisauropus* and *Varanopus* in the Lower Permian Abo Formation, central New Mexico: Hallesches Jahrbuch für Geowissenschaften, v. B23, p. 69–78.

Lucas, S.G., Spielmann, J.A., and Lerner, A.J., 2009, The Abo Pass tracksite: A Lower Permian tetrapod footprint assemblage from central New Mexico: New Mexico Geological Society, Guidebook 60, p. 285–290.

Lucas, S.G., Krainer, K., Voigt, S., Berman, D.S., and Henrici, A., 2014, The Lower Permian Abo Formation in the northern Sacramento Mountains, southern New Mexico: New Mexico Geological Society, Guidebook 65, p. 287-302

Lucas, S.G., Krainer, K., Chaney, D.S., DiMichele, W.A., Voigt, S., Berman, D.S., and Henrici, A.C., 2012a, The Lower Permian Abo Formation in the Fra Cristobal and Caballo Mountains, Sierra County, New Mexico: New Mexico Geological Society, Guidebook 63, p. 345-376.

Lucas, S.G., Harris, S.K., Spielmann, J.A., Berman, D.S, Henrici, A.C., Krainer, K., Rinehart, L.F., DiMichele, W.A., Chaney, D.S., and Kerp, H., 2012b, Lithostratigraphy, paleontology, biostratigraphy and age of the upper Paleozoic Abo Formation near Jemez Springs, northern New Mexico, USA: Annals of the Carnegie Museum, v. 80, p. 323-350.

Lucas, S.G., Krainer, K., Chaney, D.S., Dimichele, W. A., Voigt, S., Berman, D.S., and Henrici, A.C., 2013c, The Lower Permian Abo Formation in central New Mexico: New Mexico Museum of Natural History and Science, Bulletin 59, p. 161-179.

Lucas, S.G., Krainer, K., and Kues, B.S., 2002, Type section of the Upper Carboniferous Bursum Formation, south-central New Mexico, and the Bursumian Stage: New Mexico Geological Society, Guidebook 53, p. 179-192.

Lucas, S.G., Rowland, J.M., Kues, B.S., Estep, J.W., and Wilde, G.L., 1999, Uppermost Pennsylvanian and Permian stratigraphy and biostratigraphy at Placitas, New Mexico: New Mexico Geological Society, Guidebook 50, p. 281-292.

Mack, G.H., and Bauer, E.M., 2014, Depositional environments, sediment dispersal, and provenance of the Early Permian (Leonardian) Glorieta Sandstone, central New Mexico: New Mexico Geological Society, Guidebook 65, p. 261-271.

Mack, G.H., and Dinterman, P.A., 2002, Depositional environments and paleogeography of the Lower Permian (Leonardian) Yeso and correlative formations in New Mexico: The Mountain Geologist, v. 39, p. 75-88.

Mack, G.H., and Suguio, K., 1991, Depositional environments of the Yeso

Formation (Lower Permian), southern Caballo Mountains, New Mexico: New Mexico Geology, v. 13, p. 45-49.

Mamet, B., and Roux, A., 1975, Dasycladales dévoniennes et carbonifères de la Téthys occidentale: Revista Española de Micropaleontología, v. 7, p. 245-295.

Mamet, B., and Roux, A., 1978, Algues viséennes et namuriennes du Tennessee (Etats-Unis): Revue de Micropaléontologie, v. 21, p. 68-97.

Massa, D., and Vachard, D., 1979, Le Carbonifère de Lybie Occidentale: biostratigraphie et micropaléontologie; position dans le domaine téthysien d'Afrique du Nord: Revue Institut Français Pétrole, v. 34, p. 3-65.

McKeighen, H.W., Mckeighen, K.L., Jr., Lucas, S.G., Spielmann, J.A., and Harris, S.K., 2010, *Dimetrodon* (Eupelycosauria: Sphenacodontidae) from the Lower Permian Abo Formation in Torrance County, New Mexico: New Mexico Geology, v. 32, p. 65-66.

Milner, S., 1978, Genesis, provenance, and petrography of the Glorieta Sandstone of eastern New Mexico: New Mexico Bureau of Mines and Mineral Resources, Circular 165, 25 p.

Montenat, C., de Lapparent, A.F., Lys, M., Termier, H., Termier, G., and Vachard, D., 1977, La transgression permienne et son substrat écambrien dans le Jebel Akhdar, montagnes d'Oman, Péninsule Arabique: Annales de la Société géologique du Nord, v. 96, p. 239-258.

Myers, D. A., 1973, The upper Paleozoic Madera Group in the Manzano Mountains, New Mexico: U.S. Geological Survey, Bulletin 1372-F, 13 p.

Myers, D.A., 1977, Geologic map of the Scholle quadrangle, Socorro, Valencia, and Torrance Counties, New Mexico: U.S. Geological Survey, Geologic Quadrangle Map GQ-1412, scale 1:24,000.

Myers, D.A., 1988, Stratigraphic distribution of some Pennsylvanian fusulinids from the Wild Cow and Bursum formations, Manzano Mountains, New Mexico: U.S. Geological Survey, Professional Paper 1446-B, 42 p.

Needham, C.E., and Bates, R.L., 1943, Permian type sections in central New Mexico: Geological Society of America Bulletin, v. 54, p. 1653-1668.

NMBGMR (New Mexico Bureau of Geology and Mineral Resources), 2003, Geologic map of New Mexico: Socorro, New Mexico Bureau of Geology and Mineral Resources, scale 1:500,000.

Olson, E.C., 1958, Fauna of the Vale and Choza. 14. Summary, review and integration of geology and the faunas: Fieldiana Geology, v. 20, p. 387-448.

Olson, E.C., 1977, Permian lake fauna: a study in community evolution: Palaeontological Society of India Journal, v. 20, p. 146-163.

Oviatt, C.G., 2010, Geology of the Abo 7.5-minute quadrangle, Torrance County, New Mexico: New Mexico Bureau of Geology and Mineral Resources, Open-file Digital Geologic Map OF-GM, scale 1:24,000.

Oviatt, C.G., 2011, Geologic map of the Punta de Agua quadrangle, Torrance County, New Mexico: New Mexico Bureau of Geology and Mineral Resources, Open-file Digital Geologic Map OF-GM 220, scale 1:24,000.

Papenfuss, G.F., 1955, Classification of the algae, *in* Kessel, E.L., ed., A century of progress in the natural sciences 1853-1953: California Academy of Science, San Francisco, p. 115-224.

Pascher, A., 1931, Systematische Übersicht über die mit Flagellaten in Zusammenhang stehenden Algenreihen und Versuch einer Einreihung dieser Algenstämme in die Stämme des Pflanzenreiches: Beihefte zum Botanischen Centralblatt, v. 48, p. 317-332.

Pettijohn, F.J., Potter, P.E., and Siever, R., 1987, Sand and Sandstone (2nd ed.): New York, Springer-Verlag, 553 p.

Pia, J. von, 1920, Die Siphoneae verticillatae vom Karbon bis zur Kreide: Abhandlungen der zoologisch-botanischen Gesellschaft in Wien, v. 11, p. 1-263.

Pille, L. and Vachard, D., 2011, Diploporaceae (calcareous green algae dasycladales) from the late Visean (Mississippian) of Montagne Noire (southern France): Revue de Micropaléontologie, v. 54, p. 1-58.

Potievskaya, P.D., 1962, Predstaviteli nekotorykh semeystv melkikh foraminifer iz nizhney permi severozapadnoy okrainy Donbassa (Representatives of some families of Lower Permian smaller foraminifers from the northwestern border of the Donets Basin): Akademiya Nauk Ukrainskoi SSR, Instituta Geologicheskikh Nauk, Trudy, seriya stratigrafii i paleontologii, v. 44, p. 49-94 (in Russian).

Reitlinger, E.A., 1950, Foraminifery srednekamennougolnykh otlozhenii tsentralnoi chasti Russkoi platformy (isklyuchaya semeistvo Fusulinidae) (Foraminifera from Middle Carboniferous deposits of the central part of the Russian Platform (excepting the family Fusulinidae): Akademiya Nauk SSSR, Trudy Instituta Geologicheskikh Nauk, 126, geologichevskaya seriya 47, p. 1-126 (in Russian, French translation BRGM no. 1456).

Romer, A.S., and Olson E.C., 1954, Aestivation in a Permian lungfish: Breviora, v. 30, p. 1-8.

Schneider, J.W., Lucas, S.G., Wernebrurg, T., and Rössler, R., 2010, Euramerican Late Pennsylvanian/Early Permian arthropleurid/tetrapod associations–-implications for the habitat and paleobiology of the largest terrestrial arthropod: New Mexico Museum of Natural History and Science, Bulletin 49, p. 49-70.

Scott, L.A., Elrick, M., Connell, S., and Karlstrom, K., 2005, Preliminary geologic map of the Scholle Quadrangle, Valencia, Torrance, and Socorro counties, New Mexico: New Mexico Bureau of Geology and Mineral Resources, Open-file Digital Geologic Map OF-GM 99, scale 1:24,000.

Seager, W.R., and Mack, G.H., 2003, Geology of the Caballo Mountains, New Mexico: New Mexico Bureau of Geology and Mineral Resources, Memoir 49, 136 p.

Shuysky, V.P., 1987, Sistema nadrodovykh taksonov iskopaemykh izvestkovykh vodoroslei classa Siphonophyceae (Systematics of suprageneric taxa of fossil calcareous algae of the class Siphonophyceae); *in* Amon E.O., ed., Geologiya i paleontologiya Urala (Geology and Paleontology of Urals): Akademiya Nauk SSSR, Uralskii Nauchnyi Tsentr, Institut Geologii i Geokhimii (1986), p. 33-40 (in Russian).

Stanesco, J.D., 1991, Sedimentology and depositional environments of the Lower Permian Yeso Formation, northwestern New Mexico: U.S. Geological Survey Bulletin 1808, p. M1-M12.

Thompson, M.L., 1954, American Wolfcampian fusulinids: University of Kansas, Paleontological Contributions, Protozoa, v. 5, p. 1-226.

Vachard, D., 1977, Etude stratigraphique et micropaléontologique (algues et foraminifères) du Viséen de la Montagne Noire (Hérault, France): Mémoires Institut Géologique Université Louvain, v. 29, p. 111-195.

Vachard, D., 1990, New data on foraminifera, algae and pseudo-algae of the Viséan and Bashkirian (Lower-Middle Carboniferous) from Northeast Thailand: Geologisches Jahrbuch, v. B73, p. 91-109.

Vachard, D., and Beckary, S., 1991, Algues et foraminifères bachkiriens des coal balls de la Mine Rosario (Truebano, Léon, Espagne): Revue de Paléobiologie, v. 10, p. 315-357.

Vachard, D., and Krainer, K., 2001, Smaller foraminifers of the Upper Carboniferous Auernig Group, Carnic Alps (Austria/Italy): Rivista Italiana di Paleontologia e Stratigrafia, v. 107, p. 14-168.

Vachard D., Krainer, K., and Lucas, S.G., 2015, Kungurian (late Early Permian) algae, microproblematica, and smaller foraminifers from the Yeso Group and San Andres Formation (New Mexico; USA): Palaeontologia Electronica, v. 18.1, 21A.

Vdovenko, M.V., Rauzer-Chernousova, D.M., Reitlinger, E.A., and Sabirov, A.A., 1993, Spravochnik po sistematike melkikh foraminifer paleozoya (Guide for the systematics of Paleozoic smaller foraminifers): Rossiiskaya Akademiya Nauk, Komissiya po Mikropaleontologii, "Nauka", p. 1-128 (in Russian).

Wilde, G.L., 2006, Pennsylvanian-Permian fusulinaceans of the Big Hatchet Mountains, New Mexico: New Mexico Museum of Natural History and Science, Bulletin 38, 331 p.

Wilpolt, R.H., and Wanek, A.A., 1951, Geology of the region from Socorro and San Antonio east to Chupadera Mesa, Socorro County, New Mexico: U.S. Geological Survey, Oil and Gas Investigations Map OM-121.

Wilpolt, R.H., MacAlpin, A.J., Bates, R.L., and Vorbe, G., 1946, Geologic map and stratigraphic sections of Paleozoic rocks of Joyita Hills, Los Piños Mountains, and northern Chupadera Mesa, Valencia, Torrance, and Socorro Counties, New Mexico: U.S. Geological Survey Oil and Gas Investigations, Preliminary Map 61.

Wood, G.H., Jr. and Northrop, S.A., 1946, Geology of the Nacimiento and San Pedro Mountains and adjacent plateaus in parts of Sandoval and Rio Arriba Counties, New Mexico: U.S. Geological Survey, Oil and Gas Investigations Preliminary Map 57.

Woodward, L.A., 1987, Geology and mineral resources of Sierra Nacimiento and vicinity, New Mexico: New Mexico Bureau of Mines & Mineral Resources, Memoir 41, 84 p. and map, scale 1:100,000.

Zheng, H., 1991, Some porcelaneous Foraminifera from the late Paleozoic Taiyuan Formation of North China : Acta Micropaleontologica Sinica, v. 8, p. 281-288 (in Chinese with English abstract).

APPENDIX

Here, we describe two new microfossil taxa from Abo Pass. Abbreviations for algae: H = height of a segment, D = outer diameter, d = inner diameter, s = thickness of wall, p = diameter of pores (= diameter of laterals), p ext = outer diameter of laterals, p int = inner diameter of laterals. Abbreviations for foraminifers, D = diameter, w = width, s = wall thickness, h = height of last whorl or height of last chamber. All type specimens (holotypes and paratypes) are housed in the collection of the New Mexico Museum of Natural History and Science and have NMMNH catalogue numbers.

Phylum CHLOROPHYCOPHYTA Papenfuss, 1955

Class CHLOROPHYCEAE Kützing, 1843

Order DASYCLADALES Pascher, 1931

Family DIPLOPORACEAE (Pia, 1920) ex Shuysky (1987) emend. Pille & Vachard, 2011

Tribe VELEBITELLEAE Vachard, 1977

Genus *Velebitella* Kochansky-Devidé, 1964

Type species: *Velebitella triplicata* Kochansky-Devidé, 1964.

Synonym: *Pseudovelebitella* Mamet & Roux, 1978.

Definition: Thallus cylindrical segmented. Laterals L1, phloiphorous, metaspondylous, in tuft at the top of a vestibule. Each verticil of laterals is restricted to the central third of the segments.

Composition: *Velebitella triplicata* Kochansky-Devidé, 1964; *V. simplex* Kochansky-Devidé, 1964; "*V.* n. sp." sensu Kochansky-Devidé and Gusic, 1971 (see Vachard in Montenat et al., 1977); *V. simplicissima* Vachard in Massa & Vachard, 1979; *V. emaciata* Vachard, 1990; *V. emaciata* sensu Vachard and Beckary, 1991 (another species); *V. americana* n. sp. Excluded species: *V.*? *pareyni* Mamet & Roux, 1975 (= *Windsoporella* according to Pille and Vachard, 2011); non *V. similis* Endo, 1969 (a fragment without any taxonomic significance).

Occurrence: Bashkirian of Spain and northern Thailand. Moscovian of Libya. Gzhelian of Croatia and Slovenia. Early-Middle Permian of Croatia, Slovenia, Greece, Tunisia, Turkey, Armenia, Iran, Afghanistan, Northern Thailand. Late Permian of Oman and Croatia.

Velebitella americana Vachard, Krainer & Lucas, n. sp.

Fig. 20D-H, J-N

Etymology: First *Velebitella* discovered in America.

Holotype: Fig. 20L. Sample ACE 17-17. NMMNH P-74839 from NMMNH locality 10181.

Paratypes: Fig. 20D-H, J-K, M-N. NMMNH P-74840-74848 from NMMNH locality 10181.

Type locality: Abo Pass (New Mexico, USA).

Type level: Yeso Group (early Kungurian).

Diagnosis: A *Velebitella* with elongate segments, cup-shaped laterals in the verticils, wall moderately broad, and a vestibule formed by invagination of the central cell.

Description: The segments are rectangular in longitudinal section, and circular in transverse section. No thalli with several segments were oberved (but they are also rare in *V. simplex* and *V. triplicata*). The central cavity is cylindrical and relatively broad. The wall is moderately thick (more than *V. simplex*, less than *V. triplicata*). The vestibule is represented by an invagination of the central cavity (consequently, the inner surface of the thallus is slightly curved with a form in accolade). The central third is relatively trapezoidal but not prominent. Each tuft probably includes 6-8 laterals. The laterals are cup shaped, with a small, cylindrical, proximal part and wide cupule-like distal part. There are probably 19-12 vestibules and tufts in each verticil. Measurements of holotype H = 0.650 mm; D = 0.270 mm; d = 0.130/0.200 mm; s = 0.035/0.070 mm; p ext = 0.050 mm; p int = 0.015 mm; measurements of type material, H = 0.300-1.500 mm; D = 0.150-0.400 mm; d = 0. 080-0.300 mm; s = 0.035-0.070 mm; p ext = 0.045-0.100 mm, p int = 0.005-0.015 mm.

Material: Approximately 20 specimens.

Repository of the types: Collection of the New Mexico Museum of Natural History and Science.

Comparison: *V. americana* is somewhat similar to *V. simplex* in the shape of the segments and relatively thin walls; but it differs from this species, and also from all the Paleotethyan species by the cup-shaped laterals, whereas the other species have acrophorous or phloiophorous laterals.

Occurrence: Leonardian/early Kungurian (Yeso Group).

Class MILIOLATA Lankester, 1885

Order CORNUSPIRIDA Vdovenko et al., 1993

Family CALCIVERTELLIDAE Reitlinger in Vdovenko et al., 1993 emend. Gaillot and Vachard, 2007

Subfamily CALCIVERTELLINAE Loeblich and Tappan, 1964

Genus *Calcitornella* Cushman and Waters, 1928.

Type species: *Calcitornella elongata* Cushman and Waters, 1928

Description: Test attached, bilocular. The spherical proloculus is followed by an undivided tubular chamber, first coiled and then uncoiled and undulating. Wall porcelaneous, thick. Aperture at the end of the tubular chamber.

Synonyms: *Ammovertella* (pars), *Stacheia* (pars), *Nubecularia* (pars).

Composition: *Calcitornella elongata* Cushman and Waters, 1928; *C. collisformis* Zheng, 1991; *Stacheia dickinsi* Crespin, 1958; *Calcitornella gebzeensis* Dager, 1978; *Tolypammina glomospiroides* Bogush and Yuferev, 1966; *C. grandizigzaga* Zheng, 1991; *C. heathi* Cushman and Waters, 1928; *Nubecularia stephensi* Chapman and Howchin, 1905; *Ammovertella vaga* Reitlinger, 1950.

Remarks: The attached genera of Miliolata dominated during the Pennsylvanian-early Cisuralian before the dominance of the free Miliolata. Contrary to the great majority of the groups of Paleozoic foraminifers, their radiation center is most probably located in North America rather than in the Paleotethys. The holotype is Virgilian in age, in the Cisco Group of Texas.

Occurrence: Bashkirian to Anisian; ?Ladinian (acme in Late Pennsylvanian-early Cisuralian); cosmopolitan (at least from Bashkirian to Midian).

Calcitornella interpsammica Vachard, Krainer and Lucas n. sp.

Fig. 20Q-T

Etymology: Living between (inter) the sand grains (psammos).

Holotype: Fig.20R (top). Sample DEC 99-8. NMMNH P-74849 from NMMNH locality 10182.

Paratypes: Fig. 20Q-R (bottom), S-T. NMMNH P-74850-74853 from NMMNH locality 10182.

Type locality: Abo Pass (New Mexico, USA).

Type level: San Andres Formation (early Kungurian).

Diagnosis: A species of *Calcitornella* found in situ in the conditions of an interpsammic life position, and also characterized by few whorls, weak deviations of axis, and relatively thick walls.

Description: Some specimens including the holotype are found encrusting quartz grains (Fig. 20Q-R) and are surrounded by other quartz grains (Fig. 20Q-T). The coiling, first streptospiral, occasionally becomes planispiral in the two last whorls (Fig. 20S-T). Measurements of holotype, D = 0.400 mm; w = 0.350 mm; s = 0.025 mm; s = 0.025 mm; number of whorls: 3; h = 0.080 mm; proloculus diameter = 0.035/0.070 mm ; measurements of type material, D = 0.200-0.500 mm; w = 0.150-0400 mm; s = 0.010-0.025 mm, number of whorls: 2-4; h = 0.040-0.100 mm; proloculus diameter = 0.050 mm.

Material: A dozen specimens.

Repository of the types: Collection of the New Mexico Museum of Natural History and Science.

Comparison: Some sections are similar to sections of *Calcitornella heathi* (compare Fig. 20S and Vachard et al., 2015, pl. 6, fig. 8b) but the dimensions and ages differ, as well as the systems of attachment (compare with Vachard and Krainer, 2001, pl. 12, figs. 13, 20). *Calcitornella glomospiroides* has more whorls, more irregularly arranged thicker walls, and a different system of attachment.

Occurrence: Early Kungurian (San Andres Formation).