Upper Paleozoic stratigraphy around the Sierra Nacimiento, San Pedro Mountains, and Jemez Mountains, Northern New Mexico

Spencer G. Lucas and Karl Krainer, [eds.]

2024, pp. 141-156. https://doi.org/10.56577/FFC-74.141

in:

Geology of the Nacimiento Mountains and Rio Puerco Valley, Karlstrom, Karl E.;Koning, Daniel J.;Lucas, Spencer G.;Iverson, Nels A.;Crumpler, Larry S.;Aubele, Jayne C.;Blake, Johanna M.;Goff, Fraser;Kelley, Shari A., New Mexico Geological Society 74 th Annual Fall Field Conference Guidebook, 334 p.

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UPPER PALEOZOIC STRATIGRAPHY AROUND THE SIERRA NACIMIENTO, SAN PEDRO MOUNTAINS, AND JEMEZ MOUNTAINS, NORTHERN NEW MEXICO

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Abstract—Upper Paleozoic (Mississippian, Pennsylvanian, and Permian) strata are exposed around the Sierra Nacimiento, San Pedro Mountains, and Jemez Mountains in northern New Mexico. At scattered outcrops, the Mississippian rocks are assigned to the Arroyo Peñasco Formation, overlain locally by the Log Springs Formation. In the Guadalupe Box area, the Lower Pennsylvanian Osha Canyon Formation overlies Mississippian strata. The Middle Pennsylvanian Sandia Formation overlies the Osha Canyon Formation and crops out at various other locations where it overlies Proterozoic basement, Mississippian strata, or the Osha Canyon Formation. The Middle Pennsylvanian Gray Mesa Formation overlies the Sandia Formation at all outcrops where both units are present. The uppermost Pennsylvanian strata in the Sierra Nacimiento-Jemez Mountains are assigned to the Middle-Upper Pennsylvanian Guadalupe Box Formation. The Permian section begins with the Abo Formation, overlain by the Yeso Group, which consists of the De Chelly Sandstone overlain by the San Ysidro Formation. The uppermost Permian strata in this region belong to the Glorieta Sandstone. Microfossils (primarily foraminiferans) and invertebrate macrofossils (primarily brachiopods) assign the Arroyo Peñasco Formation an Early-Middle Mississippian (Osagean-Meramecian) age, the Log Springs Formation a Late Mississippian (Chesterian) age, the Osha Canyon Formation an Early Pennsylvanian (Morrowan) age, the Sandia Formation an early Middle Pennsylvanian (Atokan) age, the Gray Mesa Formation a late Middle Pennsylvanian (Desmoinesian) age, and the Guadalupe Box Formation a late Middle Pennsylvanian-Late Pennsylvanian (Desmoinesian-Virgilian) age. Diverse data, most of it from outside of the Sierra Nacimiento-San Pedro Mountains-Jemez Mountains, indicate the Abo Formation is of early Early Permian (Wolfcampian) age, and the Yeso Group and Glorieta Sandstone are of late Early Permian (Leonardian) age.

INTRODUCTION

In northern New Mexico, the Jemez Mountains are a large volcanic edifice of late Cenozoic age bordered by the San Pedro Mountains and the Sierra Nacimiento, a basement-cored uplift of the Laramide orogeny of Late Cretaceous-Eocene age (Fig. 1). Upper Paleozoic (Carboniferous and Permian) strata are exposed around these uplifts and have been studied for nearly a century. Here we provide a brief review of the stratigraphy of the Mississippian, Pennsylvanian, and Permian rocks around the Sierra Nacimiento, San Pedro Mountains (coinciding with San Pedro Peaks and San Pedro Park), and Jemez Mountains.

SOME HISTORY

Marcou (1858) first identified Paleozoic strata in the Jemez Mountains, showing the range as having a Precambrian core draped by Carboniferous strata. However, this was a partly incorrect guess, as Marcou never visited the Jemez Mountains; he simply assumed it had the same basic geology as the Sangre de Cristo and Sandia Mountains, which he had visited (Lucas, 2001).

Darton (1928) presented the first detailed observations of the Paleozoic strata in the Sierra Nacimiento-San Pedro Mountains-Jemez Mountains, bringing together earlier observations (e.g., Newberry, 1876; Williston and Case, 1912) with his own detailed work (p. 155–164) and geologic mapping (plate 37). Darton assigned the Paleozoic section to the Magdalena Group overlain by the Abo Formation and "probable" strata of the Chupadera Formation (a stratigraphic term Darton used that combined the Yeso, Glorieta, and San Andres formations into one unit; Lucas, 2009; Fig. 2). Darton's mapping accurately depicted the general distribution of these rocks along the Guadalupe and Jemez Rivers north of San Ysidro, along the western flank of the Sierra Nacimiento to the San Pedro Mountains and along the Rio Puerco drainage to where it meets the Rio Chama.

Wood and Northrop (1946) mapped much the same area as Darton but at a more detailed scale. They assigned the Pennsylvanian strata to the Magdalena Group divided into the Sandia Formation overlain by the Madera Limestone, which was further divided into a lower, gray limestone member and an upper, arkosic limestone member (Fig. 2). Permian rocks were assigned to the Abo Formation and northern equivalent Cutler Formation (with the boundary of the two at 36°N latitude), and the overlying Yeso and San Andres Formations (Fig. 2). Wood and Northrop (1946) followed usage at the time (e.g., Read et al., 1944; Read and Wood, 1947) by dividing the Sandia Formation into a lower limestone member that might be older than Pennsylvanian and an upper clastic member of Pennsylvanian age. They also divided the Yeso Formation into two new members: the lower Meseta Blanca Member and upper San Ysidro Member. They considered the Glorieta Sandstone to be the lower member of the San Andres Formation and also identified an "upper, fine grained red sandstone member" of the San Andres. Lengthy lists of Pennsylvanian invertebrate macrofossils provided by Wood and Northrop (1946) identified about 185 species divided into five faunal zones that range in age from Morrowan to Virgilian. The Morrowan fossils came from strata they mapped as Sandia Formation (also see Northrop and Wood, 1945; Northrop, 1961, 1974; DuChene, 1974).

The Pennsylvanian-Permian stratigraphy of the Sierra Nacimiento-Jemez Mountains of Wood and Northrop (1946) was little changed for more than half a century. The only changes were introducing the name Osha Canyon Formation for the Morrowan strata (DuChene et al., 1977) and applying the name Bernal Formation to the upper member of the San Andres Formation (for a review, see Woodward, 1987).

However, major changes took place in the current millennium, beginning with Kues (2001), who applied the names Gray Mesa and Atrasado Formations to the post-Sandia Pennsylvanian section. Krainer et al. (2005) introduced the name Guadalupe Box Formation for the strata Kues (2001) had assigned

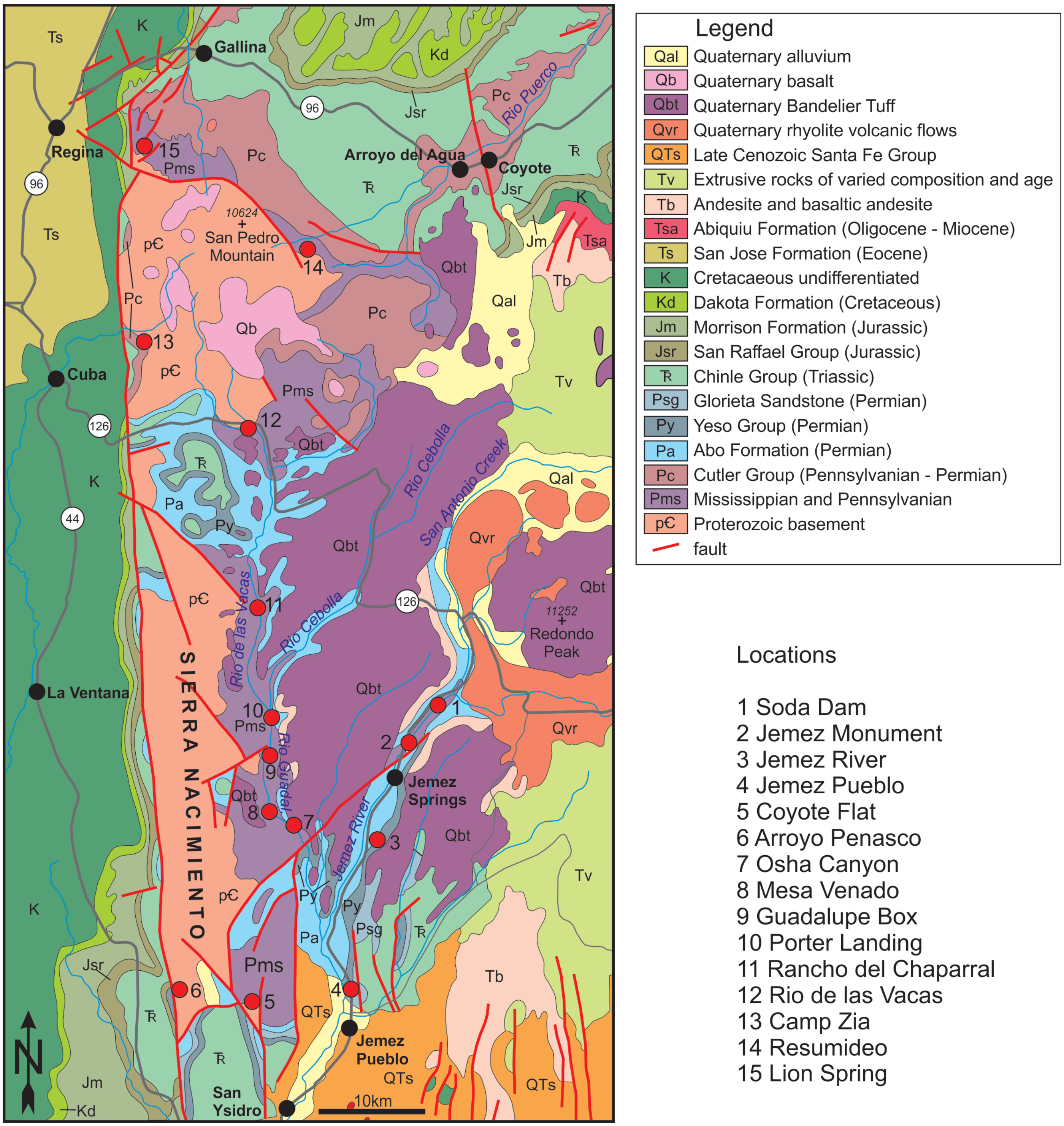

FIGURE 1. Index map showing locations of the measured stratigraphic sections in Figures 3–7. Geologic map based on NMBGMR (2003). Locations given in red circles and include: 1 = Soda Dam (Fig. 3), 9 = Osha Canyon / Guadalupe Box area (Figs. 4–5), 3 = Jemez River (Fig. 6), and 4 = Jemez Pueblo (Fig. 7).

to the Atrasado Formation. Lucas et al. (2005) revised much of the Permian stratigraphy, dividing the Abo Formation into two members, raising the Yeso Formation to group rank, and replacing the name Meseta Blanca Member with De Chelly Sandstone, as was first suggested by Baars (1962). Much earlier, Lucas and Hayden (1989) had demonstrated that the upper member of the San Andres of Wood and Northrop (1946), which is the Bernal Formation of Woodward (1987), is actually of Triassic age and should be assigned to the Moenkopi Formation. Many of these changes have been incorporated in recent geologic mapping (Kelley et al., 2003). The lithostratigraphy advocated here (Fig. 2) embodies all these relatively recent revisions.

LITHOSTRATIGRAPHY

Mississippian

In the Sierra Nacimiento-San Pedro Mountains-Jemez Mountains, the Mississippian is represented by a thin (<100 m) succession of siliciclastic and carbonate sedimentary rocks divided into the Arroyo Peñasco Formation and overlying Log Springs Formation. In this volume, Krainer and Lucas (2024) present a detailed review of these strata, so we only include a brief summary here.

The Arroyo Peñasco Formation consists mostly of marine sedimentary rocks, particularly limestone and minor siltstone and sandstone. It is divided into the (ascending) Del Padre Sandstone (Member), Espiritu Santo Member, and Tererro Member. The Arroyo Peñasco Formation is best exposed at Arroyo Peñasco (type section), with a thickness of 17.5–40 m, at Soda Dam in the Jemez Mountains (7.5 m thick; Fig. 3) and at Lion Spring in the San Pedro Mountains (12.4–40 m thick).

Darton (1928)	Wood & Northrop (1946)			Woodward (1987)	this paper	
Chupadera Formation?	San Andres F.		red ss. m.	Bernal Formation	Moenkopi F. (Triassic)	
			Glorieta Sandstone M.	Glorieta Sandstone	Glorieta Sandstone	
	Yeso Formation		San Ysidro Member	Yeso Formation	Yeso Group	San Ysidro Formation
			Meseta Blanca M.			DeChelly Ss.
Abo Formation	Abo Formation			Abo Formation	Abo F.	Cañon de Espinoso M.
						Scholle M.
Magdalena Group	Magdalena Group	Madera limestone	arkosic limestone member	Madera Formation	Guadalupe Box Formation	Jemez Springs Member
						San Diego Canyon Member
			gray ls member		Gray Mesa Formation	
		Sandia Formation	upper clastic member	Sandia Formation	Sandia Formation	
				Osha Canyon F.	Osha Canyon F.	
				Log Springs. F.	Log Springs. F.	
			lower limestone member	Arroyo Peñasco Formation	Arroyo Peñasco F.	Espiritu Santo Member
						Del Padre M.

FIGURE 2. Evolution of upper Paleozoic lithostratigraphic nomenclature in the Sierra Nacimiento-San Pedro Mountains-Jemez Mountains. See Figure 9 for the geologic ages of these lithostratigraphic units.

The Del Padre Member is thin (2.6–5.7 m) and composed of pebbly sandstone; massive, horizontally laminated and cross-bedded sandstone; and red siltstone. The sandstone is composed almost entirely of quartz (quartzarenite). Due to the poor sorting and rounding values, sandstone of the Del Padre Member is interpreted as nonmarine deposits but could also simply reflect proximity to basement rocks.

The Espiritu Santo Member is thin at Soda Dam (approximately 5.5 m; Fig. 3) and up to approximately 37 m thick at Arroyo Peñasco (Armstrong, 1955, 1967). At Lion Spring, the Espiritu Santo Member is composed of thick-bedded gray limestone that is partly recrystallized. Limestone that is not recrystallized is composed of different types of grainstone to packstone containing varying amounts of peloids, micritic intraclasts, smaller benthic foraminiferans, echinoderm fragments, ostracods, and a few other fossils. At the beginning of deposition of the Espiritu Santo Member, a pelloidal lime mudstone facies with shallow marine fauna including foraminiferans and ostracods covered a large area that encompassed the Sierra Nacimiento-San Pedro Mountains (Armstrong, 1967). This pelloidal lime mudstone facies was bordered to the east (Sangre de Cristo Mountains) by an intertidal and supratidal facies. The supratidal facies prograded westward over the aforementioned marine carbonate muds. In the Sierra Nacimiento-San Pedro Mountains, this progradation is evidenced by the following upsection progression within the Espiritu Santo Member (Armstrong, 1967): (1) lower interval of shallow marine subtidal to intertidal pelloidal lime mudstone, and (2) an upper interval where oolitic grainstone to lime mudstone (shallow marine) is the dominant facies.

According to Armstrong and Mamet (1974, 1979), in the Nacimiento and San Pedro Mountains the Espiritu Santo Member is overlain by the Manuelitas Member of the Tererro Formation, based on foraminiferans. However, we found that in the field such a subdivision into two lithologic units, Espiritu Santo and Manuelitas Members, is not possible. The Tererro Member has a distinctive bed (the Manuelitas Bed) that consists of an oolitic grainstone-packstone facies. However, we have not found field evidence for the Manuelitas bed in the study area, so the Tererro Formation appears to be absent. This is consistent with the observation that the basal conglomerate of the Log Springs Formation contains reworked Manuelitas Bed lithologies, so this bed and the Tererro Member are interpreted to have been eroded in a tectonic pulse, or possibly a sea level fall, between the ages of the Espiritu Santo Member and Log Springs Formation (Krainer and Lucas, 2024).

The Log Springs Formation was named by Armstrong (1955) for a succession of red beds (ferruginous shale, sandstone, and conglomerate) that is 18–47.5 m thick and rests unconformably on carbonate deposits of the Arroyo Peñasco Formation that are locally karstified. At Lion Spring (San Pedro Mountains) and at Arroyo Peñasco (Sierra Nacimiento), the Log Springs Formation unconformably rests on the Arroyo Peñasco Formation (Krainer and Lucas, 2024). At both locations, the Log Springs Formation is thin (9.2 m and 14 m, respectively) and composed largely of nonmarine red beds

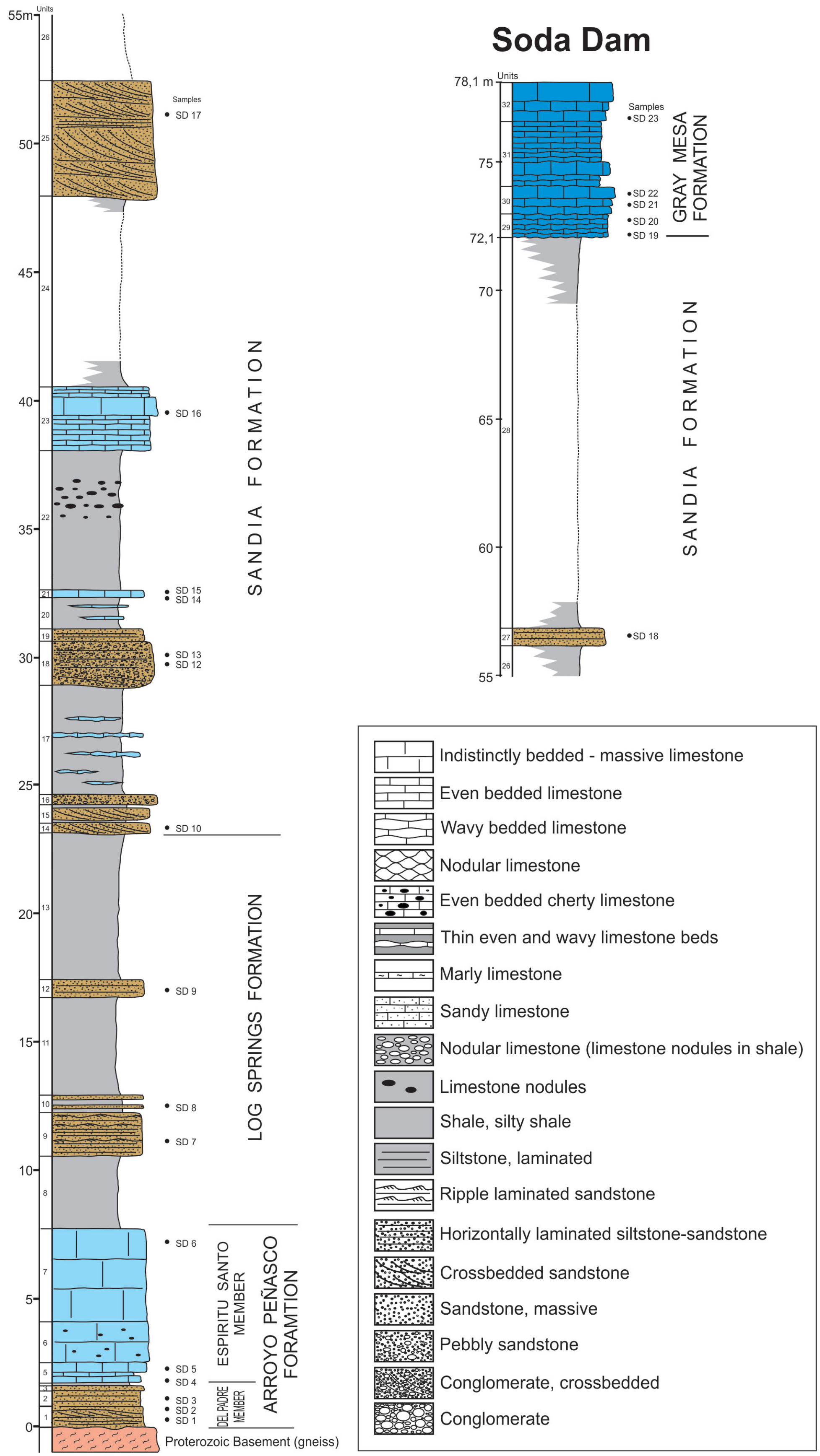

FIGURE 3. Soda Dam stratigraphic section of the Arroyo Peñasco, Log Springs, Sandia, and lowermost Gray Mesa Formations. See Krainer and Lucas (2013) and Figure 1 for the location of the section. The color shading corresponds to different lithotypes and/or bedding: gray = fine-grained siliciclastics, brown = coarse-grained siliciclastics, light blue = even bedded limestone, dark blue = wavy bedded limestone, purple = nodular limestone.

(shale, siltstone, sandstone, conglomerate). At Soda Dam (Fig. 3), the Log Springs Formation is ~15 m thick and is composed mostly of purple and greenish shale.

At Log Springs (the type section), the Log Springs Formation rests on Proterozoic basement and is described in Krainer and Lucas (2024). The formation is 47.5 m thick and can lithologically be divided into (1) a basal siliciclastic unit, (2) thin limestone intervals alternating with covered (assumed shale) intervals, and (3) an upper siliciclastic unit. The upper siliciclastic unit is 13.5 m thick and composed of red siltstone and intercalated sandstone of various lithotypes.

At Log Springs in the southern Sierra Nacimiento, the Mississippian Arroyo Peñasco Formation rests on Proterozoic basement. The Arroyo Peñasco Formation is 34 m thick and can be divided into (1) the basal siliciclastic Del Padre Member (2.5 m), composed of different types of sandstone and gray, laminated sandy limestone (mixed siliciclastic-carbonate sandstone (1 m), overlain by (2) the Espiritu Santo Formation, composed of a succession of single limestone beds and thin-bedded limestone intervals separated by covered intervals that most likely represent shale/siltstone units (31.5 m).

The overlying Log Springs Formation is 13.5 m thick and composed of red siltstone and intercalated sandstone beds. Siltstone intervals are 1.2–4 m thick, and sandstone beds are 0.2–0.8 m thick. Sandstone is represented by various lithotypes including fine-grained massive sandstone, fine-grained cross-bedded sandstone, and coarse-grained pebbly sandstone (details in Krainer and Lucas, 2024).The Log Springs Formation is overlain by the Osha Canyon Formation.

Pennsylvanian

In the Sierra Nacimiento-San Pedro Mountains-Jemez Mountains, Pennsylvanian strata are assigned to the (ascending) Osha Canyon, Sandia, Gray Mesa and Guadalupe Box Formations (Fig. 2).

Osha Canyon Formation

The Osha Canyon Formation crops out only in the Guadalupe River drainage along the southeastern flank of the Sierra Nacimiento and at Arroyo Peñasco. At its type section just north of Guadalupe Box (ggfffdddd, 1973, 1977; DuChene et al., 1977; Krainer and Lucas, 2005), the Osha Canyon Formation is a relatively thin (up to 27.3 m thick) lithostratigraphic unit of mainly limestone and shale underlain by red and greenish shale of the Mississippian Log Springs Formation and is sharply overlain across an erosional contact by coarse-grained, trough cross-bedded fluvial sandstone of the Sandia Formation (Fig. 4).

The Osha Canyon Formation at the type section (Fig. 4) is composed of red, purple and greenish, carbonate-rich (marly) shale (80.6% of the type section); interbedded light-gray and reddish, ledge-forming limestone beds (10.3%); and a mixed siliciclastic-carbonate sandstone (9.1%) at the top of the section. Marly (carbonate-rich) shales are poorly exposed and contain abundant, well-preserved brachiopods and a few small

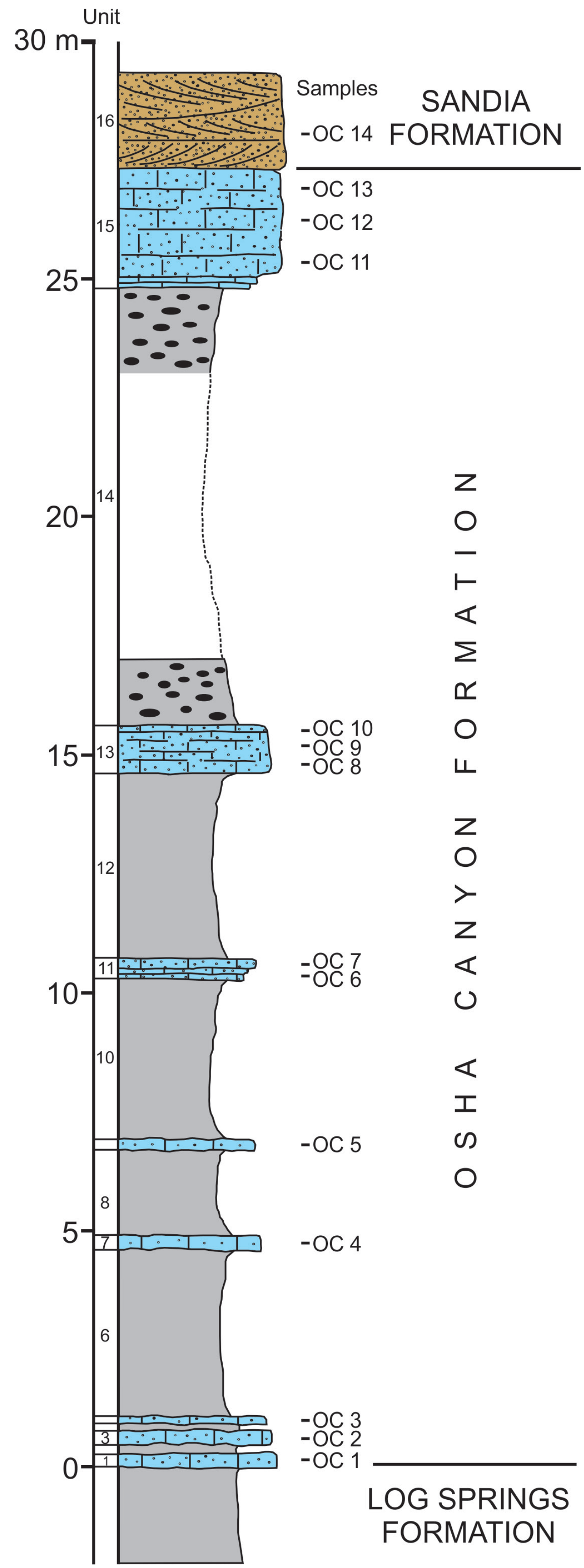

FIGURE 4. Osha Canyon Formation type section. See Figure 3 for lithologic legend, and see Krainer and Lucas (2005) and Figure 1 for the location of the section. Explanations of lithologic symbologies and shading are given in Figure 3 and its caption.

solitary corals and bryozoans in the middle part of the section (Fig. 4, units 10, 12). Brachiopods are also present in the shale of units 6 and 8 (Fig. 4), and a few brachiopods are also found in the greenish, mostly covered shale containing small gray limestone nodules in the upper part of the section (Fig. 4, unit 14). The base of the Sandia Formation is disconformable on the Osha Canyon Formation.

Sandia Formation

The Sandia Formation is well known in central and northern New Mexico as a mixed siliciclastic-carbonate stratigraphic unit less than 200 m thick. It is characterized by coarse quartzose sandstone and conglomerate interbedded with mudrock, limestone, finer sandstone and, locally, thin coal beds (Krainer and Lucas, 2013). In the Sierra Nacimiento-San Pedro Mountains-Jemez Mountains, the Sandia Formation is thickest (up to 64 m) north of Jemez Springs. Krainer and Lucas (2013) described sections of the Sandia Formation at Guadalupe Box, Osha Canyon, Soda Dam, Mesa Venado, Porter Landing, Rancho del Chaparral, Rio de las Vacas, and Resumidero (see Woodward [1996] and Lucas and Krainer [2013] for locations of these sections).

The Sandia Formation section at Soda Dam (Fig. 3) may be considered characteristic of the unit. Here, the Sandia Formation is ~49 m thick and composed mostly of shale (variegated gray and green, 79% of the section), with some beds containing numerous brachiopods. Coarse quartz sandstone and quartz-pebble conglomeratic sandstone compose about 16% of the section, and a few limestone intervals are present (4% of the section).

The Sandia Formation rests on Proterozoic basement (Resumidero, Rio de las Vacas, Rancho del Chaparral, Mesa Venado), on Log Springs Formation (Lion Spring), Soda Dam, and on Osha Canyon Formation (Osha Canyon, Guadalupe Box). The Sandia Formation is absent at Camp Zia where the Abo Formation rests on Proterozoic basement, and at Coyote Flat where the Guadalupe Box Formation rests on Proterozoic basement.

Thickness of the Sandia Formation in the Sierra Nacimiento-San Pedro Mountains-Jemez Mountains ranges from 8 m to 64 m. Thin successions of Sandia Formation are exposed at Rancho del Chaparral (8 m) and Resumidero (13 m). The thickest Sandia sections are at Rio de las Vacas and Soda Dam (approximately 64 m). Thin successions are entirely composed of siliciclastic rocks (Resumidero, Rancho del Chaparral, Porter Landing, Osha Canyon). Thicker successions (Rio de las Vacas, Mesa Venado, Soda Dam, Guadalupe Box) are dominantly siliciclastic with thin intercalated limestone units, particularly in the upper part.

At Guadalupe Box, the Sandia Formation is 34 m thick and forms a well-developed, fining-upward (transgressive) succession composed of a basal sandstone interval, a middle shale-siltstone interval, and an upper shale-limestone-sandstone interval. At Mesa Venado, the Sandia Formation shows a similar upward-fining trend from sandstone, partly pebbly, and intercalated shale at the base, overlain by shale with intercalated thin limestone beds (see Krainer and Lucas 2013). At Osha Canyon, the Sandia Formation is composed of several fining-upward fluvial cycles and a thin marine horizon at the top (as interpreted by Krainer and Lucas, 2013).

In general, as inferred by Krainer and Lucas (2013), the depositional environment of siliciclastic deposits of the Sandia Formation ranges from fluvial to fluvio-deltaic, brackish coastal swamp, coarse-grained high-energy nearshore, and fine-grained middle-outer shelf settings. Intercalated limestone with a low-diversity fossil assemblage accumulated in a restricted, shallow marine shelf environment. Limestone containing a diverse fossil assemblage formed in open, normal marine, low- to high-energy shallow shelf environments (Krainer and Lucas, 2013).

The Sandia Formation is a synorogenic unit that marks the onset of the Ancestral Rocky Mountain deformation (Kues and Giles, 2004; Krainer and Lucas, 2013). In the Sierra Nacimiento-San Pedro Mountains-Jemez Mountains, it is characterized by distinct lateral changes in thickness and facies as a result of the Ancestral Rocky Mountain deformation. Further evidence of active tectonism can be interpreted by these observations: (1) the Sandia Formation locally overlies Proterozoic basement, various Mississippian units, or the Osha Canyon Formation, and (2) the Sandia Formation is absent at some locations where younger strata rest on pre-Sandia rocks (Krainer and Lucas, 2013).

Gray Mesa Formation

What was termed the gray limestone member of the Madera Group by geologists during the 1940s is now termed the Gray Mesa Formation (e.g., Kues, 2001; Krainer and Lucas, 2004; Nelson et al., 2013b). In the Sierra Nacimiento-San Pedro Mountains-Jemez Mountains this unit crops out primarily in the drainages of the Guadalupe and Jemez rivers, though outcrops are also present in the Sierra Nacimiento at Rancho del Chaparral, Porter Landing, Mesa Venado and Soda Dam (Krainer and Lucas, 2013).

The section of Gray Mesa Formation at Guadalupe Box (Fig. 5) well represents the unit in the Sierra Nacimiento-Jemez Mountains. Here, the Gray Mesa Formation is an 18.5-m-thick succession of different types of limestone with intercalated sandstone and thin shale, interrupted by a covered slope in the middle part. The limestone facies includes thin- to thick-bedded gray cherty limestone with silicified brachiopods (Fig. 5, units 7, 8); thin, nodular to wavy limestone beds with shale intercalations (Fig. 5, units 4, 6, 13, 16); and gray, nodular, poorly-bedded limestone (Fig. 5, units 1, 2, 9, 15). The nodular limestone at the base of the Gray Mesa Formation (Fig. 5, unit 1) contains a sandy matrix with abundant micas, whereas that of unit 9 contains greenish-gray marly matrix. Limestones with feldspar grains (Fig. 5, units 5, 14, 17, 20) are light gray, massive to indistinctly bedded, and 0.3–1.2 m thick. The sandstone horizons of units 3 and 11 are light gray, massive to indistinctly bedded, and 0.7–0.8 m thick. In units 4 and 6, greenish-gray silty shale alternates with thin limestone beds. Unit 13 consists of reddish shale with limestone nodules and thin nodular lime-

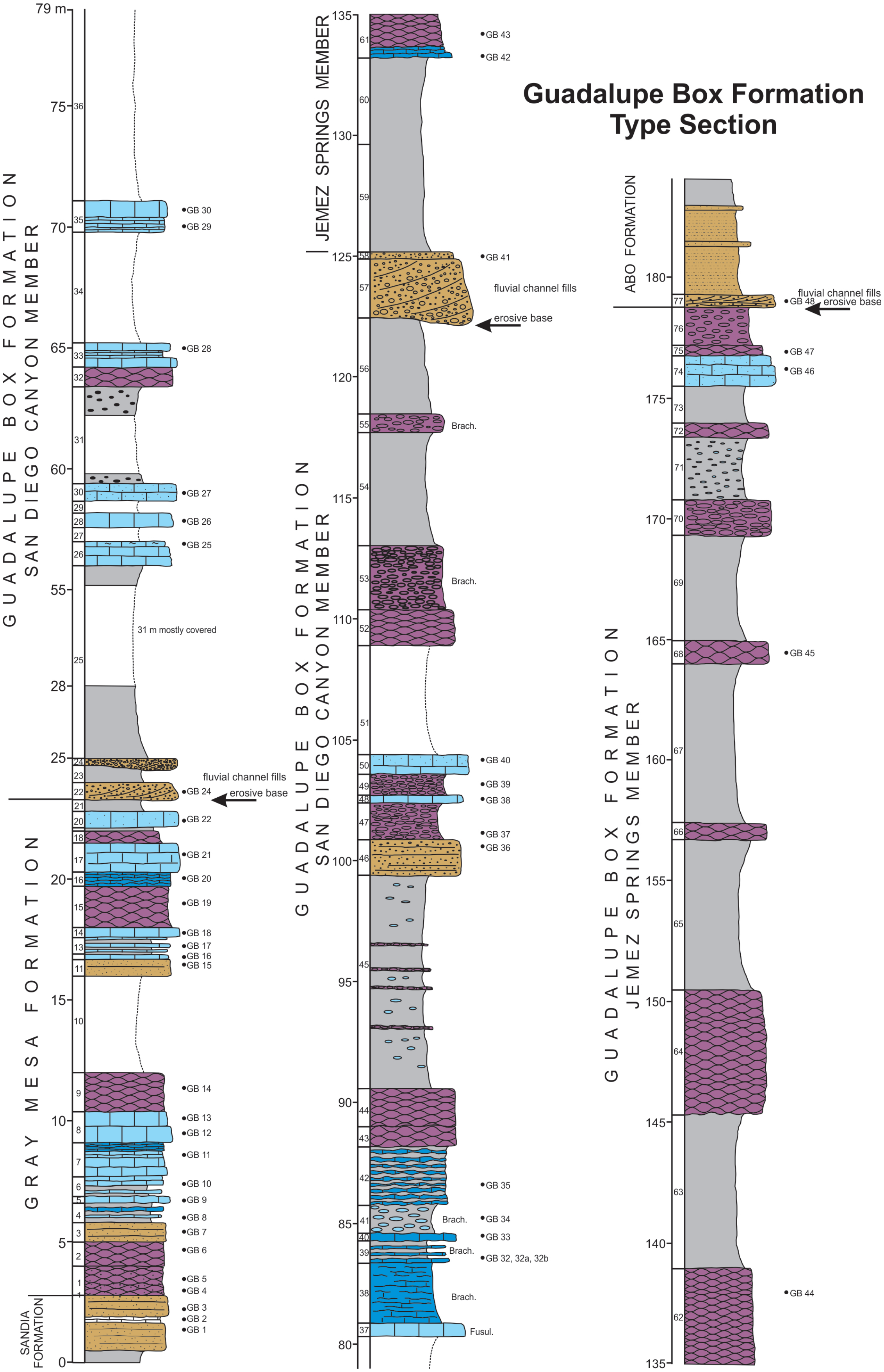

FIGURE 5. Section of Gray Mesa Formation and Guadalupe Box Formation at Guadalupe Box. See Krainer et al. (2005) and Figure 1 for the location of the section. Explanations of lithologic symbologies and shading are given in Figure 3 and its caption.

stone beds. This unit contains brachiopods. The uppermost part of the Gray Mesa Formation consists of red shale (Fig. 5, units 19 and 21) intercalated with a limestone bed. The limestone facies of the Gray Mesa Formation consist of bioclastic wackestone, packstone, and grainstone.

Guadalupe Box Formation

Around the Sierra Nacimiento-San Pedro Mountains-Jemez Mountains, the strata overlying the Gray Mesa Formation were assigned to the Atrasado Formation by Kues (2001). However, this stratigraphic interval is much thinner than and differs lithologically from the type Atrasado Formation, particularly because it lacks the distinctive stratigraphic architecture of the Atrasado that allows it to be divided into nine members across much of central New Mexico (e.g., Lucas et al., 2009, 2021; Nelson et al., 2013a). Thus, Krainer et al. (2005) recognized a new formation confined to the Sierra Nacimiento-San Pedro Mountains-Jemez Mountains that they named the Guadalupe Box Formation and divided into two members: the lower San Diego Canyon Member and the upper Jemez Springs Member (Fig. 2).

The type section of the Guadalupe Box Formation (Fig. 5) nicely represents the unit. Here, the Guadalupe Box Formation is a 155.5-m-thick succession of covered slope intervals (assumed shale) composing 35% of the section, exposed shale intervals (35.5%), limestone (26.6%), and sandstone (3.3%). In the type section of the Guadalupe Box Formation, the shale is red and micaceous in the lower part (Fig. 5, units 23, 25) and middle part (Fig. 5, units 54, 56). Unit 31 is mostly covered dark-red shale containing small limestone nodules. Unit 69 consists of variegated greenish and purple shale, and unit 73 is purple shale. Most of the other shale intervals are greenish-gray shale, partly micaceous and locally containing abundant limestone nodules (Fig. 5, units 47, 49, 53, 55, 70, 76). The greenish shales with limestone nodules of units 34, 53, and 55 contain fossils (mostly brachiopods and locally crinoid fragments).

Limestone of the Guadalupe Box Formation includes: (1) thin- to thick-bedded limestone, mostly gray, but locally reddish (e.g., the lower part of unit 61); on top of unit 26 a thin limestone containing abundant phylloid algae is developed; the limestone bed of unit 37 contains fusulinids; (2) thin limestone beds with wavy to nodular bedding planes, alternating with greenish shale (units 39, 42) containing abundant brachiopods and diverse bryozoans; (3) gray, micritic. nodular limestone that is indistinctly bedded (nodular limestone is the most abundant limestone lithotype); and (4) sandy limestone, 0.3–1.3 m thick, massive to indistinctly bedded, containing abundant quartz and feldspar grains up to 1 cm in diameter (units 30, 48, 50, 74). The most abundant microfacies of the limestones is bioclastic wackestone; subordinate microfacies are bioclastic lime mudstone, peloidal lime mudstone, lime mudstone, algal wackestone, bioclastic grainstone and mixed carbonate-siliciclastic beds, and fossiliferous siltstone.

Siliciclastic sediments of the Guadalupe Box Formation at the type section include the following types: (1) sandstone made of a mixture of siliciclastic and carbonate grains (which we refer to as mixed carbonate-siliciclastic sandstone), poorly laminated, containing abundant coarse granitic debris and a few brachiopods (Fig. 5, unit 46); (2) intercalated thin layers of fine-grained, calcite-cemented sandstone containing abundant mono- and polycrystalline quartz grains, altered detrital feldspars (mostly alkali feldspars), granitic and metamorphic rock fragments, and rare detrital micas (e.g., unit 46); (3) sandstone, coarse-grained, mostly pebbly with individual clasts up to a few centimeters in diameter; and (4) pebbly sandstone, which in unit 57 is 2.4 m thick, trough cross-bedded, poorly sorted, and contains angular to subangular quartz and granitic rock fragments; this sandstone erosively cut into the underlying red shale, and above it is a 0.3-m-thick, coarse-grained arkosic sandstone (unit 58). These sandstones (#4 lithotype) are poorly sorted, mostly angular-subangular, and composed of mono- and polycrystalline quartz, abundant detrital feldspars, mostly untwinned perthitic alkali feldspars, and microcline. Granitic rock fragments composed of large alkali feldspars and quartz are present. Detrital muscovite and biotite are rare. The sandstone is cemented by coarse, blocky calcite, randomly replacing detrital feldspar and quartz grains. Two sandstone beds with an erosive lower contact and separated by a thin red shale interval form the base of the Guadalupe Box Formation (Fig. 5, units 22, 24). The lower bed is 0.7 m thick and displays trough cross-bedding; the upper bed is 0.3 m thick and appears massive. Both beds contain abundant reddish granitic rock fragments.

The fluvial pebbly sandstone of unit 57 in the middle of the succession divides the Guadalupe Box Formation into two members, which differ lithologically. The type section of the lower San Diego Canyon Member, coincides with units 22–58 of the Guadalupe Box Formation type section (Fig. 5). The upper member is the redefined Jemez Springs (Shale) Member of Sutherland and Harlow (1967). At its type section, the San Diego Canyon Member is 102.7 m thick (units 22–58, from 23.3 m to 125 m; Fig. 5) and shows a trend in the lower part that begins with fluvial channel fills and culminates in a 20-m-thick marine succession of fossiliferous shales, siltstones, marls, and marly limestones (units 37–44) that we interpret as transgressive. The upper part of the member also exhibits an upward trend that we infer to represent a regression. Marine strata (limestone nodules in shale, locally with brachiopods, and limestone beds) lie above a ~1-m-thick, mixed carbonate-siliciclastic sandstone (unit 46); these marine strata are overlain by a predominately terrestrial succession of red shales of units 54 and 56 (separated by ~0.5-m-thick nodular limestone with shale) and capped by a fluvial channel fill of unit 57. The progression from marine upward to nonmarine strata is taken by us as prima facie evidence of a regression. Limestones in the San Diego Canyon Member mostly are composed of muddy microfacies (lime mudstone, wackestone) and contain diverse marine fauna; there are also rare calcareous algae (e.g., algal wackestone of unit 26).

The Jemez Springs Member is 53.8 m thick (units 59–76; 125–178.8 m) and composed mostly of greenish-gray shale. In the upper part is also purple shale and intercalated gray nodular limestone. Shale intervals are 1.6–6.3 m thick, and the nodular limestones are 0.6–5.2 m thick. Bedded limestones composed of bioclastic wackestone/grainstone with diverse fauna are present but rare (units 61 and 74). The typical microfacies of the nodular limestones is lime mudstone and peloidal lime mudstone with only a few small skeletons. Nodular limestones in the upper part of the succession (e.g., Fig. 5, units 66, 68, and 75) display features that are typical of calcic paleosols.

At Jemez Monument, the type section of the Jemez Springs Member (Jemez Springs Shale Member of Sutherland and Harlow, 1967) is composed mainly of shale, subordinately of siltstone and different types of limestone (with bioclastic wackestone being the most common microfacies in the limestone). Compared to the Jemez Springs Member at Guadalupe Box, the shale and limestone of the Jemez Springs Member at Jemez Monument are much more fossiliferous, particularly in the upper part, thus showing a more open-marine aspect for most of the section.

Permian

The Permian section around the southern edges of the Sierra Nacimiento-San Pedro Mountains-Jemez Mountains belongs to the (ascending) Abo Formation, Yeso Group (De Chelly Sandstone and San Ysidro Formation), and Glorieta Sandstone. To the north of the Sierra Nacimiento and Jemez Mountains, along and south of the Rio Puerco and Chama River drainages, the Permian section consists of the Cutler Group (El Cobre Canyon and Arroyo del Agua formations) capped by a remnant of the lower part of the Yeso Group.

Cutler Group

On the northern flank and to the north and northeast of the Sierra Nacimiento-San Pedro Mountains-Jemez Mountains, a thick succession of siliciclastic red beds is exposed in the drainages of the Rio Puerco and the Chama River. These rocks have long been assigned to the Cutler Formation (e.g., Wood and Northrop, 1946; Baars, 1962), and Lucas and Krainer (2005) assigned them to a group rank and defined two distinct, mappable formations: (1) El Cobre Canyon Formation—up to 500 m of brown siltstone, sandstone, and extraformational conglomerate; and (2) the overlying Arroyo del Agua Formation—up to 120 m of orange siltstone, sandstone, and minor intraformational and extraformational conglomerate (also see Kelley et al., 2006; Timmer et al., 2006).

We have extensive unpublished data on these units to be presented elsewhere and limit ourselves to the following observations here:

1) To the northeast, the El Cobre Canyon Formation rests on Proterozoic basement in the subsurface, but in the Gallinas-Arroyo del Agua area it rests on marine limestones interbedded with red siliciclastics of the Guadalupe Box Formation (Krainer and Lucas, 2010).
2) Fossil pollen, macrofossil plants, and vertebrates indicate that much of the El Cobre Canyon Formation is of Late Pennsylvanian, likely Virgilian age (Lucas et al., 2010). Some of the same fossils are found in the middle-upper Guadalupe Box Formation (Fig. 9).
3) Fossil vertebrates from the upper parts of the El Cobre Canyon Formation correlate to Abo Formation vertebrates (Lucas et al., 2012).
4) The Arroyo del Agua Formation lithologically resembles somewhat the upper part of the Abo Formation but is a distinctive unit with more mudrock and calcic paleosols than the upper Abo (Krainer and Lucas, 2010).
5) The De Chelly Sandstone rests on the Arroyo del Agua Formation near Coyote (Kelley et al., 2006).
6) Thus, the Cutler strata north of the Jemez volcanics are correlative with the upper part of the Guadalupe Box Formation and the Abo Formation south of the volcanics (Krainer et al., 2005).

Abo Formation

The Abo Formation is well exposed in the drainages of the Guadalupe and Jemez Rivers, where it is up to 190 m thick and composed of siliciclastic red beds that constitute the lowest part of the Permian section. Totally of fluvial origin, Abo red beds are mostly composed of mudstone, siltstone and fine-grained sandstone. Lucas et al. (2012) described several Abo sections along the Jemez and Guadalupe Rivers; there, the unit has a maximum thickness of ~190 m. In this area, the Abo Formation can be divided into two members: (1) a lower, Scholle Member, mostly mudstone and siltstone (69–72% of the section) that is 90–115 m thick; and (2) an upper, Cañon de Espinoso Member, usually about 60 m thick with less mudstone/siltstone (25–41% of the section) and many sandstone sheets.

The contact between the Abo Formation and underlying Guadalupe Box Formation is mapped at the top of the highest marine limestone of the Guadalupe Box Formation (Woodward, 1987; Lucas et al., 2012). However, some workers (e.g., Swenson, 1977, 1981) have suggested that there is interbedding of the upper Guadalupe Box Formation (their Madera Formation) and the Abo Formation. We believe this is because they considered red beds of the Guadalupe Box Formation (see description above) to be Abo strata—a conclusion we do not support.

The Abo Formation at the Jemez River stratigraphic section (Fig. 6) is characteristic of the formation in the study area and was described in detail by Krainer and Lucas (2010). Here, the Abo Formation is 143 m thick. The base is not exposed, and Abo red beds are overlain by eolian sandstone of the De Chelly Sandstone of the Yeso Group. As elsewhere, the Abo can be divided into lower and upper members, which are described below for the Jemez River section. The lower member (Scholle Member, 83 m thick) is dominated by mudstone and siltstone that constitute 69% of the strata. In the 60-m-thick, upper member (Cañon de Espinoso Member), mudstone and siltstone constitute much less of the Abo section (25%). The lower member correlates to the upper part of the El Cobre Canyon Formation, and the upper member correlates to the Arroyo del Agua Formation of the Cutler Group (Krainer et al., 2005),

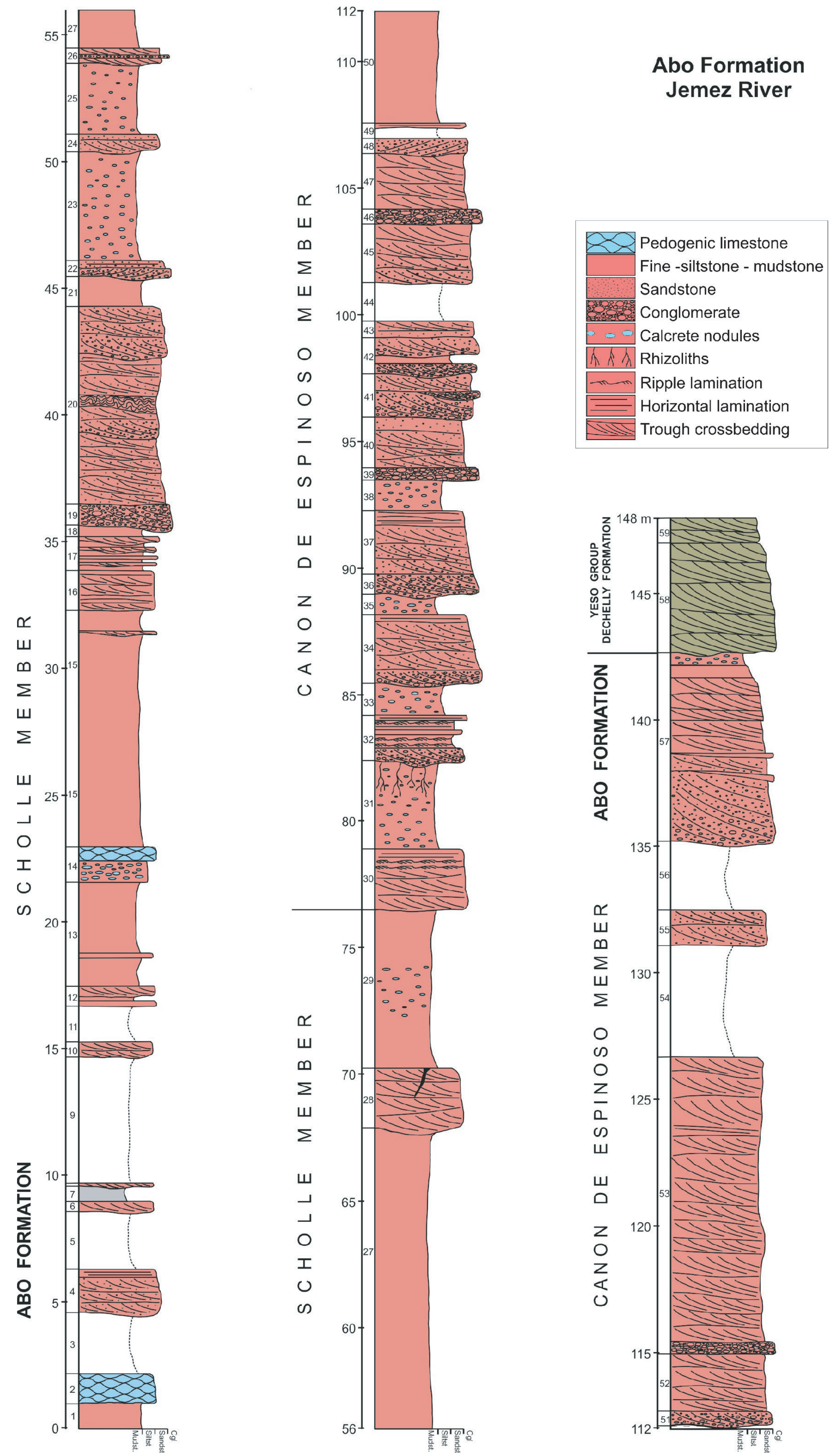

FIGURE 6. Abo Formation section on Jemez River. See Figure 7 for lithologic legend, and see Krainer and Lucas (2010) and Figure 1 for the location of the section.

and, respectively, to the Scholle Member and Cañon de Espinoso Member of the Abo type section in central New Mexico (Lucas et al., 2005).

Siltstone and mudstone units are the dominant lithofacies of the Abo Formation. These are intercalated with minor pedogenic calcic horizons, typically pedogenic limestones (calcretes) forming topographic benches or massive (bioturbated), calcic-nodular intervals in mudstones. The siltstone-mudstone facies forms sheet-like units extending laterally over at least hundreds of meters. Their geometry and fine-grained textures support an interpretation of sheetflood deposits in a floodplain paleoenvironment. Desiccation cracks indicate periodic drying out; long-term exposure led to the formation of calcic paleosols (pedogenic limestone).

The most characteristic and distinctive sandstone facies assemblages in the Abo Formation are sandstone sheets. These sheets form prominent, resistant ledges that can be traced laterally over long distances (commonly more than 100 m, up to several hundred meters). The bases of these beds are generally erosive, and there is an upward decrease in bed thickness and grain size. Thus, common lithofacies are conglomerate at the base, grading into multistoried trough cross-bedded sandstone. Rarely, fine-grained sandstone in the uppermost part is bioturbated, and synsedimentary deformation structures are locally observed in fine-grained sandstone. Single sandstone beds and lenses are mostly 10–30 cm and, rarely, up to 50 cm thick. Stacked sandstone units are up to 1 m thick. The sandstone beds occur as tabular or lens-shaped bodies; the base may be erosive. Rarely, sandstone sheets are bioturbated. Basal erosional surfaces with mudstone rip-up clasts and reworked caliche clasts indicate high-energy conditions of rapid flooding and reworking of mudstone and caliche beds from the floodplain.

The Abo Formation is very fossiliferous in the Jemez Mountains. It contains fossil footprints, plants, and vertebrate bones that are further described in Lucas et al. (2012). These are of the same taxa as Abo fossils found to the south, particularly in Socorro County (Berman et al., 2015).

Yeso Group

Around the Sierra Nacimiento, San Pedro Mountains, and Jemez Mountains, Yeso Group strata are a succession of mostly siliciclastic strata (sandstones and siltstones) and minor carbonate and gypsum beds. Since the work of Wood and Northrop (1946), the Yeso section has been divided into two lithostratigraphic units described below, variously termed members or formations.

De Chelly Sandstone

Baars (1962) noted that the unit Wood and Northrop (1946) named the Meseta Blanca sandstone member of the Yeso Formation is the same as the De Chelly Sandstone of the Four Corners region. Therefore, Lucas et al. (2005) abandoned the name Meseta Blanca and considered the De Chelly the lower formation of the Yeso Group.

De Chelly Sandstone forms spectacular cliffs in the northern part of Jemez Pueblo and in the Guadalupe River canyon below Guadalupe Box. The section at Jemez Pueblo published by Lucas et al. (2005, fig. 7) is characteristic of the formation (Fig. 7). Here, the De Chelly Sandstone is ~83 m thick and forms benches and cliffs that are reddish to orange to yellow in color. The formation is composed mostly of fine- to medium-grained quartz sandstone with a few interbeds of siltstone. Particularly striking are the thick (up to 5 m), cross-bedded strata that are characteristic of eolian dunes. Other sandstones with horizontal laminations likely represent eolian sheet sands, though ripple-laminated sandstones (not eolian ripples, as they lack the coarse-grained crests and fine-grained troughs that are the characteristic veneer of eolian ripples) near the base of the De Chelly were deposited by water. Two prominent intervals with rhizoliths are present (Fig. 8, units 23–25 and units 34–35).

Unpublished and published work by us shows that the De Chelly is present in the Zuni Mountains and Lucero uplift to the south and at Placitas at the northern end of the Sandia uplift to the southeast (Lucas et al., 1999; Lucas and Zeigler, 2004; Lucas et al., 2005). At Placitas, the eolian, dunal facies of the De Chelly interfingers with and merges into the Arroyo de Alamillo Formation. The latter formation consists of arid coastal plain deposits that extend as far south as the Caballo Mountains of Sierra County (Lucas and Krainer, 2012).

San Ysidro Formation

The upper part of the Yeso Group around the Sierra Nacimiento-San Pedro Mountains-Jemez Mountains is the San Ysidro Formation (originally the San Ysidro Member of the Yeso Formation of Wood and Northrop, 1946, raised to formation status by Lucas et al., 2005). This unit is well exposed in the valleys of the Jemez and Guadalupe Rivers. The section on Jemez Pueblo described by Lucas et al. (2005, fig. 7) is characteristic of the formation (Fig. 7). Here, the San Ysidro Formation is ~132 m thick and consists of reddish-brown and grayish-red fine sandstone and siltstone with a couple of beds of conglomerate and a single limestone bed. Most sandstone beds are horizontally laminated, as are some of the siltstone beds. Some beds have ripple laminations or are massive. One siltstone bed has numerous gypsum nodules. The Glorieta Sandstone rests on the San Ysidro Formation with a sharp contact. The San Ysidro Formation is primarily the deposits of an arid coastal plain (e.g., Lucas et al., 2005).

Glorieta Sandstone

Wood and Northrop (1946) considered the Glorieta Sandstone to be a member of the San Andres Formation and also included an immediately overlying red-bed unit of the San Andres Formation. However, the limestone-dominated unit that composes the majority of the San Andres to the south is not present in the Sierra Nacimiento or Jemez Mountains; it was apparently not deposited, or it was removed by Triassic erosion (Brose et al., 2013). Also, the Glorieta Sandstone is no longer considered a member of the San Andres Formation by most workers (e.g., Woodward, 1987; Lucas et al., 2013).

The Glorieta Sandstone crops out in the drainages of the

Guadalupe and Jemez Rivers and along the flanks of the Nacimiento uplift (Woodward, 1987; Kelley et al., 2003). It is yellowish-gray to brown, fine- to medium-grained quartzarenite (often called a metaquartzite because it is very strongly cemented) that is typically cross-bedded and up to ~30 m thick. The Glorieta Sandstone forms a cliff or bench and is sharply overlain by Triassic red beds of the Moenkopi Formation (Fig. 8). The outcrops in the southern Jemez Mountains and Nacimiento uplift are the northwesternmost outcrops of the Glorieta Sandstone (Lucas et al., 2013). The Glorieta Sandstone is primarily of eolian origin (Mack and Bauer, 2014; Krainer and Lucas, 2015).

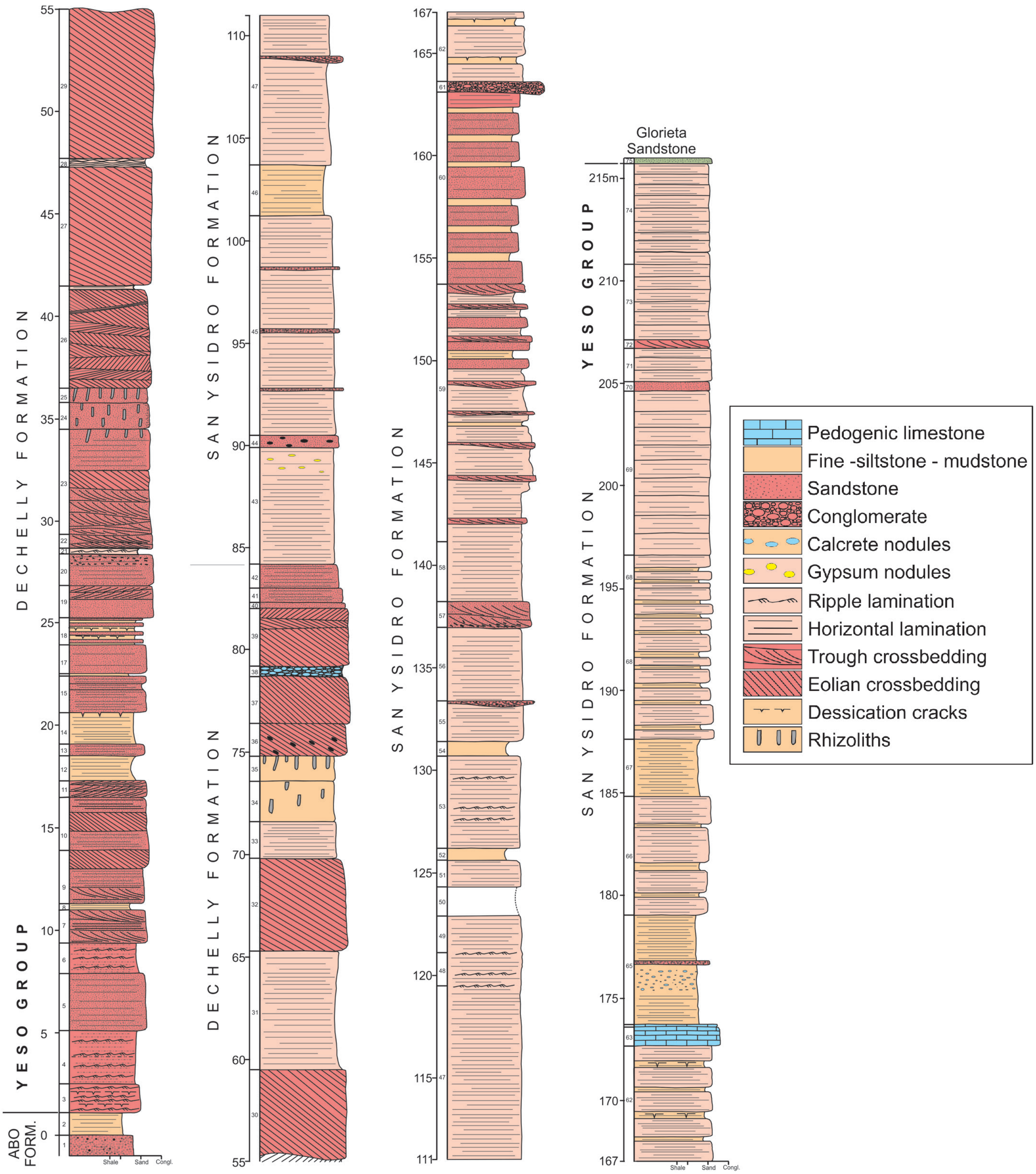

FIGURE 7. Yeso Group section on the northern edge of Jemez Pueblo. See Lucas et al. (2005) and Figure 1 for the location of the section.

Triassic Moenkopi Formation (previously called Bernal Formation)

Wood and Northrop (1946) also included a red-bed sandstone unit as the upper member of the San Andres Formation in the Jemez Mountains. This unit was later named the Bernal Formation in northeastern New Mexico (Bachman, 1953). However, the type Bernal includes two lithosomes: (1) a lower unit of fine-grained sandstone and siltstone with some intercalated beds of dolomite and gypsum shown to correlate to the upper part of the Permian Artesia Group of southeastern New Mexico (e.g., Tait et al., 1962; Kelley, 1972), and (2) an upper interval of litharenitic sandstone and conglomerate that was named the Anton Chico Member of the Moenkopi Formation by Lucas and Hunt (1987) and Lucas and Hayden (1991).

Lucas and Hayden (1989), in stratigraphic work done along the southwestern flank of the Sierra Nacimiento (Fig. 8), showed that the red beds previously included in the San Andres Formation (Wood and Northrop, 1946) or later mapped as Bernal Formation (see Woodward, 1987, for a summary), both considered Permian, actually belong to the Anton Chico Member of the Moenkopi Formation and are of Middle Triassic age. These Moenkopi strata in the Nacimiento uplift have a maximum thickness of 39 m and rest with evident disconformity on the underlying Glorieta Sandstone. Mostly sandstone and mudstone, the Moenkopi strata are grayish red, sandy, and calcareous. Sandstones are litharenites that are mostly trough cross-bedded. Conglomerates are made up of intraformational clasts of mudstone, siltstone, and calcrete pebbles. These are fluvial strata with paleocurrent directions that indicate flow was to the north-northwest.

BIOSTRATIGRAPHY AND AGE

Age assignments for the upper Paleozoic strata in the Na-

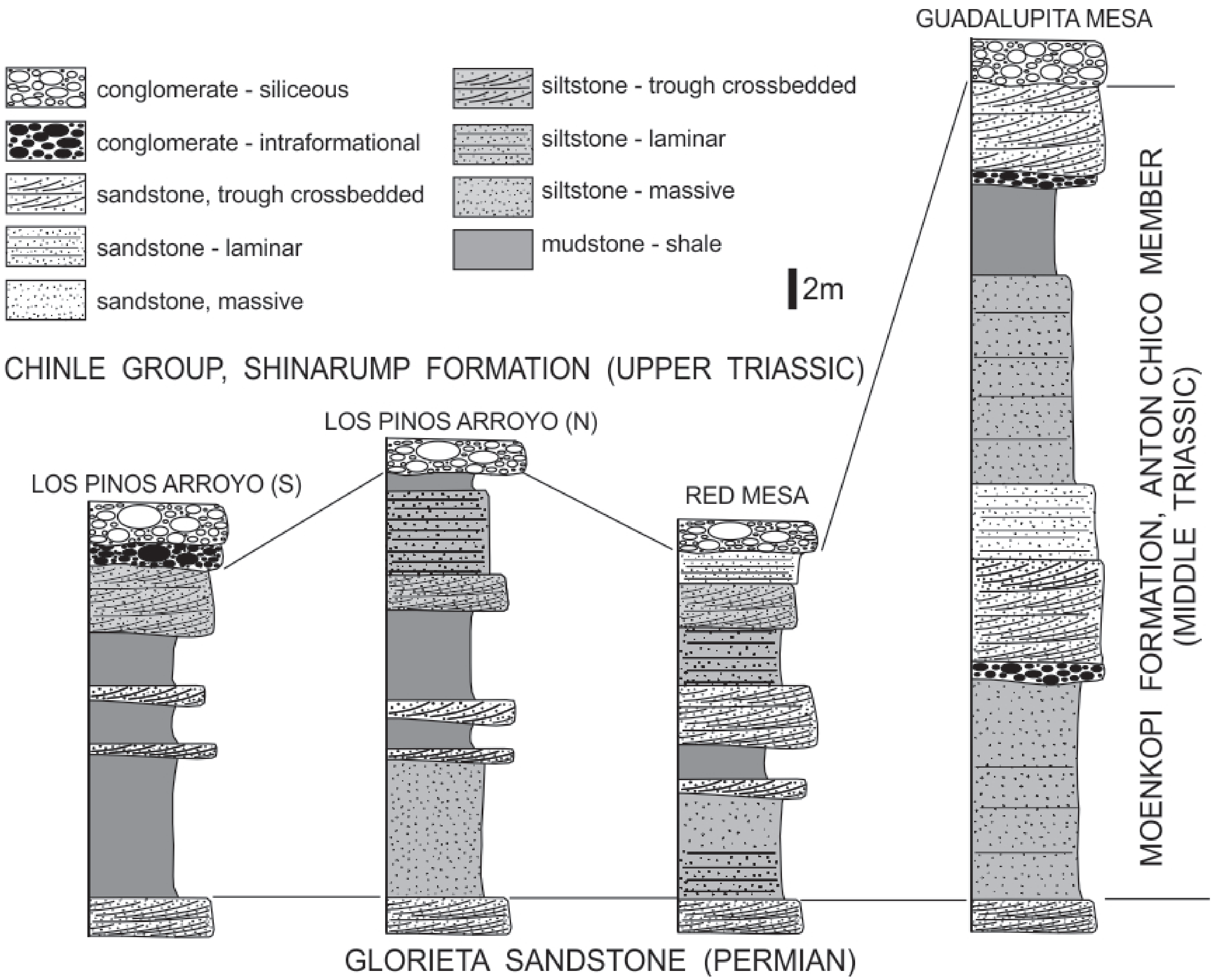

FIGURE 8. Stratigraphic sections of the Moenkopi Formation around the Nacimiento uplift—strata formerly considered to be Permian red beds ("Bernal Formation") at the top of the Paleozoic section (after Lucas and Hayden, 1989). Locations of the sections are: Los Pinos Arroyo (S) = SW 1/4 sec. 8, T16N, R1E; Los Pinos Arroyo (N) = SW 1/4 sec. 5, T16N, R1E; Red Mesa = NE 1/4 sec. 31, T16N, R1E; and Guadalupita Mesa = 760 m northeast of Guadalupe Box.

cimiento uplift-San Pedro Mountains-Jemez Mountains are based on both local and regional biostratigraphic data (Fig. 9). Marine fossils (particularly foraminiferans) from the Arroyo Peñasco Formation indicate early Osagean to Meramecian ages (see Armstrong, 1955, 1967; Fitzsimmons et al., 1956; Armstrong and Mamet, 1974, 1979; Armstrong et al., 2004; Sutherland, 1963). The Log Springs Formation is dated as Chesterian, although the age is poorly constrained due to the lack of age-diagnostic fossils (Armstrong et al., 2004).

lithostratigraphic unit		thickness (m)	age	
Glorieta Sandstone		30	Leonardian	early Permian
Yeso Group	San Ysidro Formation	132	Leonardian	early Permian
Yeso Group	DeChelly Sandstone	83	Leonardian	early Permian
Abo Formation		190	middle-late Wolfcampian	early Permian
Guadalupe Box Formation		156	Virgilian	Pennsylvanian
			Missourian	Pennsylvanian
			Desmoinesian	Pennsylvanian
Gray Mesa Formation		21	Desmoinesian	Pennsylvanian
Sandia Formation		64	Atokan	Pennsylvanian
Osha Canyon Formation		27	Morrowan	Pennsylvanian
Log Springs Formation		48	Chesterian	Miss.
Arroyo Peñasco Formation		40	Osagean-Meramecian	Miss.

FIGURE 9. Summary of the upper Paleozoic lithostratigraphic units and their maximum thicknesses and biostratigraphically assigned ages in the Sierra Nacimiento-San Pedro Mountains-Jemez Mountains. As explained in the text, the Cutler Group correlates to the upper Guadalupe Box Formation (Virgilian strata) and the lower Abo Formation.

Brachiopods indicate a Morrowan age for the Osha Canyon Formation (Wood and Northrop, 1946; DuChene et al., 1977). Regionally, fusulinids and conodonts indicate that the Sandia Formation is mostly of Atokan age, though locally its base is late Morrowan and its upper strata are early Desmoinesian (Krainer et al., 2011; Krainer and Lucas, 2013). In the Sierra Nacimiento-Jemez Mountains, all age data indicate the Sandia Formation is Atokan (Wood and Northrop, 1946; Henbest et al., 1944).

Based on microfossils, particularly fusulinids (Henbest et al., 1944; Krainer et al., 2005), the upper part of the Gray Mesa Formation at Guadalupe Box is dated as late-middle Desmoinesian. The base of the Guadalupe Box Formation is late Desmoinesian (the DS4 zone of Wilde, 1990); the middle part corresponds to the Missourian (the MC1 or MC2 biozones of Wilde, 1990), and the upper part is of late Virgilian age. The Cutler Group correlations indicated above (also see Lucas and Krainer, 2005) suggest it is of Late Pennsylvanian-early Permian age.

The Abo Formation contains vertebrates of the Coyotean land-vertebrate faunachron, which ranges in age from late Virgilian through Wolfcampian (Lucas et al., 2012). Given the late Virgilian age of the top of the underlying Guadalupe Box Formation, the absence of the Bursum Formation in the Nacimiento uplift-San Pedro Mountains-Jemez Mountains, and regional biostratigraphic data, Lucas et al. (2012) suggested there is an unconformity at the base of the Abo Formation and that it is of middle-late Wolfcampian age. Based on regional correlations and some marine biostratigraphic data, the Yeso Group is of Leonardian age, as is the overlying Glorieta Sandstone (e.g., Lucas et al., 2013, 2022).

SUMMARY

To briefly summarize, the upper Paleozoic rocks in the Nacimiento uplift-San Pedro Mountains-Jemez Mountains are a section about 791 m thick that includes marine and nonmarine strata of Mississippian, Pennsylvanian, and early Permian ages (Fig. 9). The Mississippian strata are assigned to the Arroyo Peñasco Formation and overlying Log Springs Formation. Pennsylvanian strata belong to the (ascending) Osha Canyon, Sandia, Gray Mesa, and Guadalupe Box Formations. Pennsylvanian-Permian strata in the northern part of the study area are assigned to the Cutler Group. Permian strata are assigned to the (ascending) Abo Formation, Yeso Group, and Glorieta Sandstone. Local and regional biostratigraphic data allow stage-level ages to be assigned to all of these strata.

ACKNOWLEDGMENTS

We thank various colleagues for their collaboration and discussions in the field. The U.S. Forest Service permitted some of our work in the Jemez Mountains, and the Pueblo of Jemez granted access to land. Reviews by Maya Elrick, Dan Koning, and Barry Kues improved the content and clarity of the manuscript.

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