

THE PERMIAN-TRIASSIC STRATIGRAPHIC SECTION AT THE SANDIA MOUNTAIN NATURAL HISTORY CENTER, BERNALILLO COUNTY, NEW MEXICO

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Abstract—The Sandia Mountain Natural History Center (SMNHC) is 52 hectares (128 acres) of land on the eastern dip slope of the Sandia Mountains at Cedar Crest, Bernalillo County. We describe the Permian and Triassic bedrock of the SMNHC, assigning it to the (ascending order) Permian Joyita Member of the Los Vallos Formation (Yeso Group), Glorieta Sandstone and San Andres Formation, and the Triassic Moenkopi Formation and Shinarump Formation (Chinle Group). Only the uppermost 43 m of the Yeso Group are described, and these are reddish-brown, fine- to medium-grained, mostly ripple-laminated sandstone. The Glorieta Sandstone consists of horizontally laminated, ripple-laminated and trough-crossbedded, fine-grained quartz sandstone divided into a lower part (31 m thick) and an upper part (25 m thick) separated by 12.5 m of limestone of the San Andres Formation. The intercalated San Andres strata are mostly muddy limestone and dolomitic limestone and contain a microfauna of algae and foraminifers of likely late Leonardian (Kungurian) age. Above the Glorieta Sandstone, another 25 m of San Andres Formation cap the Lower Permian strata. They are disconformably overlain by siliciclastic red beds of the Middle Triassic Moenkopi Formation, which are 64 m thick, largely covered, but where exposed consist of grayish-red mudstone and horizontally laminated and trough-crossbedded litharenitic sandstone. The uppermost 8 m of the stratigraphic section at the SMNHC are limestone-clast conglomerates and crossbedded quartz sandstone at the base of the Upper Triassic Shinarump Formation of the Chinle Group. The Permian-Triassic stratigraphic units exposed at the SMNHC represent arid coastal plain (Yeso), eolian (Glorieta), marine carbonate platform (San Andres) and fluvial (Moenkopi, Shinarump) depositional environments

INTRODUCTION

The Sandia Mountain Natural History Center (SMNHC) is 52 hectares (128 acres) of forested land located on the eastern dip slope of the Sandia Mountains at Cedar Crest in Bernalillo County (Fig. 1). The center is managed as a cooperative project of the Albuquerque Public Schools and the New Mexico Museum of Natural History and Science to educate school-age students about the local environment, notably biology and forest ecology. In an effort to add geology to that educational program, we have undertaken a detailed study of the bedrock geology of the center, which is a homoclinal stratigraphic section of sedimentary rocks of Permian and Triassic age (Figs. 2-3). Here, we present stratigraphic, petrographic and micropaleontological data on this section to interpret its age and sedimentary history.

GEOLOGIC SETTING

The SMNHC is located on the eastern dip slope of the Sandia Mountains, a fault-block mountain range that borders the eastern edge of the Rio Grande rift at Albuquerque. The Sandia Mountains are a Basin-and-Range uplift of late Cenozoic age. The steep, west face of the range is a granite massif that faces the Albuquerque basin of the Rio Grande rift and towers about 1.6 km (one mile) above the alluvial fans, terrace and river floodplain deposits upon which the city of Albuquerque is built (e.g., Kelley and Northrop, 1975; Connell, 2008).

Along the western face of the Sandia Mountains, the granitic core of the range is capped by Pennsylvanian strata—the Sandia and Gray Mesa formations of Early to Middle Pennsylvanian age. These strata thus rest directly on the Late Proterozoic (~1.46 Ga) granite at the “great unconformity.” (Locally, some thin slivers of Mississippian strata may be present: Read et al., 1999). The dip slope of the eastern side of the Sandia Mountains is largely mantled by these Pennsylvanian strata as well as by Upper Pennsylvanian strata of the Atrasado Formation (Krainer et al., 2011; Lucas et al., 2014). Down the dip slope, near its topographic base, younger Permian and Mesozoic strata are present. The SMNHC occupies a position relatively low on the eastern dip slope of the Sandia Mountains, so the exposed bedrock is composed of sedimentary rocks of Permian and Triassic age (Fig. 1).

GEOLOGIC FEATURES OF THE SMNHC

We identify three basic features of the geology of the SMNHC:

1. Permian-Triassic strata low on the dip slope of the Sandia uplift. These are the bedrock exposed at the SMNHC and form a series of approximately north-south-oriented cuestas and strike valleys (Figs.

1-3). These strata are the focus of this article.

2. Surficial deposits of colluvium and alluvium. These are of Pleistocene-Holocene age and fill valleys and mantle upland surfaces in and around the SMNHC (Fig. 1). We did not study these rocks in detail.

3. Exotic blocks and fossils of Pennsylvanian age. These are pieces of Pennsylvanian limestone, most or all from the Gray Mesa Formation, that have been transported down the dip slope to lie on outcrops of younger bedrock. We briefly discuss below two such outcrops in the SMNHC.

DISPLACED PENNSYLVANIAN ROCKS

Pennsylvanian strata are exposed to the west of the SMNHC along the crest and upper dip slope of the Sandia Mountains (Karlstrom et al., 2000; Read et al., 2000). However, two notable places in the SMNHC contain displaced pieces of Pennsylvanian bedrock. The first is located on the southern end of the Mud Springs Trail, where a block of Pennsylvanian limestone is next to the trail. This block contains a large tooth of the shark *Petalodus* (Fig. 4). The block is loose and has brown nodules of chert, unlike any of the local Permian limestone bedrock, and clearly was brought down the canyon during a flood.

We took a sample from this limestone block that is a bryozoan wackestone to floatstone that contains abundant fragments of bryozoans, some > 1 cm in size. Echinoderm fragments, brachiopods, ostracodes, spicules and smaller foraminifers (*Bradyina*, *Syzrania*, *Tubertina* and *Tetraxis*) are subordinate fossils in the block. A few fusulinids are also present. The microfacies and fossil assemblage of the block is typical of the Gray Mesa Formation.

Near the northeastern corner of the SMNHC, what instructors at the center call the “fossil area,” is a debris of cobbles of Pennsylvanian limestone full of crinoids, brachiopods, bryozoans and rugose corals. These cobbles are loose alluvium, not bedrock. The bedrock here is Triassic (Chinle Group) mudstone.

LITHOSTRATIGRAPHY, PETROGRAPHY AND PALEONTOLOGY

The stratigraphic succession at the SMNHC has been well established by geologic mapping (Kelley and Northrop, 1975; Karlstrom et al., 2000; Read et al., 2000) (Fig. 1). The section (Fig. 2) dips about 20-25 degrees to the east-southeast and consists of Permian strata of the Yeso Group (Yeso Formation of earlier usage), Glorieta Sandstone and San Andres Formation. Triassic strata belong to the Moenkopi Formation and Chinle Group. Here, we described the lithostratigraphy,

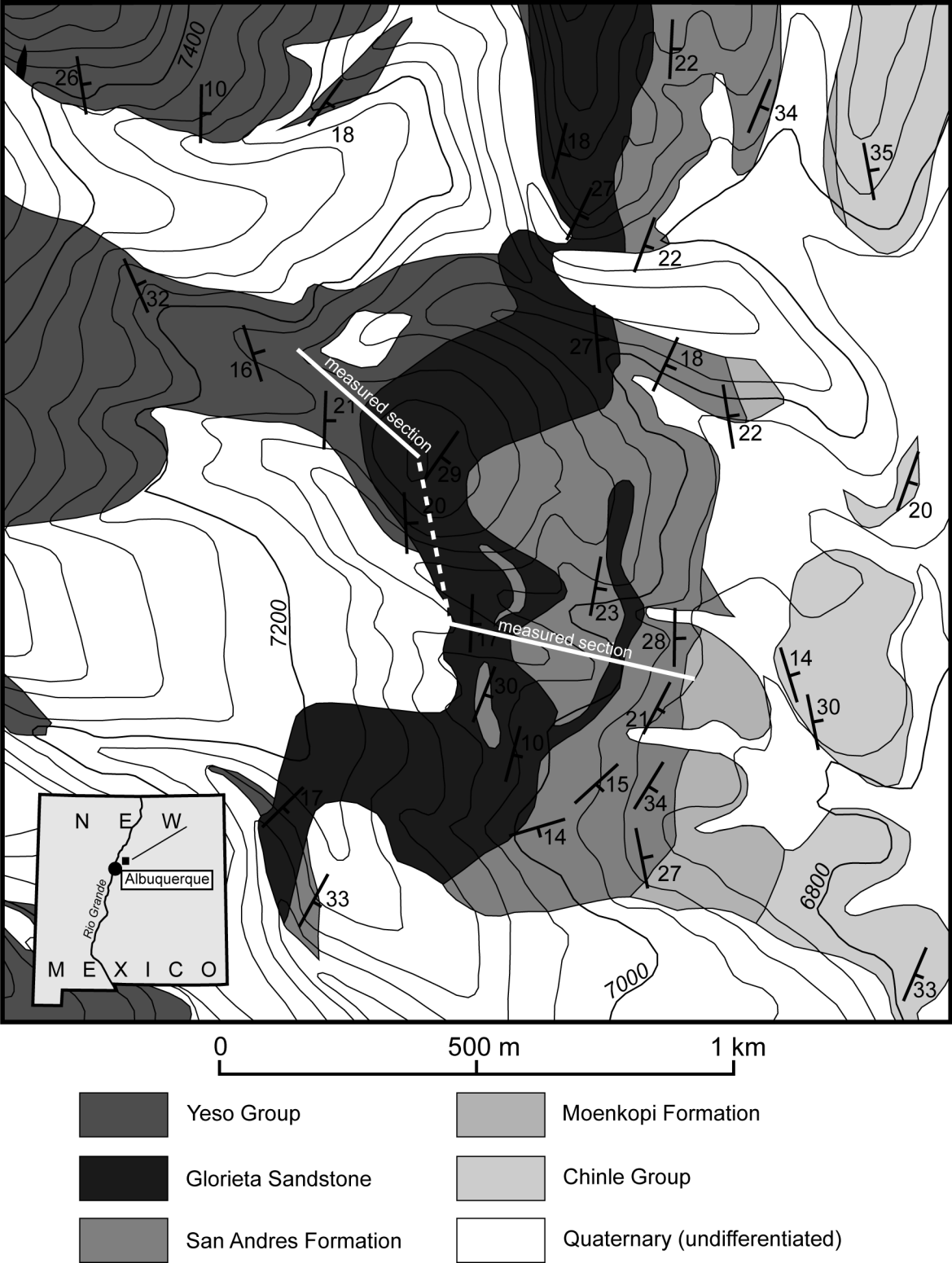


FIGURE 1. Index map and geologic map of the SMNHC and vicinity showing location of measured section in Figure 2. Geology after Karlstrom et al. (2000) and Read et al. (2000).

petrography and paleontology of these strata.

Permian Strata

Yeso Group (Joyita Member, Los Vallos Formation)

The oldest bedrock exposed at the SMNHC (actually, just west of its western border) are red beds at the top of the Lower Permian Yeso

Group. We measured 43 m of these strata, which we assign to the Joyita Member of the Los Vallos Formation (cf. Lucas et al., 2005, 2013b). These are ripple-laminated and laminated, tabular bedded sandstones. These strata are not well exposed except along steep stream banks and in the Mud Springs Trail pathway (Fig. 3A). They crop out as thin ledges and blocks of reddish-brown sandstone or underlie reddish-brown slopes covered by soil and vegetation.

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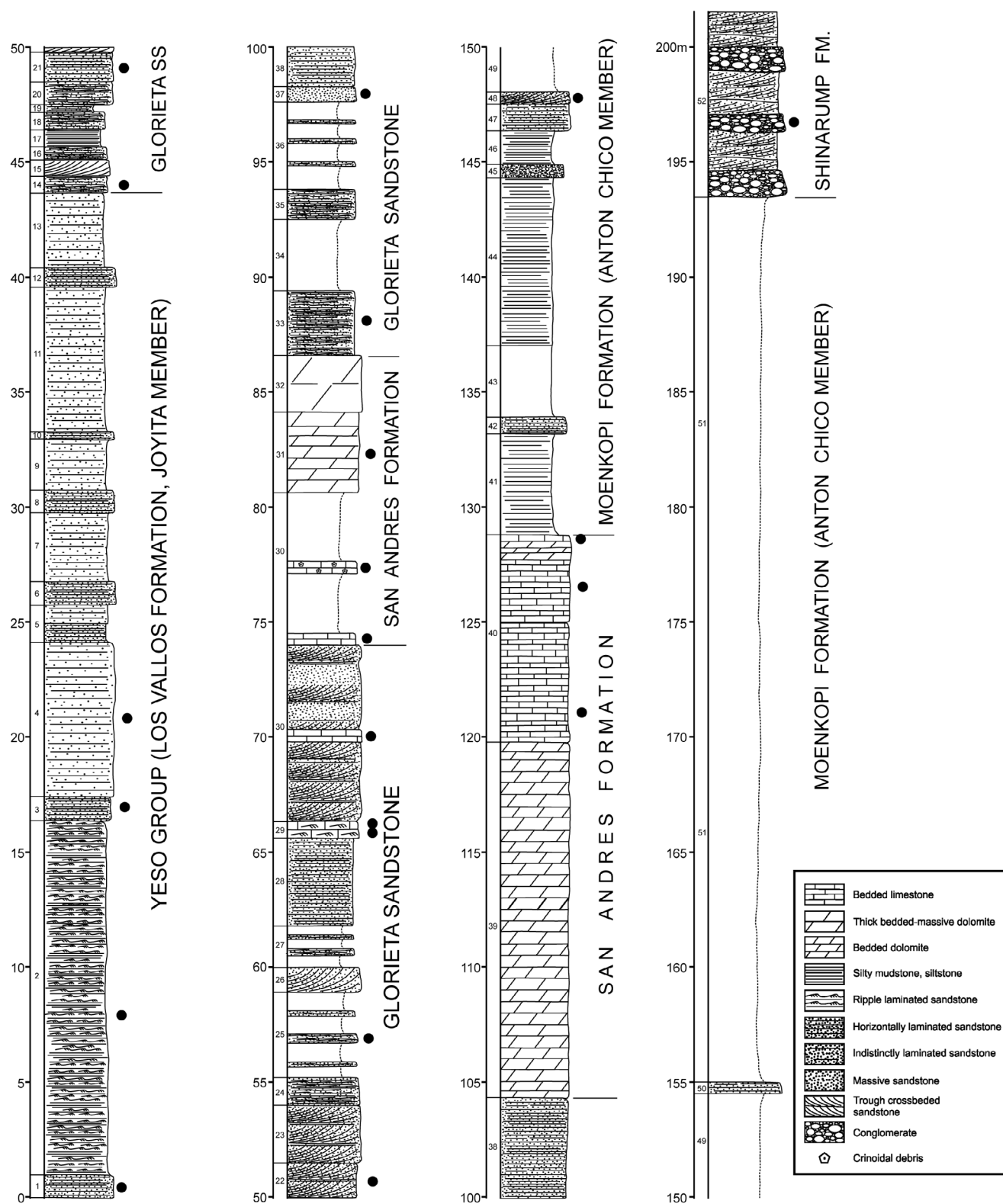


FIGURE 2. Measured stratigraphic section of Permian and Triassic rocks in the SMNHC. See Figure 1 for location of section.



FIGURE 3. Selected photographs of outcrops of Permian and Triassic rocks at the SMNHC. **A**, outcrop near base of section (Figure 2, unit 2) in Mud Springs Trail of thin-bedded and ripple-laminated sandstone of Joyita Member of Los Vallos Formation (Yeso Group). **B**, contact of lower part of Glorieta Sandstone and intercalated limestone of San Andres Formation. Rock hammer sits on contact, which is on north end of Mud Springs Trail, and is equivalent to the upper part of unit 30 in Figure 2. **C**, thick-bedded limestone of upper part of San Andres Formation. **D**, laminated sandstone of Anton Chico Member of Moenkopi Formation. **E**, limestone-pebble conglomerate at base of Shinarump Formation (Figure 2, unit 52). **F**, cross-bedded sandstone of Shinarump Formation (Figure 2, unit 52). Rock hammer is 28 cm long.

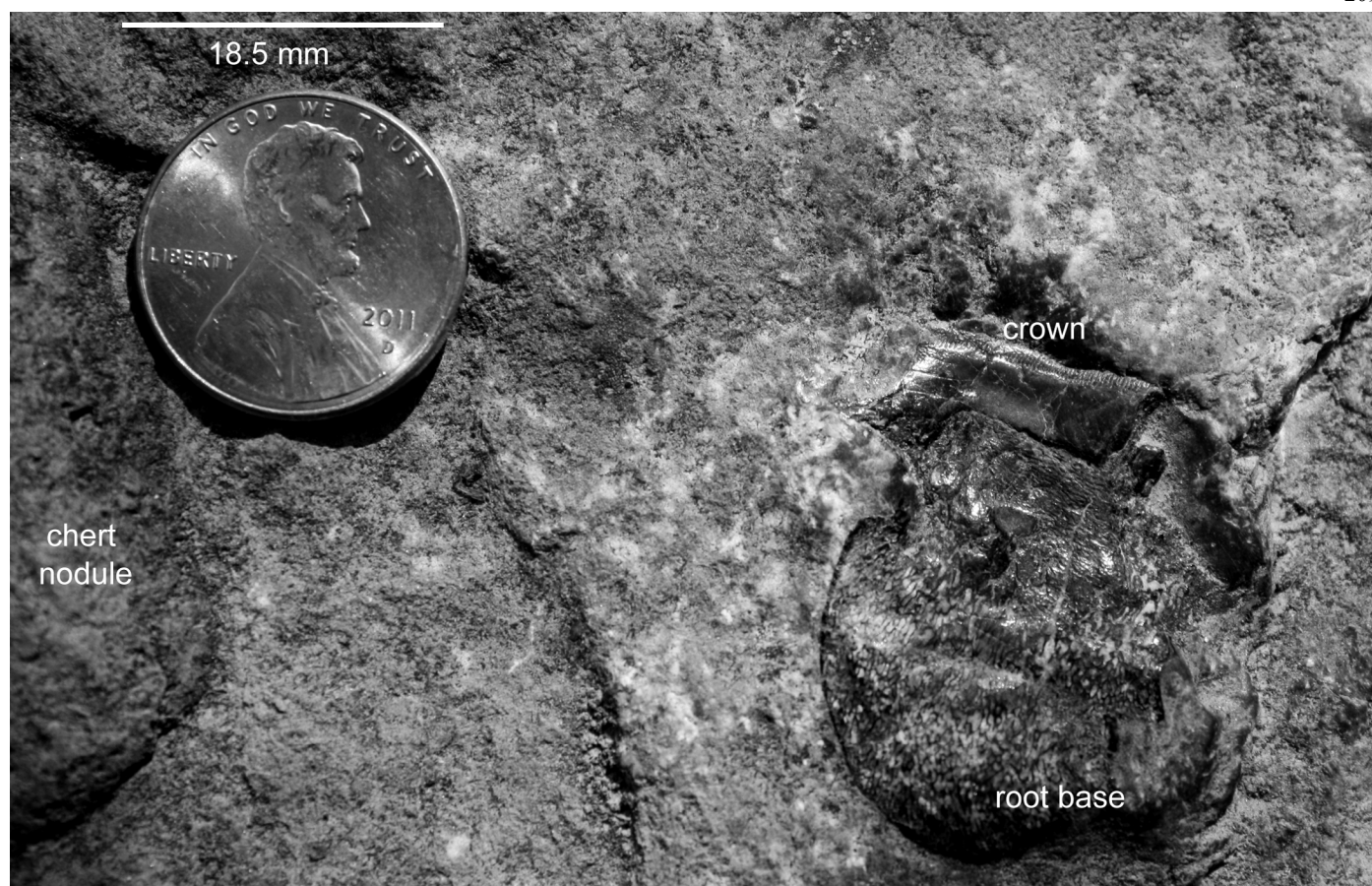


FIGURE 4. Tooth of the shark *Petalodus* in displaced block of Gray Mesa Formation on southern limb of Mud Springs Trail.

Joyita Member strata at the SMNHC are composed of different types of fine- to medium-grained sandstone: (1) horizontally laminated sandstone, (2) ripple-laminated sandstone and (3) massive sandstone. Very fine grained (grain size mostly 0.05 to 0.1 mm) sandstone (Fig. 2, units 1, 2, 3, 7) is well sorted. The detrital grains are subangular to subrounded and dominantly monocrystalline quartz (Fig. 5A, C). Polycrystalline quartz is very rare. Feldspars are a common constituent and include grains displaying polysynthetic twins (plagioclase) and perthitic grains as well as untwinned feldspars (Fig. 5B). Many feldspar grains are slightly altered. Detrital mica grains are common and represented by muscovite and green biotite. Rarely, chert grains are observed. Accessory grains are tourmaline, zircon and opaque minerals. The detrital grains are cemented by quartz, which occurs as authigenic overgrowths on detrital grains. The sandstone is red due to diagenetically formed, very fine hematite. Fine-grained sandstone (grain size 0.1 to 0.3 mm) is well sorted, and most grains are subrounded to rounded, but a few grains are well rounded. Micas are less common than in the very fine grained sandstone (unit 4).

Another sandstone type is characterized by a bimodal grain-size distribution. A few larger, mostly subrounded grains (0.2-1mm) of mono- and polycrystalline quartz, as well as detrital feldspar (microcline, untwinned and perthitic, rare polysynthetic twinned plagioclase) grains float in very fine grained sandstone (grain size mostly 0.05-0.1 mm). Sandstone with a bimodal grain-size distribution is probably of eolian origin.

Glorieta Sandstone

In central New Mexico, the Glorieta Sandstone overlies the Yeso Group (Lucas et al., 2013a, b). It is mostly yellowish brown, very mature quartzarenite that forms a cliff, ledge or cuesta. Less than 100 m thick, the Glorieta Sandstone is locally interbedded with beds of San Andres Formation lithology, which include limestone and gypsum.

At the SMNHC, the Glorieta Sandstone is divided into a lower part and an upper part by an interval of limestone and dolomitic limestone of the San Andres Formation (Figs. 2, 3B). The lower part of the Glorieta Sandstone is 31 m thick and composed of horizontally

laminated sandstone, ripple-laminated sandstone, trough-crossbedded sandstone and a few thin covered intervals. Two thin intervals of limestone (Fig. 2, units 29-30) are also present. The upper part of the Glorieta Sandstone is 17.5 m thick and consists of horizontal and ripple-laminated sandstone, rare massive sandstone and covered intervals.

In thin section (Figs. 5D-H, 6A-D), sandstone of the Glorieta Sandstone is commonly fine-grained with grain size ranging mostly from 0.1 to 0.3 mm. Sandstone is commonly well sorted, and the detrital grains are subrounded to rounded; larger grains may be well rounded. Monocrystalline quartz is by far the most common grain type. Other grain types such as polycrystalline quartz, chert, feldspar, rock fragments and micas (muscovite) are rare. Polycrystalline quartz also includes grains composed of elongate crystals ("stretched metamorphic"), indicating a metamorphic source rock. Detrital feldspar grains are fresh or appear as altered grains, some of which may be completely altered to clay minerals forming a "pseudomatrix." Most common is potassium feldspar (including microcline and untwinned grains), and plagioclase is rare. Accessory minerals are tourmaline and zircon.

Due to their mineralogical composition, most of the sandstones plot into the field of quartzarenite, and some into the field of subarkose using the classification scheme of Pettijohn et al. (1987). At the SMNHC, sandstone from the uppermost sandstone interval of Glorieta lithology contains a higher amount of detrital feldspar, particularly microcline, and this sandstone plots into the field of sublitharenite.

In the Glorieta Sandstone at the SMNHC, different types of sandstone can be distinguished with regard to their diagenesis:

1. Sandstone containing small amounts of matrix and cemented by quartz that occurs as overgrowths. Calcite cement is very rare or absent.
2. Sandstone locally containing small amounts of matrix and cemented by coarse, blocky calcite cement that replaces feldspar and quartz grains. Quartz overgrowths on detrital quartz grains are absent.
3. Sandstone in which many quartz grains display thin authigenic overgrowths; the remaining pore space is filled with calcite cement that may randomly replace detrital feldspar and quartz grains.

The textural parameters (sorting, rounding) and mineralogical

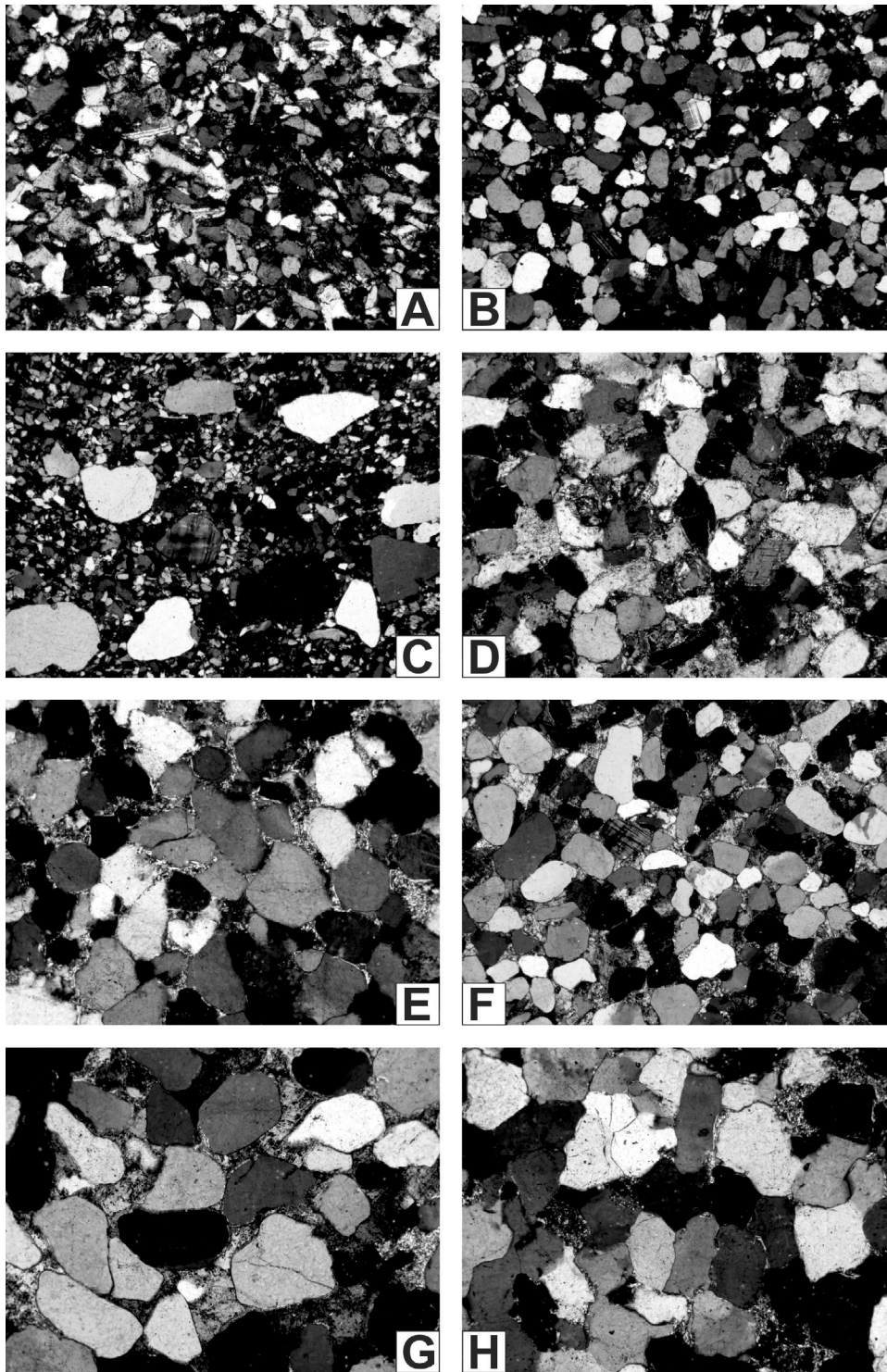


FIGURE 5. Thin section photographs of sandstones of the Yeso Group (Joyita Member of the Los Vallos Formation) (A-C) and Glorieta Sandstone (D-H). All photos under polarized light. **A**, fine-grained, well-sorted sandstone composed of abundant monocrystalline quartz grains, many detrital feldspars and a few micas (muscovite). Unit 3, width of photograph is 1.2 mm. **B**, fine- to medium-grained, well-sorted sandstone composed of subrounded to rounded grains of mostly monocrystalline quartz, and many twinned and untwinned feldspar grains (mostly potassium feldspars, rare plagioclase). Unit 4, width of photograph is 3.2 mm. **C**, sandstone displaying bimodal grain size distribution. In the finer grained “matrix” composed of angular to subangular grains, mostly quartz, larger, subrounded to rounded grains of quartz and subordinate feldspar, are floating. Unit 5, width of photograph is 3.2 mm. **D**, fine-grained sandstone composed of abundant monocrystalline, rare polycrystalline quartz and a few detrital feldspar grains. The sandstone is well sorted; the detrital grains are mostly subrounded and cemented by blocky calcite. A few quartz grains display authigenic overgrowths. Unit 14, width of photograph is 1.2 mm. **E**, fine-grained, well-sorted sandstone composed of subrounded to rounded grains, mostly monocrystalline quartz, rare polycrystalline quartz and feldspar and small amounts of matrix. Unit 21, width of photograph is 1.2 mm. **F**, fine-grained, well-sorted sandstone containing rounded grains of monocrystalline quartz, rare polycrystalline quartz and feldspar. The detrital grains are cemented by calcite. Unit 22, width of photograph is 3.2 mm. **G**, detail of F. Unit 22, width of photograph is 1.2 mm. **H**, fine-grained, well-sorted sandstone composed of subrounded to rounded grains of monocrystalline quartz cemented by quartz as authigenic overgrowths on detrital quartz grains. Small amounts of matrix are present. Unit 26, width of photograph is 1.2 mm

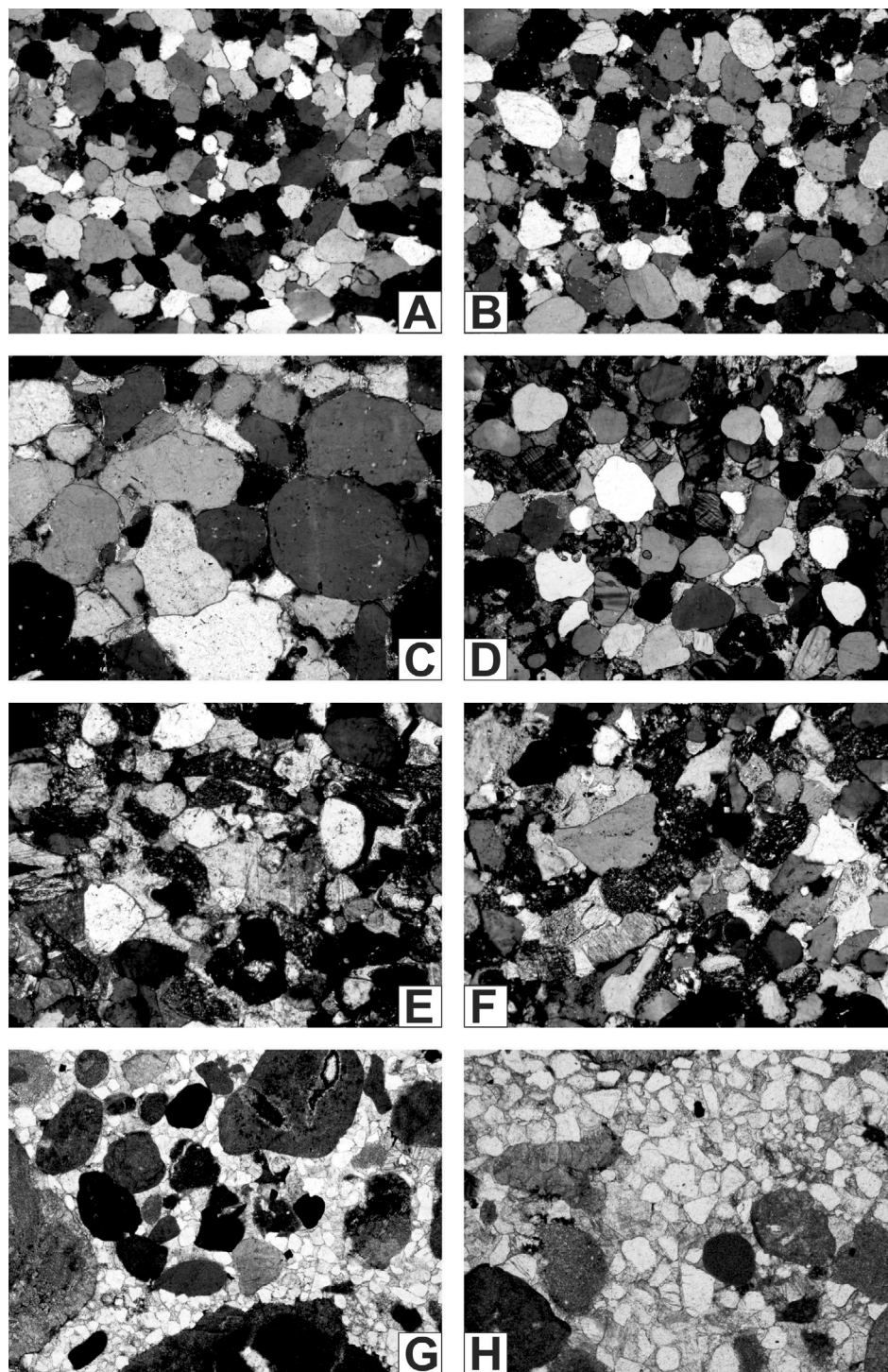


FIGURE 6. Thin section photographs of sandstones and conglomerates of the Glorieta Sandstone (A-D), Anton Chico Member (Moenkopi Formation; E-F) and Shinarump Formation (G-H). Photos A-F under polarized light, G and H under plane light. **A**, fine-grained, well-sorted sandstone composed of monocrystalline quartz, rare polycrystalline quartz and detrital feldspars. The detrital grains are well cemented by quartz, which occurs as authigenic overgrowths. Rarely, calcite cement is present. Unit 28, width of photograph is 3.2 mm. **B**, fine-grained, well-sorted sandstone composed of rounded to subrounded grains of monocrystalline, rare polycrystalline quartz and a few feldspars. The grains are cemented by calcite. Unit 33, width of photograph is 3.2 mm. **C**, detail of B. Some detrital quartz grains display authigenic overgrowths. Unit 33, width of photograph is 1.2 mm. **D**, fine-grained, well-sorted sandstone composed of subrounded to rounded grains of monocrystalline quartz and many feldspars (mostly potassium feldspars, including microcline). The detrital grains are cemented by blocky calcite. Unit 37, width of photograph is 3.2 mm. **E**, fine-grained, moderately to well-sorted sandstone containing subrounded grains of monocrystalline quartz, chert grains, some polycrystalline quartz grains, rare detrital feldspars and fine-grained schistose grains (phyllitic rock fragments). The grains are cemented by coarse blocky calcite. Unit 42, width of photograph is 1.2 mm. **F**, fine-grained, moderately to well-sorted sandstone composed of subangular to subrounded grains, mostly monocrystalline quartz and chert, subordinately polycrystalline quartz and feldspars. The grains are cemented by calcite. Unit 48, width of photograph is 1.2 mm. **G**, fine-grained conglomerate composed of different types of carbonate grains that are embedded in sandy matrix containing abundant subangular quartz grains. Unit 52, width of photograph is 6.3 mm. **H**, detail of G showing the fine-grained, sandy matrix composed of detrital quartz grains. Unit 52, width of photograph is 3.2 mm

composition of the sandstone samples we studied of the Glorieta Sandstone are very similar to those of sandstones studied by Milner (1978) from different localities in New Mexico, indicating that the composition and texture of the Glorieta Sandstone is very uniform over large areas.

The limestone beds (Fig. 2, units 29-30) intercalated in the Glorieta Sandstone at the SMNHC are wackestone to packstone, indistinctly laminated, containing some foraminifers, ostracodes and rare other skeletons (recrystallized shells). Non-skeletal grains are micritic intraclasts. Locally, the sediment is well washed (grainstone) and well cemented. The fossil assemblage is of low diversity, indicating a restricted shallow marine depositional environment. Wackestone/packstone layers alternate with thin layers of mudstone and bioclastic mudstone.

Unit 29 includes a foraminiferal wackestone to packstone with abundant foraminifers, subordinate ostracods and some other recrystallized, indeterminable skeletons (Fig. 7A-C). Locally, the grains are densely packed and cemented (packstone), and some micritic matrix is present. Low fossil diversity and the dominance and almost oligotypy of miliolate foraminifers indicates restricted shallow marine conditions. Only the following taxa were identified: *Glomomidiella* sp. 1. (Fig. 8.1-3); *G.* sp. 2. (Fig. 8.11); *Orthovertellopsis* sp. (Fig. 8.5, 7-8, 10); *Praeodiscus*? sp. (Fig. 8.9); and cf. *Tubiphytes epimonellaeformis* Vachard, Krainer and Lucas, in press (Fig. 8.12). All these taxa are present in the Yeso Group (Lucas et al., 2015; Vachard et al., 2015). Although very poor, this assemblage may be considered as characteristic of the New Mexico foraminiferal zone 13 of Lucas et al. (2015). This assemblage is transitional, because *Glomomidiella* and *Orthovertellopsis* appear in biozone 10, whereas true *Tubiphytes epimonellaeformis* are only known from biozone 15 (Lucas et al., 2015). Biozone 13 is late Leonardian (early or middle Kungurian) in age.

San Andres Formation

The San Andres Formation represents the last Permian marine transgression across central New Mexico (Brose et al., 2013). Its discontinuous outcrops across the central and northern part of the state were deposited on the far northwestern shelf of the Permian basin. From a minimum of 1-10 m thick in northern New Mexico, the San Andres Formation thickens southward to as much as 181 m thick in south-central New Mexico (Krainer et al., 2012; Brose et al., 2013).

At the SMNHC, the lower part of the San Andres Formation, which is interbedded in the Glorieta Sandstone, is 12.5 m thick and composed of bedded, muddy limestone and thick-bedded to massive dolomitic limestone. The upper part of the San Andres Formation, which overlies the Glorieta Sandstone, is 25 m thick and consists of medium-bedded dolomitic limestone and thin-bedded micritic limestone. Limestone of the San Andres Formation is gray and generally forms thick-bedded ledges (Fig. 3C).

Unit 30 (Figs. 2, 7D, F) is a bioclastic mudstone to wackestone, slightly recrystallized, containing many foraminifers, ostracodes, some larger shell fragments (probably derived from bivalves), rare echinoderms and gastropods and other recrystallized skeletons. The wackestone contains a few detrital quartz grains. A few micritic intraclasts are present. Skeletal grains, intraclasts and quartz grains are embedded in recrystallized micritic matrix. Locally, the sediment is bioturbated. Bioturbated peloidal wackestone to packstone is intercalated.

Unit 31 (Figs. 2, 7E) is also a wackestone containing recrystallized skeletons, ostracodes, rare large gastropods, probable bryozoans, intraclasts and a few small detrital quartz grains. Unit 40 (Figs. 2, 7G) is a mudstone, locally bioturbated, containing a few ostracodes and other recrystallized skeletons. The top of unit 40 (Fig. 7H) is a wackestone to floatstone containing recrystallized shell fragments (?bivalves), and other skeletons (gastropods, ostracodes, rare echinoderms and ?algae).

Triassic Strata

Moenkopi Formation (Anton Chico Member)

Across northern New Mexico, the Anton Chico Member of the Moenkopi Formation is a relatively thin (less than 100 m thick), siliciclastic succession of red-bed sandstone, conglomerate and mudstone of fluvial origin (Lucas and Heckert, 1995; Lucas, 2004). These are strata of early Middle Triassic (Perovkan/Anisian) age (Lucas and Schoch, 2002).

At the SMNHC, the Moenkopi Formation measures 64 m thick, but only the lower, approximately 20 m are well exposed (Figs. 2, 3D). They are composed of grayish-red mudstone and a few intercalated sandstone beds (0.7-1.2 m thick) that display horizontal lamination and trough crossbedding.

Sandstone of the Moenkopi Formation (Fig. 2, units 42, 48, 52) is well sorted, fine grained (mostly 0.1-0.3 mm), and the detrital grains are dominantly subrounded (Fig. 6E-F). The detrital grains are abundant monocrystalline quartz grains, a few polycrystalline quartz grains, rare detrital feldspar (altered potassium feldspar) grains, many chert grains, fine-grained schistose metamorphic grains (phyllitic rock fragments), opaque grains and a few carbonate grains. Micas (muscovite and biotite) are rare. Many quartz grains of unit 48 are coated by hematitic rims. A few quartz grains display authigenic overgrowths.

Detrital grains of the sandstone in units 42 and 48 are cemented by coarse blocky calcite, which randomly replaces detrital quartz grains. Detrital grains of the sandstone of unit 52 are cemented by authigenic quartz overgrowths, which in most cases cannot be distinguished from the detrital grains due to the lack of dark rims. Moenkopi sandstone differs in composition from the Glorieta Sandstone by being much less mature mineralogically (i.e., it contains many chert grains and metamorphic rock fragments).

Chinle Group (Shinarump Formation)

The uppermost 8 m of the section at the SMNHC are assigned to the Upper Triassic Shinarump Formation of the Chinle Group (Lucas and Heckert, 1995; Lucas, 2004). These strata have previously been termed Agua Zarca or Santa Rosa Formation, both names applied to the same lithosome in northern (Agua Zarca Formation) and eastern (Santa Rosa Formation) New Mexico. Lucas (2004) abandoned the term Agua Zarca Formation in northern New Mexico, replacing it with the older, equivalent term Shinarump Formation. The Santa Rosa Formation in eastern New Mexico consists of three members (sandstone-mudstone-sandstone), and Lucas and Heckert (1995) suggested applying it only in areas where the member subdivisions are evident. These are not present at the SMNHC, so we use the term Shinarump Formation to refer to the basal sandstone/conglomerate interval of the Chinle Group, replacing earlier usage (Lucas and Heckert, 1995) of Agua Zarca Formation.

Lucas and Heckert (1995) estimated a total thickness of the Shinarump Formation (their Agua Zarca Formation) in the Cedar Crest area of as much as 100 m. At the northeastern end of the SMNHC, red-bed mudrock that overlies the Shinarump Formation is exposed and should be assigned to the Salitral Formation of the Chinle Group (Lucas and Heckert, 1995). We did not include these strata in our measured section because cover makes it impossible at the SMNHC to determine the total Shinarump Formation thickness and to locate the Shinarump-Salitral contact.

At the SMNHC, the exposed portion of the Shinarump Formation is about 8 m thick. These strata are trough crossbedded sandstone and intercalated, mud-supported limestone conglomerate (Figs. 2, 3E-F).

The conglomerate of unit 52 (Figs. 2, 6G-H) is polymict and contains different types of carbonate clasts (mostly < 1 cm). The grain contacts between the detrital grains are commonly sutured, indicating pressure solution. The limestone clasts include different types of micritic limestone, rarely containing fossils that are likely reworked from the San Andres Formation. A few carbonate grains seem to be derived from caliche carbonates. The limestone clasts are embedded in a matrix of sandstone composed of subangular to subrounded quartz grains (mostly 0.1-0.5 mm; mostly mono- and rare polycrystalline quartz) and a few detrital carbonate grains. Detrital feldspar grains are very rare. The detrital grains are cemented by sparry calcite, which locally replaces the detrital quartz grains.

SEDIMENTARY HISTORY

The five formation-rank units that form the exposed bedrock at the SMNHC represent depositional systems that range from marine carbonate platform to nonmarine river floodplain. The facies of the Yeso Group (Joyita Member), composed of dominantly horizontally laminated, ripple-laminated and massive sandstone, is very similar to that in the Mesa del Yeso area northeast of Socorro in Socorro County (Lucas et al., 2005) and in the southern Fra Cristobal Mountains of Sierra County (Lucas and Krainer, 2012; Lucas et al. 2013b). We interpret the sandstones as eolian sand sheet deposits. During deposition of the Joyita Member, an extensive arid coastal plain extended towards the south as far as the southern Fra Cristobal Mountains (Mack and

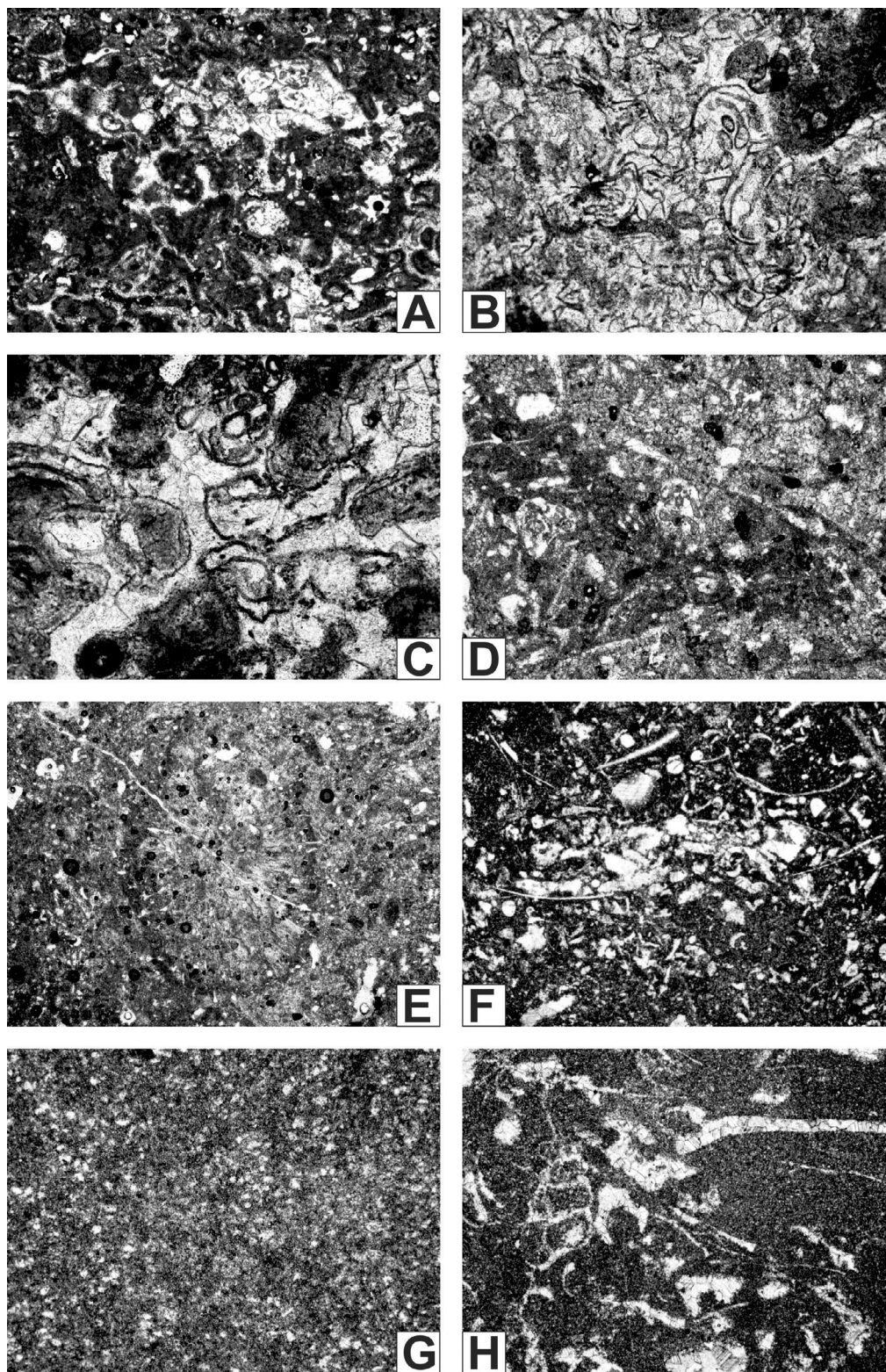


FIGURE 7. Thin section photographs of microfacies from limestones and dolomitic limestones of the Glorieta Sandstone (A-C) and San Andres Formation (D-H). All photos under plane light. **A**, foraminiferal wackestone to packstone, recrystallized, containing foraminifers, ostracodes and intraclasts. Unit 29, width of photograph is 3.2 mm. **B**, foraminiferal grainstone to packstone with abundant foraminifers *Glomomidiella* sp. 1 (see detail in Fig. 8.1). Unit 29, width of photograph is 1.2 mm. **C**, packstone to grainstone containing foraminifers *Glomomidiella* sp. 1 and intraclasts. Unit 29, width of photograph is 1.2 mm. **D**, bioclastic wackestone, recrystallized, containing foraminifers *Orthovertellopsis*? sp., ostracodes, bivalve shells and many unidentified skeletons. A few detrital quartz grains are present. Unit 30, width of photograph is 3.2 mm. **E**, recrystallized wackestone containing small intraclasts, ostracodes, other skeletons and a bryozoan (center; see also Fig. 8.6). Unit 31, width of photograph is 6.3 mm. **F**, bioclastic wackestone with recrystallized skeletons, including bivalve shells, ostracodes and gastropods. Unit 30D, width of photograph is 6.3 mm. **G**, recrystallized mudstone. Unit 40, width of photograph is 3.2 mm. **H**, recrystallized bioclastic wackestone to floatstone containing recrystallized bivalve shells, gastropods (left), ostracodes and other skeletons embedded in recrystallized matrix. Unit 40 top, width of photograph is 6.3 mm.

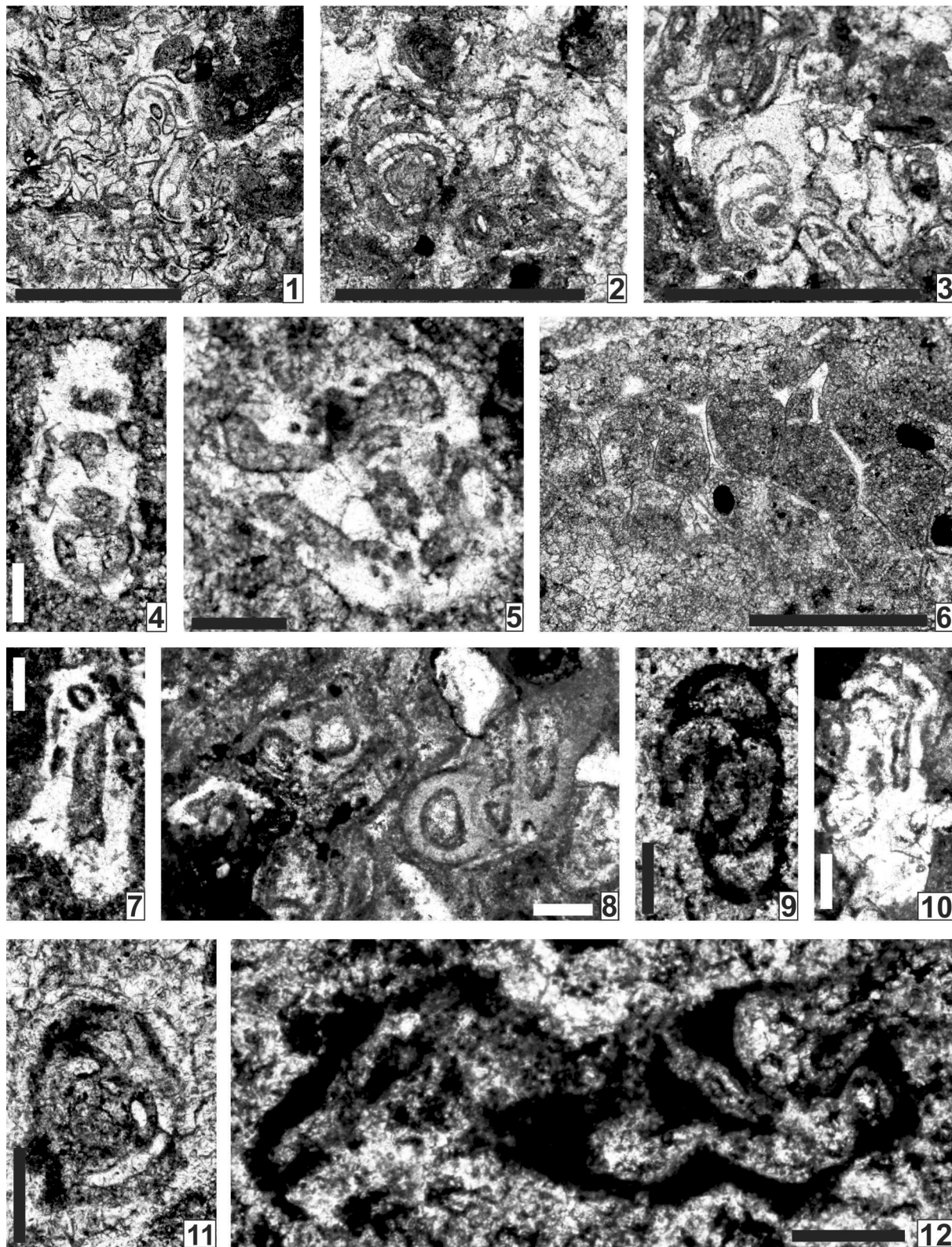


FIGURE 8. Thin section photographs of fossils from thin limestone beds intercalated in the upper part of the Glorieta Sandstone at the SMNHC. Scale bar for figures 1-3 and 6 is 0.5 mm, for all other figures is 0.1 mm. **1-3**, *Glomomidiella* sp. 1. Three microfacies with various random sections of this taxon. **1**. Sample GSM 29e. **2**. Sample GSM 29f. **3**. Sample GSM 29g. **4-5, 7-8, 10**, *Orthovertellopsis* sp. **4**. (oblique transverse section). Sample GSM 30b. **5**. Axial section. Sample GSM 30d. **7**. (oblique subaxial section). Sample SM 29-1. **8**. (two subaxial sections). Sample SM 29-2. **10**. (oblique subaxial section). Sample SM 29-4. **6**. (Bryozoa. Oblique section at the periphery of a zoarium) (see a whole colony Fig. 7E). Sample GSM 30e. **9**, *Praeneodiscus?* sp. (axial section). Sample SM 29-9. **11**, *Glomomidiella* sp. 2. (subaxial section). Sample SM 29x-1. **12**, cf. *Tubiphytes epimonellaeformis* Vachard, Krainer and Lucas, in press. (longitudinal section). Sample SM 29-20.

Dinterman, 2002; Lucas et al., 2013b).

The Glorieta Sandstone is dominantly crossbedded and horizontally laminated sandstone, and subordinately ripple-laminated sandstone. We interpret 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, which alternate with the crossbedded sandstone, are interpreted as interdune deposits.

Eolian dunes are more common in the lower part of the section. In the upper part of the section, above the intercalated San Andres Formation interval, horizontally laminated, ripple laminated and massive sandstone dominate, which probably represent eolian sand sheet deposits. A few intercalated crossbedded sandstones probably represent eolian dunes.

In the lower part of the Glorieta Sandstone, a few meters below the intercalated San Andres horizon, two marine carbonate horizons are intercalated. The lower limestone interval (Fig. 2, unit 29), composed of wackestone, packstone and mudstone with a low-diversity fossil assemblage, indicates deposition in a restricted, shallow marine depositional environment. This limestone documents the first short marine transgression within the Glorieta Sandstone depositional system.

The upper limestone interval, also composed of wackestone but with a slightly higher fossil diversity, indicates deposition in a shallow, less restricted marine setting of another short marine transgression. In their regional study of the Glorieta Sandstone, Mack and Bauer (2014) also reported intercalated fenestral dolostone of a high intertidal to supratidal environment and fossiliferous dolomite indicating a shallow marine setting.

At the SMNHC, all microfacies types of the San Andres Formation contain a fossil assemblage of low to moderate diversity, and this indicates that the sediments accumulated in a shallow, restricted marine depositional environment. Compared to the type section in the San Andres Mountains, where the San Andres Formation is much thicker and composed of limestone of a normal shallow marine environment of mostly low to moderate water turbulence (Krainer et al., 2012; Brose et al., 2013), the San Andres Formation at the SMNHC is much thinner and displays a more restricted depositional environment.

The Triassic Moenkopi Formation and Chinle Group were deposited in vast fluvial systems that extended from Texas-New Mexico to Wyoming-Idaho (see Lucas, 2004 and references cited therein). The Moenkopi Formation at the SMNHC is composed mainly of fine-grained floodplain deposits with intercalated sheetsand and small fluvial channel deposits. The exposed basal portion of the Shinarump Formation represents gravelly and sandy fluvial channel deposits.

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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: AAPG Memoir 31, p. 11-47.
- 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., 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.
- 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 1:50,000.
- 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. Rocky Mountain Section Society of Economic Paleontologists and Mineralogists, p. 4-1-4-12.
- Karlstrom, K.E., Connell, S.D., Ferguson, C.A., Read, A.S., Osburn, G.R., Kirby, E., Abbott, J., Hitchcock, C., Kelson, K., Noller, J., Sawyer, T., Ralser, S., Love, D.W., Nyman, M. and Bauer, P.W., 2000, Geology of Tijeras quadrangle, Bernalillo County, New Mexico: NMBMMR Open File Map Series OF-GM-4, scale 1:24,000.
- Kelley, V.C. and Northrop, S. A., 1975, Geology of Sandia Mountains and vicinity: New Mexico Bureau of Mines and Mineral Resources, Memoir 29, 136 p.
- 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.K., Lucas, S.G. and Vachard, D., 2011, Lectostratotype section of the Pennsylvanian Sandia Formation, Bernalillo County, New Mexico: New Mexico Museum of Natural History and Science, Bulletin 53, p. 71-85.
- Lucas, S.G., 2004, The Triassic and Jurassic systems 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. 137-152.
- Lucas, S.G. and Heckert, A.B., 1995, Triassic stratigraphy around the Sandia uplift, central New Mexico: New Mexico Geological Society, Guidebook 46, p. 233-241.
- 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 Schoch, R.R., 2002, Triassic temnospondyl biostratigraphy, biochronology and correlation of the German Buntsandstein and North American Moenkopi Formation: Lethaia, v. 35, p. 97-106.
- 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 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 Vachard, D., 2015, The Lower Permian Hueco Group, Robledo Mountains, New Mexico (U.S.A.): New Mexico Museum of Natural History and Science, Bulletin 65, p. 43-95.
- 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, v. 59, p. 181-199.
- Lucas, S.G., Krainer, K., Allen, B.D. and Vachard, D., 2014, The Pennsylvanian section at Cedro Peak: A reference section in the Manzanita Mountains, central New Mexico: New Mexico Geology, v. 36, p. 3-24.
- 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.
- 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.
- Pettijohn, F.J., Potter, P.E. and Siever, R., 1987, Sand and sandstone: Springer, New York, 553 p.
- Read, A.S., Karlstrom, K.K. and Ilg, B., 1999, Mississippian Del Padre Sandstone or Proterozoic quartzite: New Mexico Geological Society, Guidebook 50, p. 41-45.
- Read, A.S., Karlstrom, K.E., Connell, S., Kirby, E., Ferguson, C.A., Ilg, B., Osburn, G.R., Van Hart, D. and Pazzaglia, F.J., 2000, Geology of Sandia Crest quadrangle, Bernalillo and Sandoval Counties, New Mexico: NMBMMR Open File Map Series OF-GM-6, scale 1:24,000.
- Vachard D., Krainer, K., Lucas, S.G., 2015, Kungurian (late Early Permian) algae, micropaleontological, and smaller foraminifers from the Yeso Group and San Andres Formation (New Mexico; USA): Palaeontologia Electronica (in press).

