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PERMIAN STRATIGRAPHY EAST OF SOCORRO, CENTRAL NEW MEXICO

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Abstract—This paper reviews the Permian stratigraphic section in the Joyita Hills–Cerros de Amado–Carthage area east of Socorro. Here, the Permian section is ~900 m thick and is assigned to the (ascending) Bursum Formation, Abo Formation (Scholle and Cañon de Espinoso members), Yeso Group (Arroyo de Alamillo Formation and overlying Los Vallos Formation divided into Torres, Cañas, and Joyita members), Glorieta Sandstone, San Andres Formation, and Artesia Formation. The Bursum Formation is as much as 120 m thick and consists of interbedded red-bed siliciclastics (mudstone, sandstone, and conglomerate) and marine limestones. The Abo Formation is as much as 210 m thick and consists of siliciclastic red beds divided into the Scholle Member (mudstone with channelized beds of crossbedded sandstone and conglomerate) overlain by the Cañon de Espinoso Member (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, consists of ~107 m of red-bed siltstone, sandstone (mostly ripple laminated and horizontally laminated with some gypsiferous beds), and a few beds of dolomite. The overlying Torres Member of the Los Vallos Formation is ~156 m thick and mostly consists of gypsiferous siltstone, claystone, gypsum, and a few prominent beds of dolomite and gypsiferous sandstone. The overlying Cañas Member is 66 m thick, consists mostly of gypsum, and includes a few beds of gypsiferous siltstone and dolomite. The Joyita Member is ~12 m thick and consists of siltstone and red-bed sandstone that is crossbedded and ripple laminated. The Glorieta Sandstone is up to 85 m thick and consists of crossbedded, laminar, and ripple-laminated quartzose sandstone. The San Andres Formation encompasses as much as 125 m of mostly limestone (lime mudstone) or mostly gypsum. The Artesia Formation is up to 12 m thick and consists of red-bed siltstone and fine sandstone, with minor beds of gypsum and dolomite. It is overlain by Middle Triassic strata of the Moenkopi Formation. Local paleontological data coupled with regional correlations indicate that the Bursum Formation is early Wolfcampian, the Abo Formation is middle Wolfcampian–early Leonardian, the Yeso Group is Leonardian, the Glorieta and San Andres formations are late Leonardian, and the Artesia Formation is Guadalupian (Roadian-Wordian) in age.

INTRODUCTION

East of Socorro, a structurally complex area that extends from the Joyita Hills on the north through the Cerros de Amado to Carthage (on the south) exposes Permian strata on multiple fault blocks (Fig. 1). These strata are a thick and lithologically diverse section of nonmarine and marine rocks of early-middle Permian (Wolfcampian-Wordian) age (Fig. 2). The type section of the lower Permian Yeso Group, a unit widespread across New Mexico, is in this area, and the Permian strata east of Socorro contain a diverse fossil record important to the interpretation of paleoenvironments and to regional correlations. Therefore, much has been published about these Permian strata (see Lucas and Krainer, 2017, for a review of previous studies). Here, we present a brief review of the Permian stratigraphy east of Socorro, based largely on earlier publications by Lucas et al. (2005, 2013a–d), Krainer and Lucas (2009, 2013), Brose et al. (2013), Lucas and Krainer (2017), and unpublished mapping by John Nelson and Scott Elrick.

BURSUM FORMATION

The oldest Permian strata east of Socorro are assigned to the Bursum Formation. Krainer and Lucas (2009, 2013) presented a detailed review of the Bursum Formation stratigraphy east of Socorro, so we only present a brief synopsis here. The Bursum Formation is a transitional facies between underlying, dominantly shallow-marine, Upper Pennsylvanian carbonate deposits (Atrasado Formation) and overlying, lower Permian continental red beds (Abo Formation; Fig. 3).

East of Socorro, the Bursum Formation is as much as 120 m thick and composed of alternating shallow marine limestone and shale and nonmarine red beds. These alternating marine and nonmarine sediments locally form well-developed cyclic successions (Krainer and Lucas, 2009, 2013). However, there are significant vertical and lateral variations in thickness and facies (Fig. 3; Nelson et al., 2017), which is expressed by identifying three of the named members of the Bursum Formation (Lucas and Krainer, 2004) east of Socorro: (a) dominantly calcareous shale and limestone, Bruton Member; (b) red-bed mudrock and sandstone, Red Tanks Member; and (c) conglomeratic Oso Ridge Member (Krainer and Lucas, 2009).

Tectonic activity related to the Ancestral Rocky Mountains orogeny had a major impact on Bursum deposition in Socorro County. Most dramatically, the Bursum truncates the entire Pennsylvanian succession with an angular unconformity in the Joyita Hills, and the Abo Formation in turn truncates the Bursum, also with local angularity (Kottlowski and Stewart, 1970). Elsewhere in the county, tectonic activity appears to have controlled deposition of three distinct Bursum lithofacies: (1) relatively thin successions of nodular to bedded marine limestone and non-fissile, variegated claystone paleosols reflect deposition on stable, relatively high tectonic blocks where sea-level change was the dominant driver of sedimentation; (2) thicker packages of laminated gray to green shale, siltstone, and fine sandstone containing fossils of land plants and small invertebrates accumulated in fresh to brackish water on tectonic blocks that subsided rapidly; and (3) conglomerate and coarse arkosic sandstone occurring widely at the base of the Bursum and locally in the middle and upper parts reflect

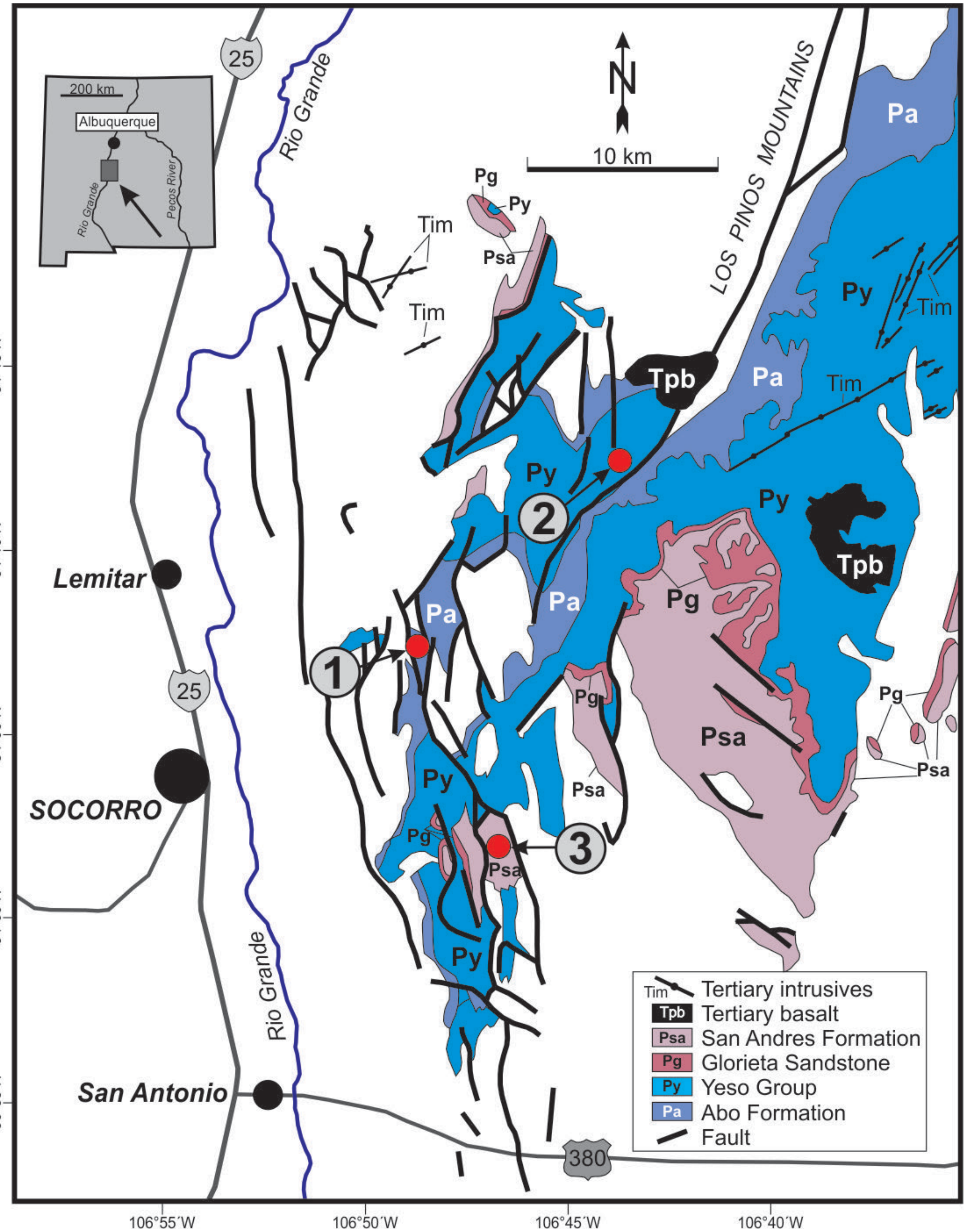

FIGURE 1. Generalized geologic map of the Permian strata exposed east of Socorro. Geology modified from NMBGMR (2003). Bursum and Artesia outcrop areas are too small to show legibly at the map scale. Locations of the measured sections of Permian strata are: 1 = Abo Formation at Minas del Chupadero (Fig. 4); 2 = type Yeso section (Fig. 5) and Glorieta Sandstone section at Mesa del Yeso (Fig. 6); and 3 = Glorieta-San Andres-Artesia formations sections at Gonzalez Well (Fig. 7). The Bursum sections in Figure 3 are located in Krainer and Lucas (2009, fig. 1).

distinct pulses of uplift in the Joyita Hills and elsewhere (Nelson et al., 2017).

ABO FORMATION

The lower Permian red beds above the Bursum Formation across central New Mexico are the Abo Formation (Lucas et al., 2013c). Lucas et al. (2005) named two formal members of the Abo Formation, the Scholle Member overlain by the Cañon de Espinoso Member. As elsewhere, in Socorro County the Abo is characterized by its predominant red-brown color and is composed almost entirely of nonmarine siliciclastic rocks.

East of Socorro, the Abo Formation ranges from about 120 m to as much as 210 m thick and is readily divided into the lower Scholle Member (~37–69 m thick) and the thicker, overlying Cañon de Espinoso Member (~50–175 m thick; Fig. 4).

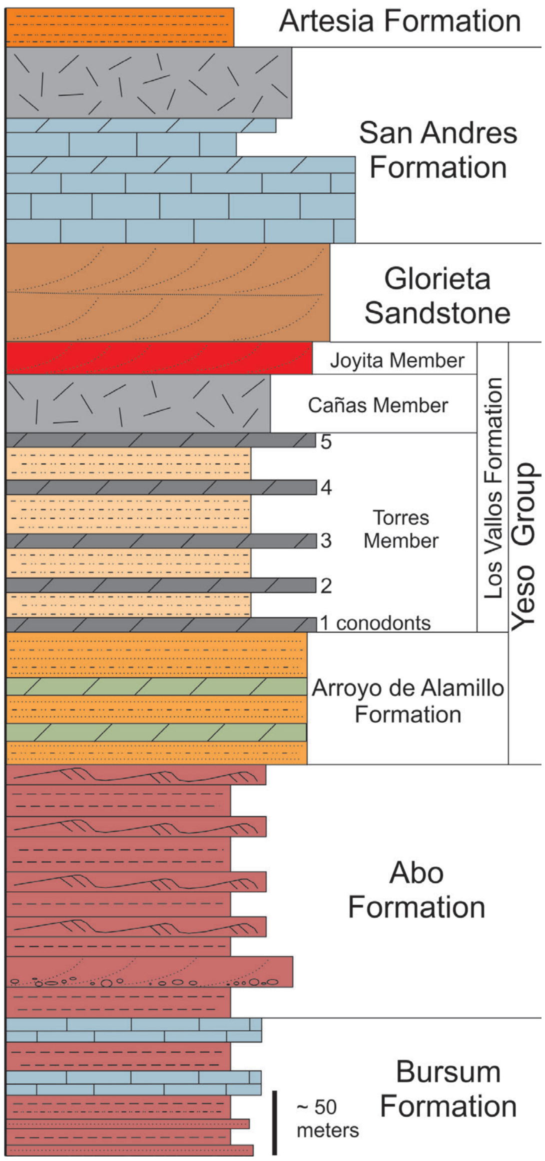

FIGURE 2. Generalized Permian stratigraphic section for central New Mexico. The numbers 1–5 in the Torres Member indicate prominent carbonate beds at the tops of the cycles discussed in the text.

The Scholle Member is mostly non-fissile mudstone beds, some of which contain numerous calcrete (limestone) nodules; in places, these nodules are coalesced into limestone ledges of relatively mature calcretes. Arkosic and subarkosic sandstone and conglomerate beds of the Scholle Member are generally trough crossbedded and form isolated, channel-form bodies incised into mudstone. Conglomerate beds are intraformational—commonly clast supported, moderately to poorly sorted, and composed of abundant, subrounded to rounded carbonate clasts ripped up from Abo calcretes. Some of the conglomerates also contain large amounts of reddish siltstone clasts (also Abo rip-up clasts) up to a few cm in diameter. Sandstones of the Scholle Member are dominantly arkose, subordinately subarkose, and lithic arenite (Lucas and Krainer, 2017).

The Cañon de Espinoso Member east of Socorro is composed of mudstone; like the Scholle Member, it is interbedded with ledge-forming layers of coarse siltstone to very fine sandstone (Fig. 4). The siltstone/sandstone beds in the Cañon de Espinoso Member are distinctive, mostly forming relatively thin (<10 m), laterally extensive (in some cases extending for km) sheets with climbing-ripple lamination. These sandstone sheets yield most of the invertebrate and tetrapod trace fossils and fossil plant impressions (dominantly conifers) that are known from the Abo Formation (e.g., DiMichele et al., 2013; Voigt and Lucas, 2017). Sandstones of the Cañon de Espinoso Member are classified as subarkose and are cemented by quartz and calcite (Lucas and Krainer, 2017).

East of Socorro, the highest limestone bed in the Bursum Formation is usually pedogenically modified and/or karstified beneath the basal Abo mudstone. We take this to indicate a disconformity at the Bursum-Abo contact, though the magnitude of the hiatus (which is close to the early-middle Wolfcampian boundary) may not be long in geological time. The Abo-Yeso contact, however, has long been considered conformable, with an interbedding of non-fissile mudstone and sandstone beds of Abo lithology with dolostones and finer-grained, lighter-colored, and more mature sandstones of the Arroyo de Alamillo Formation (Lucas et al., 2013b). The lowest sandstone of the Arroyo de Alamillo Formation is texturally and mineralogically more mature than any Abo sandstone stratigraphically below it (Lucas et al., 2005). In the sections we measured east of Socorro, we chose the lowest dolostone or sandstone of Yeso lithology to be the base of the Arroyo de Alamillo Formation (Fig. 5).

YESO GROUP

Arroyo de Alamillo Formation

Lee (1909) originally included the strata we assign to the Arroyo de Alamillo Formation 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 (Figs. 2, 5). Needham and Bates (1943; also see Darton, 1922, 1928) drew the Abo-Yeso contact this way. However, Wood and Northrop (1946), Wilpolt et al. (1946), Bates et al. (1947), and Wilpolt and Wanek (1951) removed the upper sandstone-dominated

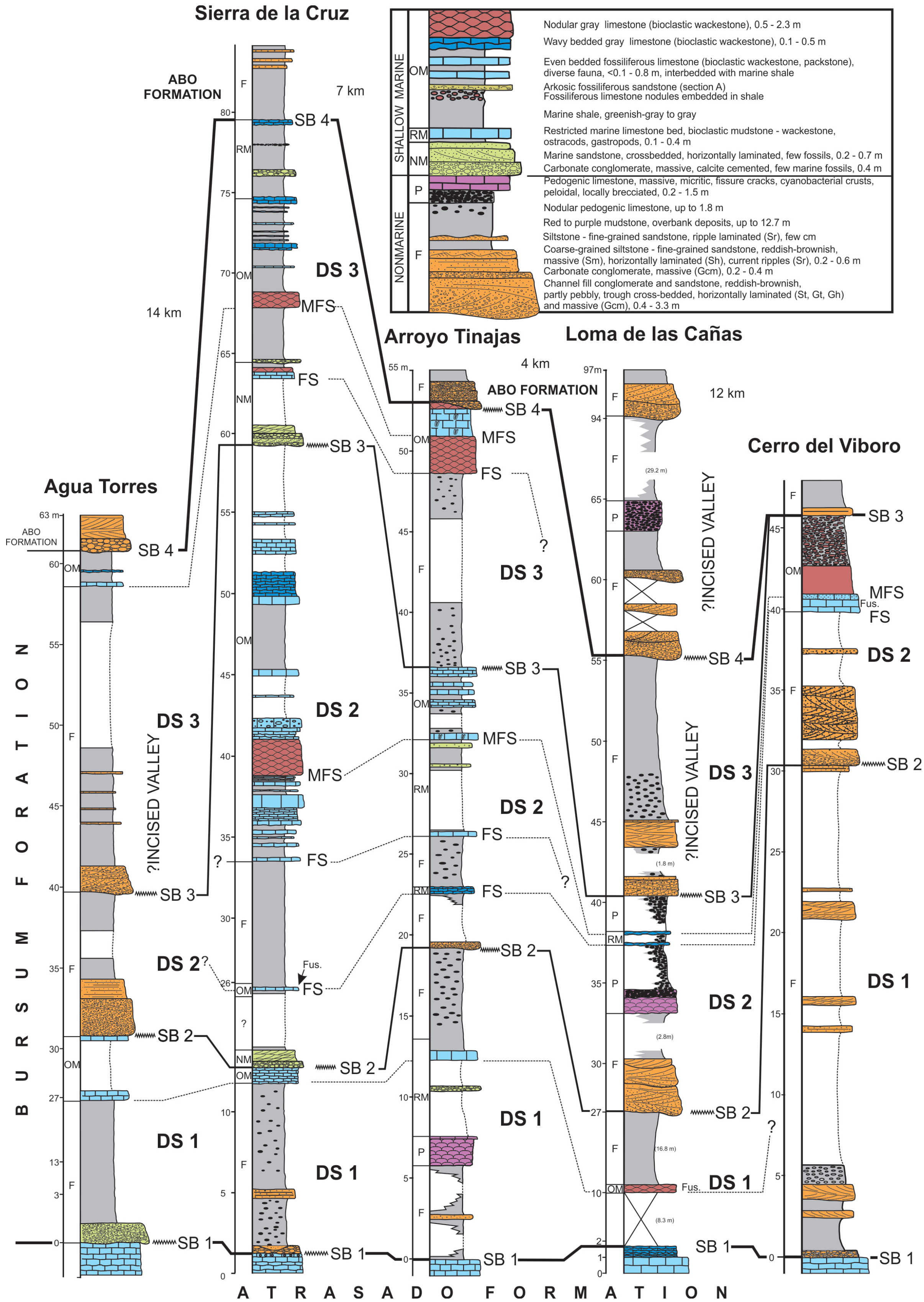

FIGURE 3. Representative measured stratigraphic sections of the Bursum Formation east of Socorro (modified from Krainer and Lucas, 2009, fig. 4). See Krainer and Lucas (2009, fig. 1) for locations of sections. Abbreviations related to sequence stratigraphy include: DS = depositional sequence, SB = sequence boundary, FS = flooding surface, and MFS = maximum flooding surface. Box in upper right provides generalized descriptions for various paleoenvironments (facies) found in the Bursum: F = fluvial, NM = normal marine, OM = open marine, RM = restricted marine, and P = pedogenic.

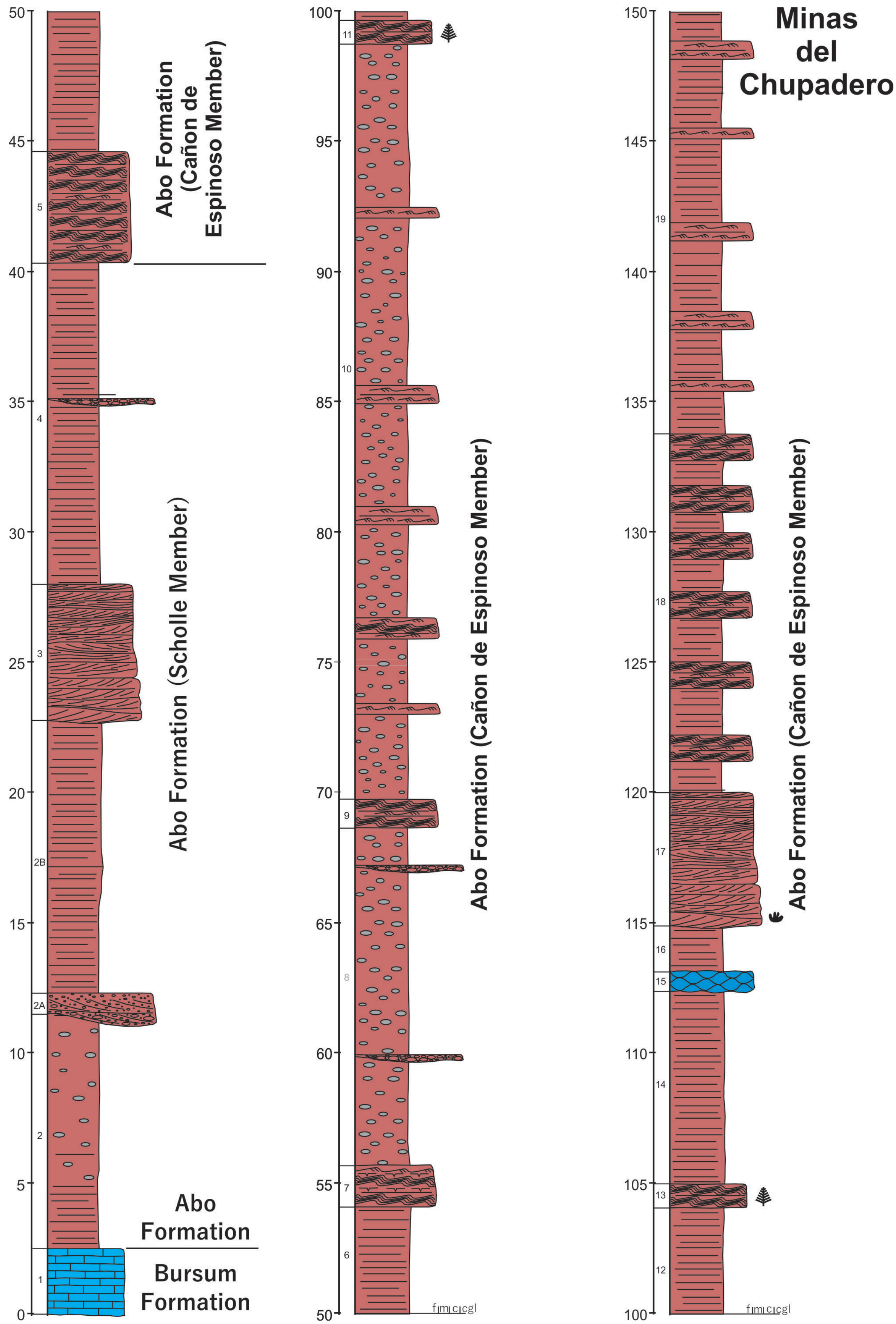

FIGURE 4. Representative measured stratigraphic section of the Abo Formation at Minas del Chupadero. See Lucas and Krainer (2017, appendix) for location of section. Horizontal clast size scale: f = fine-grained, m = medium-grained, c = coarse-grained, cgl = pebbly sandstone, conglomerate.

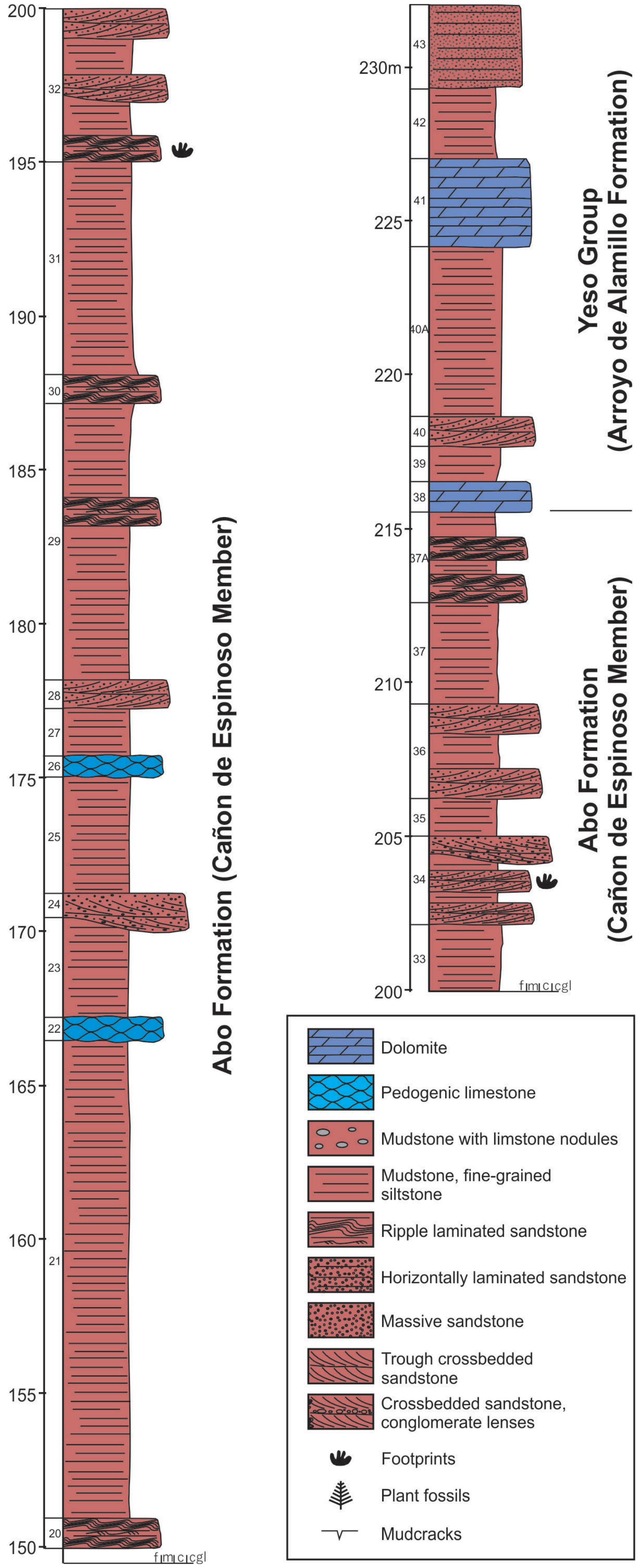

FIGURE 4. (Continued).

strata of the Abo Formation and reassigned them 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, as proposed by Lucas et al. (2005, p. 107). Cather et al. (2013) advocated retention of the Meseta Blanca Formation for what we call the Arroyo de Alamillo Formation because they did not recognize that Meseta Blanca is a synonym of DeChelly (as was cogently argued by Baars, 1962) and argued that the facies change was too gradual to be mappable. We counter that outcrop belt terminations and zones of no exposure found along Township 3N, where Lucas et al. (2005) propose drawing the lateral gradational contact, circumvent the problem of potentially drawing this contact in areas of exposure. Thus, in addition to being lithologically distinct from other formations in the Yeso Group (Lucas et al., 2005), the Arroyo de Alamillo Formation is mappable and suitable as a formation-rank unit in the Quebradas region.

East of Socorro, the lower part of the Yeso Group is the Arroyo de Alamillo Formation, which ranges from approximately 70–110 m thick. At the Yeso Group type section (Fig. 5), the Arroyo de Alamillo Formation can be lithologically divided into a finer-grained lower part and a coarser-grained upper part. In the lower part, intercalated beds of coarse siltstone/sandstone comprise 18.2%, whereas, in the upper part, they are 38.5% of the section. The most abundant lithofacies type is silty mudstone and siltstone, which in the lower part is mostly greenish, and in the upper part mostly reddish. Thickness of individual silty mudstone and siltstone intervals is mostly 0.5–2 m, rarely thicker. The following minor lithofacies are interbedded: (1) fine-grained sandstone with horizontal lamination and small-scale current ripples at the base, 0.3–0.4 m thick (4.6% of the total thickness); (2) thin, nonlaminated and laminated, mixed siliciclastic-carbonate, sandy limestone beds, 0.2 m and 0.4 m thick (8.8%); (3) thin beds of greenish, rarely reddish, calcareous, coarse-grained siltstone and fine-grained sandstone with small-scale ripples (including relatively symmetrical wave ripples) and cubic halite pseudomorphs commonly 1–5 mm, rarely up to 2 cm in size, where the original halite crystals have been replaced by mudstone (1.0%); (4) coarse-grained siltstone and fine-grained sandstone, reddish, brownish, and greenish, commonly 0.1–0.3 m, rarely up to 1.5 m thick (2.5%); and (5) sandy limestone, indistinctly laminated, well sorted and grain supported (3.3%).

The upper part of the Arroyo de Alamillo Formation at its type section is mostly composed of red siltstone that contains halite pseudomorphs in a 0.5 m thick interval in the uppermost part. Siltstone intervals commonly are 0.5–2 m thick. Different types of red sandstone are intercalated: (1) sandstone with large-scale, low-angle crossbedding; (2) fine-grained sandstone with horizontal lamination; (3) fine-grained sandstone with small-scale ripples; and (4) trough crossbedded sandstone. The sandstones are fine to medium grained, well to very well sorted, subrounded-rounded, and grain supported. Sandstones are classified

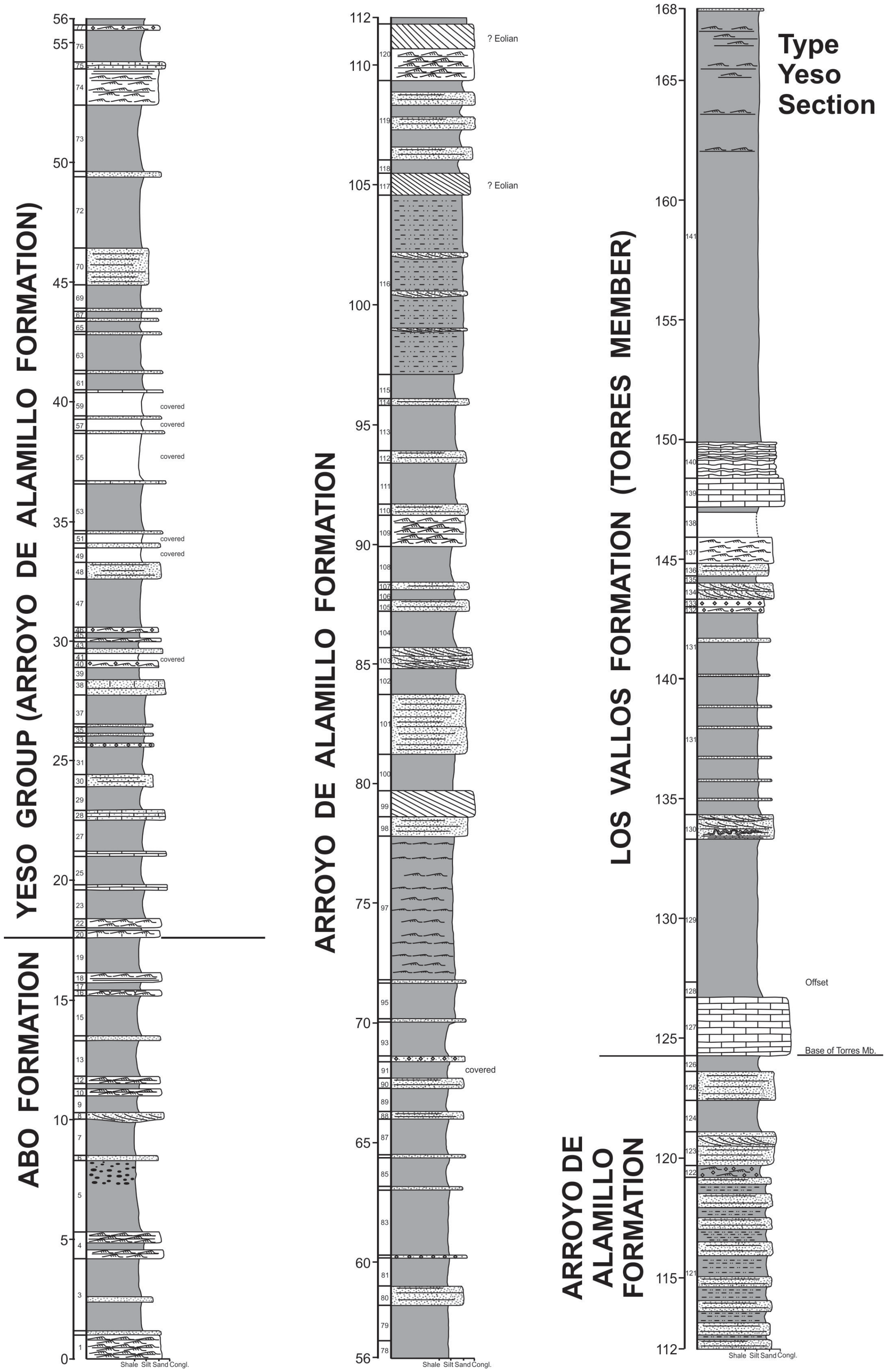

FIGURE 5. Type section of the Yeso Group. See Lucas and Krainer (2017, appendix) for location of section.

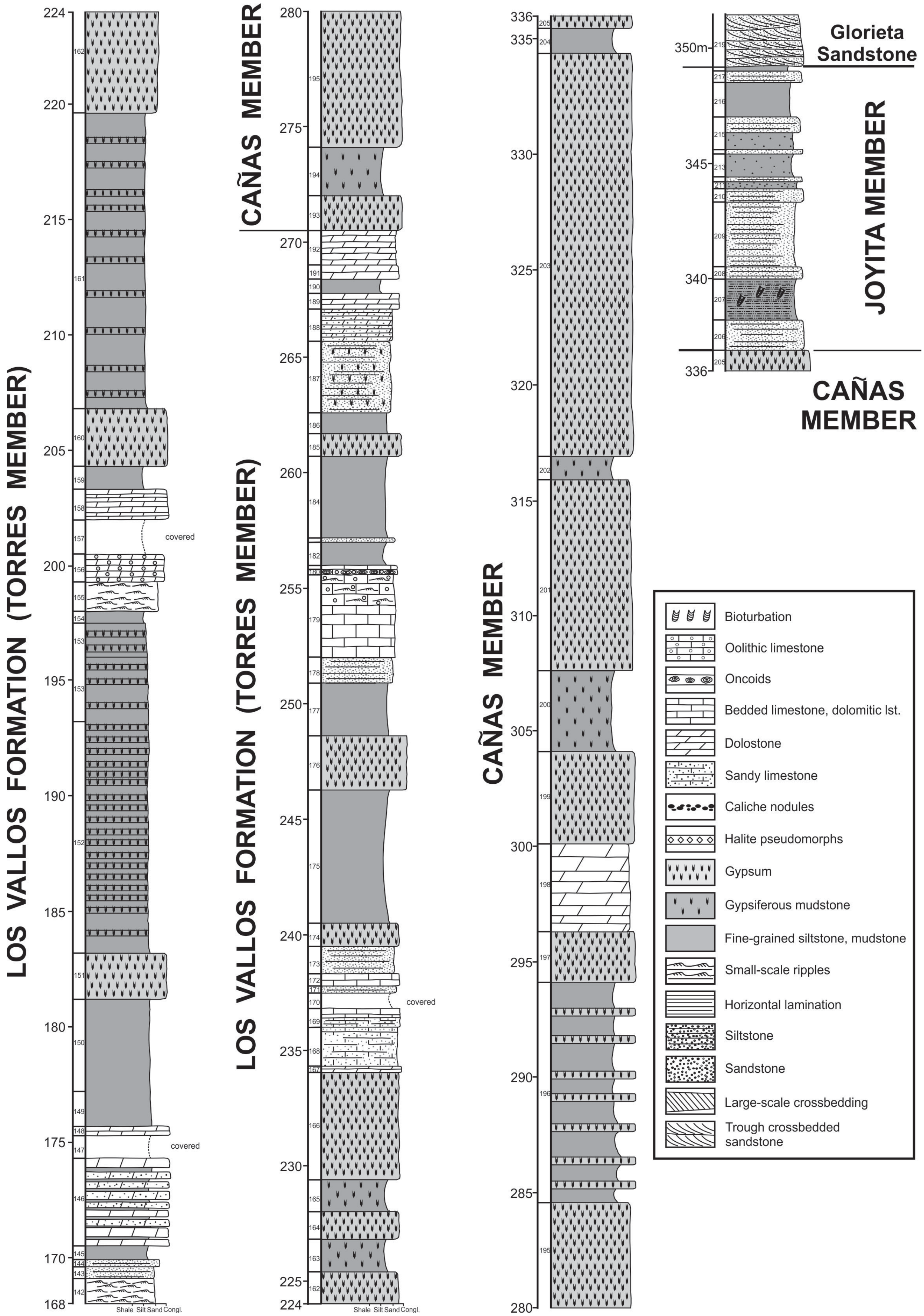

FIGURE 5. (Continued).

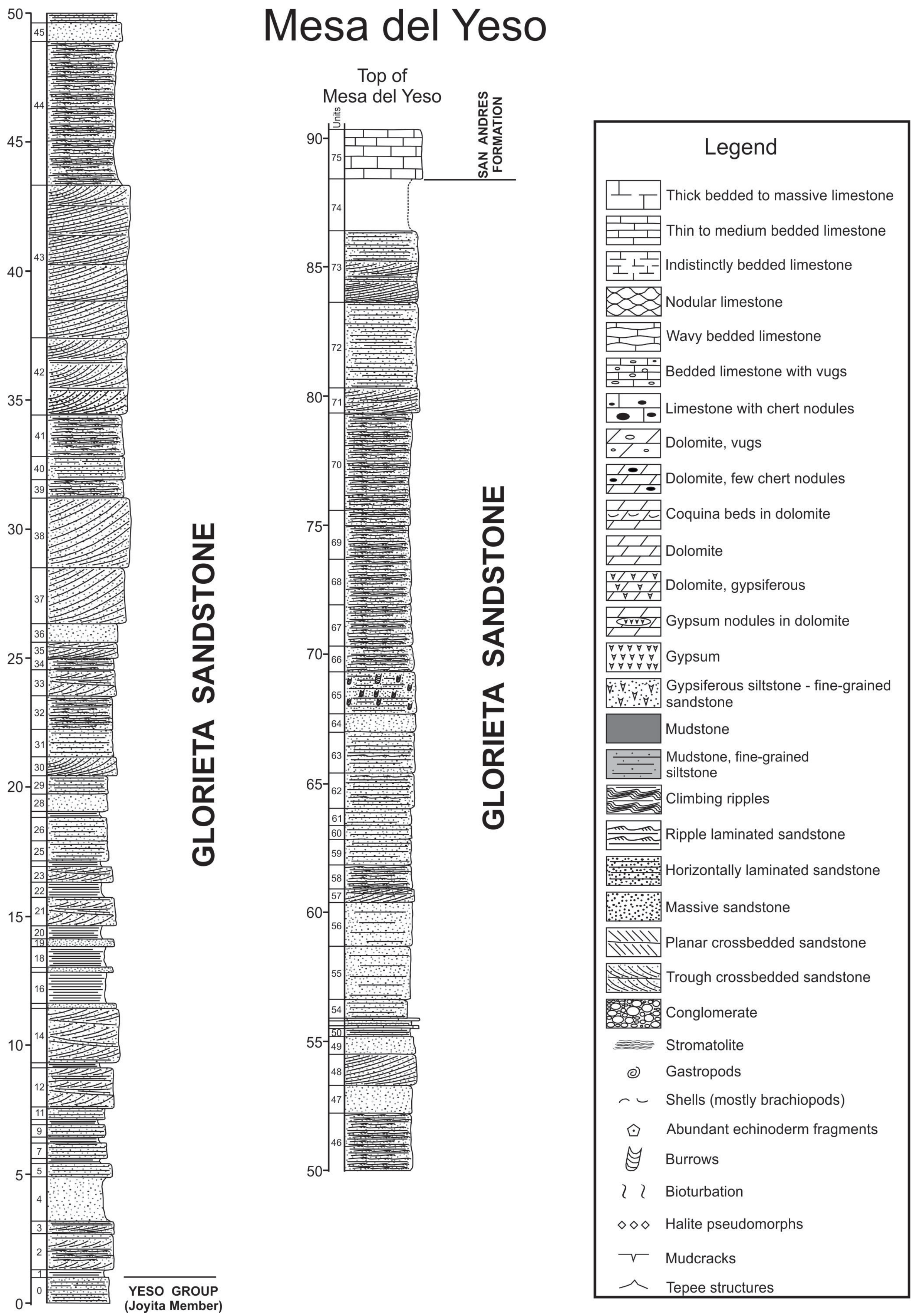

FIGURE 6. Measured section of the Glorieta Sandstone at Mesa del Yeso. See Lucas and Krainer (2017, appendix) for location of section.

as subarkose. This upper unit resembles the Abo Formation in its uniform red-brown color, but the non-fissile claystones characteristic of the Abo are not present. The upper red-brown, sandstone-rich interval is not developed south of Cañoncito de la Uva.

Los Vallos Formation

East of Socorro, the Los Vallos Formation consists of three members (ascending): Torres, Cañas, and Joyita (Figs. 2, 5). At the Yeso Group type section, the base of the ~146 m thick Torres Member is a distinctive, 2.5 m thick gray limestone/dolomite immediately above the Arroyo de Alamillo Formation (Fig. 5). This gray limestone/dolomite at the base of the Torres Member is a prominent stratigraphic marker and is important in mapping. Indeed, this limestone/dolomite is a regional-scale stratigraphic marker bed across central New Mexico (Lucas et al., 2005, 2013b).

The Torres Member averages about 150 m in thickness and displays a well-developed cyclic pattern of five to seven transgressive-regressive cycles (Figs. 2, 5). In the lower two cycles gypsum is generally absent, but upper cycles contain thick (commonly several meters) beds of gypsum, albeit locally absent due to solution and tectonic deformation. Each cycle starts with a few-meters-thick carbonate horizon overlain by siliciclastic sediments that in the lower two cycles show a coarsening-upward trend, and the upper part of a cycle contains laminated and nodular gypsum beds. Carbonate beds are gray to buff and dominantly lime mudstone to peloidal wackestone; oncoids are locally present. Bivalves, gastropods, brachiopods, and foraminifera are present but not useful for age determination. Within the Torres Member, red to gray massive to laminated siltstone predominates, constituting 60.7% of the section, followed by carbonate rocks (16.1%), gypsum (14%), and sandstone (9.2%).

At the Yeso Group type section (Fig. 5), the Cañas Gypsum Member is 66.4 m thick and mostly composed of terracotta-colored (rarely greenish) siltstone intercalated with gypsum layers (25.6%), and several thick (up to 17.5 m) successions of gypsum, comprising 68.6% of the succession. In the middle of the member, a 3.8 m thick interval of gray, indistinctly bedded and indistinctly laminated dolomite is present (5.8%). The base of the Cañas Member is drawn on top of a distinct gray to dark gray, thin-bedded, micritic dolomitic limestone, which, according to Colpitts (1986), locally is a fossiliferous peloidal packstone. At its type locality along Arroyo de las Cañas, the Cañas Member is about 20 m thick and almost entirely gypsum except for limestone and siltstone beds near the top (Lucas and Krainer, 2017). In several places we have observed the Cañas Member to be absent due to solution (indicated by karst features) and to enigmatic bedding-parallel faulting.

Most of the gypsum beds of the Torres and Cañas members are poorly exposed. Where outcrop conditions are good, three types of fine crystalline gypsum can be distinguished: (1) "wavy" laminated (folded) gypsum composed of alternating dark and light gray gypsum and thin, dark gray and reddish mudstone laminae; (2) indistinctly laminated gypsum with even lamination; and (3) nodular gypsum with light gray gypsum nodules up to a few cm in diameter surrounded by dark gray mudstone.

The stratigraphically highest interval of the Yeso Group east of Socorro is the clastic red beds of the Joyita Member. At the Yeso Group type section (Fig. 5), the contact between the Joyita and Cañas members is drawn at the base of the first greenish-gray sandstone resting on gypsum. The member is a 12.3 m thick succession of alternating red siltstone (39%); massive, locally bioturbated red siltstone to fine sandstone (22.8%); and greenish-gray, brownish and red, massive to horizontally laminated sandstone (38.2%). Gypsum is absent.

In a measured section near Arroyo de las Cañas in the southern part of the report area, the Joyita Member is 26 m thick and composed of very fine– to fine-grained sandstone with a few interbeds of siltstone (Lucas and Krainer, 2017). Grayish orange is the prevalent color, but some layers are gray, yellowish gray, and red. The rock is weakly cemented and lamination indistinct. We have not observed fossils in the Joyita Member anywhere in the report area. The Glorieta Sandstone overlies the Joyita with a contact that is sharp in some areas and gradational in others.

GLORIETA SANDSTONE

Lithologically distinctive, the Glorieta Sandstone has been variously classified as a formation and as a member of the San Andres Formation. In Socorro County it is sufficiently thick to be mapped as a formation, ranging from <25 m thick in the south to >75 m thick in the north (Milner, 1978). The Glorieta is composed almost entirely of fine-grained (locally very fine to medium), well-rounded, well-sorted quartz sand. The color is light gray to yellowish gray in most exposures. The sandstone varies from friable to well indurated and generally has calcite cement. Bedding is medium to thick; large-scale crossbedding is the prevalent sedimentary structure. No fossils have been observed in the report area.

At Mesa del Yeso east of Socorro, about 87 m of Glorieta Sandstone overlie the Joyita Member of the Los Vallos Formation of the Yeso Group (Fig. 6). These strata are sandstone, except for one thin interval of limestone about 55 m above the base of the Glorieta Sandstone. The color of the Glorieta Sandstone is dominantly pale yellow-brown to dark yellow-brown; subordinately, the sediments are colored red, dark brown, and rare pale green. The grain size is dominantly very fine– and fine-grained sandstone; siltstone is subordinate. The sandstone is well sorted and composed of rounded to well-rounded quartz grains (quartz arenite).

The main lithotypes of the Glorieta Sandstone at the Mesa del Yeso section are: (1) massive, fine-grained sandstone beds (0.3–1.6 m thick); (2) horizontally laminated siltstone to fine-grained sandstone (0.2–2.6 m thick); (3) indistinctly ripple-laminated, fine-grained sandstone (0.5–5.6 m thick); (4) fine-grained sandstone with small-scale crossbedding (0.5–2.1 m thick); and (5) fine-grained sandstone displaying large-scale crossbedding with individual sets up to 2.5 m thick. Intercalated are (6) red mudstone and siltstone (0.2–1.2 m thick); (7) red,

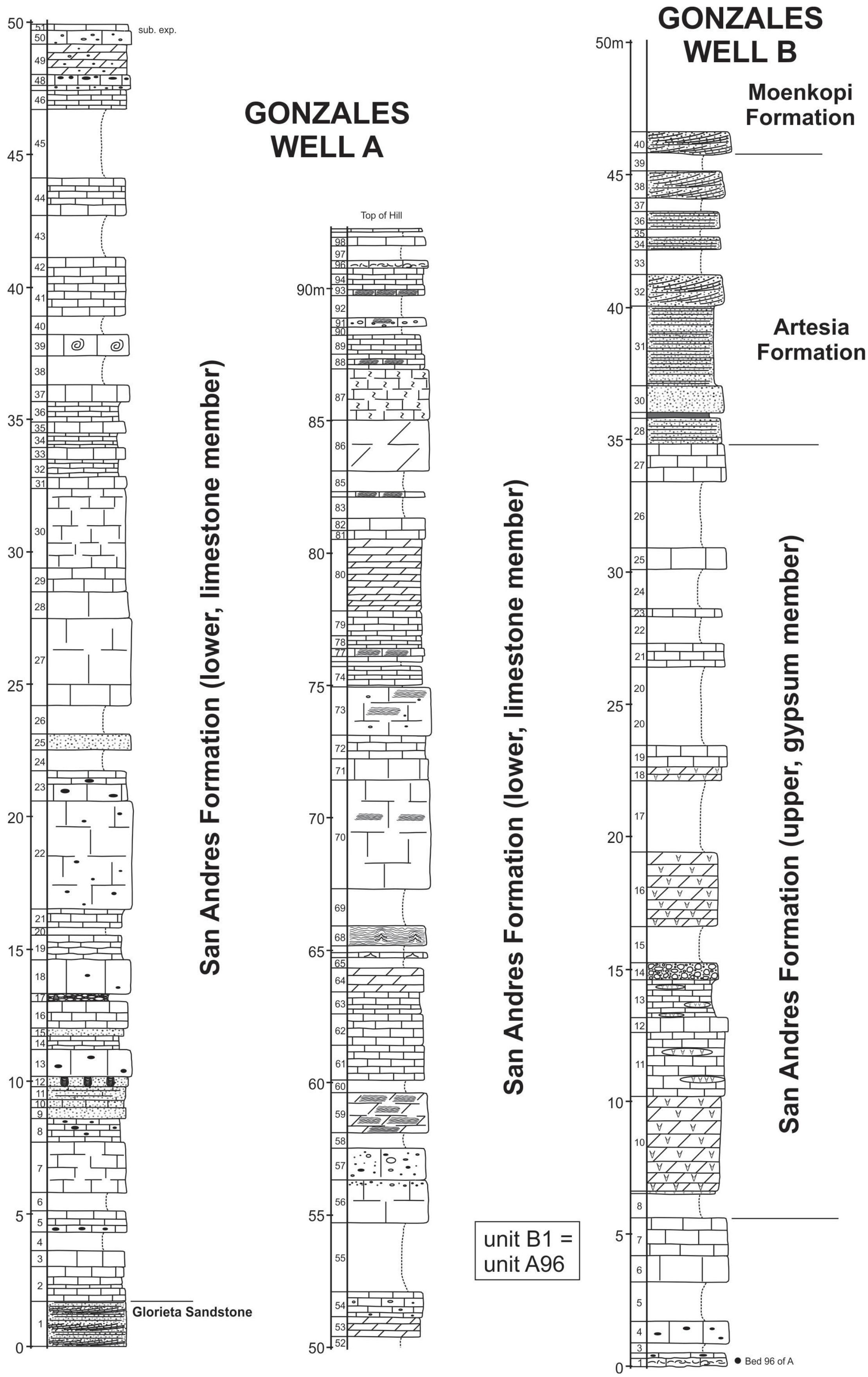

FIGURE 7. Stratigraphic sections of the San Andres and Artesia formations at Gonzalez Well. See Lucas and Krainer (2017, appendix) for location of sections. See Figure 6 for lithologic legend.

fine-grained sandstone, partly displaying small-scale crossbedding (0.6–1.1 m thick); and (8), two thin carbonate beds (2 cm and 20 cm thick) at 55–56 m above the base of the stratigraphic section.

The Glorieta erodes to rounded cliffs and ledges overlain by darker-bedded limestone and dolomite of the San Andres Formation. The formation contact is generally sharp, but we have observed beds of sandstone like that of the Glorieta in the lower San Andres, and the two formations definitely intertongue in the Fra Cristobal Range of northern Sierra County.

SAN ANDRES FORMATION

The San Andres Formation is primarily limestone that is exposed discontinuously across approximately two-thirds of New Mexico, with a few 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. The upper contact of the San Andres Formation in central New Mexico is an unconformity overlain by younger Permian (Artesia Formation) or Triassic (Moenkopi Formation, Chinle Group) strata.

East of Socorro, Lucas and Krainer (2017) described two sections of all or much of the San Andres Formation at Gonzalez Well (Fig. 7) and Cerro Venado (Lucas and Krainer, 2017, fig. 17). These sections demonstrate that the San Andres Formation is either limestone dominated (Gonzalez Well) or gypsum dominated (Cerro Venado). This great lateral variability in lithology of the San Andres Formation is also evident in the measured stratigraphic sections of the unit east of Socorro published by Wilpolt and Wanek (1951, sheet 2).

At the Gonzales Well A section (Fig. 7), the uppermost part of the Glorieta Sandstone is overlain by 90 m of San Andres Formation, and the uppermost part of the San Andres Formation is not exposed. Here, the San Andres Formation is composed of the following lithofacies: (1) massive to indistinctly bedded limestone (up to 4.1 m thick); (2) thick-bedded limestone (up to 3 m thick); (3) thin- to medium-bedded limestone (up to 4.5 m); (4) very rare nodular limestone (unit 17; 0.3 m); (5) sandstone that is intercalated in the lowermost part as an 1.6 m thick interval (units 9–12), 0.3 m thick sandstone bed (unit 15), and 0.6 m thick sandstone bed (unit 25); and (6) covered intervals that are up to 2.6 m thick.

Limestone is partly dolomitic and commonly lime mudstone. Near the base of the San Andres Formation, the limestone is bituminous. In the lower part of the section, a few limestone beds contain chert nodules. In the upper part of the section, individual beds contain calcite-filled voids up to several cm in diameter (probably representing replaced gypsum nodules). In the upper half of the section, microbial mats (stromatolites) and rare tepee structures are observed in some of the limestone intervals. Locally, the muddy limestone beds are bioturbated. Fossils observed on outcrop are rare scaphopods near the base (top of unit 2), rare gastropods (unit 39), and abundant brachiopods near the top (unit 96). Many beds contain shell debris.

The upper part of the San Andres Formation is exposed at section Gonzales Well B (Fig. 7). The distinctly brachiopod-rich unit 1 at section B correlates with the brachiopod-rich unit 96 of section A, which means the entire San Andres Formation is ~125 m thick at Gonzalez Well. At Gonzales Well B, the upper interval of the San Andres Formation has a thickness of 29.2 m and is composed of gypsiferous dolomitic limestone and micritic, partly dolomitic limestone alternating with covered intervals (up to 3 m thick).

At Cerro Venado (Lucas and Krainer, 2017, fig. 17), the San Andres Formation is approximately 143 m thick (exposed thickness) and contains an evaporitic facies consisting mostly of gypsum. Numerous thin dolomite lenses and beds are intercalated, and some thicker dolomite units are present that are either bedded or indistinctly bedded to massive.

ARTESIA FORMATION

In central New Mexico, the stratigraphically highest Permian strata belong to the middle Permian (Guadalupian) Artesia Formation (= "Bernal Formation" of some earlier authors: Lucas and Hayden, 1991). Artesia Formation strata are the thin (10–30 m thick), unconformity bounded, western edge of the Artesia Group of southeastern New Mexico (found as far north as about the latitude of Albuquerque), between the primarily lower Permian San Andres Formation and the Middle Triassic Moenkopi Formation (Tait et al., 1962; Kelley, 1972; Lucas and Hayden, 1991; Lucas, 2013). The Artesia Formation in central New Mexico is mostly reddish-brown and reddish-orange siltstone and very fine– to fine-grained sandstone with a few beds of gypsum and dolomite/limestone. Many clastic beds are gypsiferous, bedforms are usually tabular, planar laminated, or ripple laminated, and some beds are bioturbated.

Most exposures of the Artesia in Socorro County are incomplete and confined to the banks of arroyos. One of the few complete sections is at Gonzales Well B (Fig. 7), where the formation is 11 m thick. Here, the basal, fine-grained sandstone of the Artesia Formation rests on a slightly karstified, erosional surface on top of the uppermost limestone unit of the San Andres Formation. The Artesia Formation is composed of red beds including the following lithofacies: (1) indistinctly bedded, partly laminated red siltstone (0.2–3 m thick); (2) very fine– to fine-grained sandstone, commonly horizontally laminated (0.4–1 m thick); (3) fine-grained, trough-crossbedded sandstone (1 m and 1.2 m thick); and (4) covered intervals (0.3–1 m thick). The red beds of the Artesia Formation are overlain sharply and disconformably by texturally and mineralogically immature, crossbedded sandstone of the Middle Triassic Moenkopi Formation.

BIOSTRATIGRAPHY AND AGE

Diverse fossils are known from the Permian strata east of Socorro, including invertebrate trace fossils, vertebrate footprints,

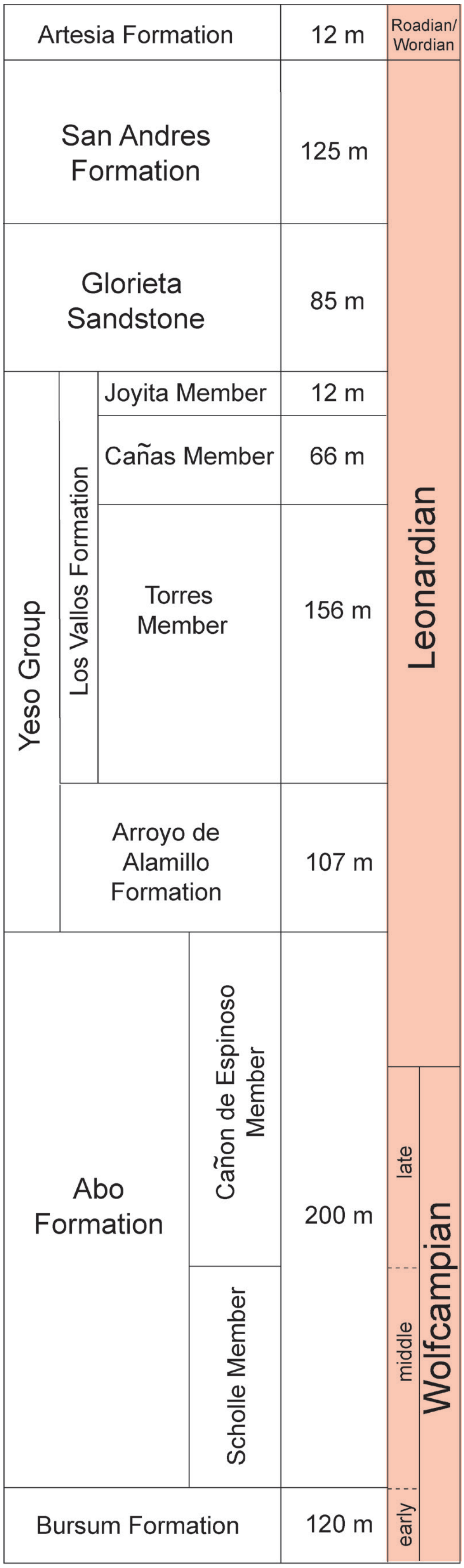

FIGURE 8. Summary of the Permian section east of Socorro showing lithostratigraphic nomenclature, approximate thicknesses of units, and age assignments.

fossil wood and plant foliage, vertebrate bones and teeth, and invertebrate micro- and macrofossils. Age assignments of the Permian strata east of Socorro (Fig. 8) are based on some of these fossils (notably the fusulinids and some of the vertebrate tracks and bones) and on regional correlations based on fossils found elsewhere (Lucas and Krainer, 2017).

Fusulinid data from the Bursum Formation east of Socorro were presented by Kottlowski and Stewart (1970), Altares (1990), Beck and Johnson (1992), and Allen et al. (2013). These authors reported fusulinids of early Wolfcampian (Newwellian) age, from stratigraphically low in the Bursum Formation, suggesting that the entire Bursum Formation east of Socorro is likely of early Wolfcampian age.

W.A. DiMichele and others have collected an unpublished paleoflora from the Bursum Formation east of Socorro dominated by conifer branches and foliage, cordaitalean foliage, and callipterid peltasperms, indicative of a seasonally dry climate but not of a precise age (Lucas et al., 2013d). Fossil vertebrates from the Bursum Formation are a mixture of marine fishes, mostly selachians, and terrestrial tetrapods, notably eryopid temnospondyl amphibians and sphenacodontid eupelycosaurs (Berman et al., 2015). These fossils testify to the mixture of marine and nonmarine paleoenvironments during Bursum deposition, but they are not precise age indicators.

The Abo Formation northeast of Socorro yields trace fossils (mostly tetrapod footprints), and fossils of plants and vertebrates, all of nonmarine origin. Trace fossils from the Abo Formation are an ichnoassemblage of rhizoliths, arthropod locomotion and feeding traces and tetrapod footprints of the *Scoyenia* ichnofacies; these are of no precise age significance. The vertebrate trace fossils are summarized by Voigt and Lucas (2017) and are typical Abo track assemblages dominated by the tracks of small temnospondyls (*Batrachichnus*) and araeoscelid diapsids (*Dromopus*). The ichnofauna of the Abo Formation in central New Mexico is of early Permian age based mainly on some of the tetrapod ichnotaxa (Voigt and Lucas, 2017). A significant change in the tetrapod ichnofauna is recorded for the uppermost part (0–6 m below the top) of the Abo Formation, where captorhinomorph footprints (*Varanopus*, *Hyloidichnus*, *Erpetopus*) are dominant and even more common than the otherwise ubiquitous *Batrachichnus* and *Dromopus* (Lucas et al., 2013a; Voigt and Lucas, 2017). The first appearance of the invertebrate ichnotaxon *Sphaerapus* in the upper third of the Abo Formation also may be stratigraphically significant. These uppermost Abo Formation footprints identify the *Erpetopus* biochron, which is no older than early Leonardian (late Artinskian). Thus, the Wolfcampian-Leonardian boundary is in the upper Abo Formation (e.g., Marchetti et al., 2022).

East of Socorro, vertebrate body fossils from the Scholle Member of the Abo Formation consist of palaeonisciform fishes; the temnospondyl amphibians *Eryops*, *Trimerorhachis*, *Zatrachys,* and *Platyhystrix*; captorhinimorphs; the lepospondyl *Diplocaulus*; and the eupelycosaurs *Ophiacodon*, *Sphenacodon,* and *Dimetrodon.* This is a tetrapod-dominated assemblage of the Coyotean land-vertebrate faunachron, which is of latest Virgilian–middle Wolfcampian age (Lucas, 2018).

The Arroyo de Alamillo Formation east of Socorro contains tetrapod footprint assemblages dominated by the tracks of captorhinimorphs (*Varanopus*, *Erpetopus*) but also including the tracks of small temnospondyls (*Batrachichnus*) and araeoscelids (*Dromopus*) (Lucas et al., 2013b; Voigt and Lucas, 2017). A few conifer and peltasperm fossils are the fossil plants known from the Arroyo de Alamillo Formation in this area (Lucas et al., 2013b). Most important is that the footprints are representative of the *Erpetopus* biochron of Voigt and Lucas (2017), which actually begins late in Abo time (see above) and is of Leonardian-Guadalupian age.

Using Yeso Group thin sections from the Fra Cristobal and Caballo Mountains of Sierra County, Vachard et al. (2015) recovered a foraminifer-dominated microfossil assemblage from the Torres Member. However, thin sections of carbonate beds in the Torres Member east of Socorro contain few such microfossils. Lucas et al. (2022) document conodonts from the basal carbonate interval of the Torres Member in the Caballo Mountains of Sierra County that indicate an early Leonardian (middle Kungurian) age.

We do not know of any previously identified fossils from the Glorieta and San Andres formations east of Socorro other than some San Andres microfossils documented by Lucas and Krainer (2017). Elsewhere in New Mexico, the San Andres Formation and some limestone interbeds of the Glorieta Sandstone have yielded microfossil assemblages dominated by algae and foraminiferans of late Leonardian (late Kungurian) age (Vachard et al., 2015). Macrofossils from the San Andres Formation in southern New Mexico include ammonoids of late Leonardian age (cf. Brose et al., 2013).

The age of the San Andres Formation thus has been mostly determined from foraminiferan, ammonoid, 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). The underlying Glorieta Sandstone is Leonardian in age as it is bracketed by Leonardian strata of the Yeso group (below) and the lower San Andres Formation (above; Fig. 8). The Artesia Formation strata are Guadalupian (Roadian-Wordian) in age based on regional correlations (Lucas, 2013).

CONCLUSIONS

1) The Permian stratigraphic section east of Socorro is ~900 m thick and is assigned to the (ascending order): Bursum Formation, Abo Formation (Scholle and Cañon de Espinoso members), Yeso Group (Arroyo de Alamillo Formation and overlying Los Vallos Formation divided into Torres, Cañas, and Joyita members), Glorieta Sandstone, San Andres Formation, and Artesia Formation.
2) The Bursum Formation is up to 120 m thick and consists of interbedded red-bed siliciclastics (mudstone, sandstone, and conglomerate) and marine limestones.
3) The Abo Formation is as much as 210 m thick and is siliciclastic red beds divided into the Scholle Member (~37–69 m of mudstone with channelized beds of crossbedded sandstone and conglomerate) overlain by the Cañon de Espinoso Member (~50–175 m of mudstone, siltstone, and many thin, laterally extensive beds of sandstone that display climbing ripple lamination).
4) The lower formation of the Yeso Group, the Arroyo de Alamillo Formation, is ~107 m of red-bed sandstone (mostly ripple laminar and laminar with some gypsiferous beds) and very minor dolomite. The overlying Torres Member of the Los Vallos Formation is ~156 m thick and is mostly gypsiferous siltstone, claystone, gypsum, and a few prominent beds of dolomite and gypsiferous sandstone. The overlying Cañas Member is 66 m thick, mostly gypsum, and includes a few beds of gypsiferous siltstone and dolomite. The Joyita Member is ~12 m thick and is red-bed sandstone that is crossbedded, ripple laminated and, in some beds, gypsiferous.
5) The Glorieta Sandstone is up to 85 m thick and consists of crossbedded, laminar, and ripple laminar quartzose sandstone.
6) The San Andres Formation is up to 125 m of mostly limestone (lime mudstone) at Gonzales Well and at Cerro Venado is dominantly gypsum (sabkha facies).
7) The Artesia Formation is up to 12 m thick and consists of red-bed siltstone and very fine to fine sandstone and minor beds of gypsum and dolomite. It is disconformably overlain by Middle Triassic strata of the Anton Chico Member of the Moenkopi Formation.
8) Local paleontological data coupled with regional correlations indicate that the Bursum Formation is early Wolfcampian in age; the Abo Formation is middle Wolfcampian–early Leonardian; the Yeso Group, Glorieta Sandstone, and San Andres Formation are Leonardian in age; and the Artesia Formation is of Guadalupian (Roadian-Wordian) age.

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The abrupt truncation of the olive-brown Red House Formation (Pennsylvanian) marks the location of the east strand of the Little San Pascual Mountain fault system. To the left of the fault lies reddish Popotosa Formation (Late Miocene) capped by the light-colored Sierra Ladrones Formation (Early Pleistocene). Photo by Daniel Koning.