



Lithostratigraphy, biostratigraphy and sedimentology of the Upper Paleozoic Sangre De Cristo Formation, southwestern San Miguel County, New Mexico

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LITHOSTRATIGRAPHY, BIOSTRATIGRAPHY AND SEDIMENTOLOGY OF THE UPPER PALEOZOIC SANGRE DE CRISTO FORMATION, SOUTHWESTERN SAN MIGUEL COUNTY, NEW MEXICO

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ABSTRACT—In southwestern San Miguel County, New Mexico, the upper Paleozoic Sangre de Cristo Formation is ~300 m thick. Most of the lower-middle parts of the formation are poorly exposed, but the base of the formation crops out as extra-basinal conglomerate resting with evident disconformity on the Middle Pennsylvanian Porvenir Formation. The upper 160 m of the Sangre de Cristo Formation are continuously exposed, and are mostly red-bed, non-fissile mudstone, and less common sandstone, conglomerate and calcrete. The contact of Yeso Group strata on Sangre de Cristo Formation strata is very similar to the conformable Abo-Yeso contact to the south. Most of the sandstones of the Sangre de Cristo Formation are subarkose to arkose, and a few sandstones and pebbly sandstones containing abundant reworked carbonate grains are classified as lithic arenites. Trace fossils of invertebrates and vertebrates (mostly arthropod and tetrapod walking traces) are locally common in the upper part of the Sangre de Cristo Formation. The tetrapod ichnofauna is quite similar to vertebrate trace fossil assemblages described from the Abo Formation of central New Mexico. Plant fossils are sparse in the Sangre de Cristo Formation and are mostly macrofossil foliar remains preserved as impressions. The flora of the Sangre de Cristo Formation red beds appears to be much the same as that of the finer grained units (Abo and Robledo Mountains Formations) to the south, and likely indicates seasonally dry climates and that much of Early Permian New Mexico was covered with conifer forests of great extent and low biodiversity. The fossil vertebrate assemblage from the upper Sangre de Cristo Formation encompasses xenacanth sharks, lungfishes, lepospondyl and temnospondyl amphibians, diadectomorphs and eupelycosaur and represents a mixture of aquatic, semi-aquatic, semi-terrestrial and terrestrial fauna. The tetrapod footprints and vertebrate body fossils indicate a late Wolfcampian age. The Sangre de Cristo Formation comprises sediments that were deposited on a broad alluvial fan in response to tectonic movements of the Ancestral Rocky Mountain deformation. These sediments are nonmarine red beds dominated by fine-grained deposits of the overbank environment and subordinately composed of coarser deposits of sandstone sheets that represent isolated broad, shallow channels of low gradient and low stream power.

INTRODUCTION

The Upper Pennsylvanian-Lower Permian Sangre de Cristo Formation is a succession of red-bed siliciclastic strata that accumulated in the Rowe-Mora basin (Taos trough) of northern New Mexico during one or more orogenic pulses of the Ancestral Rocky Mountains orogeny (Soegaard and Caldwell, 1990; Baltz and Myers, 1999). One of the most extensive outcrop areas of the Sangre de Cristo Formation strata is in the Pecos River drainage near Ribera and Villanueva in southwestern San Miguel County (Fig. 1). Easily accessed badlands, highway cuts and other exposures here have long been known to be fossiliferous, especially for vertebrate footprints and bones (Langston, 1953; Vaughn, 1964; Hunt et al., 1990; Berman, 1993). However, few of these paleontological data have been published, and their stratigraphic and sedimentological context has not been well defined. Here, we undertake such definition by presenting data on the lithostratigraphy, paleontology and lithofacies of the Sangre de Cristo Formation in southwestern San Miguel County. We use these data to discuss the formation's age, correlation and sedimentology.

LITHOSTRATIGRAPHY

Stratigraphic Nomenclature

Hills (1899, 1900, 1901) referred in passing to the “Sangre de Cristo conglomerate” and “Sangre de Cristo formation” in the Sangre de Cristo Mountains west of Trinidad, Colorado. The first to describe the formation in any detail was Melton (1925), who characterized the Sangre de Cristo as dominantly red conglomerate, arkose, and shale of Pennsylvanian and Permian age, attaining a thickness of more than 3960 m (13,000 ft) near Crestone, Colorado. Meanwhile, Darton (1922, 1928) assigned partly correlative red beds exposed in northern New Mexico to the Abo Formation (also see Needham and Bates, 1943).

Read et al. (1944), Northrop et al. (1946), and Read and Wood (1947) introduced the name Sangre de Cristo Formation for these strata. This assignment has been continued (e.g., New Mexico Bureau of Geology and Mineral Resources, 2003), even though the Sangre de Cristo Formation in northern New Mexico lacks the marine interbeds, particularly in its lower part, which are

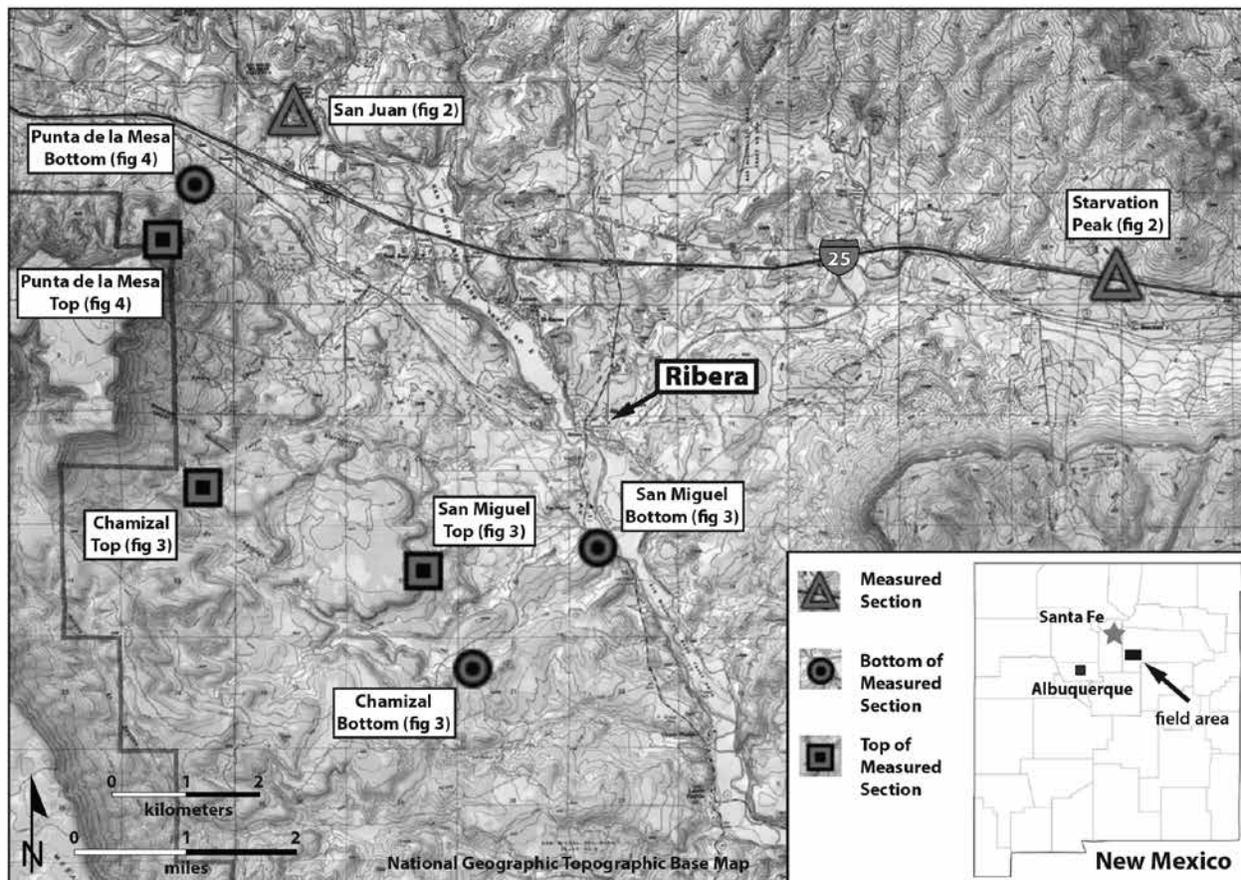


FIGURE 1. Index map of part of southwestern San Miguel County, New Mexico, showing locations of measured stratigraphic sections in Figures 2–4.

characteristic of the Sangre de Cristo Formation in its type area in Colorado. Furthermore, strata termed Sangre de Cristo Formation in northern New Mexico were deposited in a basin separate from the basin in which Sangre de Cristo Formation strata were deposited in Colorado. The Cimarron uplift of northern New Mexico, across which Triassic strata rest on Precambrian basement, separated the Central Colorado trough to the north from the Rowe-Mora basin to the south (e.g., Baltz and Myers, 1999, fig. 4).

Sangre de Cristo Formation strata are very similar lithologically to those of the Abo Formation to the south and southwest. Indeed, our study area in southwestern San Miguel County is less than 150 km northeast of Abo Pass, type locality of the Abo Formation; and only about 100 km northeast of strata termed Abo Formation exposed on the northern flank of the Sandia uplift (Lucas et al., 1999, 2005, 2013c) and about 70 km to the east-northeast of strata termed Abo Formation in the Jemez Mountains of Sandoval County (Lucas et al., 2012). Overall, the Abo Formation is finer grained than the Sangre de Cristo, being composed of mudstone, siltstone, fine-grained sandstone, and minor intraformational conglomerate. The Sangre de Cristo Formation contains significant layers of coarse-grained sandstone and conglomerate composed of extra-basinal clasts such as quartz, feldspar, and chert pebbles.

We agree with Baltz and Myers (1999) that strata termed Sangre de Cristo Formation in northern New Mexico would have been better referred to as the Abo Formation. However, our studies are in a preliminary state, so we continue to use the prevailing lithostratigraphic nomenclature, as applied on geologic maps of the study area (Johnson, 1969, 1971). We discuss below the possibility of member-level subdivisions of the Sangre de Cristo Formation in our study area, but we also propose no formal lithostratigraphy pending further study.

Data

Map data suggest a thickness of about 300 m for the Sangre de Cristo Formation in the study area (Read et al., 1944; Johnson, 1969; Baltz and Myers, 1999). However, despite the wealth of exposures of the Sangre de Cristo Formation near Ribera and Villanueva, it was not possible to measure a complete stratigraphic section of the unit. This is because outcrops of the upper and lower parts of the formation are widely separated geographically by tracts having little or no bedrock exposure. The base of the Sangre de Cristo Formation, where it rests on the Pennsylvanian Porvenir Formation, is exposed north of Interstate Highway 25 (I-25). However, younger Sangre de Cristo strata north of and adjacent to I-25 are mostly covered on low cuestas

and strike valleys. Two sections we measured (Fig. 2) present limited stratigraphic data on the lower part of the Sangre de Cristo Formation north of I-25.

Roadcuts along I-25 reveal portions of the middle Sangre de Cristo Formation that are poorly represented in natural outcrops. Outcrops are much more extensive south of I-25, and we were able to measure multiple sections that capture a thickness of about 160 m of the upper part of the Sangre de Cristo Formation in this area (Figs. 3, 4). However, much of the lower part of the Sangre de Cristo Formation is not represented by detailed lithostratigraphic data.

Contacts

The contact of the Sangre de Cristo Formation with the underlying Porvenir Formation is well exposed at our Starvation Peak section (Fig. 2). Here, coarse-grained, extra-basinal (quartzite- and limestone-pebble) conglomerate at the base of the Sangre de Cristo Formation rests with sharp contact on marine limestone at the top of the Porvenir Formation. This contact is less well exposed on dipslopes to the north. Conodonts from the upper part of the Porvenir Formation at our Starvation Peak section (Fig. 2) are of Desmoinesian age (J. Barrick, written commun., 2015).

Early workers (Read et al., 1944; Read and Wood, 1947; Sutherland, 1972) regarded the contact of the Sangre de Cristo Formation on underlying marine rocks of Pennsylvanian age in the Rowe-Mora basin as a broad zone of interfingering. However, Baltz and Myers (1999) regarded the contact as a regional unconformity at which the Sangre de Cristo Formation is scoured into strata of Desmoinesian (Porvenir Formation) or Missourian-Virgilian (Alamitos Formation) age. They noted, as was later documented in detail by Krainer et al. (2004), that the youngest marine strata locally preserved beneath the Sangre de Cristo Formation are of early Wolfcampian (earliest Permian) age. We are inclined to agree with Baltz and Myers (1999) that the base of the Sangre de Cristo Formation in southwestern San Miguel County is an unconformity, though our limited data do not provide convincing documentation of this conclusion.

In contrast to its lower contact, the contact of Yeso Group strata on Sangre de Cristo Formation strata is very well exposed along the flanks of Glorieta Mesa (Figs. 3, 4). We place this contact at the lowest bed of sandy dolomite or the base of the first gypsiferous sandstone bed. Thus, the contact between the Sangre de Cristo Formation and the Yeso Group is very similar to the Abo-Yeso contact to the south and west, which is generally regarded as a conformable contact (Lucas et al., 2013a, c)

Thickness

As already stated, map data indicate an approximate thickness of about 300 m for the Sangre de Cristo Formation in the study area. Our sections capture about 160 m of this thickness, mostly in uninterrupted outcrops of the upper half of the formation (Figs. 3, 4).

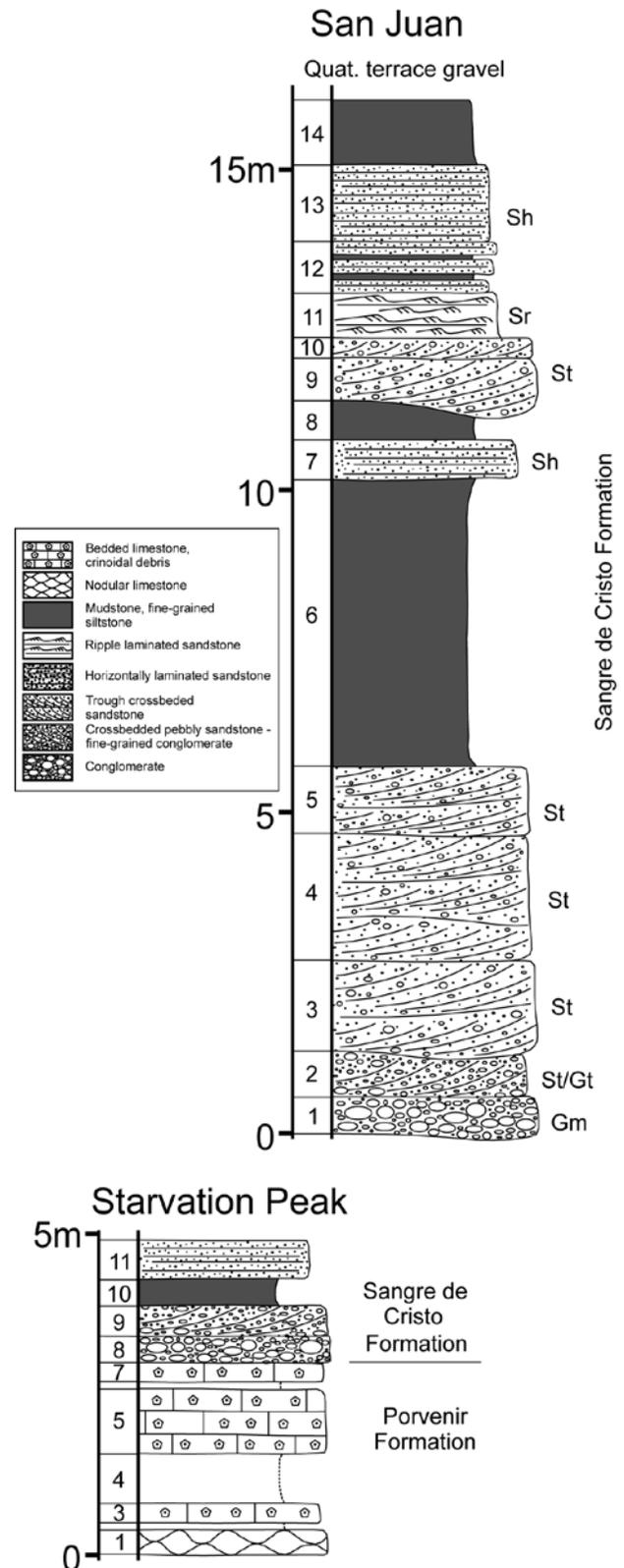


FIGURE 2. Measured stratigraphic sections of two intervals of the lower part of the Sangre de Cristo Formation, north of Interstate 25. Lithofacies codes of Miall indicated by abbreviations (Gm, St, etc.). Starvation Peak section measured at UTM zone 13, 466842 E, 3916885 N (NAD 83). San Juan section measured at UTM zone 13, 454896 E, 3919316 N (NAD 83).

Lithology and Stratigraphic Architecture

The Sangre de Cristo Formation in the study area is mostly red-bed, non-fissile mudstone, which represents 60–75% of the thickness of the stratigraphic sections measured (Figs. 2-5). Less common lithologies are sandstone, conglomerate and calcrete (pedogenic limestone) (Fig. 5). These are all sediments of nonmarine origin.

Parts of the lower 140 m of the formation are seen at our sections at Starvation Peak and San Juan (Fig. 2). This interval of the formation is evidently mudstone dominated and mostly covered. Most outcrops consist of coarser and more resistant beds and intervals of sandstone and conglomerate (Fig. 2). These resistant strata are mostly arkosic, trough-crossbedded conglomerates and conglomeratic sandstones. Our sections represent about 20 m of this 140-m-thick lower interval of the Sangre de Cristo Formation.

The upper 160 m of the Sangre de Cristo Formation are completely represented by our measured stratigraphic sections (Figs. 3–5). These strata are also mudstone dominated, but we can divide them into two intervals, a lower unit A, about 60–80 m thick, and an upper unit B, about 50–80 m thick. Units A and B are distinguished by the relative abundance in unit B of thin, laterally extensive sheet sandstone bodies that display abundant climbing ripple lamination.

Unit A is mostly mudstone, 70–75% of the measured sections (Figs 5A-B). Trough-crossbedded conglomerate, conglomeratic sandstone and coarse-grained sandstone make up the rest of the unit in almost equal amounts (Fig. 5A). Calcrete beds are a minor component of unit A, represented by about 5% of the measured sections, though many mudstone beds have numerous calcrete nodules. Beds of conglomerate/sandstone are present as either relatively thin (<1 m thick) single beds or multistoried successions of beds more than 10 m thick.

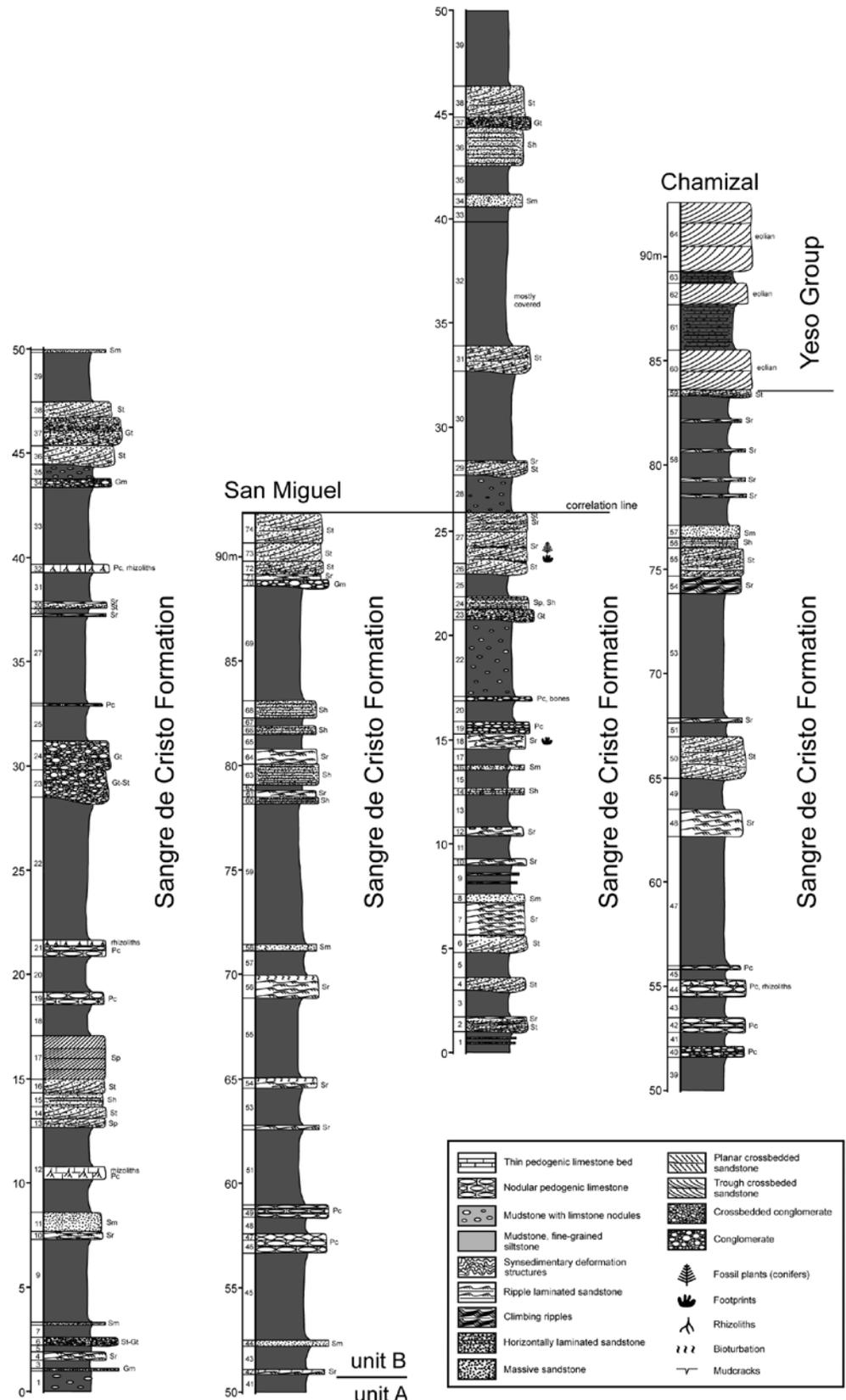


FIGURE 3. Measured stratigraphic sections of the upper part of the Sangre de Cristo Formation, south of Interstate 25. Lithofacies codes of Miall indicated by abbreviations (Gm, St, etc.). San Miguel section base UTM 459326 E, 3913000 N, top 456801 E, 3912676 N. Chamizal section base UTM 457505 E, 3911258 N, top 453630 E, 3913887 N. All coordinates zone 13, NAD 83.

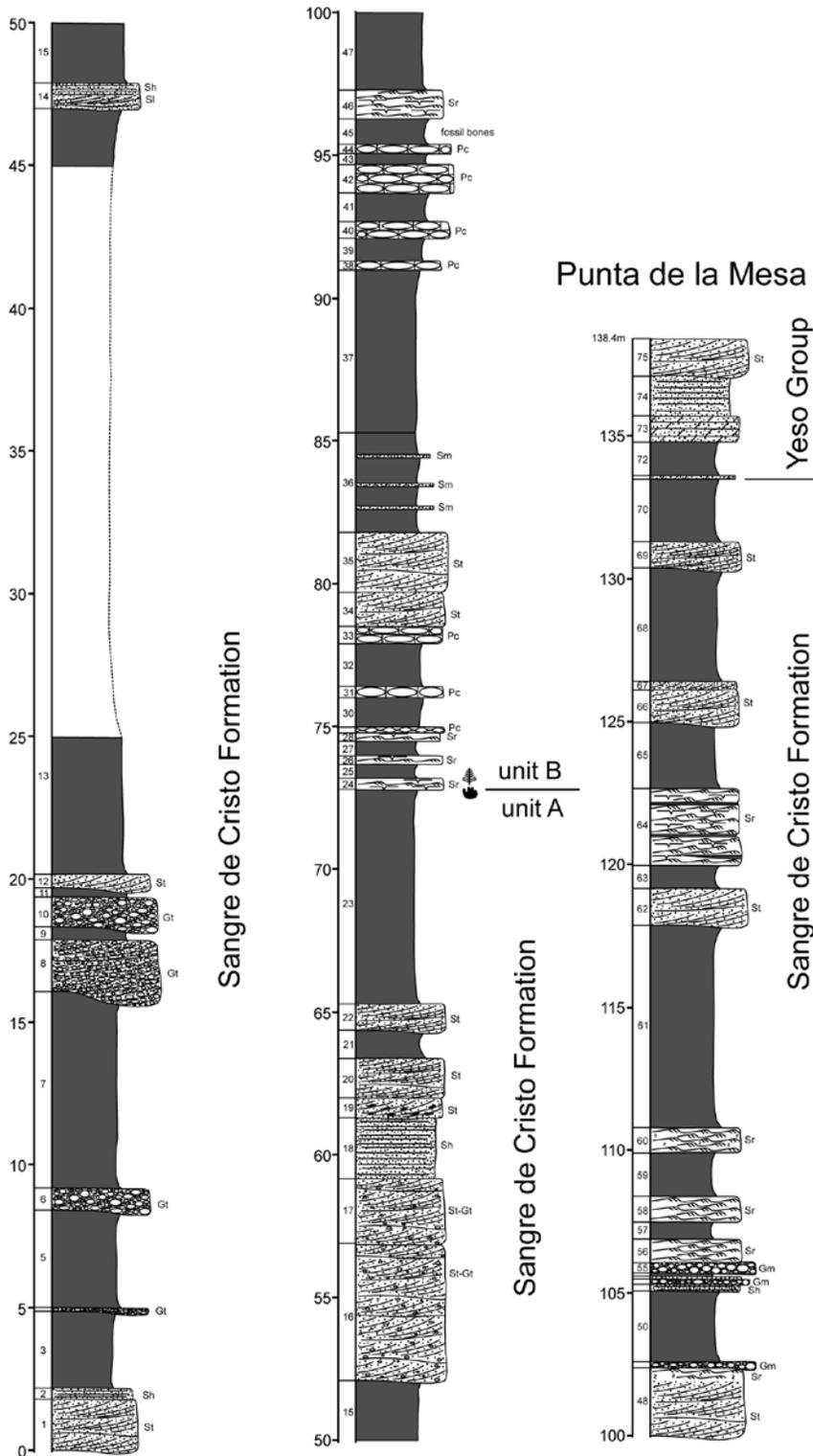


FIGURE 4. Measured stratigraphic section of the upper part of the Sangre de Cristo Formation, south of Interstate 25 at Punta de la Mesa. Lithofacies codes of Miall indicated by abbreviations (Gm, St, etc.). Base UTM zone 13, 453515 E, 3918261 N and top 453099 E, 391744 N (NAD 83). See Figure 3 for legend to lithologic symbols.

Like unit A, mudstone is the dominant constituent of unit B, about 60–70% of the measured sections (Figs. 3, 4). However, trough-crossbedded conglomerate, conglomerate and coarse-grained sandstone are a lesser component of unit B, about 10% (Fig. 5C-D). Calcrete also is not a major constituent, 3–5% of the thickness, though a few relatively thick and persistent intervals of calcrete are present in unit B (Fig. 5E-F). The primary distinction of unit B is the presence of substantial amounts of ripple-laminated sandstone in relatively thin, laterally extensive sheets that represent 13–34% of the thickness of the unit.

Thus, there is a change in stratigraphic architecture from unit A to unit B. In unit A, conglomerate and sandstone bodies are channelized into mudstone as isolated bodies or are amalgamated to form benches of some lateral extent. In unit B, however, much thinner and laterally extensive sandstone bodies that are finer grained and ripple laminated are a prominent portion of the section.

These two lithostratigraphic units, A and B, are similar to the two named members of the Abo Formation at its type section, the lower, Scholle Member, and the upper, Cañon de Espinosa Member (Lucas et al., 2005). Whether these divisions of the Sangre de Cristo Formation should be named, or whether the Abo member names should be applied to them, will require further study.

Petrography

We prepared petrographic thin sections of selected beds of the Sangre de Cristo Formation (Fig. 6). In general, sandstones of the Sangre de Cristo Formation are moderately to poorly sorted and composed of subangular to subrounded grains. The most common grain type is monocrystalline quartz. Polycrystalline quartz is rare and occurs as grains with large subindividuals that are derived from granitic source rocks and as fine-grained, rarely schistose grains of a metamorphic source. Detrital feldspar grains are abundant (potassium feldspars and plagioclase). Potassium feldspar occurs as mostly untwinned grains, and microcline is very rare. Perthitic feldspars are common. Plagioclase displays polysynthetic twins. Fresh feldspar grains are rare. Most detrital feldspars are slightly to strongly altered, and a few grains are completely altered to clay minerals. In pebbly sandstone, some detrital feldspar grains are >7 mm in size. Plagioclase occurs as smaller grains. Detrital micas are present in small amounts and occur as muscovite and altered, partly chloritized biotite. Chlorite is rare.

Granitic rock fragments composed of coarse quartz and feldspar or several intergrown feldspar grains are common. They are more abundant in coarse, pebbly sandstone than in fine-grained sandstone. Metamorphic rock fragments composed of fine-grained quartz and mica and displaying well-developed schistosity are rare. Individual sandstone beds contain sedimentary rock fragments in the form of micritic to microsparitic carbonate grains that commonly contain small (<0.1 mm), angular quartz grains.

In most sandstone beds, coarse blocky calcite is the dominant cement type, although some quartz grains display authigenic quartz overgrowths. Rarely, detrital feldspar grains also show thin authigenic overgrowths. Textural relationships indicate that feldspar overgrowths formed first, followed by quartz overgrowths,

and, during a late diagenetic phase, calcite cement formed. Calcite cement locally slightly replaces quartz and particularly detrital feldspar grains.

A few pebbly sandstone beds are entirely composed of sedimentary rock fragments. These beds are poorly sorted; the detrital grains are mostly subrounded to rounded. Micritic carbonate grains are by far the most abundant grain type. These grains partly display calcite-cemented fissures. Many carbonate grains contain small, angular quartz grains (<0.1 mm). Some carbonate grains display dark brown weathered rims. A few carbonate grains contain abundant small quartz grains, and others are strongly recrystallized. Siltstone grains are composed of angular to sub-angular quartz grains, a few feldspar grains and rare muscovite

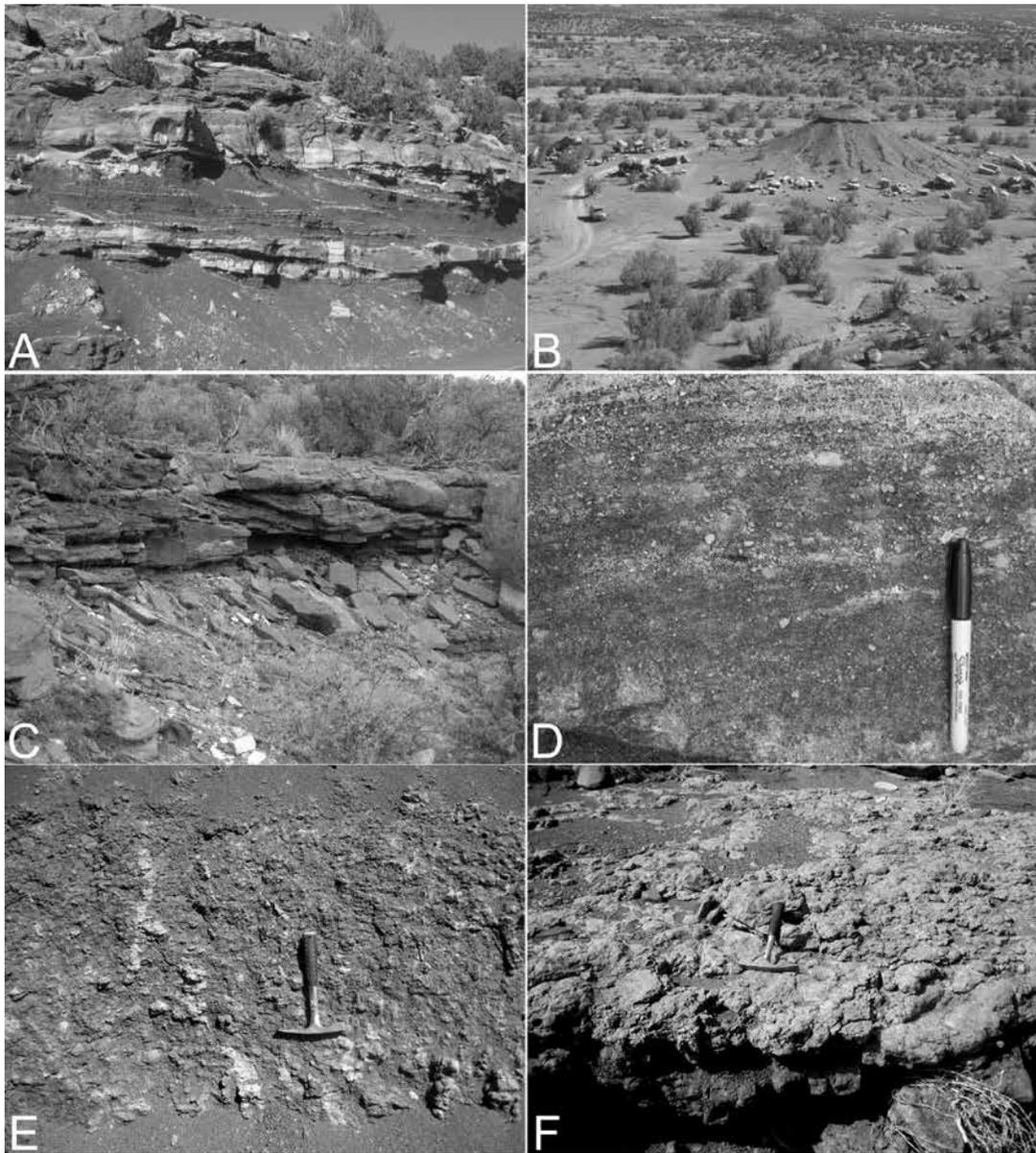


FIGURE 5. Photographs of selected outcrops of the Sangre de Cristo Formation. A. Sandstone channels cut into unit A mudstone along Pecos River near Lower Pueblo, sec. 26, T13N, R14E. B. Badlands developed in mudstone of unit A south of San Miguel, sec. 16, T13N, R14E. C. Lateral accretion sandstone body, unit 29 of Chamizal section. D. Arkosic (feldspathic) conglomeratic sandstone, unit 26 of Chamizal section. E. Stage III calcrete displays rhizoliths and nodules in mudstone, unit 21 of San Miguel section. F. Stage V calcrete ledge, unit 40 of Chamizal section. (See also Color Plate 14)

grains embedded in fine-grained carbonate matrix. The detrital grains are densely packed, and the matrix is siltstone composed of angular to subangular quartz grains, a few feldspar grains (mostly 0.05–0.1 mm) and fine-grained carbonate.

Due to the high amount of detrital feldspars, most of the sandstones of the Sangre de Cristo Formation are classified as subarkose to arkose. A few sandstones and pebbly sandstones containing abundant reworked carbonate grains are classified as lithic arenites (classification scheme of Pettijohn et al., 1987).

The mineralogical composition of the sandstones suggests dominantly granitic source rocks (most of the quartz grains, detrital feldspars and granitic rock fragments). The presence of a few metamorphic rock fragments indicates that metamorphic rocks were subordinately exposed in the source area. Carbonate grains are locally abundant and we interpret them to be intraformational, derived from the reworking of pedogenic carbonates (caliche). The texture and mineralogical composition of the Sangre de Cristo Formation sandstones are very similar to those of the Alamitos Formation of the Rowe-Mora basin (Krainer et al., 2004) and in the Cutler Group in the Chama basin (Lucas and Krainer, 2005a, b).

PALEONTOLOGY

Trace Fossils

Trace fossils of invertebrates and vertebrates are locally common in the upper part of the Sangre de Cristo Formation. In fact, other than some nondescript bioturbation (mostly *Skolithos* and *Palaeophycus* in channel-margin sandstones), all trace fossil localities of the formation in the study area are in its upper part, in unit B. These are mostly arthropod and tetrapod walking traces, and were first documented by Hunt et al. (1990), who described the ichnology of a single site, NMMNH (New Mexico Museum of Natural History) locality 1339.

Due to recent fieldwork, the number of trace fossil sites in the upper part of the Sangre de Cristo Formation has been increased during the last five years, though most of the traces still come from one locality. Now, there are about 200 invertebrate and vertebrate trace fossils from 15 localities of the Sangre de Cristo Formation in the study area housed at NMMNH. The majority of traces are tetrapod footprints that can be assigned to six ichnotaxa (Fig. 7A-F): *Batrachichnus* (Woodworth, 1900); *Limnopus* (Marsh, 1894); *Ichniotherium* (Pohlig, 1892); *Tambachichnium* (Müller, 1954); *Dimetropus* (Romer and Price, 1940); and *Dromopus* (Marsh, 1894). These footprints are generally interpreted to represent tracks of small and large temnospondyls (*Batrachichnus*, *Limnopus*), diadectid reptiliomorphs (*Ichniotherium*), sphenacodontid (*Dimetropus*), varanopid (*Tambachichnium*) “pelycosaurs,” and araeoscelid eureptiles or other sauropsids with a lacertoid-like pes structure (*Dromopus*). The full range of tetrapod ichnotaxa is only known from NMMNH locality 1339, whereas the other localities yielded determinable tracks of no more than two different ichnotaxa. In this context, however, it should be mentioned that more than 80% of all Permian tetrapod footprints from the study area come from NMMNH locality 1339.

The tetrapod ichnofauna of the Sangre de Cristo Formation is quite similar to vertebrate trace fossil assemblages described from the Abo Formation of central New Mexico (Lucas et al., 2013c). Remarkable is the lack of *Amphisauropus* in the Sangre de Cristo Formation and the relative abundance of *Ichniotherium* and *Tambachichnium*, which is most similar to the Pennsylvanian-Permian tetrapod ichnofauna of the Maroon Formation of central Colorado (Voigt et al., 2005). *Ichniotherium* and *Tambachichnium* seem to be typical elements of Early Permian inland tetrapod communities (Hunt and Lucas, 1998; Voigt et al., 2005, 2007; Voigt and Lucas, 2012).

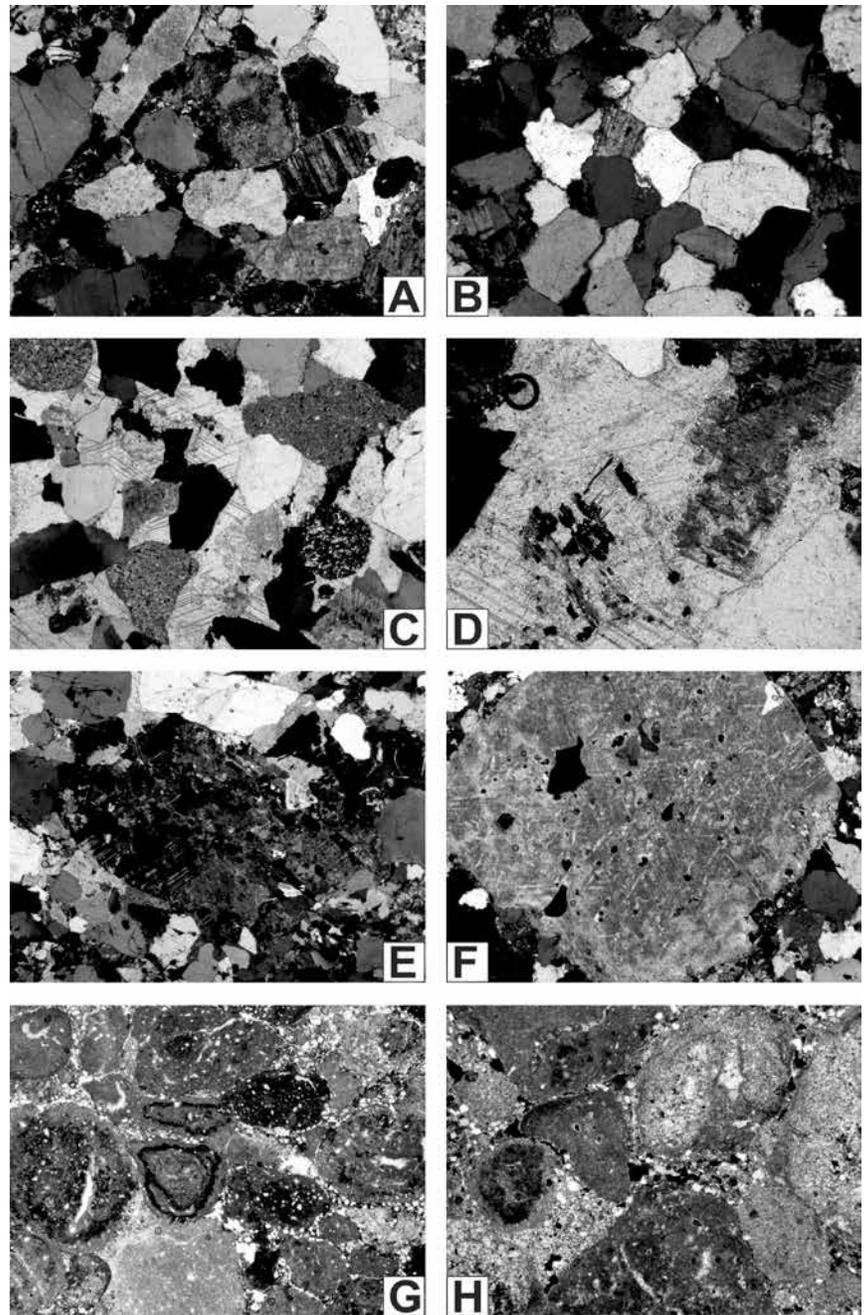
Tetrapod footprints are among the most important biostratigraphic markers from the Sangre de Cristo Formation. The recorded assemblage is a typical early to mid-Early Permian (Wolfcampian-early Leonardian/Asselian to Artinskian) tetrapod ichnofauna. *Tambachichnium* seems to be most common in Sakmarian and Artinskian red beds (Voigt, 2005), whereas the lack of *Varanopus* and *Erpetopus*, which are remarkably abundant or first occur in the topmost Abo Formation in central New Mexico (Lucas et al., 2013c), suggests that the tetrapod footprint-bearing strata of the Sangre de Cristo Formation are most likely of mid-Early Permian age and definitely not younger than late Artinskian.

In comparison to tetrapod footprints, invertebrate traces are rare in the Sangre de Cristo Formation. Two kinds of such traces from NMMNH locality 1339, *Paleohelcura* (Gilmore, 1926) and *Aenigmichnus* (Hitchcock, 1865), were described by Hunt et al. (1990). Minter and Braddy (2009) used invertebrate trace fossil data [*Diplichnites* (Dawson, 1873); *Diplopodichnus* (Brady, 1947); *Lithographus* (Hitchcock, 1858); *Tonganoxichnus* (Mángano et al., 1997); *Treptichnus* (Miller, 1889)] from the same site for ichnofacies analyses. We can confirm that maxillary palp impressions of supposed apterygote insects assigned to *Tonganoxichnus* isp. (Fig. 7G) are among the most common invertebrate traces of the Sangre de Cristo Formation. Traces on NMMNH 14084, 14133, 14136, 14143, 14145 (Fig. 7H) and 45933 with or without a medial impression resemble potential myriapod, millipede or isopod walking traces assignable to *Diplichnites* isp. Very rare traces can be compared with *Lithographus* (= *Paleohelcura sensu* (Hunt et al., 1990)) (Fig. 7I), *Sphaerapus* (Hitchcock, 1858) (Fig. 7J), and *Stiallia* (Smith, 1909) (Fig. 7K). They may have been made by scorpions, beetles, and feeding crustaceans (Minter and Braddy, 2009; Lucas et al., 2013b). *Aenigmichnus* identified by Hunt et al. (1990) is here interpreted to be an inorganic sedimentary structure, most likely a chevron tool mark, whereas *Treptichnus* mentioned by Minter and Braddy (2009) could also not be confirmed and might have been confused with the ubiquitous fossil root traces seen in some beds of the Sangre de Cristo Formation (Fig. 7L).

Paleobotany

Plant fossils proved to be quite sparse in the Sangre de Cristo Formation and, with the exception of a single discovery, are absent from the overlying Yeso Group. The great majority

FIGURE 6. Thin section photographs of representative sandstone beds of the Sangre de Cristo Formation (San Miguel section). A. Moderately sorted sandstone composed of subrounded grains of monocrystalline quartz, some polycrystalline quartz, abundant detrital feldspars and a few granitic rock fragments. A few detrital quartz grains display authigenic quartz overgrowths, and some calcite cement is present. Sample SAM 23, polarized light, width of photograph is 3.2 mm. B. Fine-grained, moderately sorted sandstone composed of subangular grains, mainly monocrystalline quartz and feldspar and a few polycrystalline quartz grains. Detrital quartz grains are cemented by quartz in the form of authigenic overgrowths. Sample SAM 4, polarized light, width of photograph is 1.2 mm. C. Medium-grained, moderately sorted sandstone containing subangular to subrounded grains of monocrystalline quartz, rare polycrystalline quartz, some feldspars and many sedimentary rock fragments (fine-grained carbonate grains). The detrital grains are cemented by coarse, blocky calcite. Sample SAM 9, polarized light, width of photograph is 3.2 mm. D. Detail of sandstone of C showing fragments of detrital feldspar grains, which are replaced by coarse calcite cement. The feldspar grain in the lower left is almost completely replaced by calcite. Sample SAM 9, polarized light, width of photograph is 1.2 mm. E. Poorly sorted pebbly sandstone with a large granitic rock fragment composed of intergrown feldspar and quartz (center of photograph). Detrital grains are cemented by calcite. Sample SAM 24, polarized light, width of photograph is 6.3 mm. F. Pebbly sandstone containing a large detrital feldspar grain that is slightly altered. Sample SAM 24, polarized light, width of photograph is 6.3 mm. G. Pebbly sandstone composed of sedimentary rock fragments (reworked pedogenic carbonate grains). The carbonate grains contain small angular quartz grains, and some detrital grains display calcite-filled fissures. The grain in the center of the photograph has a dark brown weathering rim. Sample SAM 2, plane light, width of photograph is 6.3 mm. H. Pebbly sandstone composed of reworked carbonate grains (same as G). The pore space between the detrital grains is filled with siltstone matrix composed of abundant angular quartz grains and some feldspar grains embedded in fine-grained carbonate. Sample SAM 2, polarized light, width of photograph is 3.2 mm.



of macrofossil foliar remains were preserved as impressions. With only a few exceptions, adpression fossils are attributable to the walchian conifers. These remains were sometimes cast in three dimensions, were generally found in isolation, but occasionally formed mats (Fig. 8A). Preservation was most common in thinly bedded sandstone (Fig. 8D) on the upper surfaces of beds. In some instances, the plants occurred within finer grained drapes that covered a bedding surface and indicated waning flow. Such finer grained sediment tended to obscure details of the fossil (Fig. 9G).

In two instances, flagstone quarrying, sanctioned by the U.S. Bureau of Land Management, exposed sandstone beds (Fig. 8B) in which molds of numerous, *in situ* stems were preserved. These

molds indicated the positions of small trees that had been buried by catastrophic floods (Fig. 8C); 165 of these tree molds were identified. All were similar in size and shape, and many showed evidence that the living plant had survived and recovered from burial, indicated by the presence of adventitious roots and shoots. Stems had bell-shaped bases (Fig. 8C, A at arrow), indicating central rooting systems, that were embedded in a calcic paleosol immediately below the sandstone bed. The stems decayed after death, and most were filled with a ropy carbonate precipitate (Fig. 8C, B at arrow). Isotopic analysis of the carbonate indicated it to be identical to that found in a paleosol present immediately above the stem-bearing sandstone bed. Several stems were observed to project into the bottom of this overlying paleosol.

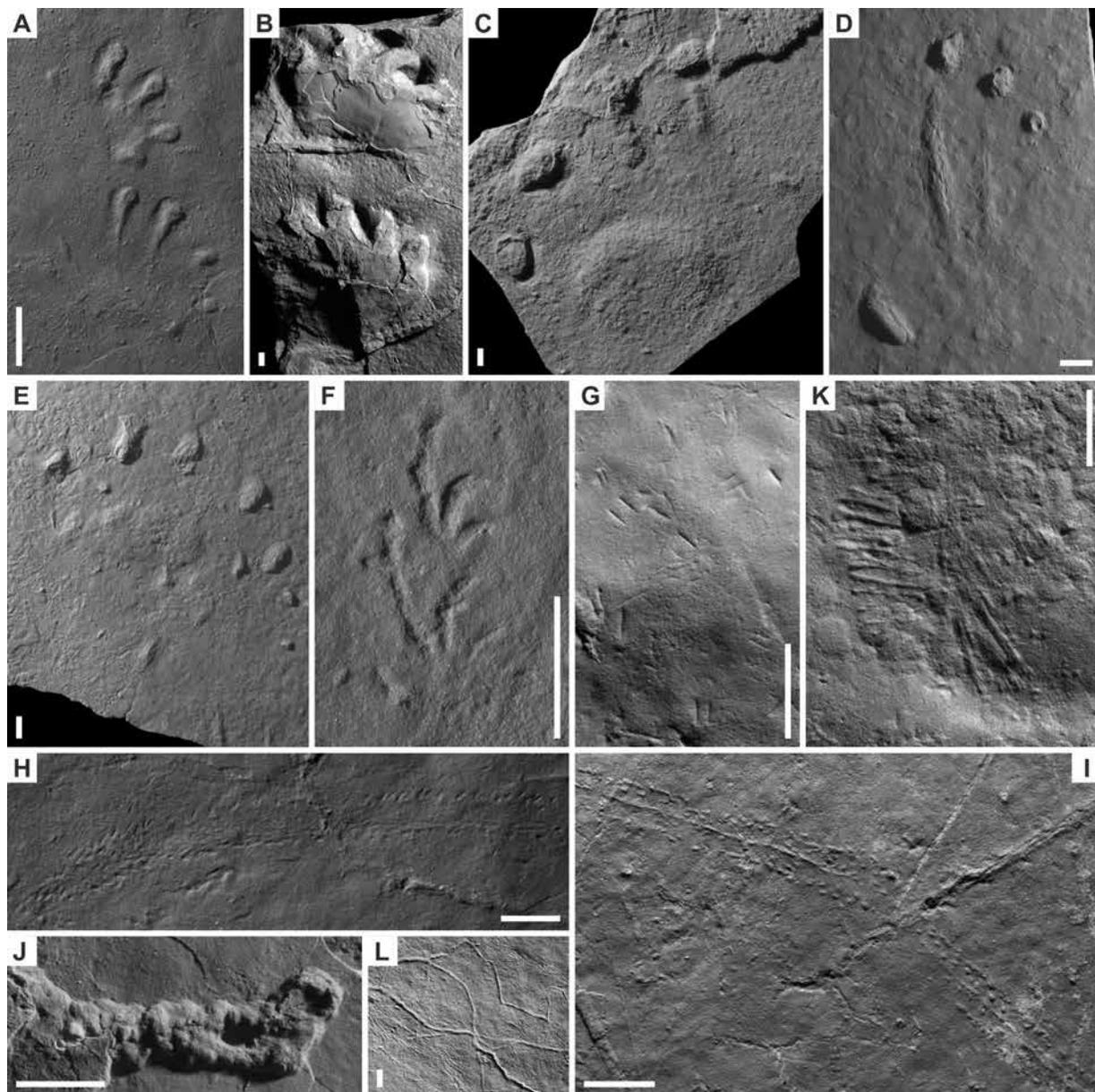


FIGURE 7. Tetrapod footprints (A-F), invertebrate trace fossils (G-K) and root traces (L) from the Sangre de Cristo Formation at NMMNH locality 1339 (A, C-F, H-I, K-L), NMMNH locality 8206 (B), NMMNH locality 8208 (G), and NMMNH locality 9508 (J). A. *Batrachichnus* (NMMNH P-14083); B. *Limnopus* (NMMNH P-61945); C. *Ichniotherium* (NMMNH P-45910); D. *Tambachichnium* (NMMNH P-45913); E. *Dimetropus* (NMMNH P-45926); F. *Dromopus* (NMMNH P-14094); G. *Tonganoxichnus* (NMMNH P-61933); H. *Diplichnites* (NMMNH P-14145); I. *Lithographus* (NMMNH P-14141); J. *Sphaerapus* (NMMNH P-70760); K. *Stiallia* (NMMNH P-45947); L. root traces (NMMNH P-45925). Scale bars equal 1 cm.

The stem molds lack node-internode organization, ruling out sphenopsid affinity. They show no evidence of an adventitious root mantle or any indication of widely spaced, ovoid leaf scars, which, in combination with the central rooting and adventitious shoots and roots, rule out affinities with marattialean tree ferns. The presence of adventitious lateral roots and shoots would appear to rule out lycopsids as well. What remains, therefore, is seed-plant affinity. Among seed plants, coniferophytes are the most likely possibility. Vague, diamond-shaped surface features and associated leaf-like remains suggest dicranophylls, but this can be no more than the most tentative of identifications. These

deposits and their enclosed plant molds have been analyzed and described in detail by Rinehart et al. (2015), who found the stems to conform to a density indicative of self-thinning.

The most commonly found elements of the sparsely preserved macroflora of the Sangre de Cristo Formation are walchian conifers. These are of two principal leaf morphologies, one corresponding to the genus *Culmitszchia* (Fig. 9A, B, G) and the other *Walchia* (Fig. 9C-D) (following the circumscription of these names by Visscher et al., 1986). These two forms are similar to Morphotypes IVa and II, respectively, as circumscribed by Looy and Duijnste (2013) from a site in the

Early Permian of north-central Texas. The Morphotype IVa forms have relatively large leaves that are borne away from the axis on which they are inserted and curve adaxially toward that axis. The fit with Looy and Duijnste's (2013) Morphotype IVa is not exact, however.

On the other hand, the *Walchia* specimens are a reasonable approximation to Morphotype II. They have small leaves (relative to Morphotype IVa specimens; compare Figure 9B-C, illustrated at the same magnification) that are relatively straight and form an approximately 30° angle with the ultimate branch on which they are borne. At one locality leaf bases also were found (Fig. 9D at arrows). These conform to walchian branch bases as described by Looy (2013); the enlargement at the base of such branches is consistent with abscission from the main stem of the plant, characteristic of conifers with a plagiotropic habit.

Rare examples of other kinds of plants also were found among the macrofossil assemblage of the Sangre de Cristo Formation. These include fragments of compound leaves of what appear to be pteridosperms (Fig. 9E-F), although the specimen illustrated in Figure 9F is within the size range and pinnule shape of marattialean fern foliage (*Pecopteris* s.l.—see Cleal, 2015 for nomenclatural problems with *Pecopteris*). Note the size differences between these two specimens—although somewhat similar in gross form, the specimen illustrated in Figure 9E is substantially larger than that of Figure 9F with much more widely spaced pinnae. Venation is not preserved in either of these specimens, so a final determination of their taxonomic affinity is not possible.

We would include the callipterids among the pteridosperms, and their rare presence in a flora rich in conifers has been recorded from red beds of the equivalent aged Abo Formation in central New Mexico (DiMichele et al., 2013). Other elements noted in the flora include suspect foliage of cordaitalean gymnosperms, notoriously difficult to identify in a fragmentary state (easily confused for stem remains because of the size and striated appearance of the leaves) and possible *Supaia* and gigantopterid foliage.

The poor preservation and sparseness of plant remains in the Sangre de Cristo Formation within the area examined makes it difficult to compare the flora with that of the age-equivalent Abo Formation in central New Mexico and Robledo Mountains Formation in southern New Mexico. Both of these units are dominated by walchian conifer remains, with a substantial admixture of the peltasperm *Supaia* in the Abo (DiMichele et al., 2013, 2015; Voigt et al., 2013). However, in all of these, conifer remains are found in sandstones and siltstones, frequently associated with thin, planar bedding and muddy drapes, suggesting flashy discharge systems. And, in all three of these lithosomes (Sangre de Cristo, Abo and Robledo Mountains Formations), the conifer remains are often found in mats, suggesting transport of large amounts of litter into the depositional environment. Thus, although tentative, the flora of the Sangre de Cristo Formation red beds appears to be much the same as that of the finer grained units to the south, which were farther from sediment source areas. All regions were likely under seasonally dry climates and may have been covered with conifer forests of great extent and low biodiversity.

Vertebrate Paleontology

Vertebrate fossils in the Sangre de Cristo Formation along the Pecos River Valley occur at scattered sites within unit A and are recovered almost exclusively from coarse-grained, arkosic stream-channel deposits. Preservation has resulted in almost all specimens being represented by fragmentary remains, so their descriptions are, and have been, limited by necessity, almost entirely to taxonomic lists (Berman, 1993; Berman et al., 2015). These fragmentary specimens include a tooth of a xenacanth shark (Fig. 10A), incomplete tooth plate of the lungfish *Gnathorhiza* (Fig. 10B), vertebrae of the amphibians *Phlegethonia* (Fig. 10C) *Diplocaulus* (Fig. 10E) and *Lysorophus* (not illustrated), a jaw fragment of the amphibian *Eryops* (Fig. 10E), jaw fragments of a captorhinid (Fig. 10F-G) and vertebrae of the eupelycosaur *Sphenacodon* (Fig. 10H). More complete specimens include two previously described forms from the Lower Permian of New Mexico: a three-dimensionally preserved skull (CM [Carnegie Museum of Natural History] 25741) of an indeterminate species of the highly terrestrial, herbivorous diadectomorph *Diadectes* (Fig. 11) in which the late Permian species reached a maximum weight of well over 100 kg (Berman et al., 1992), and a partial, articulated, postcranial skeleton of a large *Ophiacodon* (CM 47771), a basal, pelycosaurian-grade, amniote synapsid (Berman et al., 2013).

Previous descriptions of the *Diadectes* skull have centered on the temporal-occipital region, but more specifically on the long-debated controversy over the fate of the intertemporal bone, which has been a critical feature in the systematic placement of Diadectidae. This was unequivocally resolved in CM 25741 by clearly demonstrating its fate as having become incorporated into the parietal bone as a lateral lappet (Fig. 11). In cladistic analyses, the derived feature of the absence of a discrete intertemporal bone has been an important feature in resolving *Diadectes*, as well as all diadectomorphs (i.e., Diadectidae, *Limnoscelis*, and *Tseajaia*) as an amniote, rather than an anamiote. Furthermore, the analyses supported the rather controversial conclusion that Diadectomorpha should be considered the sister clade to Synapsida as a member of the crown-clade Amniota (Berman et al., 1992; Berman, 2013), rather than the primitive sister clade to the sister clade Synapsida+Reptilia.

The partial skeleton of the large *Ophiacodon* (CM 47771) described by Berman et al. (2013) is notable not only for being the largest of the genus reported from New Mexico, but also in providing an approximate biostratigraphic age for the upper half of the Sangre de Cristo Formation. Five of the six recognized species of *Ophiacodon* are widely distributed throughout the Permo-Pennsylvanian of North America, but mainly in Texas, New Mexico, and Utah, with preservation ranging from fragmentary remains to complete, or nearly complete, skeletons. They are typically interpreted as amphibious, primarily fish eaters with a gracile build and ranging in maximum weight and length from 32 kg and 130 cm to 230 kg and 300 cm (Romer and Price, 1940).

As an extremely conservative group, the species of *Ophiacodon* are distinguished mainly on the basis of size and a few structural features. Interestingly, the variants of these

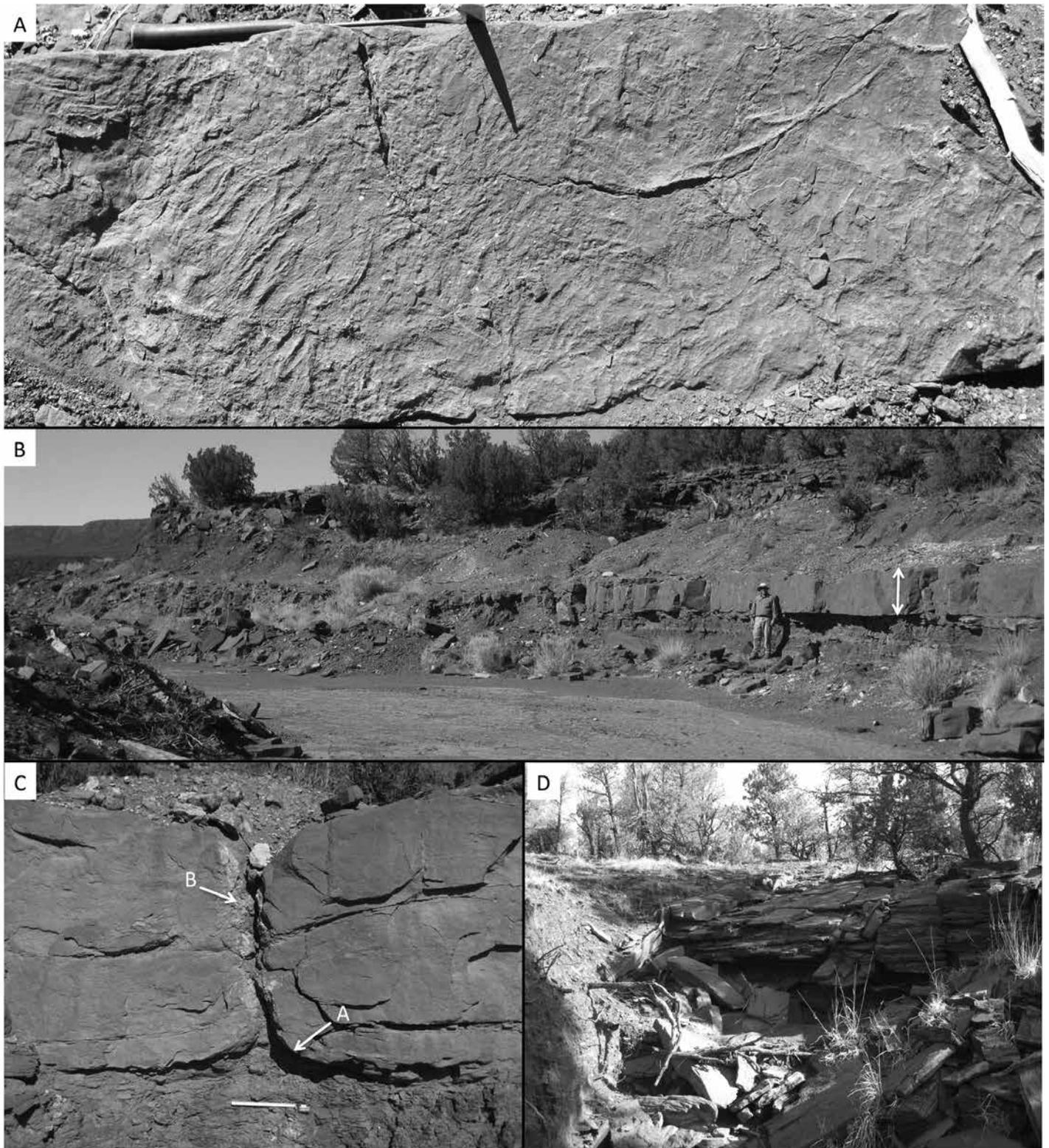


FIGURE 8. Fossil plant occurrences in the Sangre de Cristo Formation. A. Mat of walchian conifer branches on siltstone surface in BLM flagstone quarry #3 (USNM locality 43829). Field photo specimen not collected. Hammer = 41 cm. B. BLM Flagstone Quarry Lower (USNM locality 43831) with casts of upright stems exposed in longitudinal section in sandstone bed marked with double-headed white arrow. Person = 1.8 m. C. Upright stem cast of typical form (USNM locality 43831). Base of stem (A at arrow) is bell-shaped and terminates in a calcareous paleosol. Stem is partially filled with CaCO_3 , isotopically identical to carbonate nodules in paleosol overlying sandstone bed. See Rinehart et al. (2015) for details. Exposed portion of measuring tape at base of mold = 25 cm. D. Typical thinly bedded sandstone outcrop, head of Arroyo del Pueblo (USNM locality 43828), in which walchian conifer remains were found; backpack for scale.

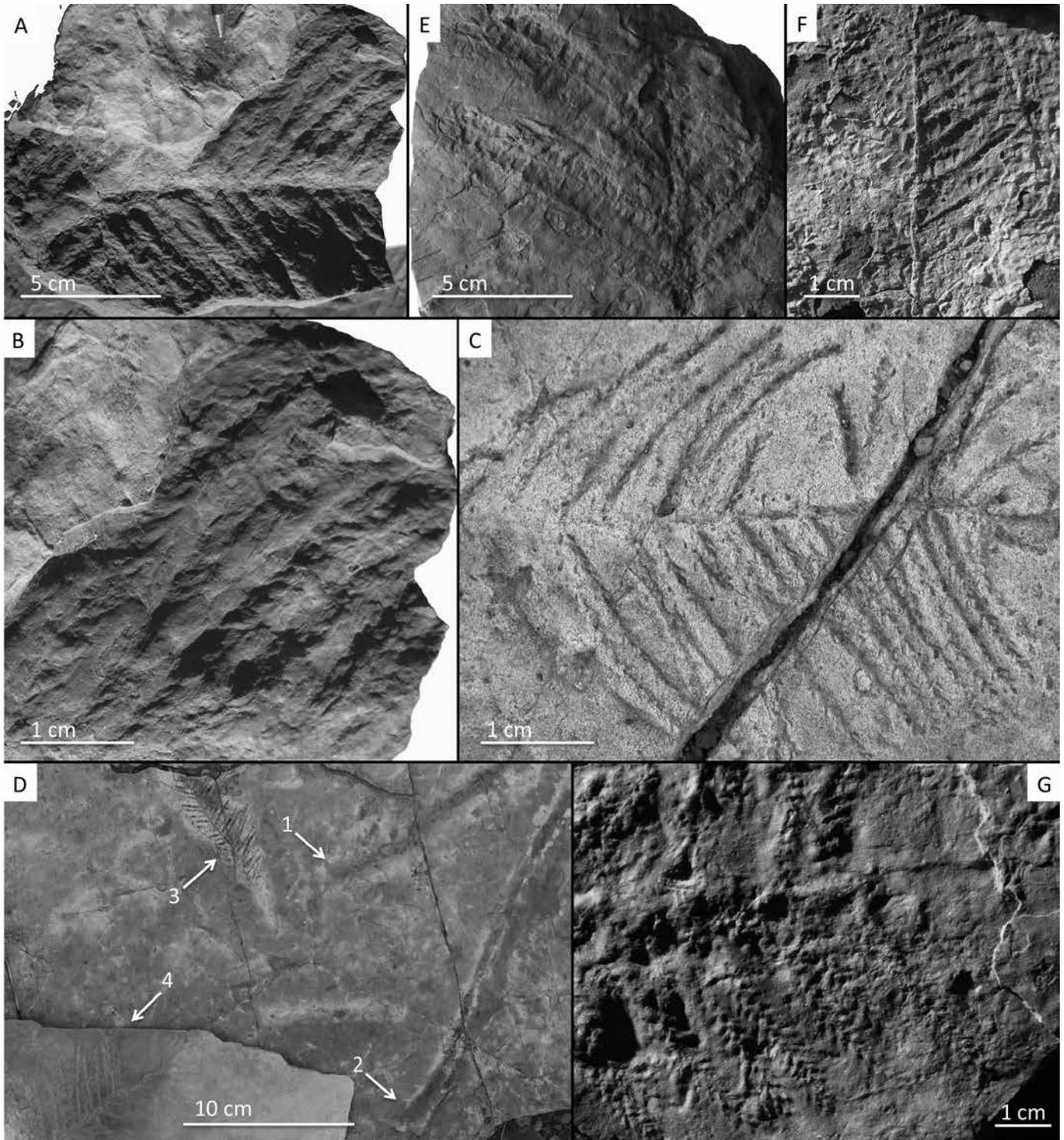


FIGURE 9. Selected fossil plants from the Sangre de Cristo Formation. A. Walchian conifer branch fragment (USNM 610504, locality 43831). B. Walchian conifer branch fragment (USNM 610504) illustrated in image (A), higher magnification to show typical walchian foliage, possibly attributable to *Culmitzschia* sp. C. Walchian conifer branch fragment (locality 43828, specimen not collected). Shown at same magnification as image (B) to emphasize difference in size and nature of the shape and angle of the leaves. D. Walchian conifer branch fragments (USNM locality 43828). Arrows 1–4; one and two indicate the bases of branches; 1 (not collected USNM 610505) and 2 (USNM 610505), which are slightly swollen, consistent with branch abscission. Three and four indicate leafy branches, 3 (USNM 610506) and 4 (not collected) of image are of the same type as that illustrated in image (C). E. Pinnate foliage of indeterminate plant, possibly the callipterid *Autunia* sp. (USNM 610503, locality 43833). F. Pinnate foliage of indeterminate plant (USNM 610507, locality 43827), possibly marattialean fern. Although similar to the specimen illustrated in image (E), note size difference. G. Walchian conifers branch fragment of form similar to that illustrated in images (A) and (B). The specimen is partially 3-dimensionally preserved and embedded in a thin drap of finer sediment, which obscures details. New Mexico Museum of Natural History and Science specimen NMMNH P-14029.

features can be arranged in a developmental series as the stratigraphic column is ascended. This has prompted the interpretation of two series, one containing two species and the other three found in New Mexico and Texas, respectively, and as possibly indicating species lineages (Romer and Price, 1940). On the basis that the Sangre de Cristo *Ophiacodon* is closely comparable to *O. retroversus* of the Texas species lineage, the lower portion of the formation was judged correlative with the Lower Permian Archer City and Petrolia formations in north-central Texas, which indicates either an upper Coyotean or Seymourian age, which straddles the Wolfcampian-Leonardian age boundary (Lucas, 2006). This correlation is consistent with the recognition of a substantial hiatus (unconformity) at the base of the Sangre de Cristo Formation across much of the Rowe-Mora basin (Baltz and Myers, 1999).

With the exception of the *Ophiacodon* cf. *O. retroversus* specimen (CM 47771), all of the vertebrates listed in Table 1 from the Sangre de Cristo Formation are consistent in indicating an Early Permian, Wolfcampian age. Collectively, the vertebrate assemblage represents a mixture of aquatic, semi-aquatic, semi-terrestrial and terrestrial fauna. Among the identified taxa are several that are important in providing an insight into the prevailing climatic conditions during the deposition of the Sangre de Cristo Formation. Most notable is the lungfish *Gnathorhiza* sp. (Fig. 10B), which on the basis of their preservation in aestivation burrows in the Lower Permian of Texas, Oklahoma, and Abo Formation in New Mexico (Romer and Olson, 1954; Olson and Daly, 1970; Berman, 1976, 1979), clearly indicates a climate punctuated by periods of severe seasonal drought. Although their presence in the Sangre de Cristo Formation can only be unquestionably documented by tooth plates, it should be noted that Vaughn (1964) reported cylinders resembling natural casts of aestivation burrows of *Gnathorhiza* from near the top of the formation, but unfortunately no bone was preserved in them that would confirm his identification.

Although identified on the basis of a single vertebra in the Sangre de Cristo Formation, *Lysorophus* has also been described as being preserved in Lower Permian, aestivation burrows in Oklahoma (Olson, 1971). Olson (1958, 1977) also suspected that *Diplocaulus*, identified from the Sangre de Cristo Formation on the basis of two vertebrae (Fig. 10D), may have been not only capable of aestivation, at least during early growth stages, but also certainly capable of surviving severe drought conditions, even as adults.

AGE AND CORRELATION

As stated above, Desmoinesian conodonts at the top of the Porvenir Formation at our Starvation Peak section provide a maximum possible age of the Sangre de Cristo Formation. No biostratigraphically useful data were discovered in the lower half of the formation during this study. Such data appear at the base of our San Miguel measured section (Fig. 3), where the *Ophiacodon* specimen discussed above was collected. Other vertebrate body fossil localities also are all from unit A. These fossils indicate an age close to the Coyotean-Seymourian boundary,

using the land-vertebrate biochronology of Lucas (2006), which is a late Wolfcampian age.

Vertebrate footprints from unit B are indicative of a similar age because they show no evidence of the changes that take place in the footprint fauna early in the Leonardian (Voigt and Lucas, 2013; Lucas, 2014). Therefore, vertebrate biostratigraphy suggests

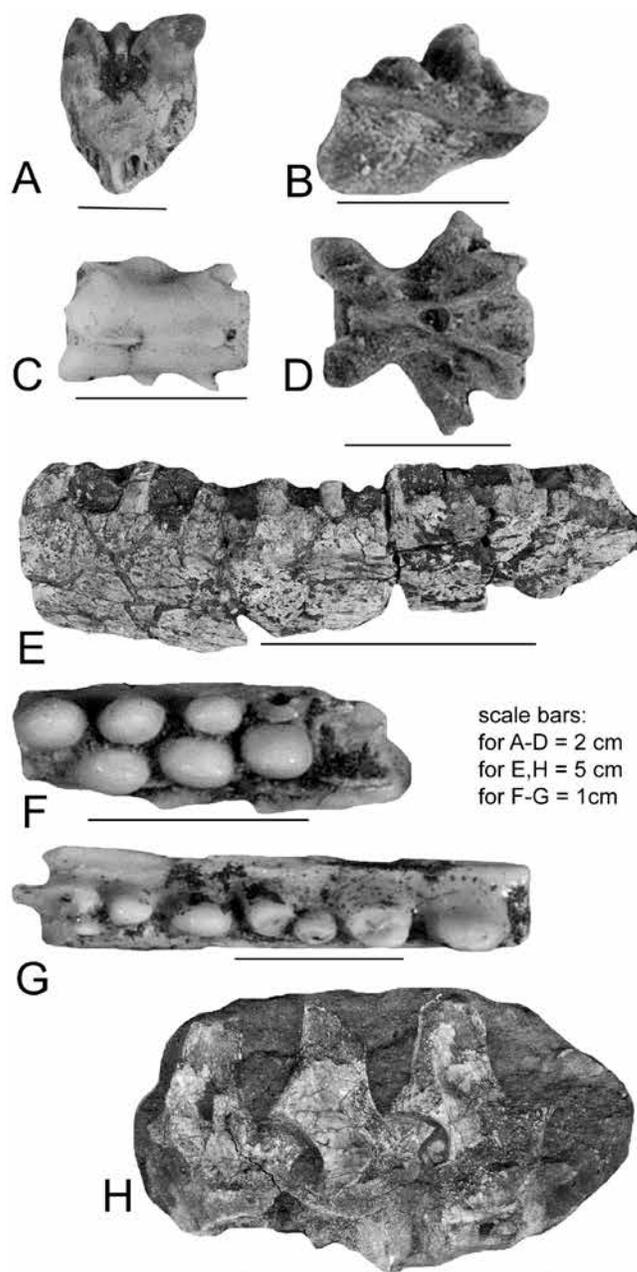


FIGURE 10. Selected fossil vertebrates from the Sangre de Cristo Formation in the Ribera-Villanueva area in southwestern San Miguel County in the collections of the Carnegie Museum of Natural History (CM). A. CM 89280, xenacanth tooth. B. CM 89281, part of tooth plate of *Gnathorhiza* sp. C. CM 89279, vertebra of *Phlegethonia* sp. D. CM 89278, vertebra of *Diplocaulus* sp. E. CM 76854, jaw fragment of *Eryops* sp. F-G, CM 89277 (F) and 89276 (G), jaw fragments of a captorhinid. H, CM 76847, vertebrae of *Sphenacodon* sp. All specimens are from CM locality 1571, except for (E) and (H), which are from CM localities 3708 and 3705, respectively.

TABLE 1: Vertebrate fossils from the Sangre de Cristo Formation and specimens, in parentheses, which are the basis of their identifications. All are cataloged into the collections of the Carnegie Museum of Natural History.

Chondrichthyes (sharks)	Temnospondyli (amphibians)	Synapsida ("pelycosaurs")	Captorhinomorpha (reptiles)
Elasmobranchii	Temnospondyls indet. (partial maxilla; dentary; dermal bones)		
Family Xenacanthidae - <i>Xenacanthus</i> , species indet. (teeth) -Dipnoi (lungfish) - <i>Gnathorhiza</i> , species indet. (tooth plates)	Family Eryopidae - <i>Eryops</i> , species indet. (jaw fragments; intercentrum; right pelvis) Superfamily Dissorophioidea Family Dissorophidae - <i>Platyhystrix</i> cf. <i>P. rugosus</i> (Case, 1910) (spine fragment) Lepospondyli (amphibians) Family Diplocaulidae - <i>Diplocaulus</i> , species indet. (vertebrae) Family Phlegethontiidae - <i>Phlegethonia</i> , species indet. (vertebra) Family Lysorophidae - <i>Lysorophus</i> , species indet. (vertebra) Diadectomorpha (?Amniota) Family Diadectidae - <i>Diadectes</i> , species indet. (skull with lower jaw; jaw fragments; vertebra and femur)	Family Ophiacodontidae - <i>Ophiacodon</i> cf. <i>O. retroversus</i> (Cope) Romer and Price, 1940 (vertebrae, pelvis, right hindlimb and pes) - <i>Ophiacodon</i> , species indet. (maxillary fragments; partial centrum; pectoral girdle; ilium) Family Sphenacodontidae -Sphenacodontids indet. (partial maxilla; jaw fragments; ilium fragments and pubis) - <i>Sphenacodon</i> , species indet. (three articulated dorsal vertebrae)	Family Captorhinidae Indeterminate genera and species (jaw fragments; maxillary fragment; maxillary fragments with single and double rows of teeth)

a late Wolfcampian (Early Permian) age for the upper half of the Sangre de Cristo Formation in southwestern San Miguel County.

The age of the lower half of the Sangre de Cristo Formation is unresolved here from direct evidence. We follow Baltz and Myers (1999; also see Krainer et al., 2004) to conclude that the entire formation is likely of Early Permian age. However, direct evidence needs to be discovered to justify that inference, as the base could be as old as Desmoinesian (Middle Pennsylvanian).

A Wolfcampian age of much or all of the Sangre de Cristo Formation in southwestern San Miguel County indicates it is correlative with most or all of the lithologically similar Abo Formation to the south and west (Lucas et al., 2013c). It also temporally overlaps much of the Cutler Group section in the Chama basin of northwestern New Mexico (Lucas et al., 2010; Berman et al., 2015).

SEDIMENTATION

Soegaard and Caldwell (1990; also see Caldwell, 1987) argued that the Sangre de Cristo Formation in northern New Mexico is a southward-thinning wedge of sediment deposited in response to a pulse of the Ancestral Rocky Mountains orogeny. Our study area

in southwestern San Miguel County is at the southernmost, distal end of this wedge, and thus is a much thinner and finer grained section than the Sangre de Cristo Formation to the north.

Lithofacies

Within the Sangre de Cristo Formation we distinguished the following lithofacies types (lithofacies codes after Miall, 1978, 1981, 1985, 1996, 2010):

- Gcm:** Clast-supported, poorly-sorted conglomerate, composed of reworked carbonate clasts (pedogenic carbonates). Rarely, granite and quartzite clasts are present (San Miguel section: Fig. 3). Individual beds are 0.1–0.4 m thick. This lithofacies is rare, comprising less than 1% of the sections.
- Gmm:** Matrix-supported, poorly sorted conglomerate composed dominantly of reworked carbonate clasts and some quartzite clasts. Grain size is up to 2 cm. This lithotype is very rare, and it forms the base of the Sangre de Cristo Formation (Starvation Peak) where it rests on crinoidal limestone of the underlying Porvenir Formation (Fig. 2).
- Gt:** Trough-crossbedded conglomerate composed of reworked carbonate clasts derived from caliche. Crossbedded

conglomerate commonly has an erosive base and its grain size is upward fining. Clast size rarely exceeds 3 cm. Individual beds are 0.1–1.4 m thick.

- d) **Se**: Sandstone containing abundant rip-up clasts (red mudstone-siltstone intraclasts) is very rare in the Punta de la Mesa section (<1%).
- e) **St**: Trough-crossbedded sandstone, medium to coarse grained and partly pebbly is a common lithotype that occurs rarely as small-scale, most commonly as medium-scale, trough cross-bedded sandstone. Thicker sandstone units are composed of stacked cosets of multistory channel fill successions with internal erosional surfaces. Near bed tops the sandstone is locally bioturbated. In the Chamizal section (Fig. 3), ripples are developed locally on top of individual sets, and on the bedding surface footprints and fossil plants occur. Locally, channels are cut into the underlying mudstone with a relief of almost 1 m. Individual intervals are mostly <2 m thick, and rarely up to 7.1 m thick. This lithofacies comprises up to 17% of the studied sections.
- f) **Sp**: Planar crossbedded sandstone is very rare (<1%), and at San Miguel consists of up to 2.1 m thick, stacked cosets.

- g) **Sl**: Fine-grained sandstone with low-angle cross-bedding is very rare (Punta de la Mesa), and overlain by horizontally laminated sandstone (<1%).
- h) **Sh**: Horizontally laminated sandstone is rare in all sections, comprising up to about 3% of the total section. This lithofacies occurs as thin beds intercalated in mudstone/siltstone or on top of crossbedded sandstone. Thickness ranges from 0.1 to 0.9 m.
- i) **Sm**: Massive sandstone is rare and commonly bioturbated; it occurs as individual beds up to 0.9 m thick or associated with horizontally laminated and ripple-laminated sandstone.
- j) **Sr**: Ripple laminated coarse siltstone to fine-grained sandstone is a common lithofacies intercalated in mudstone/fine siltstone. This lithofacies occurs as thin beds intercalated in mudstone/siltstone or as thicker units up to 2.7 m thick, associated with horizontally laminated (Sh) and massive sandstone (Sm). Rarely, ripple-laminated sandstone is developed on top of trough crossbedded sandstone (St). Ripples occur as individual ripple cross-laminated sets often separated by horizontal lamination and rarely as climbing ripple cross lamination. Dessiccation cracks are common in this facies. Some ripple laminated sandstone beds are bioturbated. Locally, tetrapod footprints and fossil plants (conifers) occur on bedding planes of Sh intercalated in Sr. This lithofacies comprises 5–7% of the total succession.
- k) **PC**: Intercalated in red mudstone are distinct, ledge-forming massive to nodular pedogenic limestone beds that are 0.1–1 m thick (comprising up to 3.8% of the succession). In the San Miguel section (Fig. 3), massive carbonate beds in the lower part display rhizoliths.
- l) Red mudstone to fine-grained siltstone is the most common lithotype and occurs mostly as massive (**Fsm**) and rarely as laminated (**Fl**) beds. A few mudstone intervals contain pedogenic carbonate nodules. Mudstone intervals are up to about 7 m thick, rarely up to 26.8 m thick. Mudstone comprises 68–73% of the thicker sections.

These lithofacies types occur as individual beds intercalated in the mudstone facies or are arranged into facies assemblages displaying a characteristic geometry and representing distinct “architectural elements” sensu Miall (1985, 1996, 2010). Each architectural element represents particular processes occurring within a depositional system.

Sandstone sheets are the most characteristic facies assemblage in the Sangre de Cristo Formation and correspond to architectural elements CH (channel) and SB (sandy bedforms) of Miall (1996). Sandstone sheets are up to several m thick. They form distinct ledges that can be traced laterally over at least 100 m. Many sandstone sheets have an erosive base. Locally, channels are cut into the underlying mudstone facies with a relief up to about 1 m.

Two types of sandstone sheets can be distinguished:

- 1) Sandstone sheets composed dominantly of lithofacies St, associated with lithofacies Sl, Sh, Sm and rare Sp and Sr. This lithofacies assemblage is common and corresponds to the architectural element CH. Intercalated thin conglomerate

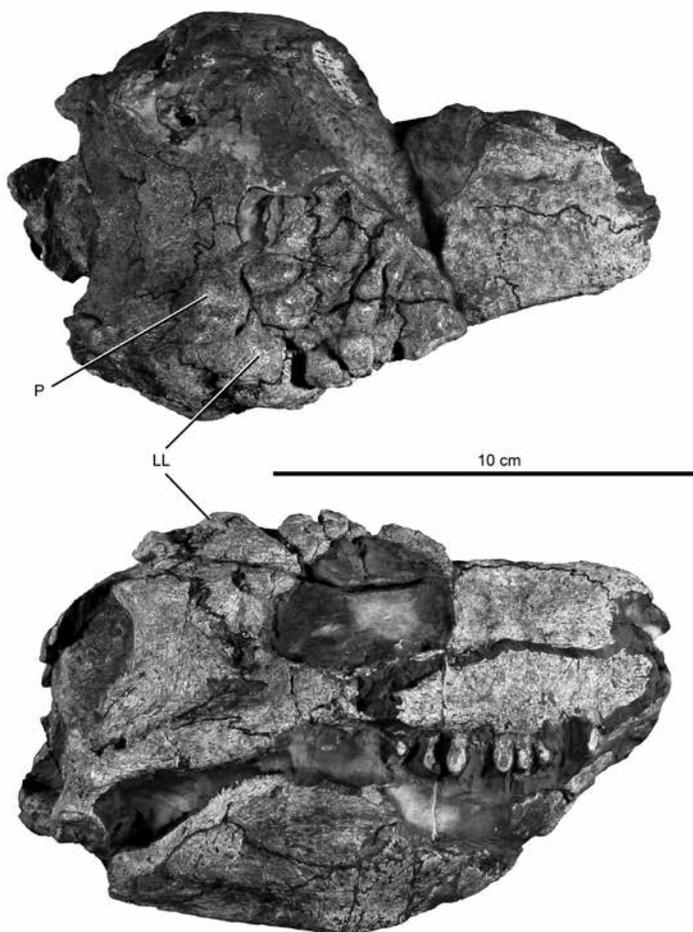


FIGURE 11. Skull of *Diadectes* sp. from the Sangre de Cristo Formation, CM 25741 in A. dorsal and B. lateral views. Abbreviations: P, parietal; LL, lateral lappet of parietal representing the incorporated right intertemporal.

beds at the base and within stacked cosets of multistory channel fill successions represent conglomerate lags at the bases of individual channels. These sandstone sheets are interpreted to have been deposited in broad, shallow channels of a braided river system. Architectural element CH composed of a similar assemblage of lithofacies types is also present in the Abo Formation of northern New Mexico (Krainer and Lucas, 2010).

- 2) The other type of sandstone sheets is dominated by lithofacies Sr, associated with Sh, Sm and rare Sl representing the architectural element SB. Mudcracks are common within the ripple-laminated sandstone. This assemblage is rare in the Sangre de Cristo Formation, but common in the Abo Formation in central and southern New Mexico (Lucas et al., 2012, 2013c).

The sandstone sheets of the architectural element SB are interpreted as deposits of broad, shallow channels of a braided stream system during periods of high influx of fine sand. Random fluctuations in flow velocity and deposition rate caused compound cross-bedding (Krainer and Lucas, 2010; Lucas et al., 2013c).

Thin intercalated beds and lenses of coarse-grained siltstone to fine-grained sandstone are 0.1–0.5 m, rarely up to 1 m thick. They occur as single sandstone beds or as stacked units. Typical lithofacies are Sr, Sh, St and Sm, forming tabular or lens-shaped sandstone bodies. Krainer and Lucas (2010) described similar intercalated sandstone beds and lenses in the Abo Formation in northern New Mexico. Intercalated sandstone beds and lenses are also a common architectural element in the Abo Formation in central New Mexico (Lucas et al., 2013c) and southern New Mexico (Lucas et al., 2012). We interpret the tabular sandstone beds as sheet splay deposits that formed by sheet-like, non-channelized flow from a crevasse channel into the floodplain. As in the Abo Formation (Krainer and Lucas, 2010; Lucas et al., 2012, 2013c), these intercalated sandstone beds represent the architectural element CS (crevasse splay) of the overbank environment *sensu* Miall (2010). Intercalated sandstone lenses most likely represent minor channel fills of feeder channels of the sheet splays (crevasse channels, architectural element CR according to Miall, 2010). According to Miall (2010), such intercalated sandstone beds and lenses of limited lateral extension are characteristic elements of the overbank environment.

The main lithofacies of the Sangre de Cristo Formation is siltstone-mudstone (lithofacies Fsm), which occurs as units up to tens of m thick that laterally extend over large distances. This facies is interpreted as floodplain deposits (architectural element FF—floodplain fines of Miall, 2010) of the overbank environment. Floodplain fines formed from overbank sheet flow and from deposition from suspension during waning flood. Absence of lamination partly results from bioturbation.

Mudstone fabrics indicative of pedogenesis are common and vary from platy to prismatic, although crumb fabrics occur rarely. Several mudstone beds display prominent pedogenic slickensides. Root traces are common features in most mudstone beds, extending to a maximum vertical length of 40 cm (Fig. 5E). Less common are calcareous nodules, which vary from small (1–2 cm)

bodies with diffuse boundaries to vertically stacked, discrete cm-scale nodules (rhizocretions).

In contrast to most of the mudstone beds in the Sangre de Cristo Formation that contain calcretes that are immature Stage I to II, the lower part of unit B contains the most mature calcrete beds (Stage III to IV of Gile et al., 1966), with stacked nodules forming coalescing upper boundaries. The overall character of the paleosols suggests a persistent semi-humid, seasonal climate during most of the interval of deposition, but with increased aridity during formation of the more mature calcretes.

Intercalated micritic limestone beds contain root traces, are of laterally variable thickness and grade to nodular calcretes. These are interpreted as floodplain pond carbonates that have undergone pedogenic alteration (palustrine limestones), indicating longer periods of soil formation under dry conditions (Tanner, 2000, 2010; Alonso-Zarza, 2003).

Depositional Environments

According to Soegaard and Caldwell (1990), deposits of the Sangre de Cristo Formation represent a foreland basin fill of braided alluvial sediments that were deposited on a broad alluvial fan in response to tectonic movements of the Ancestral Rocky Mountain orogeny. The facies of the sections we studied belong to the upper alluvial megasequence of Soegaard and Caldwell (1990), which consists of interbedded sandstone/conglomerate and mudstone. These authors distinguished two main facies: (a) major, coarse-grained braided-channel sandstone facies and (b) mudstone-dominated floodplain facies. According to Soegaard and Caldwell (1990), these sediments were derived from the Cimarron uplift (arch) to the north.

Sediments of the Sangre de Cristo Formation are red beds dominated by fine-grained deposits of the overbank environment and subordinately composed of coarser deposits of isolated broad, shallow channels of low gradient and low stream power represented by sandstone sheets. The depositional environment was very similar to that of the Abo Formation in northern and central New Mexico described by Krainer and Lucas (2010) and Lucas et al. (2013c).

Sandstone sheets with trough crossbedded sandstone being the dominant lithofacies type are interpreted as deposits of major channels in which the coarsest sediment was transported and deposited. Sandstone sheets dominated by ripple cross lamination are rare and represent deposits of broad and very shallow channels in which high amounts of silt and fine-grained sand was transported and deposited. Thin sandstone beds and lenses resulted from the progradation of crevasse channels and crevasse splay deposits from the major channels into the floodplain.

The flora of the Sangre de Cristo Formation red beds appears to be much the same as that of the finer grained units (Abo and Robledo Mountains formations) to the south, and likely indicates seasonally dry climates and that much of Early Permian New Mexico was covered with conifer forests of great extent and low biodiversity. The fossil vertebrate assemblage from the upper Sangre de Cristo Formation encompasses

xenacanth sharks, lungfishes, lepospondyl and temnospondyl amphibians, diadectomorphs and eupelycosaur and represents a mixture of aquatic, semi-aquatic, semi-terrestrial and terrestrial fauna. The tetrapod footprints and vertebrate body fossils indicate a late Wolfcampian age.

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