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2026, pp. 241-258. https://doi.org/10.56577/FFC-76.241

in:

Geology of the Albuquerque Region - Fall Field Conference 2026, Connell, Sean D.; Koning, Daniel J.;, New Mexico Geological Society 76th Annual Fall Field Conference Guidebook, 452 p. https://doi.org/10.56577/FFC-76

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New Mexico Geological Society Guidebook, 76th Fall Field Conference, 2026, p. 241–257, https://doi.org/10.56577/FFC-76.241

THE LOWER PERMIAN ABO FORMATION AND YESO GROUP IN THE SANDIA MOUNTAINS, NEW MEXICO

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Abstract—In the Sandia Mountains of central New Mexico, the lower Permian section consists of the (ascending) Abo Formation, Yeso Group, Glorieta Formation and San Andres Formation. The Abo Formation is about 210 m thick and is readily divided into the two members seen across central New Mexico: a lower, mudstone-dominated Scholle Member and an upper, Cañon de Espinoso Member that includes many laterally extensive sandstone sheets. The Yeso Group is about 140 m thick and can be subdivided into (ascending) De Chelly and San Ysidro Formations (to the north), and the Arroyo de Alamillo and Los Vallos Formations (to the south). At Placitas, two adjacent (1 km) stratigraphic sections document southward facies changes in the Yeso Group. In the lower Yeso, the eolian De Chelly Sandstone transitions into arid coastal plain deposits of the Arroyo de Alamillo Formation. Similarly, in the upper Yeso Group, the sandy San Ysidro Formation (north) changes lithofacies into a mixture of siliciclastic, gypsum and carbonate strata of the Los Vallos Formation (south). The Placitas area was thus an important area of two southward paleoenvironmental transitions in the Permian. In the stratigraphically lower one, the De Chelly erg changes to the arid coastal plain of the Arroyo de Alamillo Formation that extended south to at least Sierra County. In the upper one, there was a transition from the siliciclastic shelf deposits of the San Ysidro Formation to mixed nonmarine-marine coastal plain deposits of the Los Vallos Formation that extended nearly to the marine platform carbonates of the Northwest Shelf of the Delaware basin to the southeast (e.g., Hill, 1996; Lucas, et al., 2022).

INTRODUCTION

Across much of New Mexico, most of the lower Permian strata are assigned to the Abo Formation and overlying Yeso Group (formerly formation). The Abo Formation consists of siliciclastic red beds that were deposited by fluvial processes. Yeso Group strata are a mixture of siliciclastic, evaporite and carbonate sediments. They were deposited in shallow marine, evaporitic (coastal sabkha), arid coastal plain and eolian depositional environments, primarily on an arid coastal plain that extended across much of central and southern New Mexico.

Abo and Yeso strata are discontinuously exposed on the eastern dip slope of the Sandia Mountains, from Placitas on the north to Tijeras Canyon on the south (Fig. 1). Here, we present new stratigraphic and petrographic data on these strata to document the stratigraphy, petrography, biostratigraphy, sedimentology and correlation of Abo-Yeso strata in the Sandia Mountains.

METHODS

We measured seven stratigraphic sections of Abo-Yeso strata in the Sandia Mountains using a 1.5 m staff and pocket transit (Figs. 2–5), and hand samples were collected of selected rocks to make petrographic thin sections (Figs. 6 and 7). Fossil occurrences were documented on outcrop, and some fossils were collected and added to the collection of the New Mexico Museum of Natural History and Science (NMMNH). Lithofacies types and architectural elements identified in the text (Fm, Gt, etc.) are those of Miall (1996, 2010).

SOME HISTORY

The presence of Permian strata in the Sandia Mountains was recognized in the late 1800s (Herrick, 1900). When Lee (1909) named the Abo and Yeso formations, he described a stratigraphic section (p. 19–20, fig. 2) of those units at the northern end of the range, northeast of Placitas, near the now abandoned town of Tejon. Darton (1928, p. 93–97, figs. 21–24, 26, pl. 24) presented the most extensive early data on the Permian strata, describing and mapping their distribution in the Sandia Mountains. He assigned these strata to Lee's (1909) Abo Formation and to the overlying Chupadera Formation; a long abandoned lithostratigraphic unit named used by Darton to encompass strata now assigned to the Yeso, Glorieta and San Andres formations (Lucas, 2009). Darton's (1928) Abo Formation in the Sandia Mountains included a lower interval with marine limestones interbedded with red beds, as did Lee's (1909) Abo Formation. These are strata now recognized as Bursum Formation (Lucas et al., 2013a).

In their comprehensive investigation of the geology of the Sandia Mountains, Kelley and Northrop (1975, p. 50) described the Abo Formation as 213–274 m of red mudstone and sandstone with minor beds of conglomerate and nonmarine(?) limestone. Like Lee and Darton, they included strata we consider to be Bursum Formation in the lower Abo. They divided the Yeso Formation into the lower, sandstone-dominated Meseta Blanca Member (21–46 m thick) overlain by the San Ysidro Member, 76–122 m of alternating beds of fine-grained sandstone and siltstone (some beds gypsiferous), and a few beds of marine limestone. Kelley and Northrop (1975, map 1) mapped the distribution of the Abo and Yeso formations in

the Sandia Mountains. Lucas et al. (1999) described Abo-Yeso strata and Abo paleontology to the north of Placitas.

Lucas et al. (2005) reviewed regional stratigraphy of the Abo and Yeso Formations. They divided the Abo Formation into two members, the lower Scholle Member and overlying Cañon de Espinoso Member (Lucas et al., 2005; Lucas et al., 2013a, 2013b). They also elevated the Yeso from formation to group, and its members to formation status. Baars (1962) had long ago argued that the Meseta Blanca Member is the same unit as the De Chelly Sandstone, so Lucas et al. (2005) abandoned the name Meseta Blanca in favor of De Chelly, the name with priority. Strata of the De Chelly Sandstone, and the type Meseta Blanca are largely thick beds of sandstone with large scale trough crossbeds of eolian origin. Southward, and particularly well exposed at the Yeso type section in Socorro County, the lower Yeso is a unit of thin bedded sandstone and siltstone, often gypsiferous, interbedded with dolostone and gypsum. The lower Yeso here is broadly correlative to the De Chelly

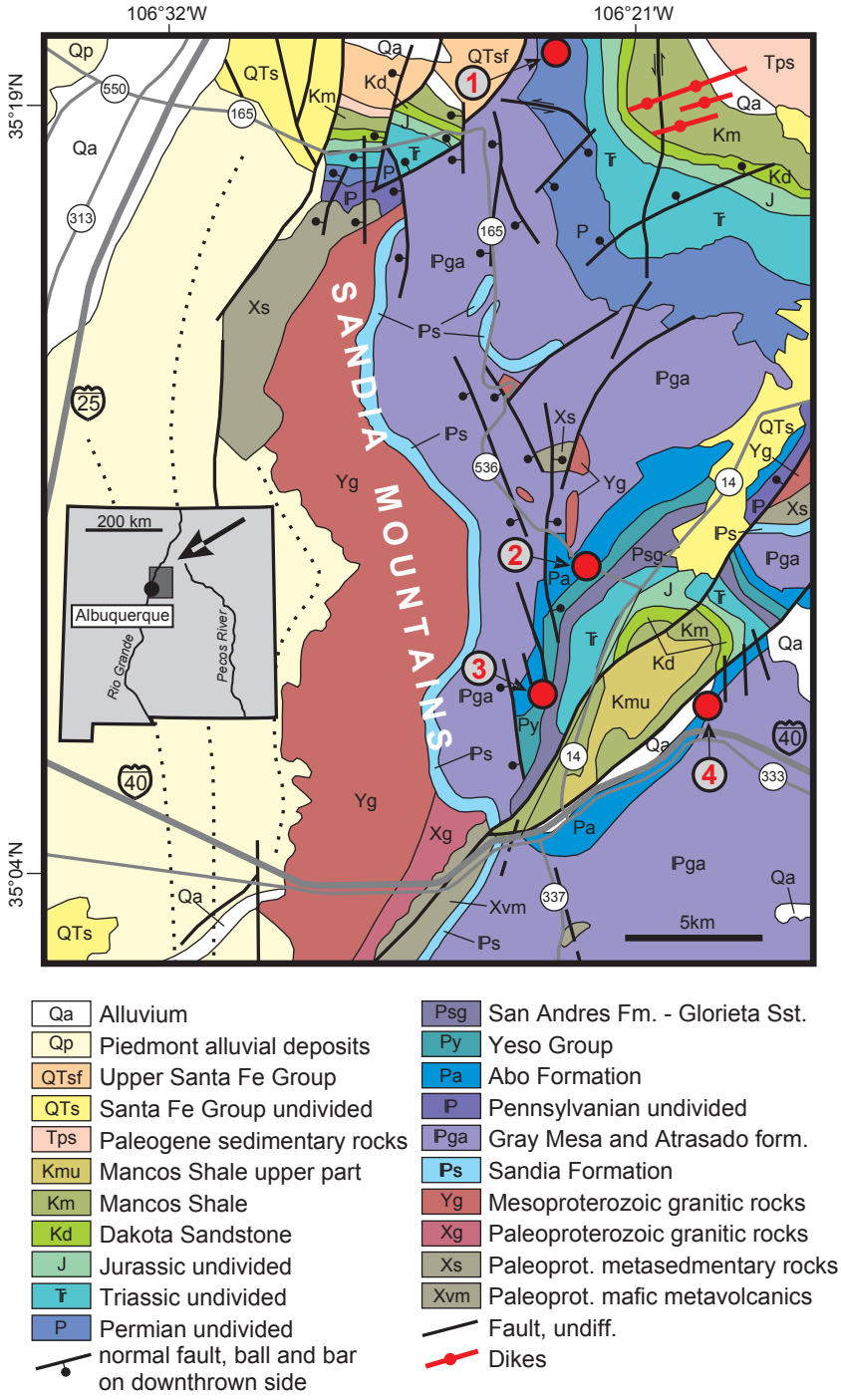


FIGURE 1. Simplified geologic map of the Sandia Mountains, after New Mexico Bureau of Geology and Mineral Resources (2003). The locations of sections measured for this report are: 1 = sections near Placitas; 2 = sections near Sandia Park (Highway 536, Ranch Road); 3 = section at the Sandia Mountain Natural History Center; and (4) sections in Tijeras Canyon (Zuzax A and B).

Sandstone to the north, but a very different lithofacies. Lucas et al. (2005) named this southern unit the Arroyo de Alamillo Formation.

In the late 1990s the STATEMAP program also mapped the geology of the Sandia Mountains and surrounding area at a scale of 1:24,000. The Abo and Yeso strata were mapped and described on the four quadrangles that encompass the Sandia Mountains—Placitas (Connell et al., 1995), Sandia Crest (Read et al., 1995), Sandia Park (Ferguson et al., 1996) and Sedillo (Read et al., 1998). The Abo and Yeso strata on these quadrangles were mapped as either Abo-Yeso undifferentiated or undivided. Also, they have been mapped as Abo Formation, which included the Bursum Formation (sometimes mapped separately as "Abo limestone") or Yeso Formation with local mapping of Yeso sandstone and limestone units (Read et al., 1995, 1998). The Abo Formation of previous workers is, minus the Bursum strata, the same unit we recognized as Abo Formation, and the Yeso Formation of these workers is the same unit we recognize as Yeso Group.

ABO FORMATION AND YESO GROUP

In the Sandia Mountains, the Abo Formation rests disconformably on the Upper Pennsylvanian (Virgilian) Bursum Formation and is conformably overlain by the Yeso Group. The basal disconformity is based on a sharp lithologic contrast, stratigraphic relief and the hiatus (i.e., missing the late Virgilian) between the Bursum and Abo Formations (cf. Lucas et al., 2005). We measured two complete and well exposed sections of the Abo Formation and Yeso Group north of Placitas that are about 2 km apart, north-south (Figs. 3 and 4), sections of the Abo-Yeso transition to the south near Sandia Park and in Tijeras Canyon (Fig. 5), and Lucas et al. (2015) described a section of the upper part of the Yeso Group at the Sandia Mountain Natural History Center in Cedar Crest (Fig. 5). Yeso Group strata are assigned to four formations: (1) De Chelly Sandstone, mostly thick bedded sandstone with large scale trough crossbeds; (2) Arroyo de Alamillo Formation, sandstone and siltstone beds, usually tabular, ripple laminar or massive, with a few beds of dolomite and gypsum; (3) San Ysidro Formation, repetitively bedded sandstone and siltstone with minor gypsum and dolomite; and (4) Los Vallos Formation, a mixture of gypsiferous siltstones, sandstones, gypsum and dolomite. Table 1 summarizes salient features of the Abo and Yeso stratigraphic units.

Placitas A Section

Abo Formation—Lithostratigraphy

At the Placitas A section (Fig. 3), the Abo Formation is 212 m thick and, using criteria developed by Lucas et al. (2005), can be divided into a lower, Scholle Member about 75 m thick (units 2–11) and an overlying Cañon de Espinoso Member

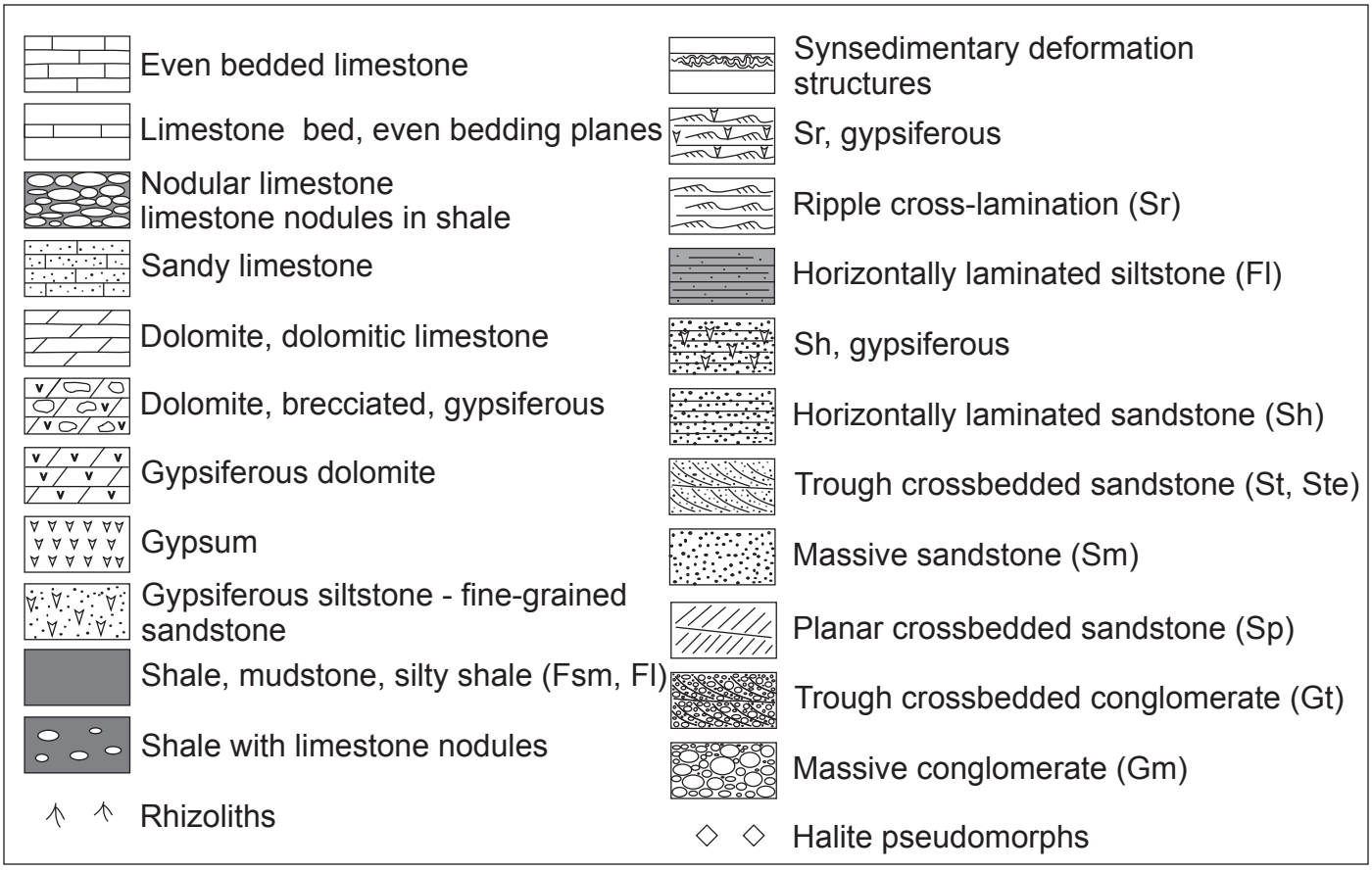


FIGURE 2. Lithologic symbol legend for the stratigraphic sections in Figures 3–5.

TABLE 1. Thicknesses and characteristics of lithologic units.

Lithostratigraphic unit	Thickness (maximum) in meters	Lithology
Yeso Group		
Los Vallos Formation		
Joyita Mbr	54	Red, fine-grained sandstone and siltstone in tabular, massive, ripple laminar and laminar beds; some beds gypsiferous.
Cañas Mbr	3?	Gypsum and gypsiferous siltstone.
Torres Mbr	34	Gypsiferous red siltstone, fine-grained sandstone, gypsum and up to six, laterally extensive dolomite beds.
San Ysidro Formation	115	Repetitive beds of brown siltstone and fine- to medium-grained sandstone (Sr, Sh, Sm, rare St); 2-4 dolomite and gypsum beds.
Arroyo de Alamillo Formation	24	Red siltstone, trough cross-bedded or laminar sandstone, massive gyspiferous sandstone, all fine- to medium-grained.
DeChelly Sandstone	59	Thick sets of large scale cross-bedded sandstone, some horizontal bedded and ripple laminar sandstone, fine- to medium-grained.
Abo Formation		
Cañon de Espinoso Mbr	137	Laterally extensive sandstone beds, fine- to coarse-grained, intercalated with red mudrock.
Scholle Mbr	75	Red mudrock, minor beds of trough cross-bedded sandstone, fine- to medium-grained, and conglomerate.

Abbreviations: Mbr = Member

(units 12–54), about 137 m thick. The Scholle Member is a mudrock-dominated unit with a couple of channel form beds of conglomerate. The Cañon de Espinoso Member also has substantial mudrock but includes intervals of sandstone in laterally extensive sheets. Red bed mudstone of the Abo Formation rests on the topmost marine limestone of the Bursum Formation. The dominant lithofacies of the Abo Formation is red mudstone to siltstone (lithofacies Fsm), and subordinately lithofacies Fl (laminated mudstone-siltstone) that underlies partly covered slopes up to 44 m thick. Some of the mudstone intervals (Fig. 3, units 5, 6 and 49) contain calcrete nodules. Different lithotypes of conglomerate and sandstone, and a few pedogenic limestone intervals (calcrete), are intercalated in red mudstone.

Trough cross-bedded conglomerate (lithofacies Gt) is composed of limestone pebbles (reworked calcrete) in the lower part of the succession (units 4 and 10; 0.8 and 0.5 m thick), as sandy conglomerate grading into trough cross-bedded sandstone in the upper part (units 50, 54; 1.7 and 3.3 m thick) and as thin lenses of intraformational pebble conglomerate (siltstone clasts) and trough cross-bedded sandstone (in units 8 and 51). Clast-supported massive conglomerate (lithofacies Gm), composed of limestone pebbles, forms thin beds (0.2–0.3 m thick, units 20, 25 and 32).

We recognize the following sandstone lithofacies: trough cross-bedded sandstone (lithofacies St), horizontally laminated sandstone (lithofacies Sh) and ripple-laminated sandstone (including climbing ripples; lithofacies Sr). Limestone is pedogenic limestone (lithofacies P) in intervals 0.2–1.5 m thick, and is partly nodular (units 23, 40). Siltstone unit 33 (0.9 m thick) contains calcrete nodules.

Abo Formation—Sandstone Petrography

Abo sandstone samples (Figs. 6A and 6B) are fine to medium-grained (0.1–0.4 mm) and moderately to well sorted. The grains are mostly subrounded to rounded. The sandstone is composed of abundant monocrystalline quartz, and subordinately of polycrystalline quartz and feldspar grains. Among the feldspars, potassium feldspars dominate, including microcline, microperthite and untwinned feldspars (orthoclase). Plagioclase is rare. Some of the feldspar grains are fresh, and many are altered and partly replaced by calcite. The sandstone contains a few granitic rock fragments. Micas are present in small amounts, as are a few opaque grains. The sandstone is cemented by quartz in the form of authigenic overgrowths on detrital quartz grains. The main cement mineral is coarse, blocky, partly poikilotopic calcite that partly replaces quartz and feldspar.

- Total quartz comprises 46–70%, feldspars 4–11% and rock fragments 2–22% of the three studied samples (Table 2). In the QFL diagram sandstones of the Abo Formation plot into the fields of subarkose, sublitharenite, and lithic arenite (classification of Pettijohn et al., 1987) (Fig. 7). Feldspar types and granitic rock fragments indicate that dominant source rocks were granitic and, subordinately, metamorphic rocks (Table 2) — likely from Ancestral Rocky Mountain uplifts (Table 2). Mineralogical composition is similar to that of other Abo sections (Lucas et al., 2013a).

TABLE 2. Percentages of individual grains, cement and matrix of studied samples of the Abo Formation, Arroyo de Alamillo Formation, San Ysidro Formation and Glorieta Sandstone, determined by point counting.

Sample	Formation	Qm	Qp	Fsp	Lg	Lm	Ls	Mica	CQz	CCb	M
PAY 13	Abo Fm.	50.8	19	3.6	2.2	0	0	0.1	2.7	21.5	0
PAY 27	Abo Fm.	20.3	26.1	11.2	16.1	0	0	1.3	1.3	23.5	0.1
PAY 53	Abo Fm.	10.8	41.6	7.2	22.1	0	0	2.9	0.1	15.2	0
PAY 55	Arroyo de Alamillo Fm.	30.8	21.3	20.3	21.2	0.5	0	0	1.5	0	4.4
PAY 59	Arroyo de Alamillo Fm.	9.5	26.8	27.1	34	0	0	0.4	0	0	2.3
PAY 65	Arroyo de Alamillo Fm.	27.5	17.6	18	12.8	0.7	0	0	0	23.5	0
PAY 69	Arroyo de Alamillo Fm.	24.7	25.9	12.1	34.8	0	0	0	1.1	0	1.5
PAY 79	San Ysidro Fm.	28.5	12.1	14.9	6.3	0	0	0.5	0	37.6	0
PAY 126	San Ysidro Fm.	31.5	26.5	9.6	8.4	0	0	0	0	24	0
PAY 147	Glorieta Sandstone	42	25.7	10.5	7.3	0	0	0	3.2	11.2	0

Footnotes: Sample number corresponds to unit numbers of the Placitas A section. Abbreviations are: Fm. = Formation, Qm = monocrystalline quartz, Qp = polycrystalline quartz, Fsp = feldspar, Lg = granitic rock fragments, Lm = metamorphic rock fragments, Ls = sedimentary rock fragments, Mica = muscovite, biotite, chlorite, CQz = quartz cement, CCb = carbonate cement, M = matrix

Yeso Group, Arroyo de Alamillo Formation—Lithostratigraphy

At the Placitas A section (Fig. 3), the Yeso Group is 138 m thick and can be divided into the (ascending) Arroyo de Alamillo Formation (23.5 m), San Ysidro Formation (81 m) and Los Vallos Formation (33.5 m). The Yeso Group is overlain by the Glorieta Sandstone. At the type section, the Glorieta Sandstone is entirely composed of sandstone, including trough cross-bedded sandstone representing eolian sand dunes, ripple-laminated sandstone representing wind ripples, and horizontally laminated sandstone and massive sandstone that are also likely eolian (Krainer and Lucas, 2015). At Placitas, the Glorieta Sandstone exhibits a similar facies. However, note that at the Placitas A section (Fig. 3), the basal bed of the Glorieta Sandstone is a collapse breccia.

The Arroyo de Alamillo Formation is a succession of alternating red siltstone and two kinds of trough cross-bedded sandstone, eolian (Ste) and fluvial (St). Eolian cross-bedded sandstones (Ste) differ from fluvial trough cross-bedded sandstone (St): eolian sandstone is finer-grained, has no erosional base, as do fluvial sandstones, does not display a fining-upward trend, and larger eolian dune sandstones commonly show grainflow strata represented by individual grainflow tongues that thin and pinch out at the base of the cross-stratified set. Eolian sandstone (Ste) also are commonly well-sorted, and the sand grains are rounded to well rounded. Fluvial sandstones (St) commonly contain subangular to subrounded grains.

Rare massive, gypsiferous sandstone is also present. Siltstone intervals are 0.6–5 m thick. Trough cross-bedded sandstone of fluvial origin (St) forms 0.7–2.3 m thick intervals.

Unit 69 is gypsiferous sandstone. One thin massive gypsiferous sandstone (Sm, unit 57; 0.3 m thick) is intercalated in the lower part. Gypsiferous sandstone of unit 65 (0.7 m thick) displays synsedimentary deformation structures (dewatering structures).

Yeso Group, Arroyo de Alamillo Formation—Sandstone Petrography

Sandstone samples are very fine- to fine-grained (0.05–0.5 mm), moderately to well-sorted, and grains are mostly subrounded. Sandstones of the Arroyo de Alamillo Formation contain higher amounts of feldspar, slightly higher amounts of rock fragments and less quartz compared to the underlying Abo Formation sandstones (Figs. 6C–F; Table 2). Common grain types are quartz (monocrystalline quartz is much more abundant than polycrystalline quartz), including rare schistose metamorphic quartz grains. Feldspar grains are abundant and mainly represented by potassium feldspars (microcline, microperthite, untwinned grains) and rare plagioclase grains. Feldspar grains are partly fresh, and partly slightly to moderately altered to clay minerals. Rarely, feldspar grains are completely altered to clay minerals, forming authigenic “pseudomatrix”.

The sandstone contains a few granitic rock fragments (Fig. 6E) and metamorphic rock fragments (Fig. 6F). Micas are represented by muscovite and biotite. Some of the samples are cemented by quartz in the form of authigenic overgrowths on detrital grains and lack calcite cement. Some contain coarse, blocky calcite cement. Locally, gypsum is present as cement. Total quartz content is 36–52%, feldspars comprise 12–27%, and rock fragments 13–35%. (four samples, see Table 2). Sandstones of the Arroyo de Alamillo Formation contain less quartz, more feldspars and more rock fragments than the Abo Formation and are classified as subarkose, sublitharenite and lithic arenite (according to the scheme of Pettijohn et al. 1987) (Fig. 7).

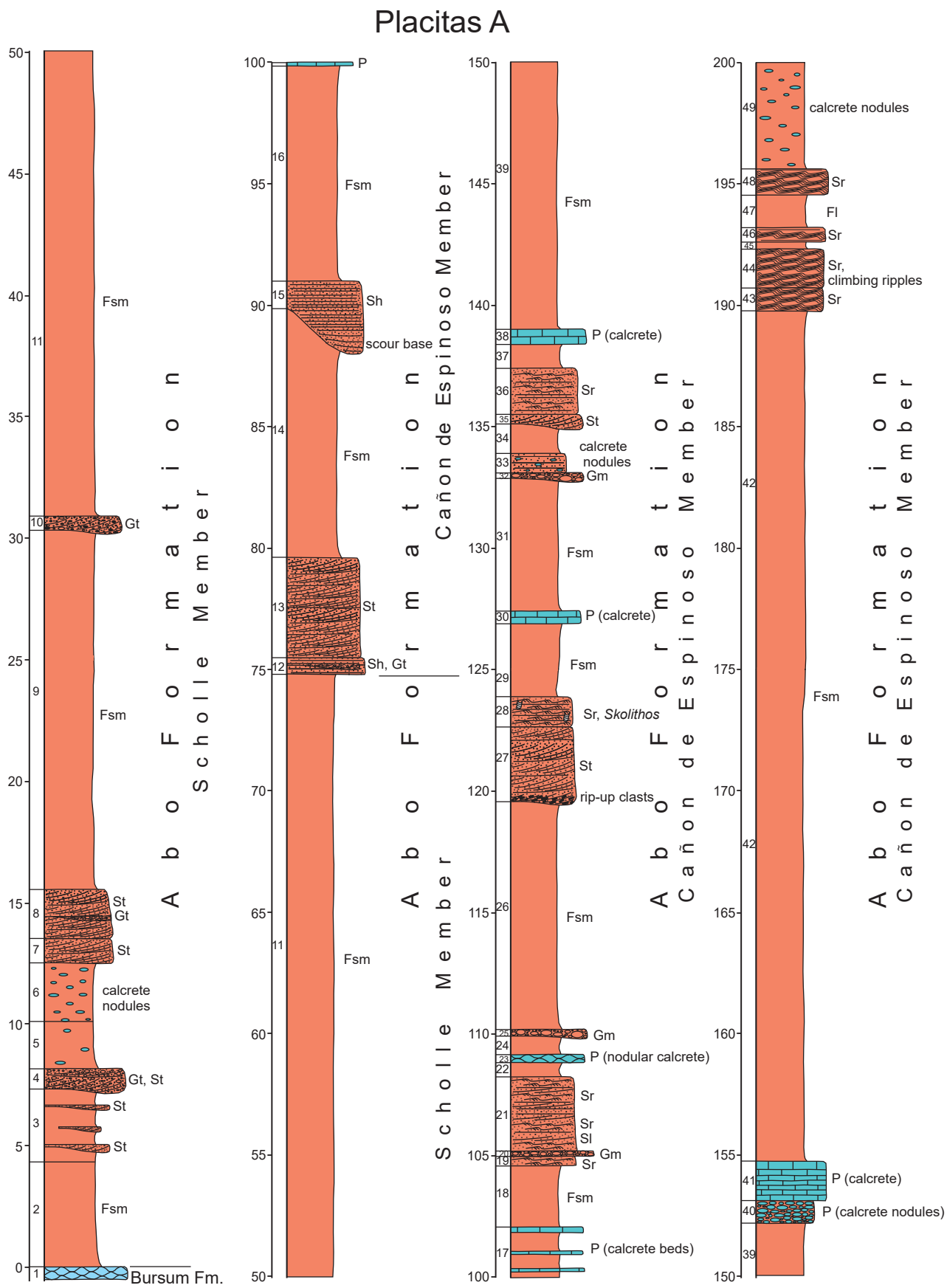


FIGURE 3. Placitas A section. Base of section at UTM coordinates 373854 mE, 3912340 mN and top at 374703 mE, 3911881mN (zone 13, NAD83). Here, and in Figure 4 and 5, lithofacies codes (St, Sm, etc.) based on Miall (1996, 2010) are indicated next to parts of the rock columns.

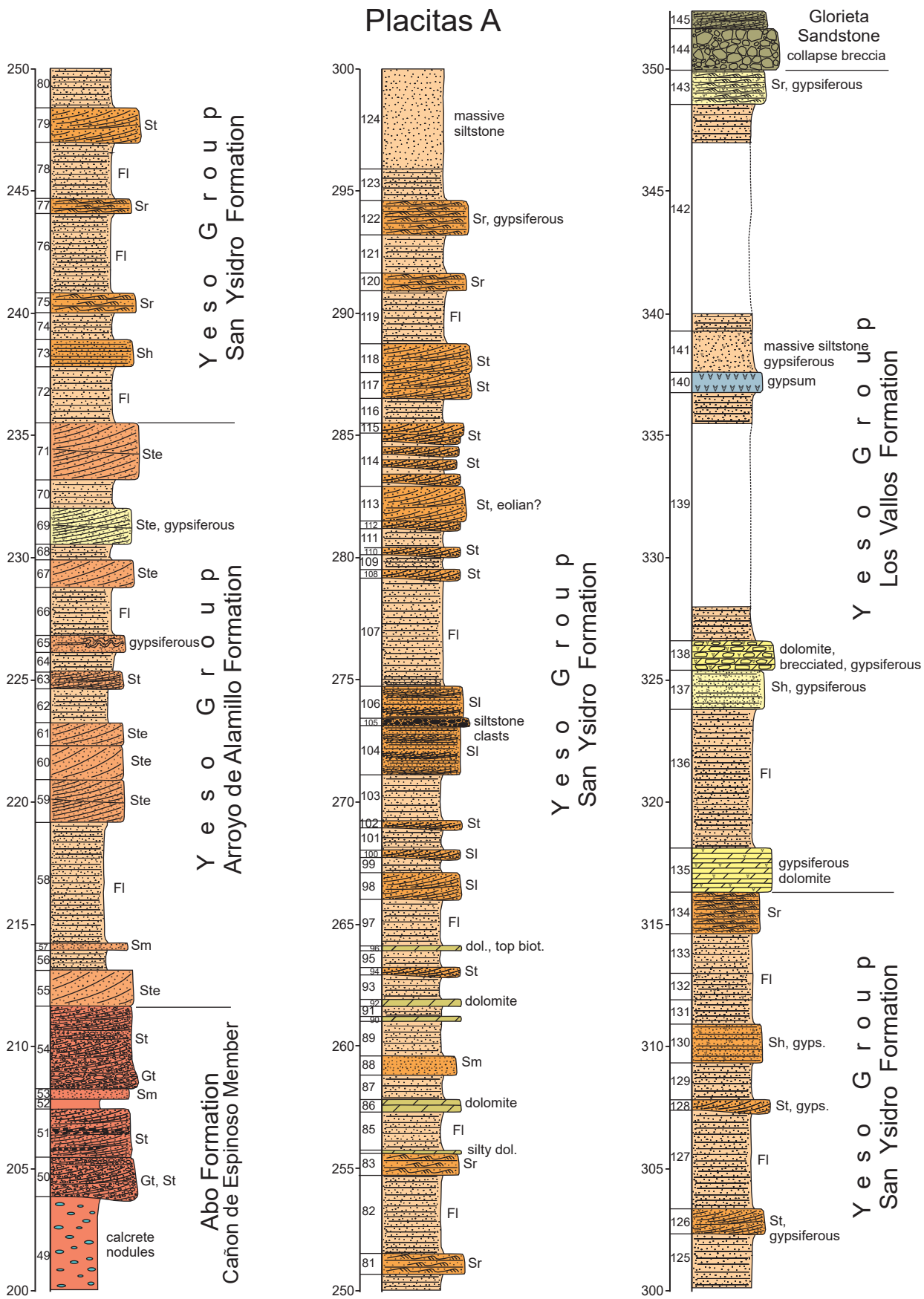


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Yeso Group, San Ysidro Formation—Lithostratigraphy

At the Placitas A section, the San Ysidro Formation is 81 m thick and composed of red siltstone with intercalated, mostly fine- to medium-grained sandstone of various lithofacies, and rare, thin dolomite beds and one thin conglomerate bed. Red siltstone intervals are 0.4–4.5 m thick, laminated, and rarely massive (unit 124).

Sandstone lithofacies are: (1) trough cross-bedded sandstone (St), forming 0.3–1.4 m thick intervals, probably partly eolian (Ste); (2) rare horizontally laminated sandstone (Sh) forming 1.1–1.6 m thick intervals, alternating with trough cross-bedded sandstone (in units 104 and 106); (3) massive sandstone (Sm) is rare (one interval, 0.8 m thick, unit 88); and (4) ripple-laminated sandstone (Sr) is present as 0.6–1.7 m thick intervals. Ripple laminated beds commonly alternate with horizontally laminated thin beds.

Pedogenic carbonate (P) appears as a few thin dolomite beds that show desiccation cracks and siliciclastic inclusions and are 0.2–0.5 m thick intercalated in siltstone in the middle of the formation (units 86, 90, 92, 96 in the Placitas A section). A thin conglomerate bed (0.3 m, unit 105) is intercalated in sandstone and composed of reworked siltstone clasts.

Note that the San Ysidro Formation is generally finer grained than the Arroyo de Alamillo Formation and thus is a slope former, not a ridge or cuesta former. Gypsiferous sandstone and ripple laminated sandstone are more abundant in the San Ysidro Formation. Dolomite intercalations are present in the San Ysidro Formation and are absent in the Arroyo de Alamillo Formation

San Ysidro Formation—Sandstone Petrography

Fine- to medium-grained sandstone is moderately to well-sorted and composed of mainly subrounded grains; some sandstones are well-sorted, display a bimodal grain-size distribution (coarse fraction 0.2–0.4 mm) and contain rounded to well-rounded grains (eolian). Composition is similar to that in the Arroyo de Alamillo Formation (though there is more quartz in the San Ysidro Formation and less rock fragments): abundant quartz grains (monocrystalline, subordinately polycrystalline quartz), and many to abundant feldspars (mainly potassium feldspars, few plagioclase grains). Feldspars are fresh (particularly microcline) to slightly to moderately altered to clay minerals. Many feldspar grains are partly to completely replaced by calcite. Rarely, a few granitic rock fragments are present. Micas are absent in the eolian sandstones.

Sandstone is cemented by coarse, blocky, partly poikilotopic calcite cement and stained red by hematite (Figs. 6G and 6H). Sandstones contain 36–41% quartz, 10–15% feldspars and 6–8%rock fragments (2 samples; Table 2). According to the mineralogical composition they are classified as subarkose (Fig. 7).

Los Vallos Formation (Torres Member)—Lithostratigraphy

This formation is composed only of the Torres Member at our Placitas A section, largely based on the presence of relatively thick dolomites, which are characteristic of the Torres Member (Lucas et al., 2005). It is a bedded, gypsiferous dolomite (1.8 m) at the base and contains three thick intervals of mostly covered red siltstone (5.7, 10.2 and 9.3 m thick, units 136, 139, 142). The lower two siltstone intervals are separated by fine-grained gypsiferous sandstone (Sh) and overlain by gypsiferous bedded dolomite that is brecciated in the upper part. The upper two siltstone intervals are separated by a couplet consisting of a gypsum interval that is 0.8 m thick (unit 140) overlain by massive gypsiferous siltstone (1.7 m; unit 141). The top of the formation is gypsiferous, ripple-laminated sandstone with thin interbeds of horizontally laminated sandstone (unit 143, 1.4 m thick).

Placitas B Section

Lucas et al. (1999) presented a detailed description of the Placitas section B (their section A), so our description is brief (Fig. 4). The topmost Atrasado Formation (main body of Wild Cow Formation of Lucas et al., 1999) is composed of yellowish-brown limestone (bioclastic packstone) and nodular limestone. The overlying Bursum Formation (uppermost Wild Cow Formation of Lucas et al., 1999) is 18.4 m thick and starts with light gray sandy siltstone (1.2 m), overlain by nodular limestone (6 m), red mudstone with intercalated nodular limestone (4.6 m), nodular limestone and red shale (1.1 m), trough cross-bedded pebbly, coarse-grained sandstone to fine-grained conglomerate composed of quartz, feldspar, chert and containing bone fragments (2 m), and a pale red silty mudstone with intercalated thin beds of ripple-laminated sandstone (3.2 m). A micritic limestone bed (0.3 m) forms the top of the Bursum Formation.

Abo Formation—Lithostratigraphy

At the Placitas B section, the Abo Formation is 113 m thick, but the section apparently is tectonically thinned (strata are faulted out), which makes it difficult to compare this section with the nearby Placitas A section, which is significantly thicker (212 m). The Scholle Member is 31 m thick (Fig. 4, units 9–11), and the Canon de Espinoso Member is 82 m thick (Fig. 4, units 12–31). Pale red and partly covered, silty mudstone and shale (lithofacies Fsm, subordinately Fl) form thick intervals (up to 23.3 m thick). Unit 13 contains fossil plant debris, fossil bones and coprolites. Mudstone unit 24 contains lenses of clast-supported, intraformational pebble conglomerate composed of calcrete and mudstone clasts (latter is up to 1 cm in diameter). Lucas et al. (1999) reported a thin lens (0.2 m) of black shale in unit 24 that contains fossil leaves, conchostracans and insect fossils, consistent with a nonmarine origin.

Conglomeratic sandstone is trough crossbedded and has fine limestone clasts that are 0.2–0.5 cm in diameter (lithofacies Gt;

unit 10). Massive (unbedded) conglomerate is clast supported (lithofacies Gm) and composed of limestone pebbles up to 1 cm in diameter and arkosic sandstone matrix. Thin interbeds of green shale occur in units 16 and 18 (4.4 and 3.1 m unit thickness). The conglomerate of unit 20 is 0.9 m thick. Lucas et al. (1999) described a thin, lenticular conglomerate (0.2 m) in unit 22 that is composed entirely of reworked crinoid fragments.

Trough cross-bedded sandstone (St) is common in the middle and upper parts of the formation, forming 1.2–5.5 m thick, multistoried intervals. Thin intervals of trough cross-bedded sandstone are at the bases of units 12 and 23, grading into ripple laminated sandstone (Sr). Horizontally laminated sandstone (Sh) to silty sandstone forms a thick interval (4 m) in the middle of the formation (unit 14), and at the top of the Abo Formation lies low-angle cross-bedded sandstone (Sl; unit 31) and ripple-laminated sandstone (Sr; unit 30). Ripple-laminated sandstone (Sr) forms 1–7 m thick intervals, interbedded with thin beds of horizontally laminated sandstone (common in the upper part).

Yeso Group, De Chelly Sandstone—Lithostratigraphy

The De Chelly Sandstone is 59 m thick (Fig. 4, units 32–40) and is composed of two thick intervals of fine-grained, large-scale (set thicknesses are a meter or more) trough cross-bedded sandstone (units 32, 35), fine- to coarse-grained, well-rounded sandstone with large-scale crossbedding (eolian dune sand), horizontally laminated sandstone (unit 33), a thick succession of ripple-laminated sandstone beds alternating with horizontally laminated sandstone (units 36 and 37) and coarse-grained, trough cross-bedded sandstone on top containing well-rounded grains (unit 38).

Yeso Group, San Ysidro Formation

The San Ysidro Formation measures approximately 115 m and is composed of a thick succession of ripple laminated and horizontally laminated sandstone (Fig. 4, units 39–41), locally containing halite pseudomorphs (unit 40) and carbonate concretions (upper part of unit 41). Occurring above are horizontally laminated sandstone (unit 42), gypsiferous limestone (unit 43), horizontally laminated and massive sandstone (unit 44), limestone alternating with gypsiferous sandstone (unit 45) and horizontally laminated and massive, very gypsiferous sandstone (unit 46).

Other Sections

In the Sandia Mountains, south of Placitas, colluvium, soil and forest cover as well as faults make it impossible to measure complete sections of the Abo-Yeso strata. Thus, we measured well exposed portions of these units at five locations (Figs. 1 and 5).

Highway 536

Along Highway 536, which climbs from the eastern foothills to the crest of the range, two roadcuts expose approximately 3 m of the uppermost Abo Formation (Cañon de Espinoso Member), the Abo-Yeso contact, and the basal 8 m of the Arroyo de Alamillo Formation. The uppermost strata of the Abo Formation are red siliciclastic mudstone with rhizoliths and an intercalated calcrete interval. The lower part of the Arroyo de Alamillo Formation has a thickness of approximately 8 m, and its base is a thin dolomite bed (0.5 m). Overlying strata are ripple-laminated, fine-grained sandstone (Sr) intercalated with siltstone and thin dolomite beds, planar cross-bedded fine-grained sandstone (?eolian; Sp), bedded dolomite and massive to horizontally-laminated fine-grained sandstone (Sm, Sh).

Incidentally, Kelley and Northrop (1975, map 1) accurately mapped the Abo-Yeso contact at our Highway 536 section. In contrast, Ferguson et al. (1996) mapped these outcrops as Abo-Yeso undivided.

Ranch Road

At the Ranch Road section the upper part of the Los Vallos Formation is exposed, including the upper 13.9 m of the Torres Member and the Joyita Member (53.7 m) of the Los Vallos Formation, overlain by Glorieta Sandstone. The dominant lithofacies of the Torres Member is gypsiferous siltstone to fine-grained sandstone that partly displays small folds (probably resulting from alteration of anhydrite to gypsum). Thin intervals of massive sandstone, sandstone with wavy beds (?eolian) and wavy and even bedded dolomite are intercalated. The Cañas Gypsum Member that lies between the Torres and Joyita Members elsewhere is not present at this locality.

The Joyita Member displays a facies similar to the Joyita Member at the Sandia Mountains Natural History Center (see below) described by Lucas et al. (2015). It is composed of tabular beds of fine-grained massive sandstone (Sm) at the base, red siltstone with intercalated ripple-laminated (Sr) and horizontally laminated (Sh) fine-grained sandstone and thin planar sandstone beds in the uppermost part. The Glorieta Sandstone overlies the Joyita Member.

Sandia Mountain Natural History Center (SMNHC)

Lucas et al. (2015) described the Permo-Triassic stratigraphic section at the SMNHC, which is in Cedar Crest in the southern Sandia Mountains. This section includes 43 m of poorly exposed siliciclastic red beds that exhibit ripple-laminated and planar-laminated sedimentary structures within tabular-bedded sandstone, that they assigned to the Joyita Member of the Los Vallos Formation (Fig. 5). The Glorieta Sandstone overlies these strata.

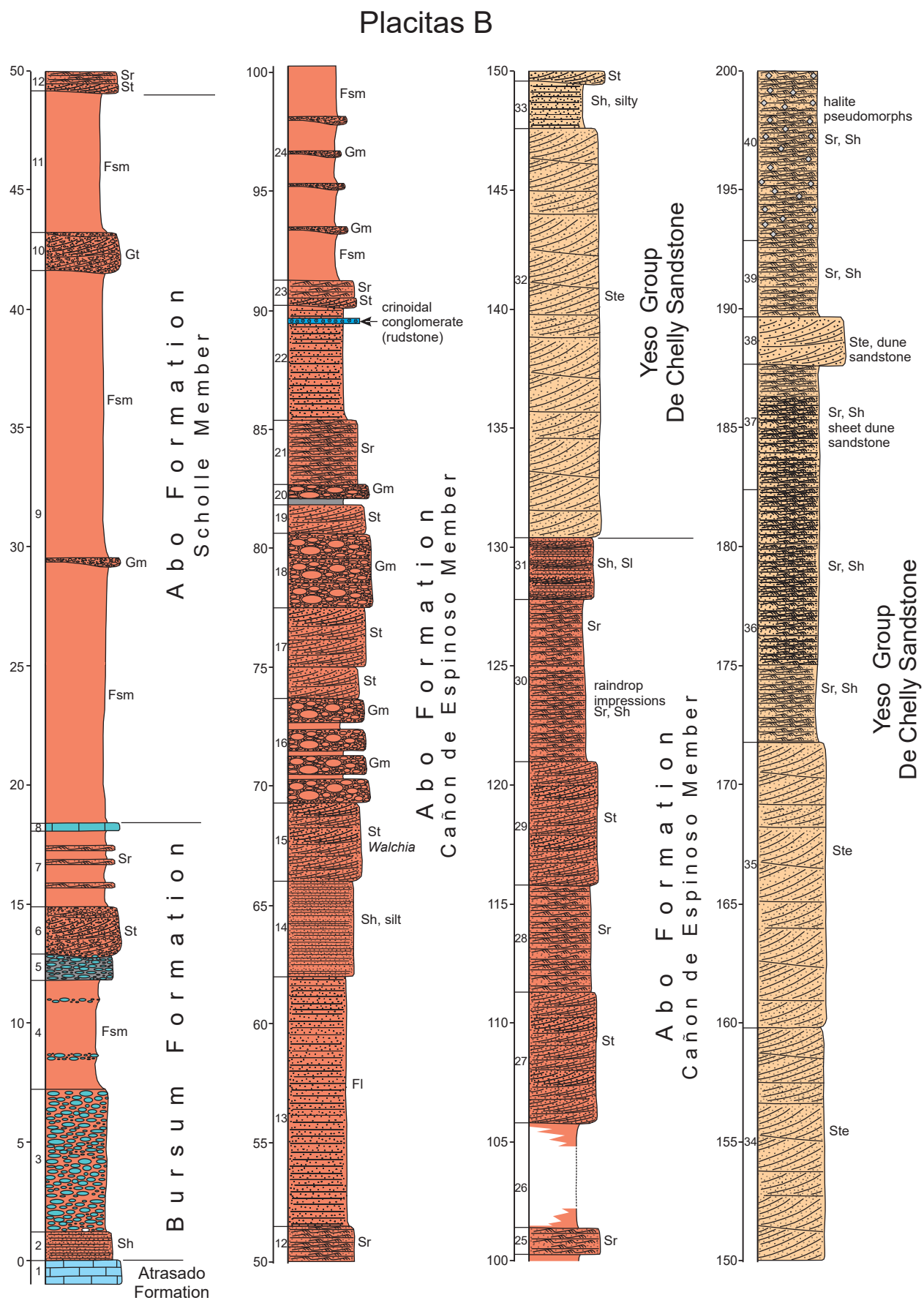


FIGURE 4. (continued) Placitas B section. Base of section at UTM coordinates 373854 mE, 3912693 mN and top at 374310 mE, 3912760 mN (zone 13, NAD27).

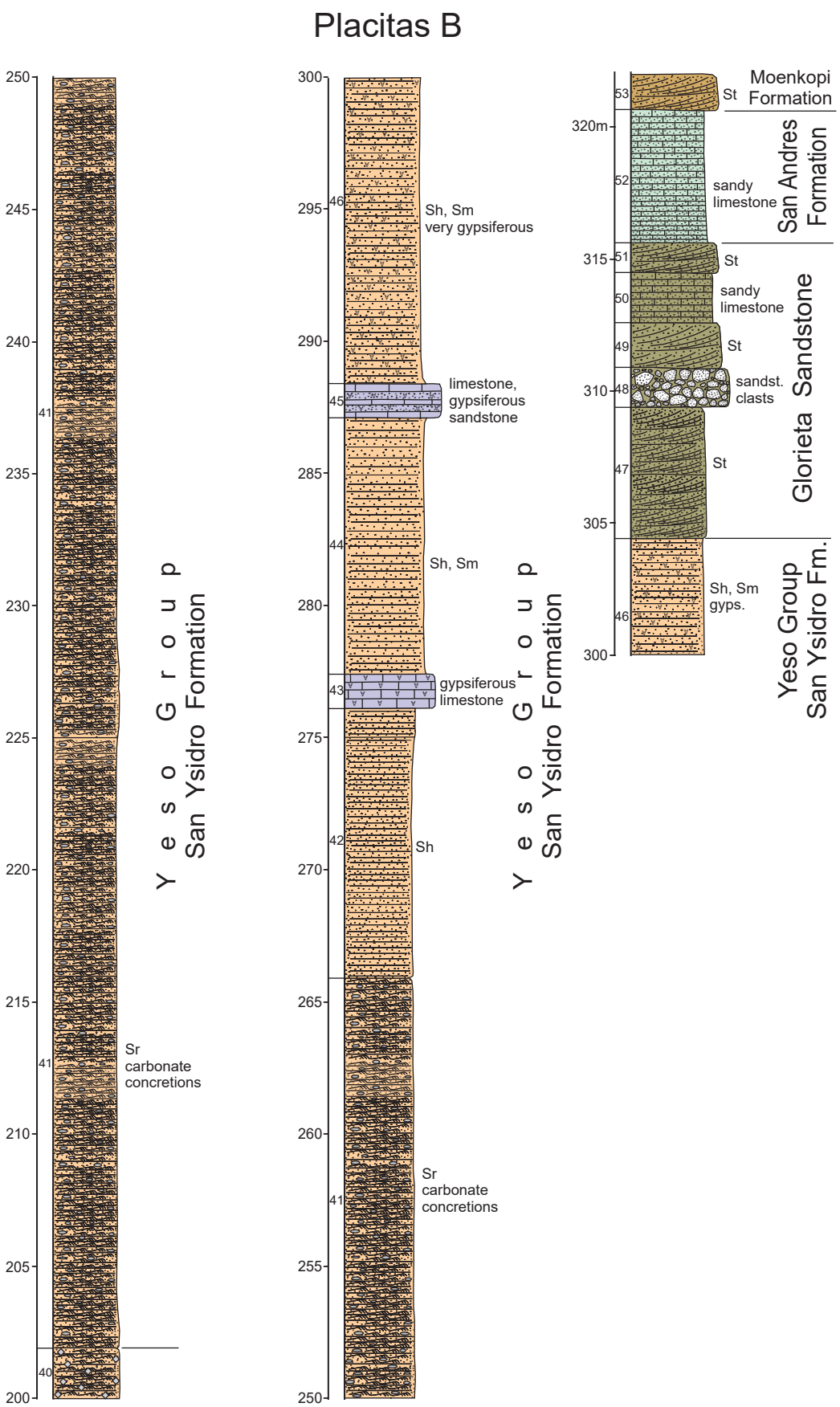


FIGURE 4. Placitas B section. Base of section at UTM coordinates 373854 mE, 3912693 mN and top at 374310 mE, 3912760 mN (zone 13, NAD27).

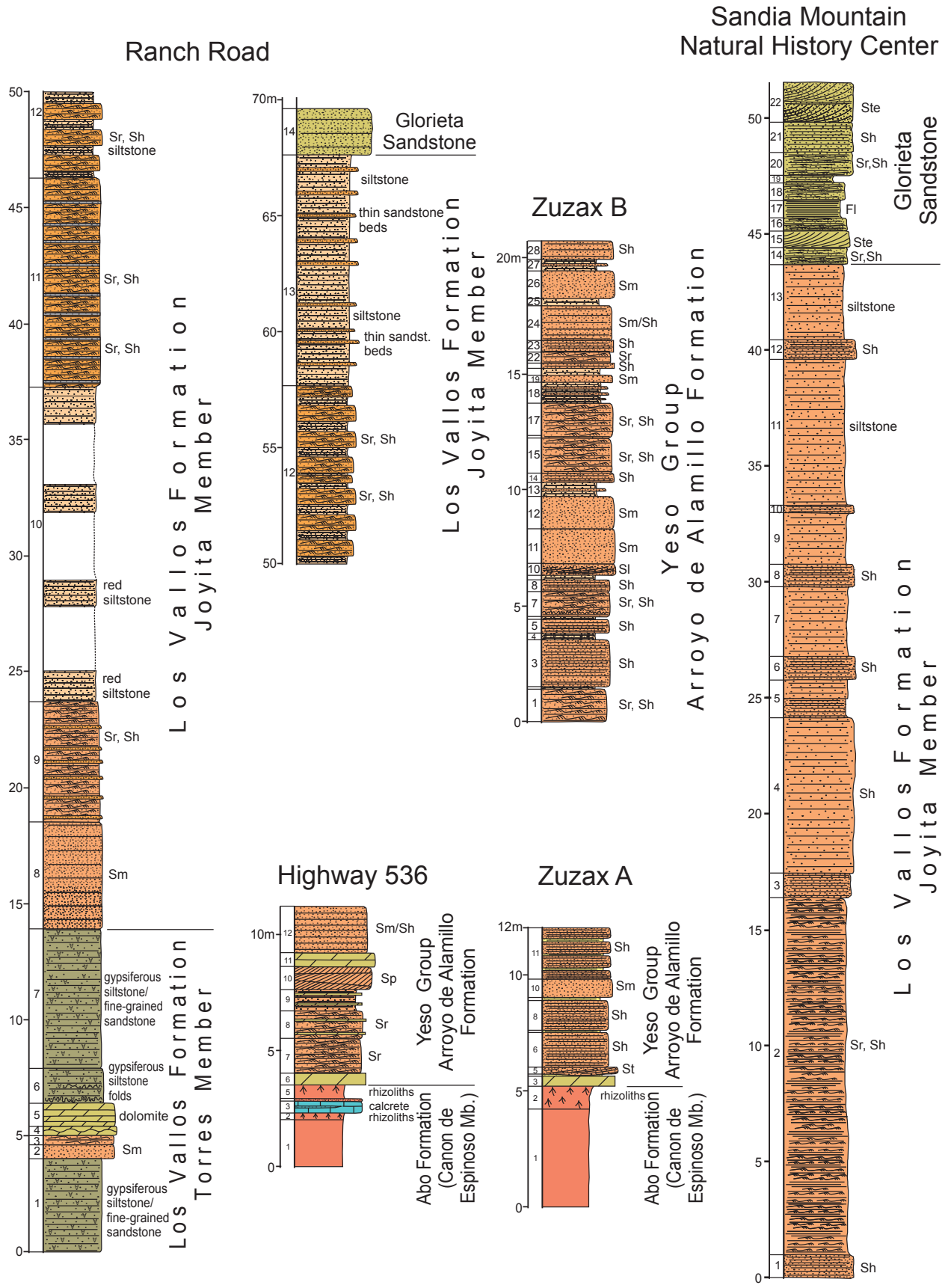


FIGURE 5. Sections of Abo-Yeso strata at Highway 536, Ranch Road, the SMNHC and Zuzax A and B. UTM coordinates of sections: Highway 536 base at UTM 375873E mE, 3892489 mN, top at 375892 mE, 3892464 mN; Ranch Road base at 375924 mE, 3892104 mN; SMNHC, see Lucas et al. (2015); Zuzax A at 376808 mE, 3885202 mN; Zuzax B base at 376566 mE, 3885153 mN, top at 376514 mE, 3885142 mN (zone 13, NAD83).

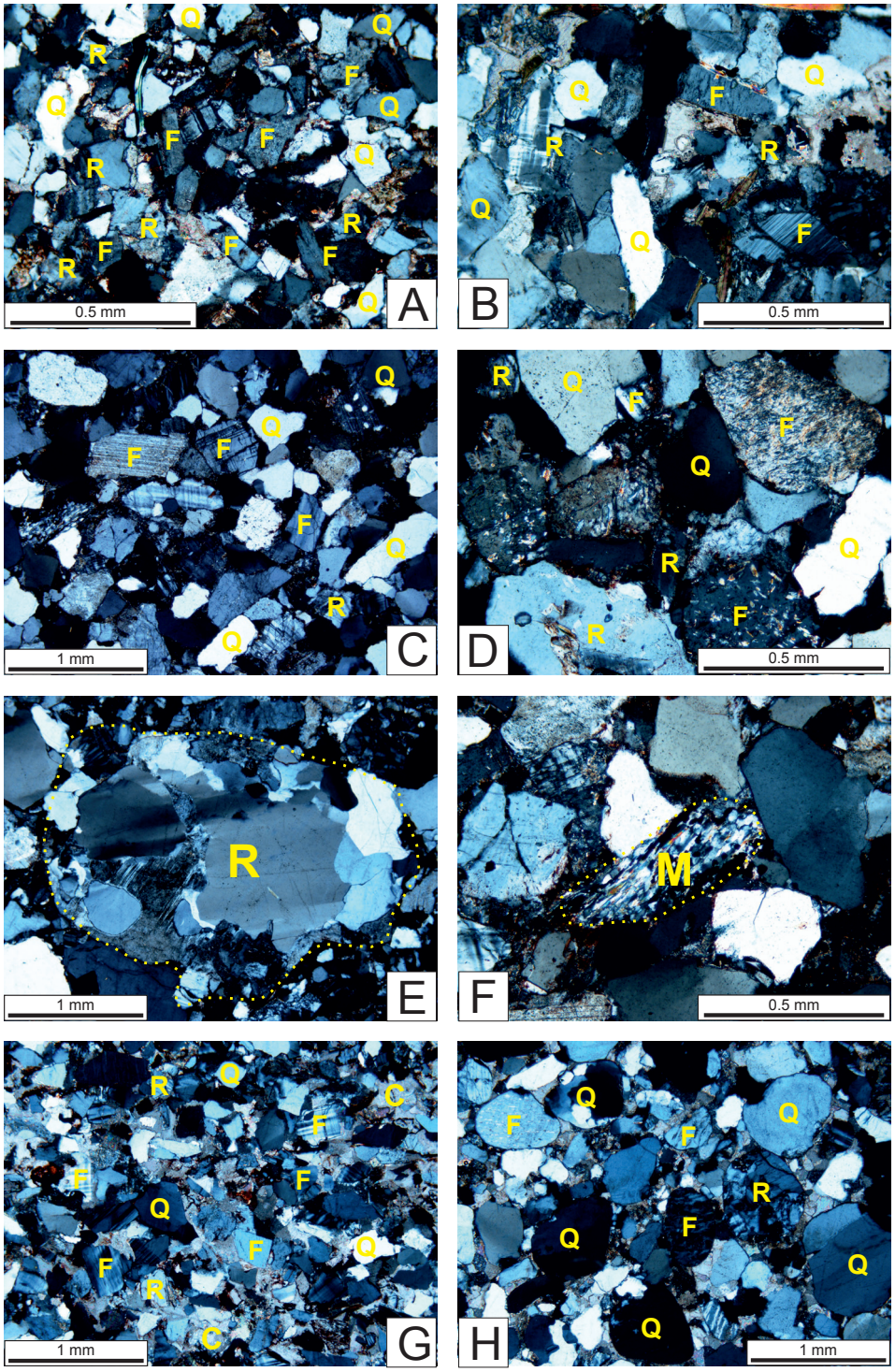


FIGURE 6. Thin section photographs of sandstone from the Abo Formation (A-B), Arroyo de Alamillo Formation (C-F) and San Ysidro Formation (G-H) at Placitas section A. All under polarized light. Abbreviations are : Q Quartz, F Feldspar, R Rock fragment (granitic), M metamorphic rock fragment, C Calcite cement. Panels are as follows. Sample numbers are unit numbers. A, Fine-grained sandstone containing abundant quartz grains, many feldspar grains and rock fragments (sublitharenite). The sandstone is cemented by quartz overgrowths and blocky calcite cement. Sample PAY 27, Abo Formation. B, Fine-grained sandstone composed of abundant quartz grains, many feldspar grains (mostly potassium feldspars) and rock fragments, cemented by quartz overgrowths and blocky calcite cement (lithic arenite). Sample PAY 53, Abo Formation. C, Fine-grained sandstone containing abundant monocrystalline quartz grains, few polycrystalline quartz grains, many feldspars (including microcline) and granitic rock fragments (sublitharenite). Sample PAY 55, Arroyo de Alamillo Formation. D, Sandstone containing altered feldspar grains. The grain in the upper right is strongly altered to clay minerals, other feldspar grains are slightly altered, rarely fresh. Sample PAY 55, Arroyo de Alamillo Formation. E, Sandstone containing a large granitic rock fragment composed of quartz and feldspars. Sample PAY 59, Arroyo de Alamillo Formation. F Sandstone containing a schistose metamorphic rock fragment (center) composed of quartz and micas. Sample PAY 55, Arroyo de Alamillo Formation. G, Fine-grained sandstone composed of abundant quartz grains, feldspar grains (including microcline), and few rock fragments, cemented by coarse blocky calcite (subarkose). Sample PAY 79, San Ysidro Formation. H Fine-grained sandstone composed of rounded to well rounded grains of quartz, feldspars and granitic rock fragments, cemented by calcite (subarkose). PAY 129, San Ysidro Formation.

Zuzax A

At the Zuzax A section the uppermost Abo Formation is composed of red siliciclastic mudstone with rhizoliths. Very similar to the Highway 536 section, the overlying lower part of the Arroyo de Alamillo Formation (exposed thickness approximately 7 m) has a dolomite bed (0.4 m) at the base, overlain by thin siltstone, and cross-bedded sandstone (?eolian; St). Most of the described Arroyo de Alamillo Formation consists of horizontally laminated sandstone (Sh) with thin siltstone intercalations and one interbed of massive sandstone (Sm).

Zuzax B

At the Zuzax B section the exposed thickness of the Arroyo de Alamillo Formation is approximately 21 m; the contact with the underlying Abo Formation and overlying Los Vallos Formation is not exposed. The Arroyo de Alamillo Formation is a succession of various lithotypes of fine-grained sandstone—Sm, Sh, Sr, and rare sandstone with low-angle trough crossbeds (Sl) that are 0.2–1.5 m thick. Intercalated siltstone beds are 0.1–0.3 m thick.

PALEONTOLOGY AND AGE

In the vicinity of the Placitas sections, Abo strata have a fossil record of tetrapod footprints, conchostracans, megafossil plants and tetrapod bones. Lucas et al. (1999), Knaus and Lucas (2005) and Martens and Lucas (2005) described these fossils. Peltasperm plants and conchostracans are present in the black shale lacustrine deposit in unit 24 of the Placitas section B. Impressions of walchian conifers and sparse trace fossils, notably a trackway of *Dimetropus,* are present in the Abo red beds near Placitas as are a few embolomere vertebrae. These are fossils of nonmarine organisms and are similar to fossils found in other Abo outcrop areas. All of these fossils are consistent with an early Permian (~ Sakmarian-early Artinskian) age for the Abo Formation established elsewhere from more extensive paleontological data and the stratigraphic relationship of the Abo to marine strata in southern New Mexico (Lucas et al., 2013a, 2025).

We encountered no fossils in Yeso Group strata in the Sandia Mountains. Its early Permian (primarily Kungurian) age is established by conodonts from the basal Los Vallos Formation in the Caballo Mountains, near Truth or Consequences, and by its stratigraphic relationships to better dated units (e.g., Lucas et al., 2022).

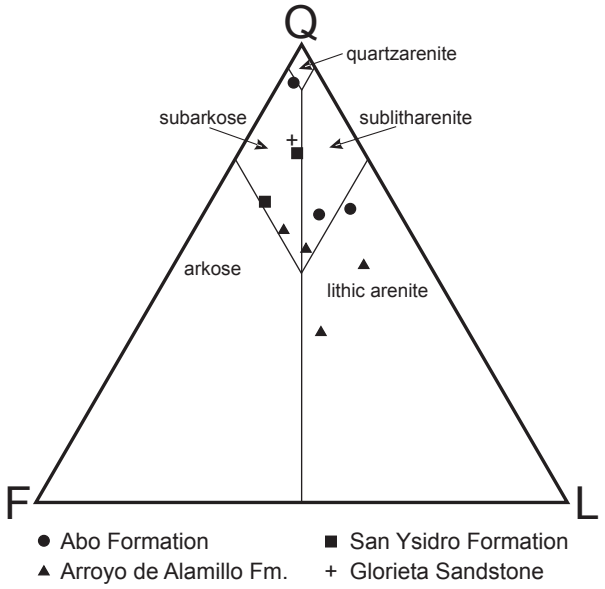


FIGURE 7. QFL diagram showing the composition of sandstones from the Abo Formation, Arroyo de Alamillo Formation, San Ysidro Formation and Glorieta Sandstone at Placitas section A. Q (total amount of quartz; Qm + Qp) plus F (total amount of single feldspar grains) plus R (total amount of rock fragments; Lg + Lm + Ls) = 100% (classification scheme of Pettijohn et al. 1987).

DEPOSITIONAL SYSTEMS

Abo Formation

The Abo Formation at Placitas A and B is composed mostly of overbank deposits (architectural element FF, overbank fines; Miall 1996, 2010). Intercalated are relatively thin, massive conglomerate beds (lithofacies Gm, debris flow deposits; architectural element SG, sediment gravity flows) and trough cross-bedded sandstone (St, minor channel fill deposits, architectural element CH, channels; Miall 1996, 2010). Thicker sandstone units that commonly display a sheet-like geometry and can be traced laterally over at least a few hundred meters are a common architectural element of the Cañon de Espinoso Member of the Abo Formation at Placitas (and elsewhere). These sandstone sheets represent deposits of broad, shallow channels of a low-sinuosity river system (architectural elements CH and SB). Limestone intervals composed of partly nodular lime mudstone that are up to 1.5 m thick and intercalated in red mudstone represent pedogenic carbonates indicating periods of carbonate soil formation under seasonally dry climatic conditions.

The Abo section at Placitas B is composed of lithofacies and architectural elements similar to those at Placitas A. But the succession is significantly thinner (probably tectonically reduced by faulting) and has a higher proportion of sandstone and conglomerate, in particular a thick interval (approximately 20 m) of sandstone and conglomerate in the middle of the succession. This abundance of conglomerates may be the result of synsedimentary tectonics (block faulting) that resulted in erosion and redeposition of previously deposited Abo sediments.

Like Abo sections elsewhere in New Mexico, the Abo Formation at Placitas is composed of three principal architectural elements: (1) mudstone-siltstone with caliche nodules and intercalated pedogenic limestone (calcrete) intervals representing floodplain deposits, (2) thin lenses and beds of sandstone and conglomerate representing minor channel fills and debris flow deposits, and (3) sandstone sheets (see Lucas et al., 2013a). In general, sediments of the Abo Formation were deposited on an extensive alluvial plain on which well-defined fluvial channels and extensive, muddy to silty floodplains were succeeded

by sandstone sheets of low-sinuosity rivers subject to episodic avulsion and sheetflooding (Krainer and Lucas, 2010; Lucas et al., 2013a). On the Abo alluvial plain, the flow direction of the rivers was primarily to the south towards the shoreline of the Hueco seaway in southern New Mexico (e. g., Kues and Giles, 2004; Lucas et al., 2013a). Lucas et al. (2024) suggested that the overall geometry of the Abo Formation deposits in parts of northern and southern New Mexico may fit the distributive fluvial system model.

Yeso Group

In the Placitas area, the southeasternmost outcrops of the De Chelly Sandstone are exposed with a thickness of approximately 60 m (Placitas B section). The De Chelly Sandstone is characterized by the occurrence of thick intervals of large-scale cross-bedded sandstone representing eolian dunes and thickens towards the northwest and southwest (Lucas et al., 2005). Intervals composed of very fine-grained, horizontally laminated sandstone and ripple-laminated sandstone alternating with horizontally laminated sandstone represent eolian sand sheet and interdunal deposits.

In the Placitas area the De Chelly Sandstone grades towards the south into the Arroyo de Alamillo Formation that at section A is approximately 24 m thick and composed of alternating sandstone intervals of small-scale trough cross-bedded eolian sand dunes, siltstones representing overbank (Fl, floodplain) deposits, and rare fluvial channel-fill deposits. The large-scale eolian sand dune deposits of section B decrease in thickness towards section A, indicating that the Placitas area represents the local margin of the De Chelly erg.

The main lithologies of the Arroyo de Alamillo Formation near Placitas are intervals of trough cross-bedded eolian sandstone (Ste; 0.7–4 m thick) and rare trough cross-bedded fluvial sandstone (St) that alternate with siltstone. We interpret the trough cross-bedded sandstone (lithofacies Ste) as small-scale eolian sand dunes, the trough cross-bedded sandstone of interval 63 as fluvial channel-fill deposits of a low sinuosity river system (architectural element CH) and the siltstones as floodplain deposits (architectural element FF). The lower thin gypsiferous sandstone bed that is intercalated in siltstone (unit 65; Fig. 3) probably resulted from sheetfloods on the floodplain because it is horizontally laminated and composed of sand-sized grains (architectural element SG, sediment gravity flow). The upper gypsiferous sandstone (unit 69; Fig. 3) displays eolian trough crossbedding and represents small-scale eolian dunes. The evaporation of groundwater within the sediment resulted in the precipitation of gypsum in the pore space of the sand, causing the formation of gypsiferous sandstone.

The parts of the Arroyo de Alamillo Formation exposed at the sections south of Placitas (Highway 536, Zuzax A and B) are characterized by a succession of red bed sandstone and siltstone with a few intercalated intervals of dolomite and gypsum. Sandstone commonly displays horizontal lamination and ripple lamination and, subordinately, small-scale trough crossbedding. Sediments of the Arroyo de Alamillo Formation were deposited by dominantly eolian and fluvial processes (eolian sand sheet deposits, small fluvial channel-fill deposits and unchannelized sheetflood deposits) on an arid coastal plain (cf. Mack and Dinterman, 2002). Thin intervals of fine-grained sediments indicating evaporitic conditions (gypsiferous siltstone, gypsum, dolomite) formed during short periods of marine flooding (Lucas et al., 2013b). Thick intervals of large-scale trough cross-bedded sandstone (eolian dune sands) are absent in the Arroyo de Alamillo Formation.

The San Ysidro Formation of the Yeso Group at the type section in the Jemez Mountains is very similar to but thicker than the San Ysidro Formation at Placitas. Towards the south the San Ysidro Formation grades into the Los Vallos Formation (divided into Torres, Cañas and Joyita members). At section A, the uppermost part of the Yeso Group is Los Vallos Formation strata, indicating interbedding of the San Ysidro Formation with the Los Vallos Formation in the Placitas area (and southward) (Fig. 8). The dolomite beds formed during short periods of marine flooding in a shallow, restricted marine environment.

The sediments of the Torres Member are interpreted as deposits of a coastal sabkha environment with intercalations of eolian sediments (fine-grained sandstone with wavy beds). The facies of the Joyita Member is interpreted as eolian sand sheet deposits (Mack and Dinterman, 2002; Lucas et al., 2015). Gypsiferous limestone and gypsiferous sandstone indicate deposition on a coastal sabkha (cf. Stanesco, 1991).

In the Placitas area the large eolian sand dunes represented by the De Chelly Sandstone grade toward the south into eolian sand sheet deposits with intercalated small fluvial channel fill deposits of an arid coastal plain represented by the Arroyo de Alamillo Formation. The Placitas area thus represents the southeastern margin of the De Chelly erg.

The San Ysidro Formation displays a southward lateral facies change from dominantly fine-grained eolian sand sheet deposits with intercalated gypsiferous limestone and sandstone (indicating deposition on a coastal sabkha) (Placitas B) to dominantly fluvial deposits with rare eolian and probable marine intercalations (Placitas A).

STRATIGRAPHIC CORRELATION

Correlation of Abo strata from the Sandia uplift to the Abo outcrops to the northwest and south indicates the continuity (with varying thickness) of the two Abo members, which are present from the Jemez Mountains in Sandoval County to as far south as the Caballo Mountains of Sierra County (Lucas et al., 2005). However, Yeso correlations indicate major facies changes along that transect (Fig. 8). Thus, Yeso correlations show fairly consistent lithofacies from Abo Pass at the southern end of the Manzano Mountains through the Fra Cristobal Mountains of Sierra County. Northward, to the northern Sandias, the Yeso thins, as do its constituent formations. The Arroyo de Alamillo Formation grades into the eolianite-dominated De Chelly Sandstone, and the mixed marine-nonmarine Los Vallos Formation transitions to a more nonmarine, more sandy (with little gypsum or carbonate) San Ysidro Formation. To the northwest, in the Jemez Mountains, the De Chelly and San

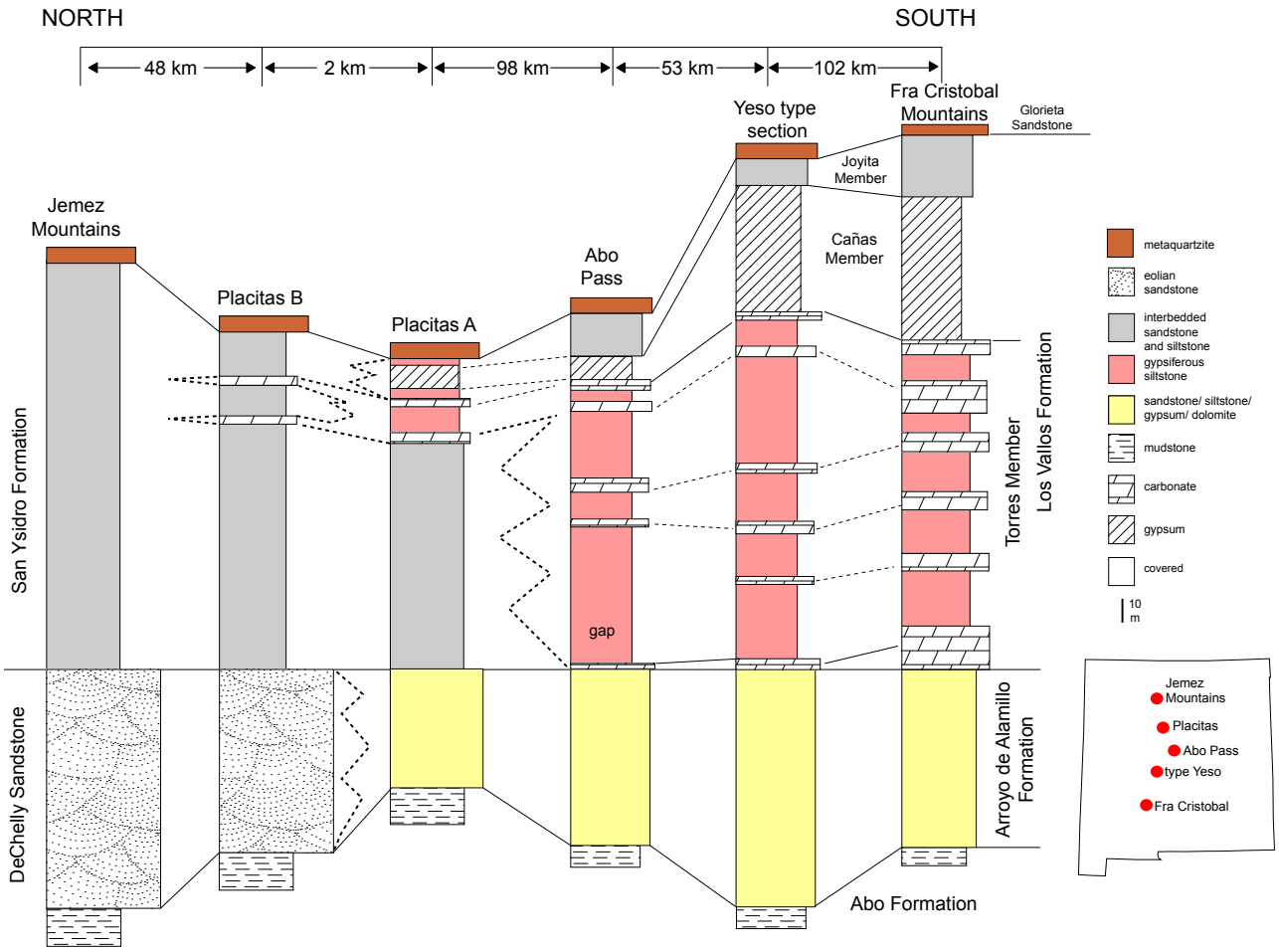


FIGURE 8. Correlation of Yeso Group sections, including the Yeso sections near Placitas described here (modified from Lucas et al., 2016). The gap labeled in the Abo Pass section is a stratigraphic interval of poor to incomplete exposure that could not be measured readily.

Ysidro formations are thicker than they are at Placitas but otherwise lithologically similar.

The Placitas area was thus a critical juncture in the Yeso depositional system. It separated the De Chelly erg and siliciclastic shelf deposits of the San Ysidro Formation from the arid coastal plain deposits of the Arroyo de Alamillo and the mixed marine-nonmarine strata of the Los Vallos Formation (Fig. 9). This likely reflected the position of Placitas in the Yeso depositional system, which extended from southeastern New Mexico just north of the Delaware basin to the southern Colorado Plateau in northwestern New Mexico. The Placitas area was thus where the De Chelly erg transitioned to the arid coastal plain deposits of the Arroyo de Alamillo Formation, and the siliciclastic shelf deposits of the San Ysidro Formation began to change to the more marine influenced coastal plain deposits of the Los Vallos Formation.

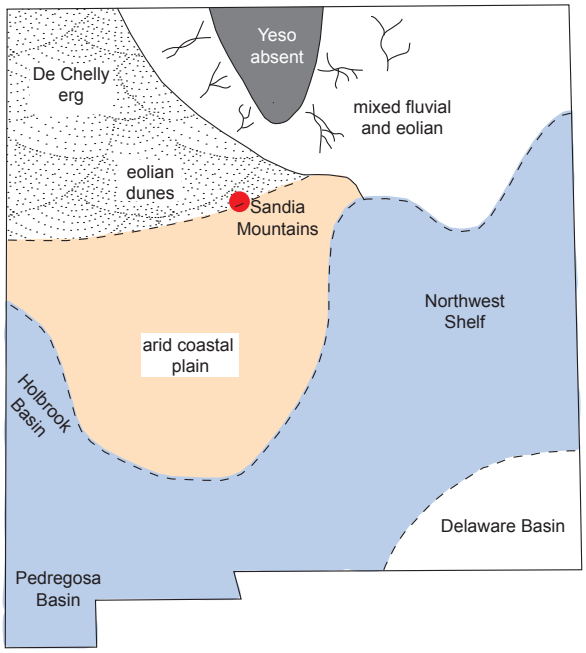


FIGURE 9. Paleogeographic map of New Mexico during deposition of the lower Yeso Group. Based on Mack and Dinterman (2002) and Lucas et al. (2013b).

ACKNOWLEDGMENTS

The late John Estep, Larry Rinehart, John Rogers and Sebastian Voigt assisted in the field. We thank Julia Wallraf (University of Innsbruck) for the preparation of petrographic thin sections. John Nelson, Kurt Rudolph and the editor, Dan Koning, provided helpful reviews of the manuscript.

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Dakota Sandstone is exposed east of the Las Placitas Historical Marker on NM 165, 3 miles (linear distance) southwest of Placitas. In this photograph, the lower slopes in the foreground consist of sandy shales and soft sandstones of the Oak Canyon Member, which are overlain by a well-indurated cuesta composed of sandstones of the Cubero Member. These shallow marine strata were deposited ~98 Ma (in the Cenomanian) during the early phases of the first great marine transgression across the Western Interior Seaway. Photograph courtesy of Spencer Lucas.