New observations and tectonic inferences on the Mississippian-Lower Pennsylvanian strata in the Sierra Nacimiento-San Pedro Mountains-Jemez Mountains, north-central New Mexico

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NEW OBSERVATIONS AND TECTONIC INFERENCES ON MISSISSIPPIAN-LOWER PENNSYLVANIAN STRATA IN THE SIERRA NACIMIENTO-SAN PEDRO MOUNTAINS-JEMEZ MOUNTAINS, NORTH-CENTRAL NEW MEXICO

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Abstract—In the Sierra Nacimiento, Jemez Mountains, and San Pedro Mountains of northern New Mexico, the Proterozoic basement is locally overlain by a thin succession of sedimentary rocks of Mississippian age. The succession is divided into the Arroyo Peñasco Formation that is 7.5–34 m thick in the studied sections and the overlying Log Springs Formation (9.2–13.5 m thick). The Arroyo Peñasco Formation is divided into the Del Padre and overlying Espiritu Santo Members. The Del Padre Member is thin and composed of poorly sorted, subangular, quartz-rich sandstone, indicating deposition in a fluvial environment. Microfacies of limestone of the Espiritu Santo Member indicate deposition in a shallow marine depositional setting. Foraminifers at Lion Spring indicate a Tournaisian (Kinderhookian-Osagean) age of the Espirtu Santo Member. The Arroyo Peñasco Formation is unconformably overlain by the Log Springs Formation (Serpukhovian/upper Chesterian), which is composed of nonmarine red beds. At Log Springs, the Log Springs Formation is unconformably overlain by the Lower Pennsylvanian (Morrowan) Osha Canyon Formation. Limestones of the Osha Canyon Formation are composed of microfacies (rudstone, packstone, rare floatstone) that indicate deposition in a shallow, normal marine environment of moderate to high water turbulence. At Lion Spring, the Log Springs Formation is overlain by the Middle Pennsylvanian Sandia Formation; the Osha Canyon Formation is absent. At Soda Dam, the Sandia Formation rests on the Log Springs Formation, which overlies the Arroyo Peñasco Formation, and the Osha Canyon Formation is absent. This distinct unconformity at the base of the Sandia Formation, which at many places rests on Proterozoic basement, marks the onset of tectonic activity of the Ancestral Rocky Mountain orogeny.

INTRODUCTION

Shallow marine carbonate and siliciclastic sediments were deposited during an Early Mississippian marine transgression across central and northern New Mexico. These sediments unconformably rest on an almost peneplained basement of Proterozoic and lower Paleozoic rocks (Armstrong et al., 2004). In the Sierra Nacimiento-San Pedro Mountains-Jemez Mountains of north-central New Mexico, the thin succession of Mississippian sediments is termed the Arroyo Peñasco Group, overlain by the Log Springs Formation (Armstrong et al., 2004).

Tectonic activity during the Late Mississippian resulted in uplift, and older Mississippian sedimentary rocks were partly or completely eroded. In the Sierra Nacimiento-San Pedro Mountains, the sediments of the Arroyo Peñasco Group are unconformably overlain by nonmarine red beds of the Log Springs Formation (Serpukhovian/upper Chesterian). A transgression during the Early Pennsylvanian (Bashkirian/Morrowan) deposited the shallow marine sediments of the Osha Canyon Formation. Tectonic uplift of the Peñasco axis (a basement-cored uplift of the Ancestral Rocky Mountains roughly coinciding with the modern Sierra Nacimiento) that started during the Mississippian continued as a series of tectonic pulses into Middle Pennsylvanian time (DuChene et al., 1977). The first tectonic pulse caused deposition of the nonmarine red beds of the Log Springs Formation. The overlying Osha Canyon Formation was deposited during a relatively short period of little tectonic activity (Krainer and Lucas, 2005). The next tectonic pulse resulted in deposition of the Sandia Formation.

Here, we present sedimentological observations (including new petrographic data) on the Mississippian and Lower Pennsylvanian sedimentary successions in the Sierra Nacimiento, San Pedro Mountains, and Jemez Mountains and discuss their significance in understanding regional late Paleozoic depositional and tectonic history. After overviewing Mississippian nomenclature, we organize our descriptions based on newly measured stratigraphic sections at these geographic locations: (1) Lion Spring in the northwestern San Pedro Peak area; (2) Arroyo Peñasco, southwestern Sierra Nacimiento; and (3) Log Springs, southwestern Sierra Nacimiento (Fig. 1). Our stratigraphic sections are illustrated in Figure 2, and photographs of selected Mississippian outcrops are shown in Figure 3.

MISSISSIPPIAN STRATIGRAPHIC NOMENCLATURE

During the 1940s, stratigraphers in northern New Mexico assigned the oldest exposed Paleozoic strata to the Sandia Formation and distinguished a lower limestone member of the Sandia Formation, suggesting a possible pre-Pennsylvanian age for this unit (e.g., Read et al., 1944; Wood and Northrop, 1946; Read and Wood, 1947). This "lower limestone member" was described from the Sierra Nacimiento-San Pedro Mountains by Wood and Northrop (1946). Armstrong (1955) proposed the term Arroyo Peñasco Formation for this unit and reported an endothyrid foraminiferan fauna of Meramecian (Viséan) age. Fitzsimmons et al. (1956) presented a list of megafossils from

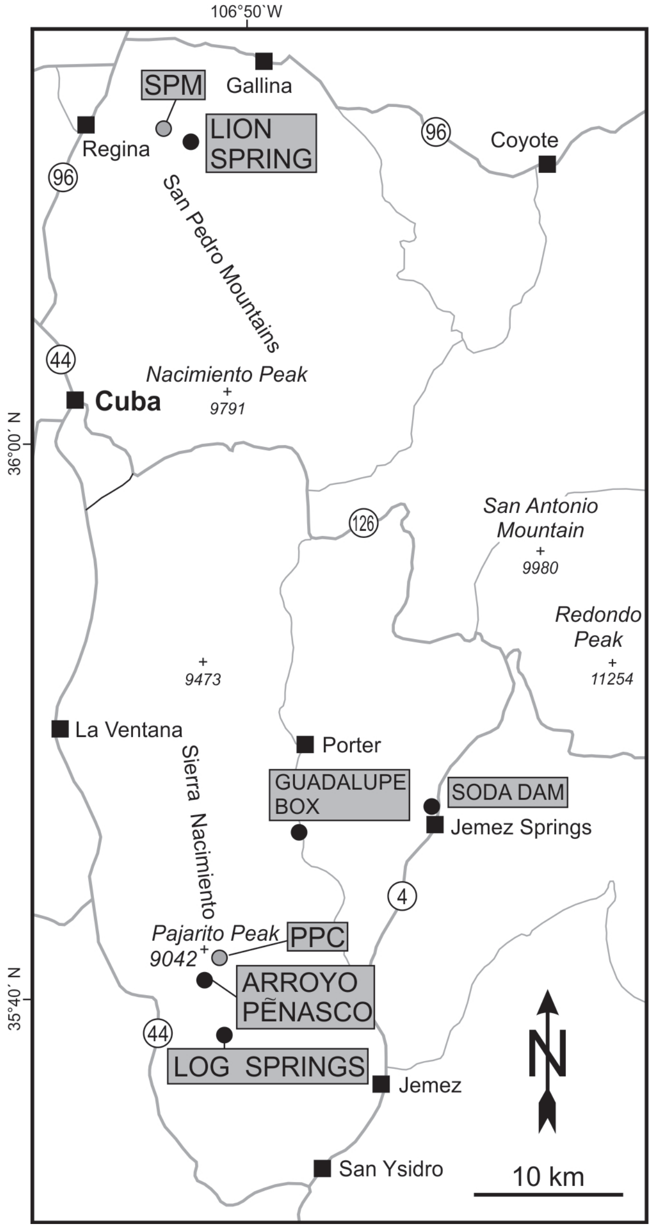

FIGURE 1. Locations of measured sections of Mississippian strata at Lion Spring (San Pedro Mountains), Arroyo Peñasco, and Lion Spring (Sierra Nacimiento). PPC = Pinos and Peñasco Canyons section of Armstrong (1967), SPM = San Pedro Mountains section of Armstrong (1967).

the type section of the Arroyo Peñasco Formation, which also were stated to indicate a Meramecian age.

Baltz and Read (1960) divided the pre-Pennsylvanian sedimentary rocks in the Sangre de Cristo Mountains of north-central New Mexico into two new formations, the Espiritu Santo and Tererro Formations. The Tererro Formation was further subdivided by Baltz and Read (1960) into the Macho, Turquillo, Manuelitas, and Cowles Members. Sutherland (1963) separated the basal sandstone of the Espiritu Santo Formation of Baltz and Read (1960) and named it the Del Padre Sandstone.

Armstrong (1967) considered the Espiritu Santo and Tererro Formations of Baltz and Read (1960) to be laterally equivalent to the Arroyo Peñasco Formation defined by Armstrong (1955) and Fitzsimmons et al. (1956). According to Armstrong and Mamet (1974, 1979), the Macho Member of the Tererro Formation is not present in the Sierra Nacimiento and San Pedro Mountains, where the upper Tournaisian (lower Osagean) Espiritu Santo Formation is overlain by the upper Viséan (upper Meramecian) Manuelitas Member (note that Armstrong et al., 2004, show the Manuelitas Member as middle Viséan; Fig 4). Because of its extent and the formations it includes, the Arroyo Peñasco Formation was raised to group rank in north-central New Mexico by Armstrong and Mamet (1974, 1979, 1990) and Armstrong et al. (2004; Fig. 4).

However, the Arroyo Peñasco Group and its subunits are too thin to be defined as a group divided into formations. The subunits ("formations") are not mappable units at most locations, so they should be regarded as of member rank (cf. Lucas et al., 2021). Thus, we downgrade the Arroyo Peñasco Group to formation rank (as originally defined by Armstrong, 1955) and its constituent formations to member rank.

For the Sierra Nacimiento-San Pedro Mountains-Jemez Mountains, we propose the following lithostratigraphic subdivision of the Mississippian succession (ascending order): Arroyo Peñasco Formation, subdivided into Del Padre Member (or Bed) and Espiritu Santo Member. According to Armstrong and Mamet (1974, 1979) and Armstrong et al. (1979, 2004), the Tererro Formation (Manuelitas Member) is present at their sections San Pedro Mountains and Pinos and Peñasco Canyons, but it is absent at Guadalupe Box and Soda Dam. Armstrong and Mamet (1974) defined the Manuelitas Member of the Tererrro Formation based on microfossils (mainly foraminifers). The Espiritu Santo Formation of the Arroyo Peñasco Group contains a fauna assigned to microfossil zone 9 (late Keokuk = late Tournaisian age), and the Manuelitas Member contains a fauna of microfossil zone MFZ14 (late Meramecian = late Viséan; Armstrong and Mamet, 1974; Fig. 4). Thus, the Manuelitas Member of Armstrong and Mamet (1974) is a biostratigraphic unit (defined by microfossil zone MFZ14) and not a lithostratigraphic unit. A lithologic subdivision of the Arroyo Peñasco Group (sensu Armstrong and Mamet 1974, 1979, 1990) and Armstrong et al. (2004) into two formations—Espiritu Santo Formation and Tererro Formation (Manuelitas Member)—in our experience is not possible in the field.

The Arroyo Peñasco Formation in the Sierra Nacimiento-to-San Pedro Mountains is overlain by the Log Springs Formation. The Pennsylvanian succession locally starts with the Osha Canyon Formation, but at many places the Sandia Formation rests directly on the Log Springs Formation or on the Proterozoic basement.

LION SPRING

At Lion Spring, the Arroyo Peñasco Formation is nonconformable on the Proterozoic basement, overlain by the Log Springs Formation and Middle Pennsylvanian Sandia Formation. The Arroyo Peñasco Formation is 12.4 m thick and divided into the Del Padre Member (5.7 m) and overlying Espiritu Santo Member (6.7 m). The overlying Log Springs Formation is 9.2 m thick (Fig. 2).

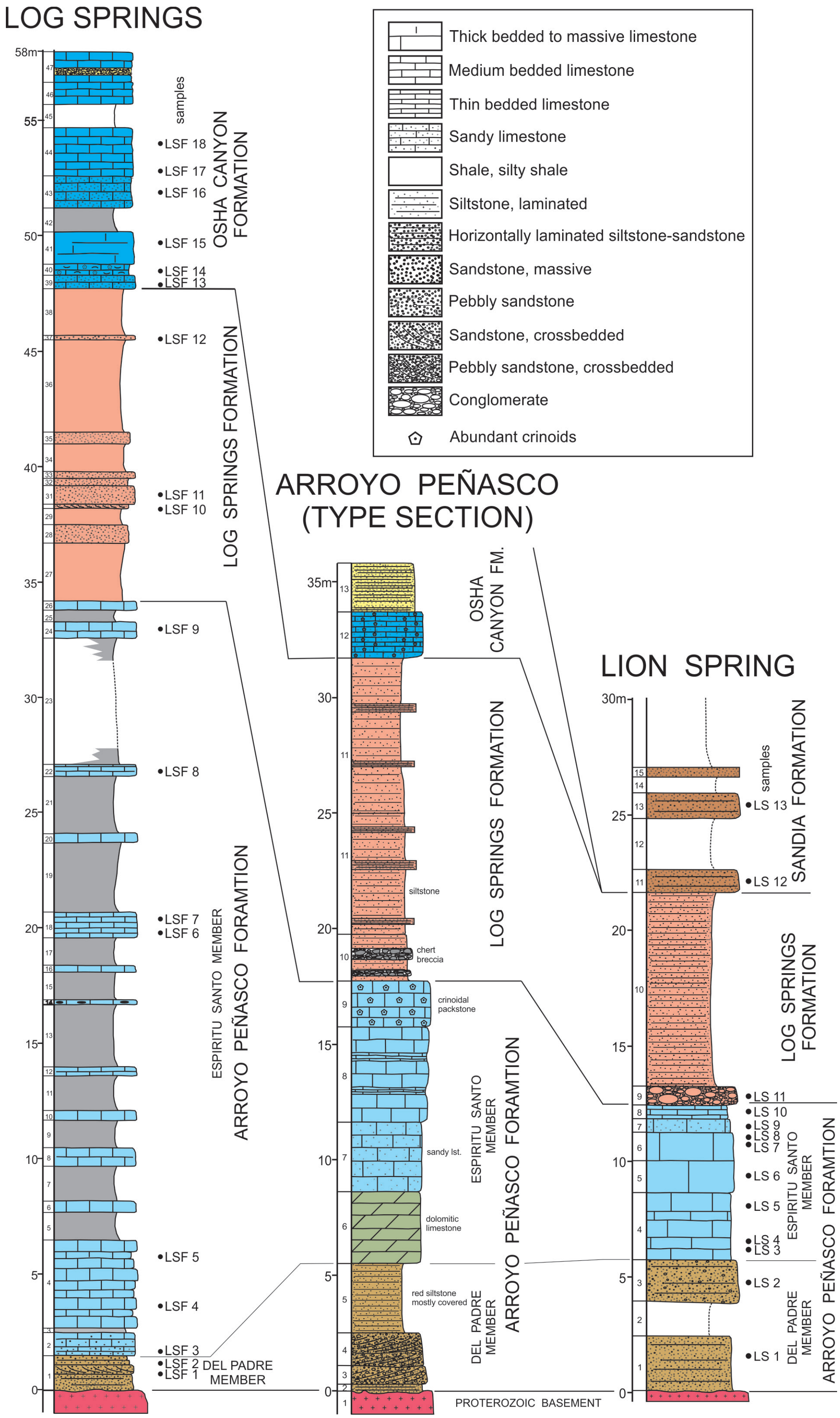

FIGURE 2. Measured stratigraphic sections through Mississippian to Lower Pennsylvanian sedimentary rocks at Lion Spring, Arroyo Peñasco, and Log Springs. For locations of the sections see Figure 1. Colors indicate the main lithofacies: gray = mudstone-shale, siltstone; brown = sandstone, conglomerate; blue = limestone; olive-green = dolomite; pinkish-peach = red bed strata; bright pink = Proterozoic basement rocks. Section coordinates in UTMs are: Lion Spring, base 13, 330364E, 4004601, top 330479E, 4004702N (NAD 27); Arroyo Peñasco, base 13, 331476E, 3946086N, top 331521E, 3946222N (NAD 83); Log Springs, base 13, 332284E, 3945207N, top 332150E, 3945643N (NAD 27).

The section we measured is much thinner than the San Pedro section of Armstrong (1967). He measured a 40-m-thick section located 3 mi (4.8 km) east of Regina, and stated that the assemblage of foraminifers from the lower 33 m are of late Tournaisian (early Osagean) age, and the rest is of late Viséan (Meramecian) age (Armstrong and Mamet 1974, 1979). Fitzsimmons et al. (1956) presented a section of the Arroyo Peñasco Formation in the San Pedro Mountains that is much thinner (21 m). Fitzsimmons et al. (1956) noted that exposures of the Arroyo Peñasco Formation in the San Pedro Mountains are very poor and often covered by soil and vegetation.

Del Padre Member (Arroyo Peñasco Formation)

Lithology

At Lion Spring, the Proterozoic basement is overlain by a thin Del Padre Member that is poorly exposed, yellowish-brownish, coarse-grained sandstone (2.4 m thick), followed by a covered interval (1.5 m) and then red, coarse-grained pebbly sandstone (1.8 m) displaying poorly developed horizontal lamination. Individual quartz clasts have diameters up to 1–2 cm (Fig. 2).

Petrography

The sandstone is poorly sorted, pebbly, and composed largely of subangular grains, mostly with diameters <1 mm, rarely up to several millimeters. The sandstone is composed entirely of quartz grains (quartz arenite), dominantly of monocrystalline quartz and subordinately of polycrystalline quartz, including stretched metamorphic quartz grains (Fig. 5A, B). Other grain types, such as feldspars, micas, or rock fragments, are absent. The sandstone contains some quartz cement in the form of authigenic overgrowths on detrital quartz grains, opaque cement (probably Fe hydroxides), and small amounts of matrix.

Espiritu Santo Member (Arroyo Peñasco Formation)

Lithology

The Espiritu Santo Member is mostly composed of indistinctly thick-bedded, gray limestone, and at its top includes a thin-bedded micritic limestone interval (0.6 m thick; Fig. 2).

Microfacies

Limestone is partly recrystallized and partly well preserved. The lowermost limestone beds (samples LS 3 and 4) are recrystallized, so the original microfacies is strongly to completely destroyed. Sample LS 3 is microsparite (recrystallized micrite) containing poorly preserved larger shell fragments, probably derived from brachiopods and ostracods. Sample LS 4 is strongly recrystallized and was probably a bioclastic

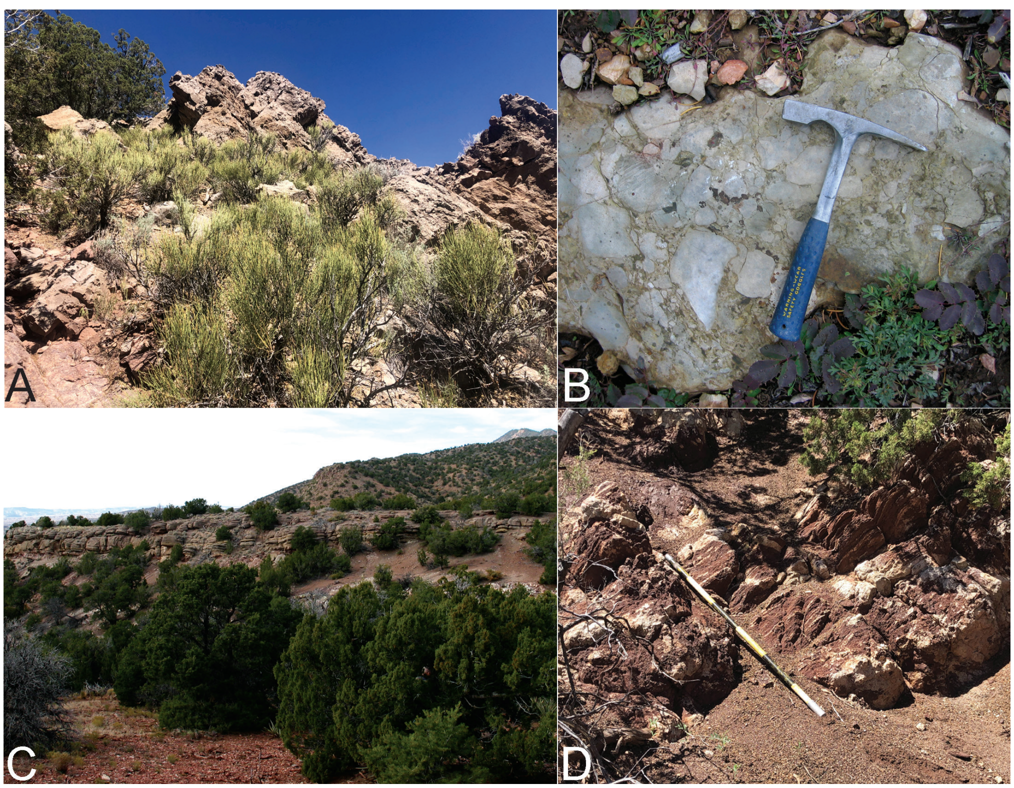

FIGURE 3. Selected Mississippian outcrops around the Sierra Nacimiento-San Pedro Mountain uplift. (A) Steeply dipping carbonate beds of the Espiritu Santo Member of the Arroyo Peñasco Formation at the Arroyo Peñasco section. Red beds on the lower left are the Del Padre Member of the Arroyo Peñasco Formation. (B) Limestone-cobble breccia of the Arroyo Peñasco Formation, unit 9 of the Lion Spring section. (C) Overview of Log Spring section. Note the red bed slope of the Log Springs Formation capped by the horizontal bench (middle of photograph) of the Osha Canyon Formation. (D) Overturned red beds of the Log Springs Formation at the Arroyo Peñasco section. The measuring stick is graduated in 0.25 m intervals.

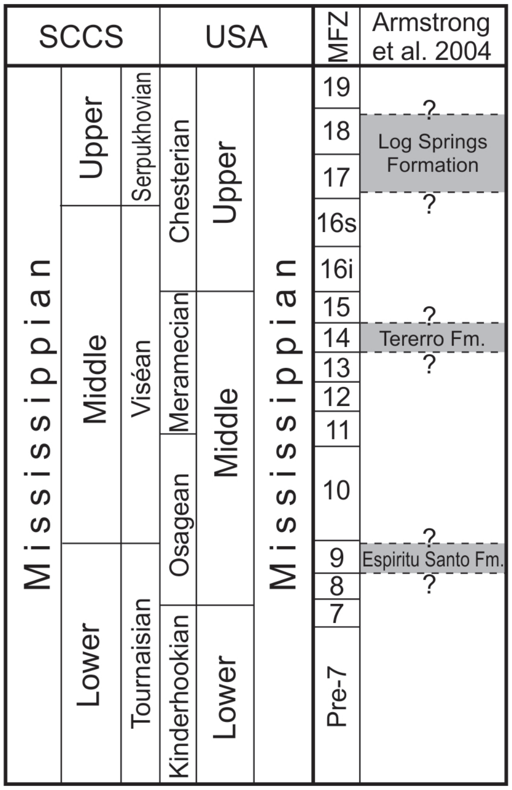

FIGURE 4. Mississippian substages of the Subcommission on Carboniferous Stratigraphy (SCCS), regional substages used in the United States, and stratigraphic chart for the Mississippian in the Sierra Nacimiento, Jemez Mountains, and San Pedro Mountains of Armstrong et al. (2004). Microfaunal zones (MFZ) are also shown.

wackestone. Other recrystallized limestone beds include samples LS 6 and LS 10 at the top of the Espiritu Santo Member (both microsparite).

Limestone that is not recrystallized (samples LS 5, 7, 8, 9) is composed of grainstone/packstone with varying amounts of peloids, micritic intraclasts, smaller foraminifers, and, subordinately, other fossils. The limestone bed of sample LS 5 is grainstone/packstone composed of abundant peloids and micritic intraclasts (Fig. 5C, D). Subordinately, shell fragments, echinoderms, ostracods, and smaller foraminifers are present. Sample LS 7 also is composed of abundant peloids and micritic intraclasts, but it contains many spherical grains (calcispheres), a few ostracods, smaller foraminifers, and rare echinoderm fragments (Fig. 5E, F).

Sample LS 8 is poorly washed grainstone/packstone that, besides peloids and micritic intraclasts, contains abundant foraminifers (including many endothyrid species). Other fossils present are echinoderm fragments and recrystallized skeletons. This microfacies type contains small amounts of micritic matrix (Fig. 5G, H).

Sample LS 9 is grainstone/packstone and is composed of micritic intraclasts, abundant recrystallized skeletons, echinoderm fragments, smaller foraminifers, ostracods, and rare gastropods and bryozoans (Fig. 6A, B). Samples LS 5, 7, and 8 contain a foraminiferal assemblage characterized by the occurrence of *Septaglomospiranella* ex gr. *primaeva*, *Septabrunsiina minuta*, *Tournayella* sp., *Spinoendothyra* sp., *Tuberendothyra* sp., *Koninckopora* sp., and *Paraarchaediscus* sp., indicating the lower/middle to upper Tournaisian (Kinderhookian-Osagean). Details of our data will be published in a separate paper (Krainer, Lucas, and Vachard, in prep.). Considering the stratigraphic locations of our three foraminifera samples, our results are not consistent with a late Tournaisian (Osagean) age for the lower to upper-middle part of the Espiritu Santo Member, as interpreted by Armstrong and Mamet (1974, 1979) and Armstrong et al. (2004).

Log Springs Formation

The Log Springs Formation starts with a poorly exposed, coarse-grained limestone conglomerate that rests on limestone of the Espiritu Santo Member with an erosional base (Figs. 2, 3B). The conglomerate is overlain by poorly exposed, reddish to partly brownish shale and siltstone with a thickness of 8.4 m. The basal conglomerate is 0.8 m thick and contains limestone clasts with diameters up to 20 cm. The conglomerate is poorly sorted, clast-supported and composed of subangular clasts, including different types of carbonate rocks (Fig. 6C). The matrix is siltstone to fine-grained sandstone containing a few quartz grains.

We recognized the following carbonate clasts, many being characteristic microfacies of the Arroyo Peñasco Formation, showing that part of the Arroyo Peñasco Formation has been reworked into the basal Log Springs Formation:

1) Grainstone/packstone composed of peloids, micritic intraclasts, spherical grains, echinoderm fragments, ostracods, foraminifers, and rare bryozoans (Fig. 6D). This microfacies is common in the Arroyo Peñasco Formation (Armstrong, 1967).
2) Grainstone/packstone containing peloids, rounded micritic intraclasts, rare ooids, echinoderm fragments, foraminifers, and recrystallized skeletons (Fig. 6E). This belongs to microfacies 4 of Armstrong (1967), ooid packstone with abundant abraded bioclasts.
3) Oolitic grainstone containing a few recrystallized skeletons (Fig. 6F). According to Armstrong (1967), this is a characteristic microfacies of the Arroyo Peñasco Formation here and in the Sangre de Cristo Mountains—microfacies 3 of Armstrong (1967), oolitic grainstone to packstone; however, as noted below, we did not observe this microfacies in the stratigraphic sections of the Arroyo Peñasco Formation of this study.
4) Fine-grained, mixed siliciclastic-carbonate sandstone composed of peloids, micritic intraclasts, quartz grains, a few echinoderm fragments, rare foraminifers, skeletal grains, and ooids.

Some of the carbonate clasts of the basal conglomerate contain late early Viséan (biozone MFZ 11B) foraminifers and algae, including *Koninckopora* and *Paraarchaediscus*. The foraminifers of the carbonate clasts will be described in detail in a separate paper.

We did not observe oolitic grainstone in the Espiritu Santo Member, whereas grainstone/packstone containing abundant peloids is a common microfacies of the Espiritu Santo Member.

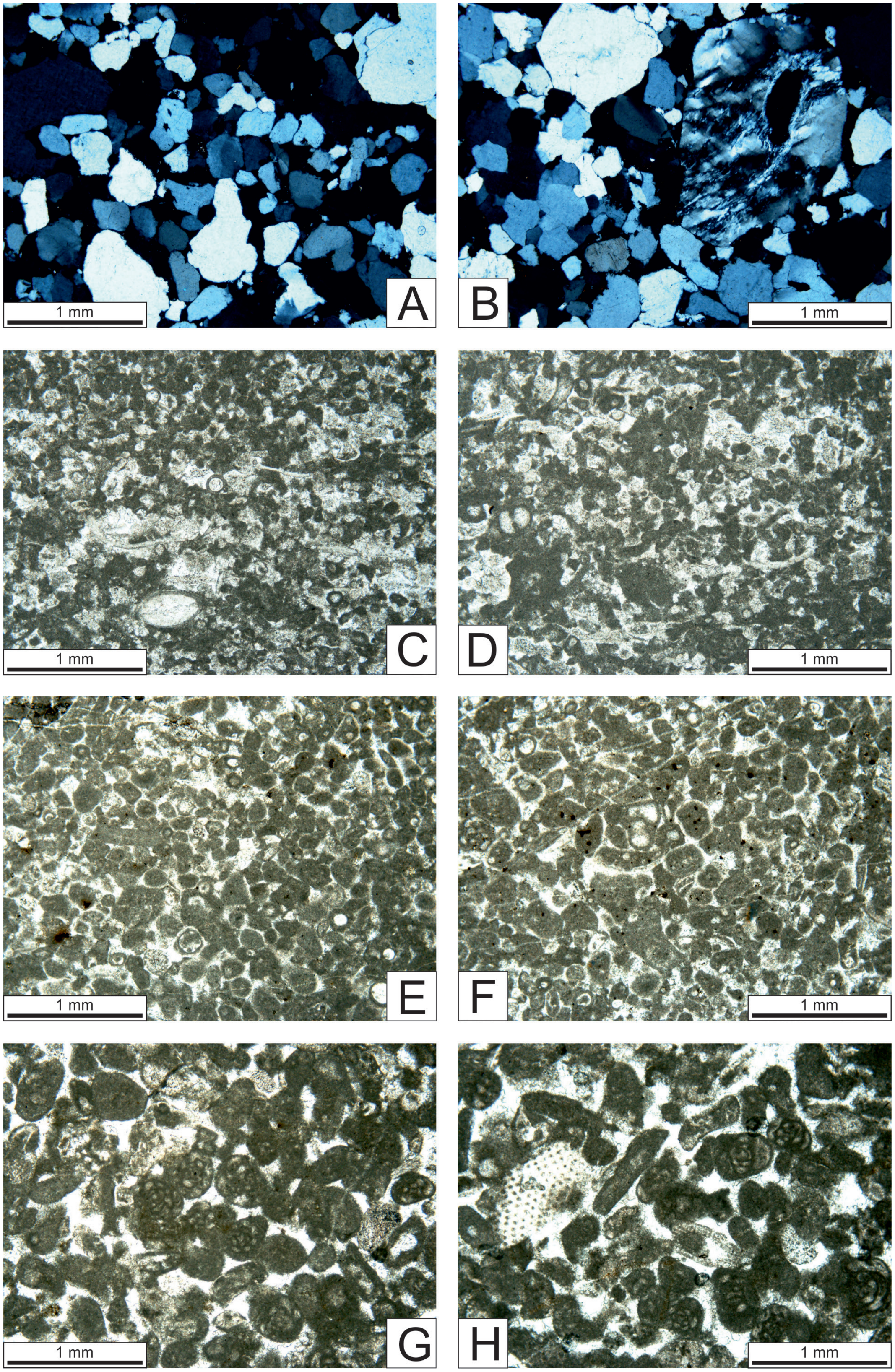

FIGURE 5. Thin section photographs of sandstone of the Del Padre Member (A, B) and limestone of the Espiritu Santo Member (C–H) of the Arroyo Peñasco Formation at Lion Spring. A and B are under polarized light; C–H are under plane light. (A) Coarse-grained sandstone composed entirely of quartz grains, dominantly of monocrystalline quartz (quartz arenite). Sample LS 1. (B) Coarse-grained pebbly sandstone, poorly sorted, containing abundant monocrystalline quartz grains and a few polycrystalline quartz grains including a large schistose (metamorphic) grain on the right. Sample LS 1. (C, D) Grainstone-packstone composed of abundant peloids and micritic intraclasts, some echinoderm fragments, ostracods, foraminifers, and calcispheres. Sample LS 5. (E, F) Grainstone containing abundant peloids and micritic intraclasts, smaller foraminifers, and calcispheres. Sample LS 7. (G, H) Grainstone-packstone containing abundant foraminifers, peloids and micritic intraclasts, and a few echinoderm fragments. Sample LS 8.

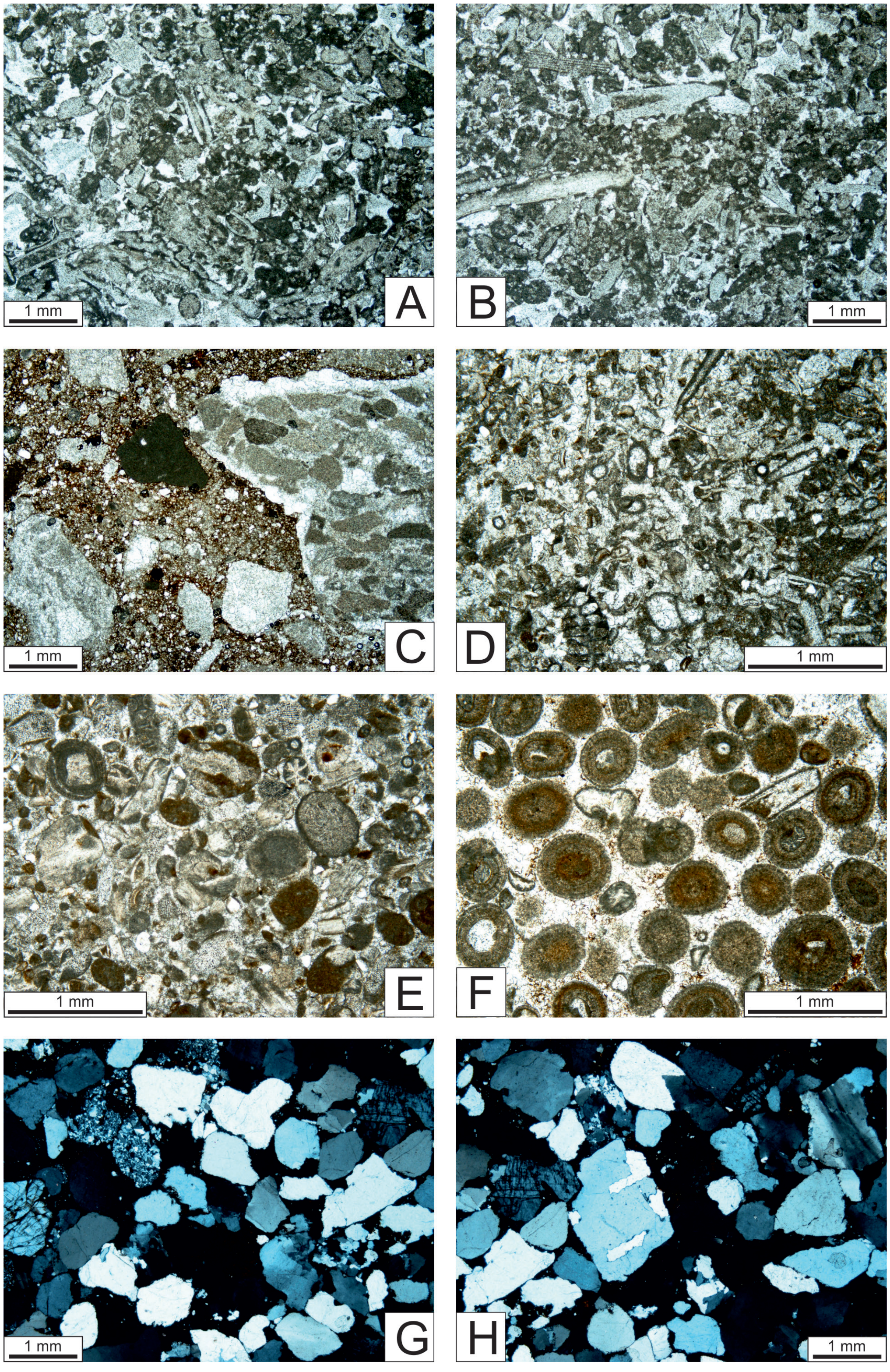

FIGURE 6. Thin section photographs of limestone of the Espiritu Santo Member of the Arroyo Peñasco Formation at the Lion Spring stratigraphic section (A, B), basal conglomerate of the Log Springs Formation (C–F), and sandstone of the Sandia Formation (G, H). A–F are under plane light; G and H are under polarized light. (A, B) Grainstone-packstone containing echinoderm fragments, a few ostracods, smaller foraminifers, recrystallized skeletons, peloids, and micritic intraclasts. Sample LS 9. (C) Basal conglomerate of the Log Springs Formation, composed of various types of reworked, poorly sorted carbonate clasts. Sample LS 11. (D) Grainstone-packstone containing recrystallized skeletons, smaller foraminifers, ostracods, echinoderms, peloids, and micritic intraclasts. Reworked clast from the basal conglomerate of the Log Springs Formation. Sample LS 11. (E) Grainstone-packstone containing echinoderm fragments, recrystallized skeletons, bryozoans, foraminifers, ostracods, peloids, micritic intraclasts, and rare ooids. Reworked carbonate clast from the basal conglomerate of the Log Springs Formation. Sample LS 11. (F) Oolitic grainstone. Reworked carbonate clast from the basal conglomerate of the Log Springs Formation. Sample LS 11. (G, H) Coarse-grained sandstone, moderately sorted, composed of subangular grains. Most abundant are monocrystalline quartz grains. Subordinate are polycrystalline quartz grains, feldspar grains (potassium feldspars), and rare granitic rock fragments. Basal part of the Sandia Formation. Sample LS 13.

Sandia Formation (Pennsylvanian)

Lithology

The Log Springs Formation is overlain by the Pennsylvanian Sandia Formation that consists of (ascending): a coarse-grained sandstone bed (1 m), a covered interval (2.2 m), a sandstone bed (1.1 m), cover (0.7 m), and a thin sandstone bed (0.4 m). Sandstone is indistinctly horizontally laminated or massive. The Osha Canyon Formation, which is distinctive because of its limestone intervals and absence of sandstone, is absent at Lion Spring (Fig. 2).

Petrography

Sandstone is coarse grained to pebbly, moderately to poorly sorted, and composed of subangular to subrounded grains. Grain size is commonly <1 mm, and individual sandstone units contain quartz clasts with diameters up to 1 cm (Fig. 6G, H). Dominant grain types are monocrystalline quartz and polycrystalline quartz. Rare chert grains are present, which are silicified bioclastic wackestone containing fossils such as shell fragments and foraminifers. The sandstone contains small amounts of feldspar. The feldspar grains are relatively fresh and dominantly potassium feldspars, including microcline and perthitic feldspar grains. The sandstone contains a few granitic rock fragments and brownish silty matrix.

ARROYO PEÑASCO

At Arroyo Peñasco, the Arroyo Peñasco Formation measures 17.7 m and is divided into the Del Padre Member (5.5 m thick) and the Espiritu Santo Member (12.2 m). The Arroyo Peñasco Formation is overlain by the Log Springs Formation (14 m thick) followed by the Lower Pennsylvanian (Morrowan) Osha Canyon Formation (Figs. 1 and 2).

The type section of the Arroyo Peñasco Formation of Armstrong (1955, 1967) is located at Pinos and Peñasco Canyons and is 40 m thick. Foraminifers in this section indicate that the succession from 8.5 to 27.4 m is of late Tournaisian (early Osagean) age, and the part from 28 to 37.2 m is of late Viséan (early Chesterian) age (Armstrong, 1967; Armstrong and Mamet, 1974, 1979). Therefore, based purely on biostratigraphic data, Armstrong and Mamet (1974, 1979) and Armstrong et al. (1979, 2004) assigned the upper part containing middle-late Viséan (early Chesterian) foraminifers to the Tererro Formation (Manuelitas Member). As at Lion Spring, our Mississippian section at Arroyo Peñasco is much thinner and includes the Del Padre Member and overlying Espiritu Santo Member. A lithologic subdivision of the Arroyo Peñasco Formation into Espiritu Santo Member and Tererro Formation (Manuelitas Member) is not possible. The Tererro Formation (Manuelitas Member) of Armstrong and Mamet (1974, 1979) is a biostratigraphic unit (biozone) and not a lithostratigraphic unit. Note that we did not sample our Arroyo Peñasco section for petrographic analyses.

Macrofossils of the Arroyo Peñasco Formation of the Sierra Nacimiento (type section) and San Pedro Mountains are listed in Armstrong (1955, 1967). Foraminifers are listed in Armstrong (1967) and Armstrong and Mamet (1974, 1979). Fitzsimmons et al. (1956) listed Scyphozoa, Anthozoa, Bryozoa, Brachiopoda and Mollusca from 10 localities in the Sierra Nacimiento-San Pedro Mountains.

Del Padre Member

Sediments of the Del Padre Member rest on granitic Proterozoic basement. Lithologic units are (ascending order): coarse-grained quartzose sandstone displaying tabular beds (0.3 m thick), cross-bedded conglomeratic sandstone with an erosive base (0.8 m thick), cross-bedded pebbly sandstone (1.4 m), and red siltstone that is mostly covered (3 m; Fig. 2). The conglomeratic sandstones are composed of quartz clasts with diameters up to 3 cm.

Espiritu Santo Member

The Espiritu Santo Member starts with thick-bedded dolomitic limestone (3.1 m); followed by thick-bedded sandy limestone (3 m); and mostly thick-bedded limestone with minor, intercalated (1) thin-bedded limestone intervals (4.1 m) and (2) thick-bedded, coarse-grained crinoidal limestone (packstone/rudstone) containing a few brachiopods (Figs. 2, 3A).

Log Springs Formation

The Log Springs Formation starts with reddish-brown siltstone and intercalated white chert breccia (2 m), overlain by reddish-brown siltstone with interbeds of tabular, coarse-grained, quartz-rich sandstone (12 m; Fig. 2).

Osha Canyon Formation

The base of the Pennsylvanian Osha Canyon Formation is represented by medium-bedded, mixed siliciclastic-carbonate sandstone (rudstone) containing abundant crinoid fragments (2 m thick) and thick-bedded, mixed-siliciclastic carbonate sandstone displaying horizontal lamination (Fig. 2). Note we define a mixed siliclastic-carbonate sandstone as one where siliciclastic grains and carbonate grains both occur, the latter including fossil fragments and carbonate lithoclasts or intraclasts, This type of sandstone is commonly carbonate-cemented.

LOG SPRINGS

The Log Springs Formation was defined by Armstrong (1955) as a 60–75 ft (18–23 m) thick succession of ferruginous shale, sandstone, and conglomerate, unconformably overlying carbonate sediments of the Arroyo Peñasco Formation that are partly karstified. The name of the formation is derived from Log Springs at Peñasco Canyon. The age is poorly constrained, and the Log Springs Formation is thought to be of Namurian (Chesterian) age (Armstrong and Mamet, 1977, 1979, 1990; Armstrong et al., 2004)

We measured a section at Log Springs that includes the Arroyo Peñasco Formation (Del Padre Member, 2.5 m, and Espiritu Santo Member, 31.5 m), overlain by the Log Springs Formation. The Log Springs Formation is 13.5 m thick and overlain by the Osha Canyon Formation (Figs. 2, 3C).

Arroyo Peñasco Formation

The Arroyo Peñasco Formation can lithologically be divided into the basal Del Padre Member (2.5 m), resting on Proterozoic basement, and the Espiritu Santo Member (31.5 m).

Del Padre Member

Lithology

The Proterozoic basement is overlain by intensively weathered sandstone, coarse-grained pebbly sandstone displaying small-scale cross-bedding, medium-grained sandstone (with total thickness of 1.5 m), and gray, laminated sandy limestone (mixed siliciclastic-carbonate sandstone, 1 m).

Petrography

The basal sandstone is coarse grained, pebbly, poorly sorted, and composed of rounded grains. Grain size is mostly <0.5 mm, and a few grains have diameters up to 5 mm.

The sandstone is composed of abundant mono- and polycrystalline quartz grains and a small amount of slightly altered feldspar grains (potassium feldspars). Granitic rock fragments are rare.

The cross-bedded sandstone (sample LSF 2) is well sorted and composed of rounded to well-rounded grains (Fig. 7A, B). Grain size is mostly 0.2–0.5 mm. The sandstone contains abundant monocrystalline quartz grains and, subordinately, polycrystalline quartz grains. Feldspars are present in moderate amounts and appear as fresh grains of potassium feldspars including microcline and perthitic feldspar grains. Granitic rock fragments are rare. The detrital grains are cemented by coarse, poikilotopic calcite cement that randomly replaces a few feldspar grains.

Espiritu Santo Member

Lithology

The Espiritu Santo Member starts with a thicker, bedded gray limestone interval that has 10–20-cm-thick beds in the lower part and up to 50-cm-thick beds in the upper part. This thicker limestone interval is overlain by a succession of thin limestone units that are separated by covered (shale/siltstone) intervals. The limestone intervals are 0.4–1.1 m thick and represented by single limestone beds and thin-bedded limestone intervals. Covered intervals are 0.5–5.5 m thick and most likely represent shale/siltstone units.

Microfacies

Many of the intercalated limestone units (samples LSF 3–6, 9) are recrystallized; the original microfacies have been destroyed. Limestone of unit 17 (sample LSF 7) is composed of fine-grained packstone containing abundant peloids and micritic intraclasts, abundant recrystallized skeletons, a few ostracods, echinoderm fragments, and a few foraminifers (Figs. 7C, D). Limestone of unit 24 (sample LSF 9) is composed of microsparite, indicating this limestone originally was micritic limestone (bioclastic mudstone-wackestone).

Log Springs Formation

Lithology

The Log Springs Formation is 13.5 m thick and consists 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 containing quartz clasts with diameters up to 1 cm.

Petrography

Cross-bedded sandstone of unit 30 (sample LSF 10) is moderately to well sorted; grain size is mostly in the range of 0.1–0.5 mm, and most of the grains are angular to subangular (Fig. 7E). The massive sandstone of unit 31 (sample LSF 11) is poorly sorted, grains are mostly 0.1–0.5 mm in diameter, and a few grains with diameters up to 2 mm are present (Fig. 7F). The uppermost sandstone bed of unit 37 (sample LSF 12) is coarse-grained, pebbly sandstone with maximum clast diameters of 4 mm. This sandstone bed is poorly sorted and composed of mainly subangular grains (Figs. 7G, H).

In all sandstone beds, quartz is the dominant grain type. In fine-grained sandstone, monocrystalline quartz is much more abundant than polycrystalline quartz. Feldspar grains are rare and represented by potassium feldspars. In the uppermost sandstone bed (unit 37) feldspars are largely replaced by calcite (Fig. 7H). Granitic rock fragments are very rare. Other grain types are absent. Sandstone is partly compacted and cemented by quartz in the form of authigenic quartz overgrowths. The pebbly sandstone of unit 37 is cemented by coarse blocky calcite (Fig. 7G, H).

Osha Canyon Formation

The Log Springs Formation is overlain by the Osha Canyon Formation. DuChene (1974) defined the Osha Canyon Formation as a new stratigraphic unit of Morrowan age that is exposed at several locations in the southern Sierra Nacimiento and Jemez Mountains. DuChene (1974) and DuChene et al. (1977) described the type section at Guadalupe Box near Osha Canyon as a succession that is 22 m thick and composed of fossiliferous limestone and shale. Brachiopods indicate a Mor-

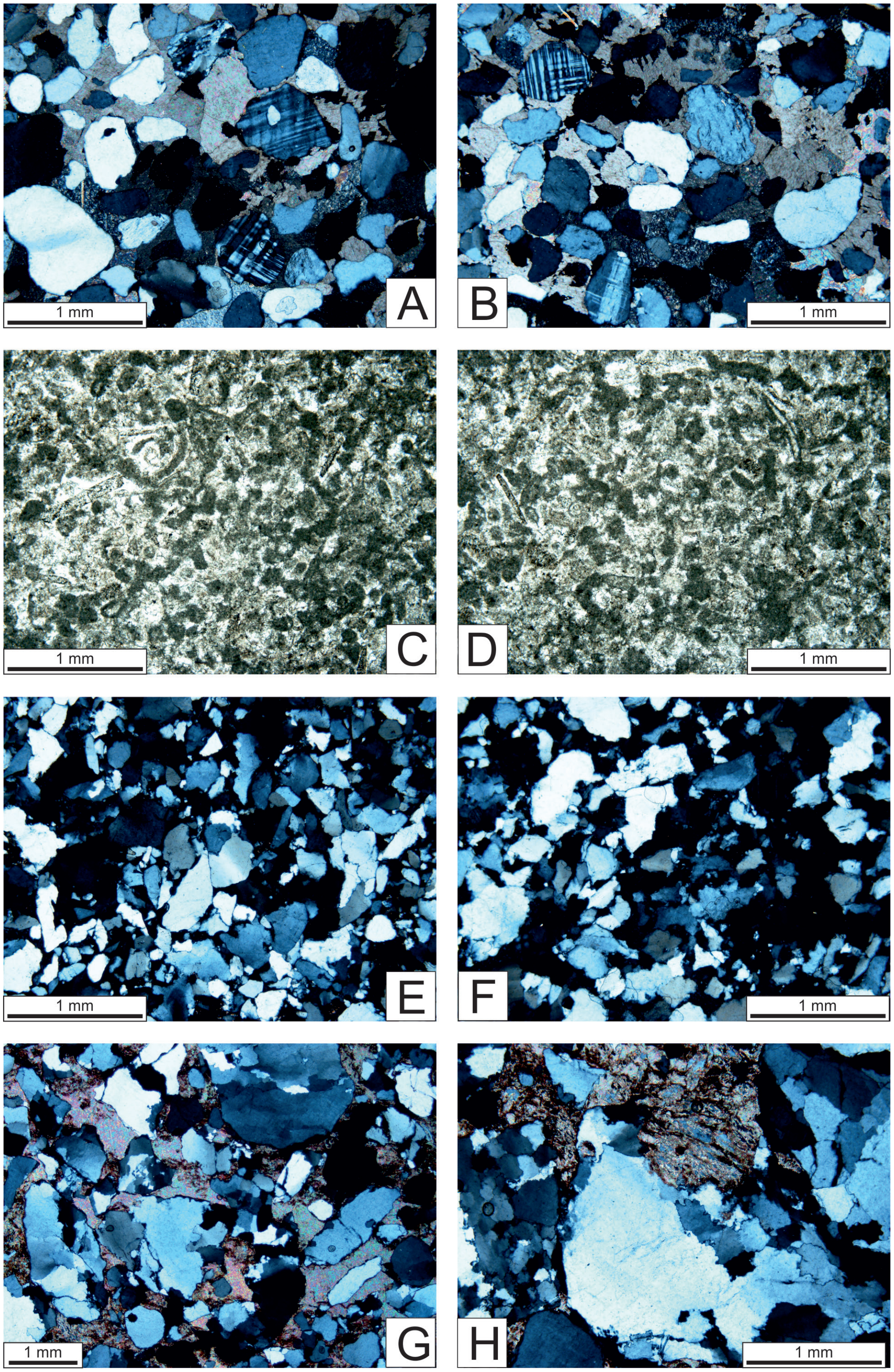

FIGURE 7. Thin section photographs of sandstone and limestone of the Arroyo Peñasco and Log Springs Formations at Log Springs. (A, B) Del Padre Member; (C, D) Espiritu Santo Member; (E–H) Log Springs Formation. A, B, and E–H are under polarized light; C and D are under plane light. (A, B) Well-sorted sandstone containing rounded grains of abundant monocrystalline quartz, subordinate polycrystalline quartz, and many potassium feldspars including microcline. The detrital grains are cemented by coarse, poikilotopic calcite cement. Sample LSF 2. (C, D) Fine-grained packstone containing abundant peloids, some micritic intraclasts, and abundant recrystallized skeletal grains including echinoderm fragments, a few ostracods, and rare foraminifers. Sample LSF 7. (E) Sandstone composed of mostly angular to subangular grains of monocrystalline and subordinate polycrystalline quartz. Feldspar grains are rare. Sample LSF 10. (F) Sandstone composed of mono- and polycrystalline quartz grains (quartz arenite) and very rare feldspar grains. Detrital quartz grains are cemented by quartz in the form of authigenic overgrowths. Sample LSF 11. (G, H) Coarse-grained pebbly sandstone, poorly sorted, composed mostly of subangular grains of polycrystalline quartz, subordinate monocrystalline quartz, and a few feldspar grains. The feldspar grains are mostly replaced by calcite cement like the feldspar grain in the center (upper half) of photo H, which is mostly replaced and shows just some small relics of feldspar. The sandstone is cemented by calcite. Sample LSF 12.

rowan, probably late Morrowan, age.

At Pinos and Peñasco Canyons, the Osha Canyon Formation consists of 9–12 m of massive fossiliferous limestone with thin shale interbeds (DuChene et al., 1977). Here the Osha Canyon Formation unconformably overlies the Log Springs Formation and is overlain by the Sandia Formation with an angular unconformity.

The Osha Canyon Formation we measured at Log Springs represents an almost complete section that is 10 m thick and composed mostly of limestone (Fig. 2). The succession starts with sandy limestone containing abundant brachiopods (unit 39, 0.6 m thick); overlain by a fossiliferous limestone bed (rudstone) containing abundant crinoid fragments (unit 40, 0.5 m); followed by laminated limestone (rudstone) with crinoid fragments, brachiopods, and abundant quartz grains (unit 41, 1.4 m); and a covered interval (1 m) probably representing shale/siltstone. Above the covered interval, mixed siliciclastic-carbonate sandstone with brachiopods is exposed (1.4 m), overlain by medium-bedded, fossiliferous limestone containing a few quartz grains (2.1 m), a covered interval (1 m) and medium-bedded limestone with a thin, intercalated bed of carbonate conglomerate (Fig. 2).

Microfacies

Limestone is composed of packstone-rudstone, rudstone, and rudstone-floatstone, all containing a diverse fossil assemblage that is dominated by fragments of echinoderms (crinoids), bryozoans, and brachiopods.

We distinguished the following microfacies types:

- Crinoid-bryozoan packstone to rudstone containing many quartz grains and rare feldspar grains (Fig. 8A, B). Present in small amounts are brachiopods, gastropods, ostracods, and trilobites. Also present are a few micritic intraclasts. The grains are cemented by coarse, blocky calcite.
- Rudstone to floatstone with bryozoans as the most abundant fossils, partly occurring as large colonies (Fig. 8C, D). Subordinately, fragments of brachiopods, echinoderms (crinoids), bivalves, ostracods, gastropods, foraminifers, and rare trilobites are present. Non-skeletal grains are represented by small quartz grains. Locally the rudstone contains micritic to pelmicritic matrix, and locally calcite cement is present.
- Rudstone containing many quartz clasts with diameters up to 5 mm, a few feldspar grains, and sparse granitic rock fragments (Fig. 8E–H). Fossils include fragments of bryozoans, echinoderms (crinoids), and brachiopods, a few foraminifers, rare trilobite fragments, and bivalves. The rudstone is well washed and contains small amounts of matrix.

SODA DAM

At Soda Dam in the Jemez Mountains, the Proterozoic basement is overlain by a thin siliciclastic succession (units 1–4 of Krainer and Lucas, 2013, fig. 6), followed by recrystallized limestone (units 5–7 of Krainer and Lucas, 2013, fig. 6). Krainer and Lucas (2013) assigned these siliciclastic and carbonate sediments to the basal Sandia Formation due to the lack of fossils in the recrystallized carbonates. However, Armstrong (1967) found a few foraminifers including *Endothyra spinosa* and *Endothyra skippae* in one sample in the upper part of the carbonate succession, indicating the upper Osagean. Therefore, the basal siliciclastic sediment of units 1–4 (Krainer and Lucas 2013, fig. 6) represents the Del Padre Bed, and the overlying recrystallized carbonate succession of units 5–7 represents the Espiritu Santo Member of the Arroyo Peñasco Formation, which has a total thickness of about 7.5 m. It is overlain by the Log Springs Formation (units 8–13), followed by the Sandia Formation. The Osha Canyon Formation is absent at Soda Dam (Fig. 9).

DEPOSITIONAL ENVIRONMENTS

Poor sorting and rounding values of the sandstone of the Del Padre Member indicate deposition in an alluvial environment. The high compositional maturity—sandstones are composed entirely of quartz—is most likely the result of intense chemical weathering (hydrolysis) of unstable grains, particularly feldspars and micas under humid, tropical climatic conditions.

In the Sangre de Cristo Mountains, according to Armstrong (1967), the Arroyo Peñasco Formation is composed of three carbonate depositional cycles. An idealized cycle is composed of the following microfacies types: (1) bioclastic wackestone rich in echinoderms, brachiopods, and corals; (2) echinoderm-bryozoan packstone and grainstone; (3) oolitic grainstone and packstone; (4) ooid packstone with abundant abraded bioclasts; (5) pelletoid packstone with quartz grains; (6) pelletoid wackestone and lime mudstone; (7) intertidal lime mudstone, stromatolites, and abundant small lithoclasts; and (8) supratidal lime mudstone with cracks, chips, and intraclasts.

At the Lion Spring section, the most abundant facies is grainstone/packstone with abundant peloids, micritic intraclasts, smaller foraminifers, and subordinately other fossils. This belongs to microfacies 5, pelletoid packstone, of Armstrong (1967). Subordinately, bioclastic wackestone (poorly preserved due to recrystallization) is present, belonging to microfacies 1 of Armstrong (1967). Microfacies 3, oolitic grainstone and packstone, and 4, ooid packstone, with abundant bioclasts are present as reworked limestone clasts in the basal conglomerate of the Log Springs Formation. However, we did not observe the other microfacies types listed by Armstrong (1967) in the Lion Spring section.

Armstrong (1967), in his paleogeographic reconstruction, posited that at the beginning of deposition of the Espiritu Santo Member, a pelletoid lime mudstone facies with a shallow marine fauna, including foraminifers and ostracods, covered a large area that included the Sierra Nacimiento-San Pedro Mountains and was bordered to the east (Sangre de Cristo Mountains) by intertidal and supratidal facies. The supratidal facies then prograded westward over the shallow marine carbonate muds. This is what is observed in our study area. In

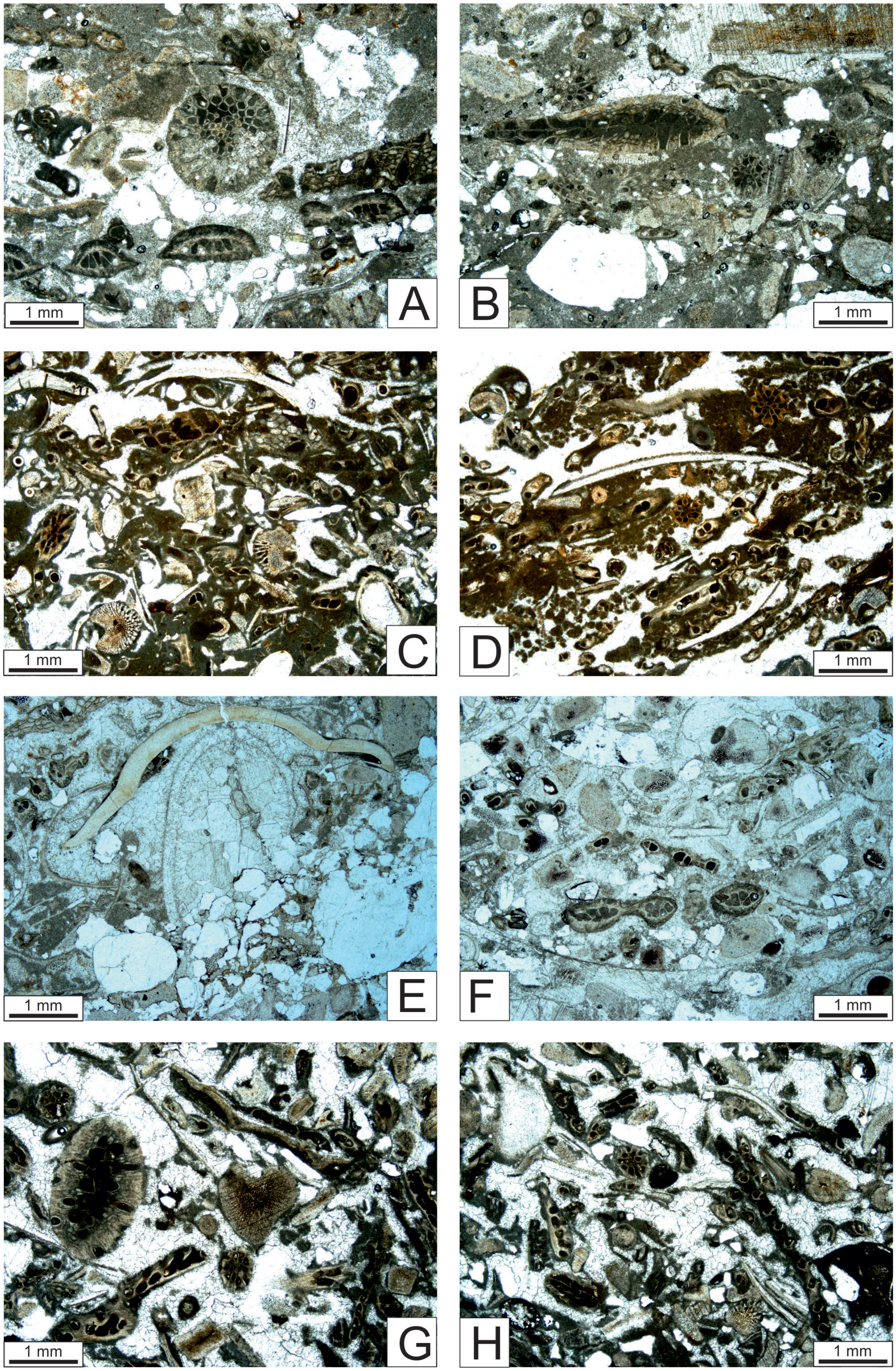

FIGURE 8. Thin section photographs of limestone of the Osha Canyon Formation at Log Springs. All under plane light. (A, B) Rudstone containing many quartz grains, many large bryozoan and echinoderm fragments, a few other fossils, rare intraclasts, and micritic matrix. Sample LSF 13. (C, D) Rudstone-floatstone in which bryozoan fragments are the most abundant fossils. Also present in small amounts are echinoderms, brachiopods, gastropods, ostracods, and a few small quartz grains. Pore space is filled with micritic matrix and calcite cement. Sample LSF 18. (E, F) Packstone to rudstone in which echinoderm, bryozoan, and brachiopod fragments are the most abundant fossils. Quartz grains are also present. Sample LSF 14. E shows a large trilobite fragment. (G, H) Rudstone, well washed, containing bryozoan and echinoderm (crinoid) fragments. Other fossils such as brachiopods, foraminifers, gastropods, and trilobites are rare. Sample LSF 17.

the Sierra Nacimiento-San Pedro Mountains, shallow marine subtidal to intertidal pelletoid lime mudstone is the dominant facies of the Espiritu Santo Member. According to Armstrong (1967), during the *Endothyra spiroides* zone found in the upper Espiritu Santo Member (early Meramecian), oolitic grainstone to lime mudstone (shallow marine to subtidal) was the dominant facies.

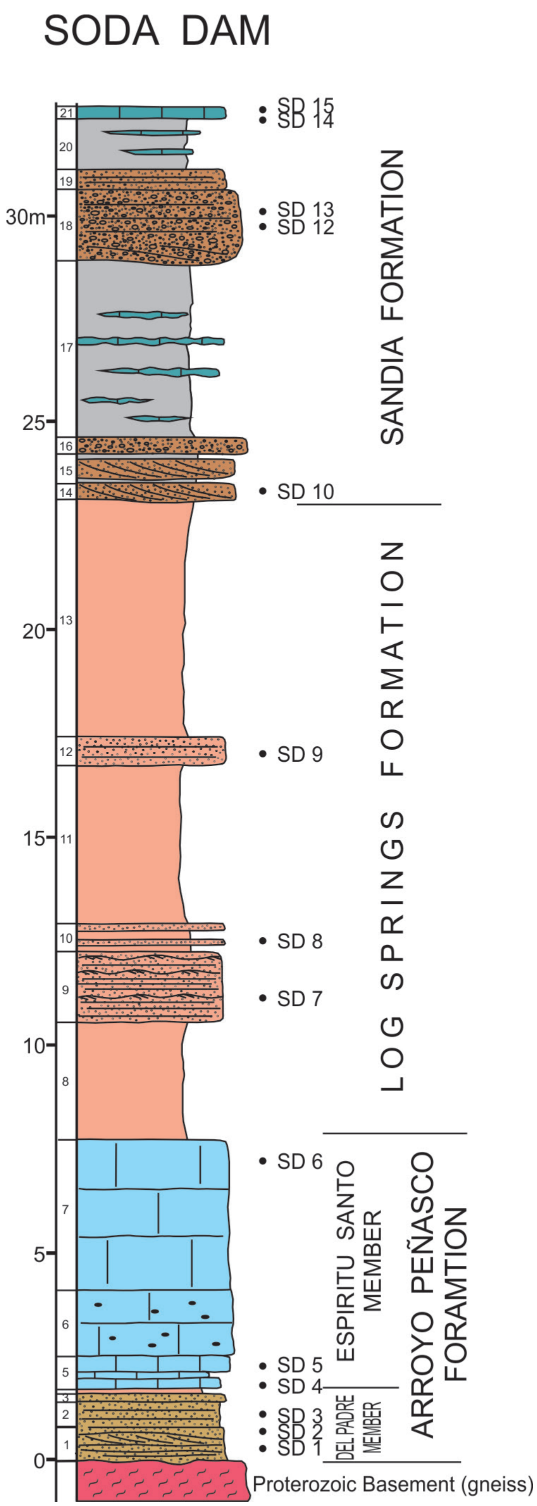

FIGURE 9. Measured stratigraphic section of the Mississippian to Middle Pennsylvanian succession at Soda Dam in the Jemez Mountains (for location, see Fig. 1). Section coordinates (UTM) are: base 13, 347457, 3901850N, top 347383E, 3961881N (NAD 27).

In the Lion Spring section, and probably also in the Arroyo Peñasco type section, the oolitic grainstone-packstone facies that is particularly characteristic of the Tererro Member (Manuelitas Bed), was eroded during a tectonic pulse and is present as reworked limestone clasts in the basal conglomerate of the Log Springs Formation.

At Log Springs, the basal siliciclastic unit of the Del Padre Member is partly poorly sorted, partly well sorted, and composed of grains that are rounded to well rounded. These high rounding values and moderate sorting values indicate the sandstones were deposited in either an eolian or nearshore depositional environment.

Intercalated limestone units of the Espiritu Santo Member at Log Springs—which are not recrystallized and composed of packstone with abundant peloids and intraclasts containing a low-diversity fauna of ostracods, echinoderms, and foraminifers—are interpreted as deposits of a shallow marine depositional environment (similar to the peloidal limestone facies of the Arroyo Peñasco Formation). The depositional environment of intercalated shale/siltstone units is difficult to reconstruct due to the lack of fossils and diagnostic sedimentary structures. Most likely, the shale/siltstone units were deposited in a marine setting.

Due to the sorting and rounding values (angular to subangular) of sandstones of the Log Springs Formation, we interpret the cross-bedded sandstone as fluvial deposits (e.g., unit 30) and the massive sandstone as sheetflood deposits that formed on an alluvial plain.

At Arroyo Peñasco and at Log Springs, the entire Log Springs Formation is siliciclastic, and we interpret the succession as nonmarine sediments that were deposited on an alluvial plain. At the Arroyo Peñasco type section of Armstrong, the Log Springs Formation unconformably rests on the Arroyo Peñasco Formation. Limestone of the Arroyo Peñasco Formation displays karst solution features at the top. The basal shale of the overlying Log Springs Formation is highly ferruginous and contains hematitic ooids. This basal shale is overlain by red shale, sandstone, and conglomerate. Fossils are absent. Conglomerates contain rounded pebbles to cobbles of chert and carbonate rocks reworked from the underlying Arroyo Peñasco Formation and reworked gneiss, greenstone, and quartz from the Proterozoic basement (Armstrong 1955, 1967).

The microfacies of limestones of the Osha Canyon Formation at Log Springs are very similar to that of the type section at Osha Canyon described by Krainer and Lucas (2005). The fossil assemblage indicates the sandy limestones and limestones composed of packstone-rudstone-floatstone accumulated in a shallow, normal marine environment under moderate to high water turbulence. Thinner limestone beds composed of rudstone are interpreted as storm layers; thicker limestone units may represent carbonate sand shoals (see discussion in Krainer and Lucas, 2005).

CONCLUSIONS

The Mississippian strata of the Sierra Nacimiento, San Pedro Mountains, and Jemez Mountains are a thin (less than 100 m) but heterogeneous succession of siliciclastic and carbonate sedimentary rocks of marine and nonmarine origin. The succession is divided into the Arroyo Peñasco Formation (subdivided into basal siliciclastic Del Padre Member and overlying Espiritu Santo Member) and the overlying Log Springs Formation. Based on foraminifers, the Espiritu Santo Member is of late Tournaisian (early Osagean) and middle-late Viséan (early Chesterian) age (Armstrong and Mamet, 1974, 1979; Armstrong et al., 2004; Fig. 3). A subdivision of the limestone facies into Espiritu Santo (late Tournaisian/early Osagean) and Tererro (late Viséan/early Chesterian) in the study area is not supported by our lithologic observations, although Armstrong and Mamet (1974, 1979) argued for it and inferred a significant break in sedimentation. The Tererro Formation (Manuelitas Member) of Armstrong and Mamet (1974, 1979) represents a biozone (microfossil zone 14) and not a lithostratigraphic unit.

The Log Springs Formation unconformably rests on the Arroyo Peñasco Formation and is composed of nonmarine red beds. The Log Springs Formation is assigned to the upper Chesterian by Armstrong et al. (2004).

The Log Springs Formation is overlain by the Lower Pennsylvanian (Morrowan) shallow marine sediments of the Osha Canyon Formation. Locally, the Osha Canyon Formation is absent (Lion Spring), and the Log Spring Formation is overlain by the Sandia Formation. At Soda Dam in the Jemez Mountains, the Sandia Formation rests on the Log Springs Formation. At many locations, the Sandia Formation rests on the Proterozoic basement.

These distinct lateral variations in thickness and facies, as well as unconformities at the bases of the Log Springs and Osha Canyon Formations, document phases of tectonic activity. The unconformity at the base of the Log Springs Formation indicates a tectonic phase during the Late Mississippian. The unconformities at the bases of the Osha Canyon and Sandia Formations were caused by the onset of tectonic activity of the Ancestral Rocky Mountains orogeny.

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