Lucas, S.G., et al. eds., 2013, Carboniferous-Permian Transition in Central New Mexico. New Mexico Museum of Natural History and Science, Bulletin 59.

FIELD GUIDE TO THE CARBONIFEROUS-PERMIAN TRANSITION IN THE CERROS DE AMADO AND VICINITY, SOCORRO COUNTY, CENTRAL NEW MEXICO

SPENCER G. LUCAS[1], W. JOHN NELSON[2], WILLIAM A. DIMICHELE[3], KARL KRAINER[4], JAMES E. BARRICK[5], SEBASTIAN VOIGT[6], DAN S. CHANEY[3], SCOTT ELRICK[2] AND JUSTIN A. SPIELMANN[1]

[1] New Mexico Museum of Natural History and Science, 1801 Mountain Rd. NW, Albuquerque, NM 87104;
[2] Illinois State Geological Survey, 615 East Peabody Drive, Champaign, IL 61820, email: jnnelson@illinois.edu;
[3] Department of Paleobiology, NMNH Smithsonian Institution, Washington, DC 20560, USA;
[4] Institute of Geology and Paleontology, University of Innsbruck, Innsbruck, A-6020, AUSTRIA; email: Karl.Krainer@uibk.ac.at;
[5] Department of Geosciences, Texas Tech University, Lubbock, TX 79409, USA, email: jim.barrick@ttu.edu;
[6] Urweltmuseum GEOSKOP/Burg Lichtenberg (Pfalz), Burgstrasse 19, Thallichtenberg, D-66871 GERMANY

OVERVIEW

This field guide contains roadlogs for a three-day trip to the Cerros de Amado and vicinity east of Socorro, northern Socorro County, New Mexico to examine rocks and fossils of Pennsylvanian and Early Permian age. The first day's tour looks at the Middle Pennsylvanian record in this area, which encompasses the oldest Carboniferous rocks present locally. The second day tour focuses on the Upper Pennsylvanian record, and the third day on the Lower Permian record.

The three roadlogs begin at what we call the Bosquecito road junction just east of the Rio Grande at Escondida Lake (Fig. 1). We also provide a separate "entry log" (based on the roadlog in the 2009 NM Geological Society Guidebook) that starts at the Macey Center of New Mexico Tech in Socorro and proceeds to the Bosquecito road junction.

Entry Log

Mileage Description

0.0 Parking lot entrance (electronic marquee) at Macey Center, New Mexico Tech Campus. Turn right. **0.1**

0.1 Turn right onto Canyon Road. Tech Golf Course constructed on Holocene and Late Pleistocene piedmont slope. **0.3**

0.4 Intersection with Buck Wolff Road, **continue straight**. NM Tech Police station on right. Buildings on right are New Mexico Bureau of Geology and Mineral Resources core storage facilities. Note Socorro Peak to west at about 7:00 with prominent "M" (for School of Mines) near summit. Socorro Peak is a west-tilted intrarift horst that exposes the northern topographic wall of the Socorro caldera. Most of the rocks that make up the peak are of Miocene age, capped at the peak by the Upper Miocene rhyolite of Socorro Peak. **0.2**

0.6 Cross flood control ditch and **take immediate right** onto East Road. Note dissected alluvial fans here that are the piedmont deposits of Socorro Peak. **0.5**

1.1 Stop sign at New Mexico Tech Research Park, **turn right** and continue on East Road. IRIS/PASSCAL, a NSF Earth Science Research facility for geophysical studies is on left after turn. **0.2**

1.3 Soil profile covered by alluvial fan debris exposed on left in Mid to Late Pleistocene sediments. **0.2**

1.5 U. S. Geological Survey groundwater research lab on right. This facility is located on ancestral Rio Grande sands and gravels. This facility was used to study infiltration and evaporation rates in these sediments. **0.1**

1.6 Muddy floodplain deposits (mostly mudstones and siltstones) of the ancestral Rio Grande are unconformably overlain by Late Pleistocene gravels in roadcuts, particularly to the left. **0.2**

1.8 Gate across road, often locked on weekends and after 8:00 p.m. in the evening. **0.1**

1.9 Socorro flood control berm visible to your right at 2:00. This berm diverts flash floods from the mountain range around the city. **0.2**

2.1 A Quaternary age fault can be seen at 10:30 as an east-facing fault scarp. Polvadera Peak at 10:00, Manzano Mountains at 12:00, Los Pinos Mountains at 1:30 and Joyita uplift (including the Cerros de Amado) at 2:00-4:30. **0.9**

3.0 Bridge over Nogal Canyon. Old sanitarium buildings against the hill to your left, are now occupied by a paintball park. Note breach in levee to left caused by recent flooding. Socorro wellhead at right. **0.2**

3.2 Former Eagle-Pitcher battery plant on right. **0.2**

3.4 Large roadcut in floodplain facies deposits of ancestral Rio Grande on left. These are fluvial and floodplain sands, silts and muds of Pliocene age. **0.1**

3.5 Cross frontage road, New Mexico State Police station on right. Continue straight through underpass under I-25 and past frontage road on east side of interstate. This underpass was filled up to a meter deep with water when the levee failed in 2006. **0.1**

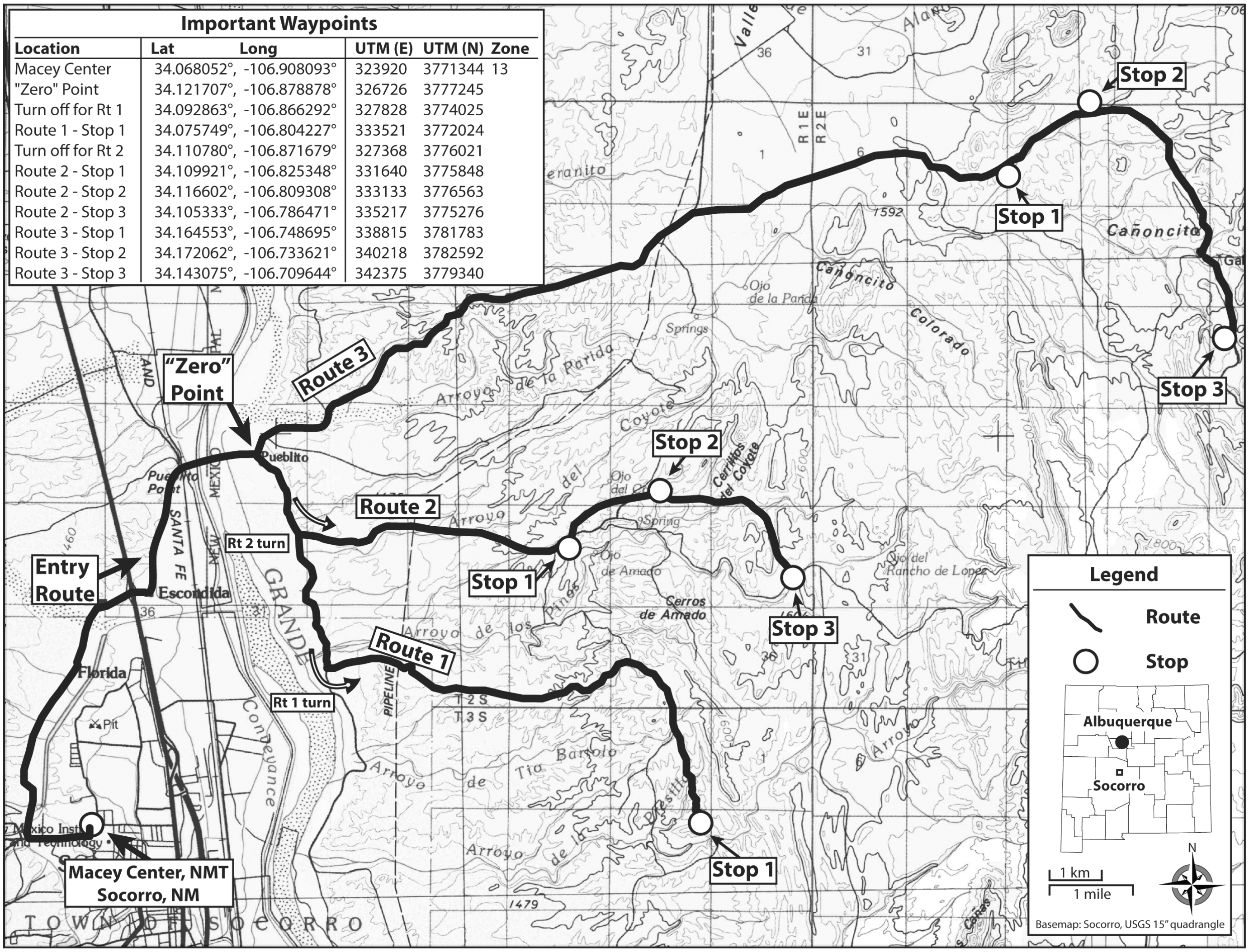
3.6 Sign for Scenic Byway at the village of Escondida, cross cattleguard. Escondida (Spanish for "hidden") is a defunct village, first known on the 1860 Census of the New Mexico Territory (Julyan, 1998). **0.1**

3.7 **Turn hard left** and stay on pavement. **0.1**

3.8 The old Escondida School on left. **0.2**

4.0 Pliocene floodplain deposits of the ancestral Rio Grande unconformably overlain by piedmont gravels of mid to late Pleistocene age in roadcuts on left. Good view to right of Rio Grande floodplain; note bosque (forest) beyond agricultural fields. The floodplain originally was covered with cottonwood bosque, and early Pleistocene plants found near the Albuquerque International Airport indicate an approximately 1.4 Ma minimum antiquity of the bosque. However, human intervention (for agricultural purposes) has generally cut the bosque back so that it only adjoins the Rio Grande along a relatively narrow strip. **0.4**

4.4 Excellent exposure of axial river deposits of the ancestral Rio Grande in large cut behind house on left. Note the trough cross



Important Waypoints

Location	Lat	Long	UTM (E)	UTM (N)	Zone
Macey Center	34.068052°,	-106.908093°	323920	3771344	13
"Zero" Point	34.121707°,	-106.878878°	326726	3777245	
Turn off for Rt 1	34.092863°,	-106.866292°	327828	3774025	
Route 1 - Stop 1	34.075749°,	-106.804227°	333521	3772024	
Turn off for Rt 2	34.110780°,	-106.871679°	327368	3776021	
Route 2 - Stop 1	34.109921°,	-106.825348°	331640	3775848	
Route 2 - Stop 2	34.116602°,	-106.809308°	333133	3776563	
Route 2 - Stop 3	34.105333°,	-106.786471°	335217	3775276	
Route 3 - Stop 1	34.164553°,	-106.748695°	338815	3781783	
Route 3 - Stop 2	34.172062°,	-106.733621°	340218	3782592	
Route 3 - Stop 3	34.143075°,	-106.709644°	342375	3779340	

FIGURE 1. Route map for roadlogs to the Carboniferous-Permian transition in the Cerros de Amado and vicinity.

bedding. Across the Rio Grande, to the east, in Arroyo de la Parida, these strata yield fossil mammals that indicate a Pliocene (~2.7-3.2 Ma) age. Road follows Middle Rio Grande Conservancy District irrigation ditch, which sustains cultivation on the modern Rio Grande floodplain below and to your right. **0.7**

5.1 Intersection with Pueblito Road, **turn right** to Escondida Lake (and Park). The lake was originally an abandoned oxbow of the Rio Grande that has been modified into the modern lake that resembles a borrow pit. The lake is stocked and provides opportunities for fishing and picnicking for visitors. Cross Burlington-Santa Fe Railroad tracks. **0.2**

5.3 Intersection with Escondida Lake access road on left. Continue straight over low flow conveyance channel of the Rio Grande and main flood control levee. Entering Rio Grande bosque. **0.1**

5.4 Cross "Four Mile" bridge over the Rio Grande. Note groundwater monitor well field to your right. **0.2**

5.6 Leave Rio Grande bosque. **0.1**

5.7 Ascending low terrace into the little village of Pueblito. According to Julyan (1998), Pueblito was probably settled during the 1850s by the former residents of La Parida, a nearby village that was lost to the Rio Grande. On the 1860 census it was called Pueblito de la Parida, and remains today as an unincorporated cluster of houses and small farms. **0.2**

5.9 Intersection with the Bosquecito Road, which runs down the east side of the Rio Grande, eventually intersecting U.S. 380 near San Antonio. The "Quebradas Backcountry Byway" branches off the Bosquecito road approximately 1 mile south of this point. **This is the zero point of the following three days of roadlogs.** Days 1 and 2 proceed south on this road, day 3 proceeds north.

FIRST DAY ROADLOG – SANDIA AND GRAY MESA FORMATIONS AT THE ARROYO DE LA PRESILLA

Summary

Today's trip is short, but traverses a very rugged road, to the head of the Arroyo de la Presilla, just south of the Cerros de Amado (Fig. 1). The stop is at one of the few places where the Proterozoic basement is exposed locally, overlain depositionally by the Middle Pennsylvanian Sandia Formation. The Sandia Formation here has yielded fossil plants, conodonts and selachians, part of the stop's focus. A walking tour from the stop allows close inspection of the excellent (and characteristic) exposures of the Sandia Formation, and of much of the overlying Middle Pennsylvanian Gray Mesa Formation.

Mileage Description

0.0 **Bosquecito road junction; turn right and proceed south. 0.1**

0.1 Pavement ends. **0.8**

0.9 Quebradas road (the BLM's "Quebradas Backcountry Byway") to left is the route of the second day roadlog; **continue straight. 0.5**

1.4 Cross cattleguard. **0.2**

1.6 **Road forks (three roads); take the middle road and then make a hard right. 0.2**

1.8 Cross cattleguard; sign on right says we are entering the Eva Hilton Lewis Ranch, which is the property of New Mexico Tech (New Mexico Institute of Mining and Technology). **0.3**

2.1 Cross Arroyo de Los Pinos. **0.1**

2.2 **Road to left, turn left.** Put vehicle in four wheel drive. **0.7**

2.9 Cross pipeline; continue straight. **0.1**

3.0 Road to left; continue straight to climb hill to right. **0.3**

3.3 We have ascended a bajada surface (coalesced alluvial fans); go to left to pass through gate. **1.0**

4.3 The road dips through a saddle. The tan and gray gravels to the left belong to the Upper Cenozoic Santa Fe Group. **0.7**

5.0 **Road forks; both forks lead to the same place, but the left fork is a better road. 0.2**

5.2 Crest of hill; the road crosses the rift-bounding fault about here. **0.2**

5.4 Outcrops to right are Pennsylvanian Sandia Formation. **0.1**

5.5 **Road enters from left, continue to right. 0.1**

5.6 Road now on Pennsylvanian limestone. **0.2**

5.8 Road enters from left; stay on main road by bearing right. **0.1**

5.9 Another road enters from left; good view of step- and ledge-forming outcrops of Gray Mesa Formation ahead. **0.1**

6.0 The road is now entrenched in an arroyo; sandstones to right are part of the Sandia Formation. **0.2**

6.2 Pass through gate. **0.2**

6.4 Ridge on left is a linear, very localized outcrop of the Proterozoic granitic basement. Road to right, stay left to cross the arroyo (this is probably the worst segment of the road on today's trip). **0.3**

6.7 Crest of hill; outcrops all along road here are faulted strata of the Sandia Formation. **0.3**

7.0 Breached stock dam that was excavated in shale of the Sandia Formation; the road now climbs the hill to the left. **0.5**

7.5 **STOP** at saddle before road proceeds steeply down the hill. The hill (ridge) immediately to the west of us is a granite ridge draped with sandstone of the Sandia Formation.

Here, at the "head" of the Arroyo de la Presilla we can examine three main features. Two are within 100 meters of the stopping point – the depositional contact of the Middle Pennsylvanian Sandia Formation on the Proterozoic basement and Herrick's (1904) lycopsid-dominated fossil plant site, his "coal-measure forest," in the Sandia Formation. The third feature is the entire Sandia Formation section and most of the overlying Gray Mesa Formation. Beautifully exposed here, examination of these units requires a walk (roundtrip) of about 3 to 5 km over rugged terrain.

1. Sandia Formation. At Arroyo de la Presilla, the Atokan Sandia Formation is 162 m thick, rests on granitic Precambrian basement and consists of a cyclic succession of siliciclastics and carbonate, nonmarine and marine strata forming well developed transgressive cycles (Figs. 2-3). The lower 46 m are almost entirely composed of siliciclastic sediments with only one thin limestone bed. The next 46 m are composed mostly of siliciclastic sediments with several intercalated fossiliferous limestone horizons. The uppermost 70 m are dominantly siliciclastics with thin limestone interbeds in the upper part.

We recognize the following lithotypes in the Sandia Formation in the Arroyo de la Presilla section (Fig. 3): conglomerate (2.5% of the section) coarse sandstone (23.5%), fine-grained sandstone/coarse siltstone (11.2%), shale/fine siltstone (11.5%, covered 44.3%) and limestone (7%). The base of the formation is a 2-m-thick conglomerate bed, that grades upward into pebbly sandstone and sandstone; stratigraphically higher conglomerate beds are thinner, about 1 m thick. These conglomerates are quartz-rich, poorly to moderately sorted and relatively fine-grained, with a maximum grain size of about 3 cm; the grains are mostly subrounded, but angular to subangular near the base. At the base of the formation a thin lag with boulders up to 20 cm in diameter is developed. The conglomerate beds have erosive bases and are indistinctly to distinctly trough cross-bedded.

Coarse-grained sandstone is commonly trough cross-bedded, rarely displays planar cross-bedding and may be pebbly. The sandstone is quartz-rich, reddish and individual quartz grains are up to 1-2 cm in diameter. Sandstone intervals are up to 4.7 m thick, fining upward, and composed of multistoried channel fills. Individual sandstone beds contain fossil plant fragments, including stem fragments up to > 1 m long. The sandstone intervals display erosive bases, and rarely (unit 53) mudstone clasts (rip-up clasts) up to 10 cm are present. The sandstone is composed of abundant mono-crystalline quartz, subordinate polycrystalline quartz, rare detrital feldspars, which are almost completely altered to clay minerals ("pseudomatrix"), very rare detrital muscovite and rock fragments of quartz and feldspar (granitic), rare chert grains and phyllitic (metamorphic) rock fragments. Some opaques--rare grains of zircon, tourmaline, apatite and sphene--are present. A few clayey sedimentary rock fragments may also be present (AP 20). Sandstones (quartzarenite) are cemented by authigenic quartz overgrowths, with locally fine crystalline quartz cement in the pore space. The sandstone is stained red by very small hematite, finely dispersed in the quartz cement. Some clayey matrix (<5%) may be present. Feldspar content is less than 5 % throughout the succession. Locally small patches of coarse calcite cement replacing quartz or fine-crystalline carbonate cement occur.

In the upper part of the formation coarse blocky poikilotopic calcite cement replaces quartz and feldspar. Also, in the upper part mixed siliciclastic carbonate fossiliferous sandstone is present with thin micritic layers (or large rip-up clasts). This sandstone is medium- to coarse-grained, subangular to subrounded, poorly sorted and indistinctly laminated.

Most abundant is monocrystalline quartz, subordinate poly crystalline quartz, some micritic carbonate grains and few detrital mica. Fossils include shell fragments of gastropods and brachiopods, crinoid fragments, few brachiopod spines, rare ostracods, large micritic rip-up clasts (several cm long) containing few gastropods, bryozoans and echinoderms.

FIGURE 2. Photograph of the old "fire-clay" pit in the Sandia Formation at the Stop at the head of Arroyo de la Presilla.

The "fire clay" of Herrick (1904) in the lower part of the section is light gray, 0.5 m thick and contains plant fossils. With considerable effort, this material was mined during the late 19th and early 20th century and packed or hauled to Socorro for making bricks. Although "fire clay" usually denotes non-fissile claystone such as the underclay of a coal seam, this deposit consists of laminated silty shale to siltstoneIt is underlain by dark gray, laminated, silty claystone containing *Lingula* and plant fossils. The overlying yellowish-brownish siltstone contains abundant impressions of *Lepidodendron* and associated wetland plants (Herrick, 1904; Darton, 1928; Lucas et al., 2003, 2009)

Thick siltstone/fine-grained sandstone intervals occur in the lower part of the Sandia Formation section, below and above the "fire clay." The thickness of these intervals is from 1.2 to 4.7 m. Thinner siltstone/fine-grained sandstone layers are also developed on the top of conglomerate/sandstone units (up to 1.3 m thick) and rarely as thin (0.3 m) intercalations in shale. The most common lithofacies are horizontally laminated and ripple laminated (small-scale current ripples) siltstone to fine-grained sandstone. Small-scale trough cross-bedding is also observed. Rarely, fine-grained sandstone is bioturbated.

From 21 to 26 m above the base of the Sandia Formation section, greenish-brownish silty shale is poorly exposed with a thin micaceous sandy siltstone intercalated in the lower part and a thin fossiliferous limestone in the upper part. The shale immediately below and particularly above the limestone contains abundant marine fossils such as crinoids, bryozoans, brachiopods and rugose corals. In the middle and upper part of the section shale intervals are mostly covered and up to 6.6 m thick in the middle part and up to 12.8 m thick in the upper part. Marine fossils such as crinoids and brachiopods occur in a 4-m-thick brownish shale in the middle part of the section (unit 46).

In the lower part of the section, only one thin limestone bed (10-20 cm thick) is poorly exposed, which is fossiliferous and contains brachiopods and bryozoans. The microfacies of this limestone is coarse-grained, poorly sorted bioclastic wackestone to packstone containing few bioclasts larger than 1 cm. The most abundant fossils are bryozoans and crinoids, subordinate are brachiopod shell fragments and brachiopod spines, echinoderm spines, gastropods and trilobite fragments, rare ostracods and smaller foraminifers (*Endothyra*). Many skeletons are encrusted by cyanobacteria, *Calcivertella* and *Claracrusta*.

In the middle and upper part of the Sandia Formation, limestone intervals are 0.3-2.2 m thick, commonly brownish weathered, gray to dark gray, with bed thicknesses of 5-30 cm. Typically, the limestones are coarse-grained, sandy and fossiliferous with abundant fragments of crinoids,

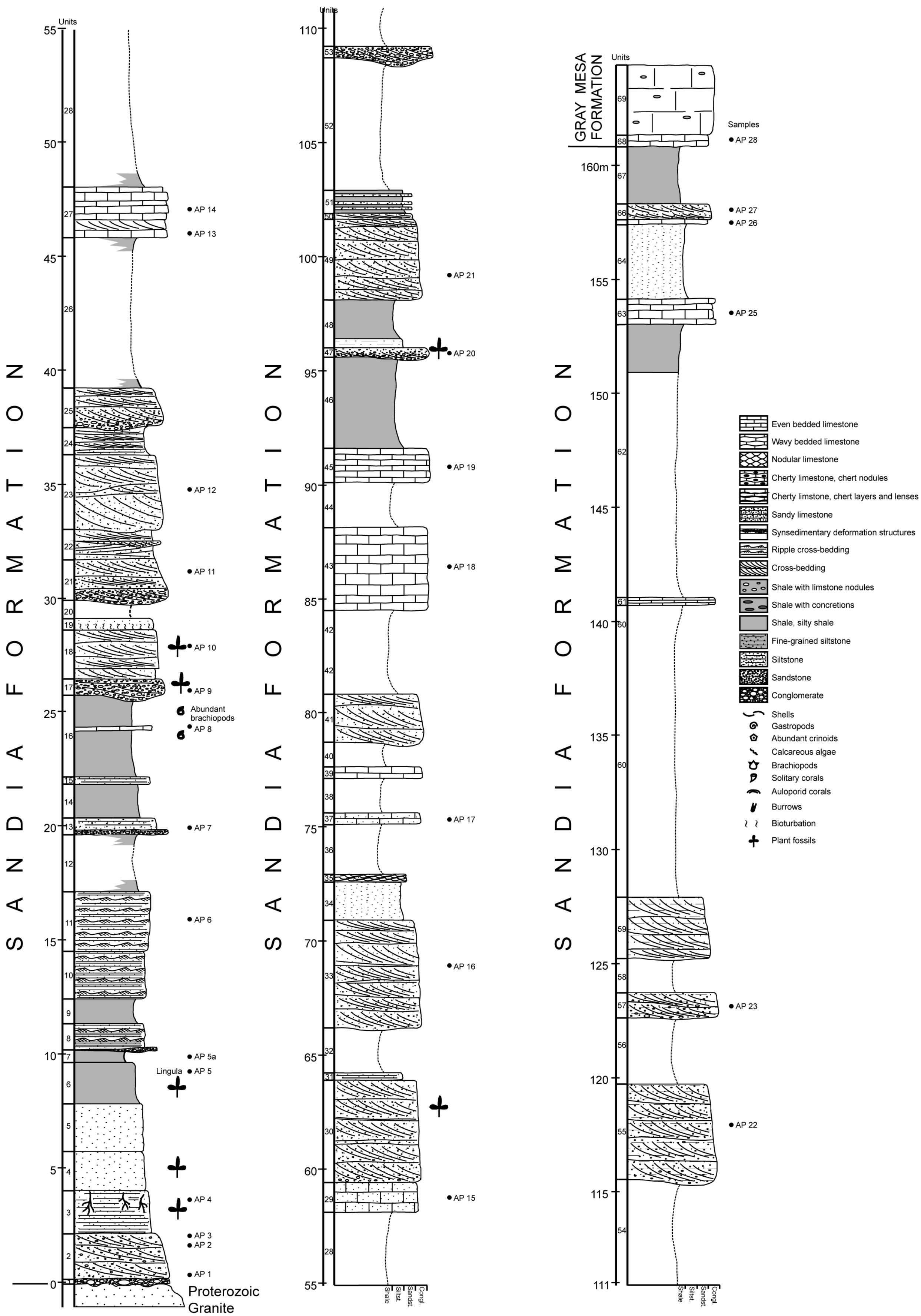


FIGURE 3. Measured section of the Sandia Formation at Arroyo de la Presilla. After Lucas et al. (2009).

brachiopods, bryozoans and (subordinately) solitary corals. Rarely the limestone displays cross-bedding (unit 27) or appears massive. The following microfacies types are observed: bioclastic wackestone to packstone and crinoidal wackestone to packstone-rudstone, and bioclastic floatstone to rudstone. A small Atokan conodont fauna of *Declinognathodus marginodosus*, *Idiognathoides sulcatus*, and *Idiognathodus incurvus*? was recovered from unit 27 (Lucas et al., 2009).

In the upper part of the section (unit 61), fusulinids and gastropods are present in a strongly altered, dark brown- to black-stained limestone bed. Quartz grains (0.1-0.3 mm, rarely up to 1 mm) are also present in amounts up to 10%. A few bioclasts are encrusted by *Calcivertella*. The rock contains micritic matrix, and locally some calcite cement. The upper most thin limestone bed (unit 65) is a recrystallized, non-laminated, fine-grained dolomitic mudstone containing abundant spicules and rare smaller foraminifers.

Bioclastic wackestone to packstone is coarse-grained, commonly grading into floatstone to rudstone, poorly sorted, indistinctly laminated and contains few bioclasts (shell fragments) up to several cm in size. The abundant, strongly fragmented bioclasts include bryozoans, crinoids and brachiopod shell fragments, subordinate are trilobite fragments, ostracods and brachiopod spines. In the upper part of the section (unit 61) fusulinids and gastropods are present in a strongly altered, dark brown to black stained limestone bed. Quartz grains (0.1-0.3 mm, rarely up to 1 mm) are also present in amounts up to 10%. Few bioclasts are encrusted by *Calcivertella*. The rock contains micritic matrix, and locally some calcite cement.

The crinoidal packstone is coarse-grained, moderately to poorly sorted, non-laminated to indistinctly laminated, with grain sizes mostly 0.5-2 mm, rarely up to > 1 cm (rudstone). This microfacies contains abundant crinoid ossicles, and detrital, angular to subangular quartz grains (monocrystalline, subordinately polycrystalline quartz mostly 0.3-1mm). Subordinate are bryozoans, brachiopod shell fragments and spines and rare trilobite fragments and ostracods. Few bryozoan fragments, rarely crinoids are encrusted by *Calcivertella*. This type is well washed and calcite cemented. Quartz is present in various amounts, mostly < 5%; individual thin layers contain 20-70% quartz.

The uppermost thin limestone bed (unit 65) is a recrystallized, non-laminated, fine-grained dolomitic mudstone containing abundant spicules and rare smaller foraminifers.

Structurally, this site reveals two east-tilted fault blocks composed of Proterozoic granite and Sandia Formation. Both are west dipping, high-angle normal faults that probably developed during Cenozoic rifting. Mineralization and hydrothermal alteration along the faults prompted efforts at small-scale mining. The eastern fault is well exposed on the north side of the main arroyo, southeast of the parking place.

2. Herrick's "coal forest." In 1904, Clarence Luther Herrick described a lycopsid flora (including three new species of *Lepidodendron*) from "fire clay" (shale) of Pennsylvanian age being mined for brick manufacturing here, at the head of Arroyo de la Presilla (Figs. 2, 4). Herrick's description of the locality was vague, and it had not been revisited in nearly a century, but in 2002 we relocated Herrick's locality.

The "fire clay" is a refractory gray to black shale in the lower part of the Sandia Formation that can be followed on strike through a series of fault blocks for more than 2 km. We suggest that the succession of Sandia Formation strata that encompass Herricks' plant locality represent fluvial deposits directly overlain by an estuarine deposit (lycopsid beds and "fire clay"). Our collections of fossil plants from the lycopsid bed (Fig. 5) include *Lepidodendron aculeatum*, *Lepidostrobus*, possibly *Synchysidendron*, stigmarian roots and strap-like leaves of the lepidodendrids, *Sphenophyllum*, and neuropterid foliage. Because the type specimens of the species of *Lepidodendron* Herrick named were destroyed in a fire in 1910, we collected new specimens to serve as "topotypes" of the species. However, most of Herrick's species appear to be within the range of variability known from the single species *Lepidodendron aculeatum.* This lycopsid locality in the Sandia Formation is significant because it indicates that a typical wetland swamp flora existed in New Mexico during early tectonism of the Ancestral Rocky Mountain orogeny.

3. Gray Mesa Formation. Descend the steep draw southeast of the parking area to the main stream bed and proceed up stream (east) approximately 400 meters beyond exposures of the eastern fault having Precambrian granite in the footwall. At this point, turn left and follow a large side ravine on the north-northwest to view the Gray Mesa Formation along the moderately steep, west-facing hillside.

At the Arroyo de la Presilla, we measured most of the Gray Mesa Formation (Fig. 6). The measured section is 192.6 m thick; the lowermost 8 m represent the uppermost Sandia Formation. The Gray Mesa Formation can be divided into the Elephant Butte Member (95 m), Whiskey Canyon Member (25 m) and Garcia Member (94 m). The Elephant Butte Member consists of different types of limestone, covered shale intervals, two thin sandstone beds, two thin limestone conglomerate beds, and a prominent, 10-m-thick sandstone interval in the lower part (units 32-35), which displays an erosive base and begins with coarse, pebbly quartzitic sandstone that is indistinctly cross-bedded. In the coarse-grained lower part, about 3.5 m above the base, a pebbly horizon is present that contains a few crinoid and brachiopod fragments.

In the lower part of the Elephant Butte Member, below the prominent sandstone interval, a 0.6-m-thick cross-bedded quartzose sandstone bed and a 0.3-m-thick carbonate conglomerate bed with limestone nodules up to 3 cm in diameter is present. In the middle of the member, a 0.9-m-thick cross-bedded calcareous sandstone bed is present, and 20 m higher in the section a 0.8-m-thick intraformational limestone conglomerate with limestone clasts up to 3 cm in diameter is present. Covered intervals (0.3-6.7 m thick) most likely represent shale, which is rarely exposed and of gray color. The thickness of the limestone units ranges from individual beds 0.1 m thick to intervals of multiple limestone beds 6.4 m thick. We distinguish the following limestone types: (1) thin, wavy bedded limestone with bed thickness mostly 10-20 cm; (2) thick-bedded limestone, with bed thickness commonly 20-50 cm; (3) thick-bedded, coarse, crinoidal limestone; (4) massive to indistinctly bedded algal limestone, 0.9-1.8 m thick; and (5) wavy bedded to nodular cherty limestone, thin bedded (mostly 10-20 cm).

Fossils observed in the field are algae (particularly in the massive algal limestone facies), crinoids (abundant in the crinoidal limestone facies), brachiopods, bryozoans and solitary corals. Fusulinids are rare, occur in units 80 and 99 in the upper part of the member. At the top of unit 84, small colonies of Syringopora are present. In many limestone units fossils are silicified. It is interesting that *Chaetetes*, which is common in the lower part of the Gray Mesa type section in the Lucero uplift (Krainer and Lucas, 2004), is completely absent in the Elephant Butte Member at the Arroyo de la Presilla. Conodont faunas with representatives of the *Idiognathodus obliquus* group, *Neognathodus bothrops*, and *Diplognathodus coloradoensis*, indicating an early

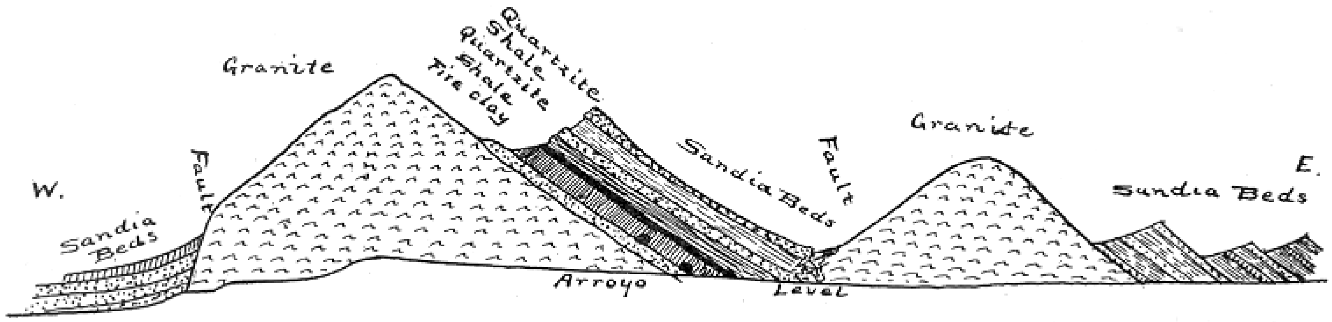


FIGURE 4. Herrick's (1904, fig. 1) geological cross section at the *Lepidodendron* locality. The plant-bearing bed is just below the "fire clay" above the Precambrian granite in the middle of the cross section.

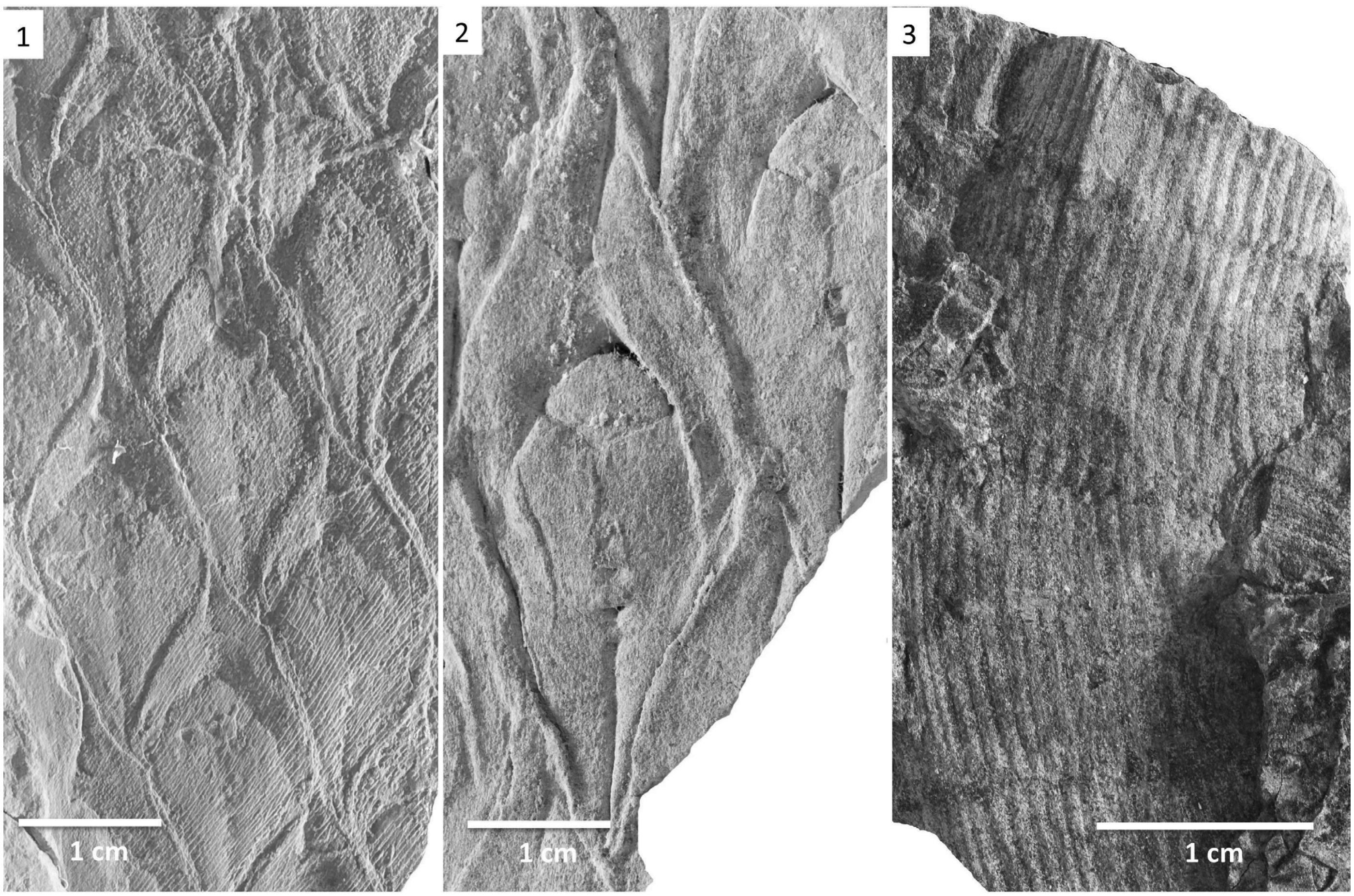


FIGURE 5. Plants from the Herrick "Coal Forest" site in the Smithsonian (USNM) collection. **1**, *Lepidodendron aculeatum*, USNM specimen 536612, USNM locality 41896. **2**, *Lepidodendron aculeatum* leaf cushion, USNM specimen 536614, USNM locality 41896. **3**, *Calamites* stem, USNM specimen 536624, USNM locality 41896. Scale bars = 1 cm.

Desmoinesian age, occur in the the Elephant Butte Member at the Arroya de la Presilla (units 16-68; Lucas et al., 2009).

We recognize the Whiskey Canyon Member as an interval about 25 m thick of very cherty limestone beds, some with abundant rugose corals, near the middle of the section of the Gray Mesa Formation (Fig. 6). Thus, this member is composed of different types of bedded limestone and some covered (shale) intervals. The cherty limestone is composed of thin and wavy cherty limestone alternating with brownish cherty silty layers. It is fossiliferous with abundant crinoids, brachiopods, rugose corals, bryozoans and local fusulinid packstone. The member also contains thick-bedded algal and crinoidal limestone, locally with minor chert, fusulinids and bryozoans. In the Whiskey Canyon Member (units 86-102), conodonts are uncommon, but members of the *Idiognathodus obliquus* group occur as do rare *Neognathodus asymmetricus*, a species indicating an early, but not earliest Desmoinesian age.

The Garcia Member (total about 94 m thick) is composed of different types of limestone, conglomerate, sandstone, shale and covered (shale) intervals. The most common limestone type is thick-bedded, locally cross-bedded crinoidal limestone. Individual units are 0.5 to 6.5 m thick. The crinoidal limestone contains some chert and locally also detrital quartz. Less abundant is thick-bedded, fossiliferous limestone containing algae,

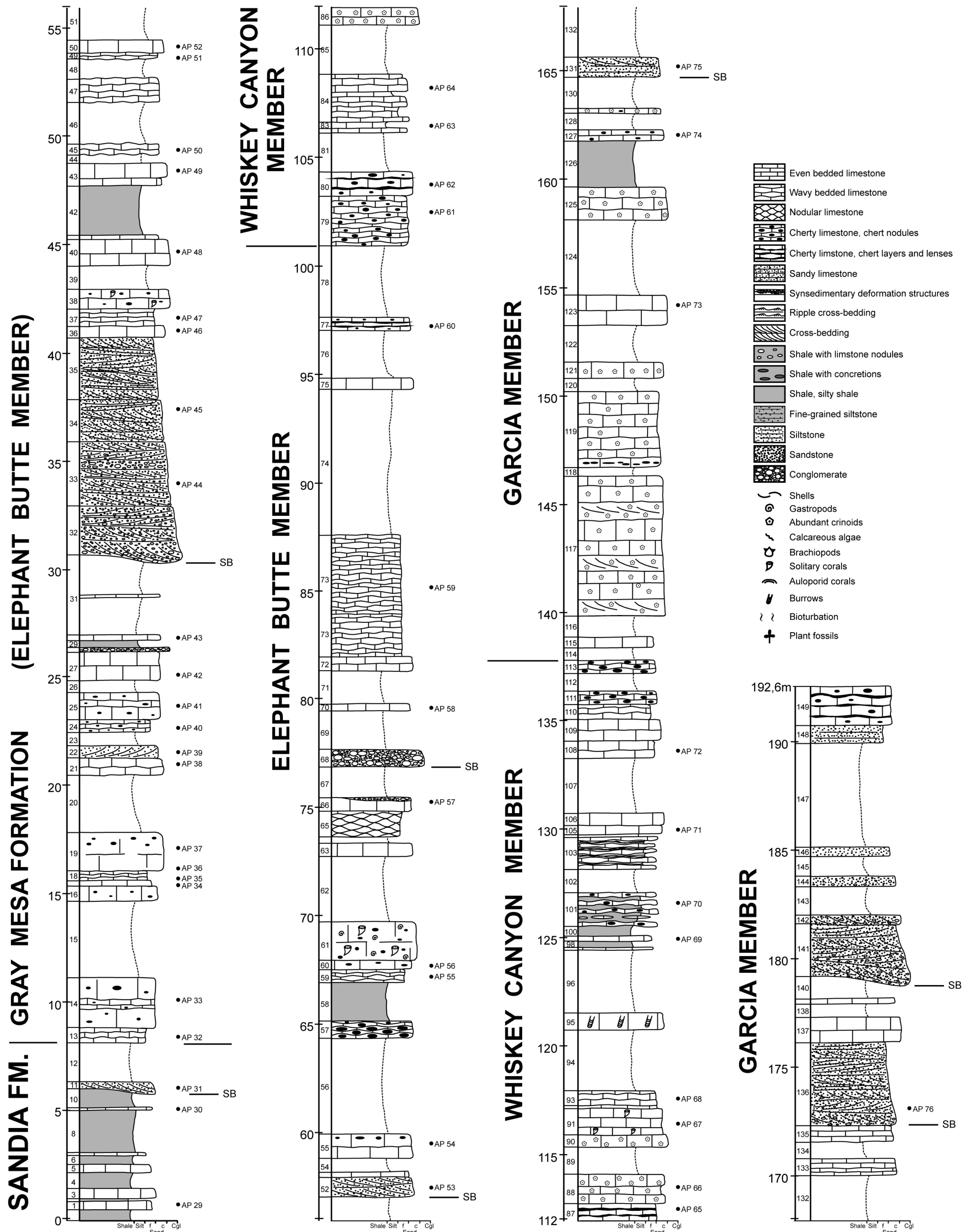


FIGURE 6. Measured section of most of the Gray Mesa Formation at Arroyo de la Presilla. After Lucas et al. (2009).

gastropods and some chert, and thin-bedded micritic fossiliferous limestone. Conglomerate/sandstone units are 0.4 to 2.5 m thick. Conglomerate beds are cross-bedded, and maximum clast size is about 2 cm, and they grade upward into cross-bedded sandstone. The sandstone is fine- to coarse-grained, arkosic, partly micaceous, partly pebbly, and dis plays trough cross-bedding, crude horizontal lamination or appears massive. The bases of the conglomerate and sandstone units are erosional, indicating sequence boundaries. The thicker conglomerate-sandstone units show a fining-upward trend, and are overlain by covered shale intervals and limestone on top, thus representing transgressive cycles. Compared to the quartzose conglomerate and sandstone of the Elephant Butte Member, the conglomerate and sandstone of the Garcia Member is arkosic and contains abundant granitic debris. One greenish-gray shale interval is exposed, the thickness is 2.1 m. Covered shale slopes are common and range in thickness from 0.4 to 4.8 m.

The lower part of the Garcia Member at this section yielded a small conodont fauna like that of the Whiskey Canyon Member. Starting at about 10 meters above of the base of the Garcia Member (units 122-133), a conodont fauna was obtained that included species similar to those from the middle Desmoinesian Verdigris cyclothem (upper Cherokee Group) in the Midcontinent and correlative strata in North America: *Idiognthdodus robustus*?, *I. iowaensis*?, and *Neognathodus medadultimus* (Lucas et al., 2009).

In the Cerros de Amado, we have found scrappy plant material in the sandstones and shales of the Garcia Member. The plants are mostly sticks, with occasional bits of foliage – none identifiable to date. The material is all allochthonous.
End of first day roadlog.

SECOND DAY ROADLOG – ATRASADO, BURSUM AND ABO FORMATIONS IN THE CERROS DE AMADO

Summary

Today's trip is short but mostly over an easily traversed, all-weather unpaved road. Its focus is on Middle-Upper Pennsylvanian strata and fossils of the Atrasado Formation, but also includes an opportunistic stop at an excellent section of the Lower Permian Abo Formation.

0.0 **Bosquecito road junction; turn right and proceed south. 0.1**

0.1 Pavement ends. **0.8**

0.9 **Turn left, to proceed east onto the "Quebradas Backcountry Byway"** and cross cattleguard. **1.7**

2.6 On Quebradas Road, cross Arroyo del Coyote. Road is climbing hill, a bajada of Cenozoic alluvial deposits. **0.8**

3.4 **Turn right at Quebradas Road sign, proceed about 0.1 mile to parking area.**
STOP 1. Overlook of Socorro, Rio Grande valley and distant mountain ranges (on a clear day). Ojo de Amado (spring) is along valley floor to southeast. View of geology south of spring is best in afternoon sun. Pennsylvanian bioherms are lined up here along the rift boundary fault. Proceed on foot down jeep trail to bottom of canyon, continue ahead (south) about 100 m. Here we will examine a superbly exposed section of much of the Middle-Late Pennsylvanian Atrasado Formation, overlain by a characteristic section (Fig. 7) of the early Wolfcampian Bursum Formation up to the base of the Abo Formation red beds:

Stop 1A. Rift-boundary fault. Here is the eastern major boundary fault zone of the Rio Grande rift. The zone juxtaposes upthrown Pennsylvanian sedimentary rocks on the east side of the arroyo with downthrown, steeply dipping, sheared Cenozoic volcanic rocks on the west side. The latter consist of volcaniclastic sandstone, conglomerate, debris-flow breccia, and minor mudstone of the lower part of the Spears Group, dated as middle to late Eocene (Cather and Colpitts, 2005). Overlying the Spears Group with an angular unconformity is horizontal gravel of the Santa Fe Group (Pliocene to Pleistocene).

Pennsylvanian rocks nearest to the boundary fault belong to the Amado Limestone Member of the Atrasado Formation (lower Missourian, Upper Pennsylvanian). Bedding is overturned, dipping 50 to 60° west. Eastward from this point, as we will shortly observe, bedding rotates through vertical to rapidly decreasing east dips with the strata right side up. The geometry of this overturned fold clearly is inconsistent with the sense and direction of Cenozoic down-to-the-west extensional faulting. The overturned fold reflects an early episode of east-verging (west side upthrown) compressional deformation, which undoubtedly took place during the Laramide orogeny (Late Cretaceous to Eocene). A series of smaller north-east-verging thrust faults and folds further represent Laramide deformation in this area (Cather and Colpitts, 2005).

This site also bears evidence of a third episode of structural deformation during the Ancestral Rocky Mountains (ARM) orogeny of Pennsylvanian time. A series of large algal bioherms (best viewed from the parking area in afternoon) in the Amado Limestone and older Gray Mesa Formation are closely aligned with the rift-boundary fault. These units rarely exhibit bioherms away from the fault. Moreover, a large bioherm occurs in the Council Spring Limestone Member close to the boundary fault a short distance southeast of where we are standing (Hambleton, 1962). Bioherms developed in relatively deep, quiet water as algae and other organisms built mounds, seeking to remain within the photic zone. Their alignment along a fault at several stratigraphic levels suggests recurrent episodes of subsidence along the fault. Walk up the arroyo toward Ojo de Amado, climbing a cow path on the north side to reach the top of the natural rock wall crossing the stream.
Stop 1B. Ojo de Amado overlook. We are standing atop vertically dipping limestone layers in the upper part of the Tinajas Member of the Atrasado Formation (Missourian, Upper Pennsylvanian). As we continue up the canyon, we will climb through the younger Council Spring, Burrego, Story, Del Cuerto and Moya members of the Atrasado (Missourian and Virgilian, Upper Pennsylvanian) (Fig. 7). Near the lowest limestone ledge is a sharp structural flexure, east of which the bedding dip rapidly declines to about 20°.

Proceed up the canyon, observing diverse rock types in the upper Atrasado Formation. The massive Moya Limestone has been deeply sculptured by flowing water, creating a small maze of potholes and widened crevices. Upon reaching the top of the Moya, climb the ledges on the north side of the canyon to reach the top of the Atrasado Formation.

At Ojo de Amado most of the Atrasado Formation (approximately 141 m) is well exposed, overlain by 24 m of Bursum Formation and Abo red beds (Fig. 7).

The section starts with the Tinajas Member, which is approximately 93 m thick and can be divided into three intervals:

a) The lower 33 m are mainly composed of gray and brownish, and rarely reddish shale. Many intercalated limestone beds are mostly 0.1-0.3 m thick, and there is one

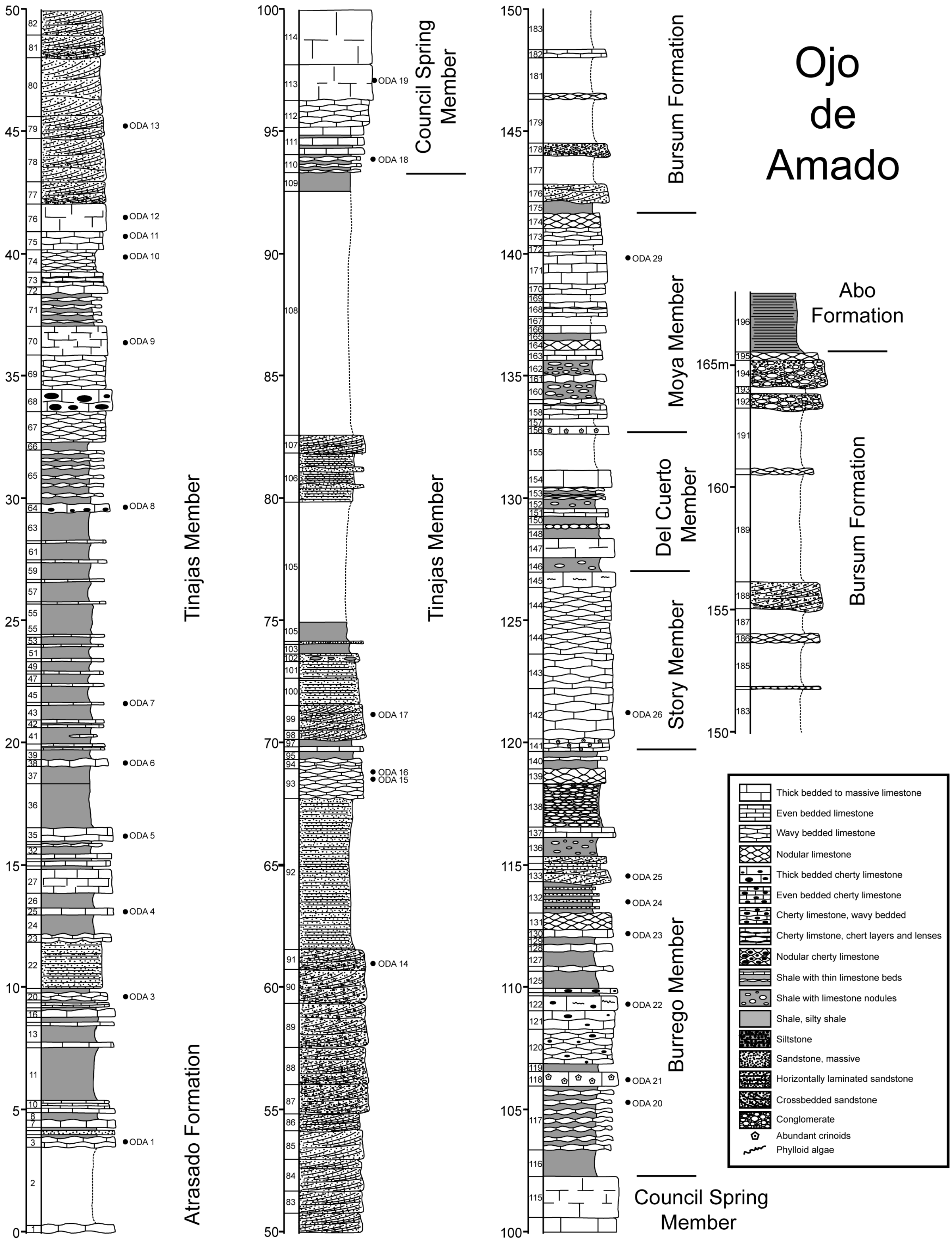


FIGURE 7. Measured stratigraphic section of much of the Atrasado Formation, the Bursum Formation and the base of the Abo Formation at Ojo de Amado.

thicker, bedded limestone interval (1 m). One limestone bed in the upper part contains chert nodules. Limestone is muddy and composed of mudstone, wackestone and rare floatstone. In the lower part, laminated calcareous siltstone (0.2 and 1.9 m thick) is intercalated.

b) The middle interval is approximately 10 m thick and dominantly limestone: wavy limestone beds alternate with thin, reddish-brown shale, nodular to wavy bedded limestone, thick bedded to massive cherty limestone and thick bedded to massive limestone. The microfacies is wackestone with a diverse fossil assemblage. Fusulinids occur in the upper part.

c) Above the middle limestone unit follows a 51-m-thick succession of mainly siliciclastic sediments with one thin limestone interval in the middle. Limestone is erosively overlain by 20 m of trough crossbedded, coarse-grained, partly pebbly sandstone (stacked sets 0.5 to 1 m thick), followed by pale green to gray, horizontally laminated silty shale and 2.1 m of thin, wavy to nodular bedded limestone (wackestone) containing fusulinids in the middle and upper part. This limestone interval is overlain by thin shale with a thin limestone bed intercalated. The next sequence starts with trough crossbedded sandstone that grades upward into horizontally laminated, fine-grained sandstone and greenish-gray shale with a thin sandstone bed intercalated, followed by a covered interval and 2.7 m of laminated siltstone with thin sandstone intercalated, and crossbedded sandstone. Above the sandstone is 10 m of cover, probably representing shale. The uppermost 0.8 m of the Tinajas Member is represented by greenish shale.

The Council Spring Member is approximately 9 m thick, starts with 0.7 m of thin wavy limestone beds (coarse crinoidal packstone/rudstone) and thin shale intercalations, followed by thicker bedded gray limestone (crinoidal wackestone/ packstone), thin bedded gray limestone (wackestone) containing crinoid stem fragments up to 10 cm long, followed by massive gray limestone (mostly crinoidal wackestone/ packstone) and thick-bedded limestone containing phylloid algae. The top of this limestone interval is probably a subaerial exposure surface.

The Borrego Member measures approximately 18 m and is composed of alternating limestone and shale. In the upper third thin massive carbonate sandstone beds ant two crossbedded carbonate sandstone beds are intercalated. Shale is reddish and gray, and individual shale intervals are up to 1.1 m thick, mostly less than 20 cm. Limestone occurs as thin wavy beds (commonly 0.2-0.3 m thick), wavy-bedded cherty limestone, thick-bedded cherty limestone containing algae and fossiliferous nodular limestone. Common microfacies are wackestone, floatstone and rudstone with a diverse fossil assemblage. The most abundant fossil fragments are echinoderms, bryozoans and brachiopods. The crossbedded carbonate sandstone is composed of grainstone/packstone/ rudstone containing strongly fragmented skeletons and many detrital quartz grains.

The Story Member is approximately 7 m thick and composed of light gray, wavy bedded limestone. The dominant microfacies is wackestone and floatstone (containing large skeletons of echinoderms, brachiopods and bryozoans). Individual limestone beds contain phylloid algae. The top is formed of a thicker limestone bed that also contains phylloid algae.

The Del Cuerto Member is ~5 m of alternating limestone, shale and thin covered (shale) intervals. Shale is pink, and individual shale units contain limestone nodules. Limestone occurs as thin beds (0.1-0.3 m) that are nodular or wavy, or as thicker limestone beds (0.6-0.8 m) that appear indistinctly bedded to massive and contain gastropods, larger crinoid fragments and phylloid algae. Subaerial exposure surfaces are developed on top of two thicker limestone beds represented by thin, dark brecciated crusts and rhizoliths (?).

The Moya Member is thin, measures ~9 m and is composed of fossiliferous nodular limestone composed of limestone nodules and shale and wavy bedded limestone in the lower part, thicker bedded cherty limestone containing abundant phylloid algae (phylloid algal wackestone to floatstone) in the middle and wavy bedded and nodular limestone in the upper part.

The lower limestone beds of the Tinajas Member in the Ojo de Amado section (units 7-29) yielded a moderately abundant conodont fauna with common, but small, specimens of the middle Missourian/Kasimovian *Streptognathodus gracilis* Zone, mostly *S. gracilis* and *S. elegantulus* (Barrick et al., this volume). Higher in the Tinajas Member (unit 64), an extremely diverse and abundant *Idiognathodus eudoraensis* fauna is present. In addition to *I. eudoraensis*, ungrooved *Idiognathodus* species occur, as well as common *Streptognathodus firmus*, including speciments transitional to the older Eurasian species *S. isakovae*. A much reduced *eudoraensis* fauna continues up through unit 68. The middle of one limestone bed in the upper part of the Tinajas Member (unit 93), produced elements of *S. pawhuskaensis*,which ranges from the late Missourian into the Virgilian, and from the late Kasimovian into the Gzhelian.

A few small *Idiognathodus* elements, most of which can be assigned to *I. toretzianus* and *I. lobulatus*, were obtained from the lower part of the Council Spring Member (unit 111). The presence of the latter species suggests a early Virgilian and an earliest Gzhelian age for the Council Spring Member. In addition to a large number of *S. pawhuskaensis* elements, a few specimens of *S. ruzhencevi* and *S. vitali* were recovered from a unit 118 in the lower part of the Borrego Member; the latter species is the index for the early Virgilian/Gzhelian vitali Zone. At the base of the Story Member at the Ojo de Amado section (unit 141), specimens transitional from *S. vitali* to *S. virgilicus* appear, which indicate the *virgilcus* Zone. No diagnostic conodonts were obtained from the Del Cuerto Member. The *S. virgilicus* fauna continues into the lower part of the overlying Moya Member (unit 159), where morphotypes similar to the middle Virgilian species *S. holtensis* appear. No age-diagnostic conodonts were obtained from the upper part of the Moya Member nor the overlying Bursum Formation at the Ojo de Amado section.

There are plant fossils, mostly allochthonous in the Atrasado Formation here, depending on how far down the arroyo one progresses. The fossils are primarily allochthonous and occur in shales of the Middle Pennsylvanian/Desmoinesian Bartolo Member and the Late Pennsylvanian/Missourian Tinajas Member of the Atrasado Formation. Compositionally, the flora is dominated by forms found most commonly in seasonally dry climatic regimes, particularly conifers, *Sphenopteridium*, and *Charliea*, mixed with wetland elements, particularly neuropterid pteridosperms.

Stop 1C. Bursum and Abo outcrops. The Bursum Formation here is rather thin and composed of mostly covered intervals of probably red mudstone/siltstone (Fig. 7). In the lower part two coarse-grained, crossbedded sandstone beds are intercalated. Above three thin (0.1-0.3 m) nodular pedogenic limestone beds and one nodular marine limestone bed (0.4 m) containing crinoidal debris are exposed.

Above a thin covered interval a 1.1 m thick coarse-grained, crossbedded sandstone bed occurs that contains granitic detritus. The top of the Bursum Formation is formed by two conglomerate beds. The lower conglomerate is 0.6 m thick, massive, poorly sorted, clast-supported and composed of abundant limestone clasts and sandy matrix. The upper conglomerate is 1.1 m thick, poorly sorted, clast-supported and contains abundant subangular grains of reworked granitic rocks with diameters up to 3 cm. This conglomerate is overlain by 0.3 m of nodular micritic limestone which forms the very top of the Bursum Formation.The Bursum (upper Virgilian to lower Wolfcampian, latest Pennsylvanian) consists of poorly exposed, gray and variegated non-fissile mudstone with a few layers of gray nodular limestone and dark gray weathering, coarse arkosic sandstone. Although the base of the Bursum is a regional unconformity, little relief is evident along the contact here. Near the top of the Bursum, large rounded quartz pebbles and fresh pink feldspar pebbles can be found. These probably were sourced from Precambrian granite in the Joyita uplift, about 20 km north of this point. The Joyita underwent tectonic uplift near the end of the Pennsylvanian, resulting in local truncation of the Pennsylvanian section with the Abo and Bursum Formations locally deposited directly on granite (Kottlowski and Stewart, 1970; Krainer and Lucas, 2009). Overlying the Bursum with apparent conformity is the Abo Formation, which is composed of predominantly brick-red mudstone, siltstone, very fine sandstone, and intraformational conglomerate. We will not linger to observe the Abo here, because it is exposed much better at the next stop. **Return to the vehicles. After the STOP, continue to drive east on the Quebradas Road. 0.9**

4.3 Abo Formation outcrop along road, overlain by Yeso Group strata north of road. About here we cross the rift-bounding fault, which juxtaposes Permian red beds (Abo Formation-Yeso Group) on the east against Pliocene (Santa Fe Group) clastics. **0.4**

4.7 Park on left side of road where narrow south-trending ravine crosses. STOP 2. Walk down the arroyo to the right to turn around and traverse Bursum-Abo-basal Yeso section here (Fig. 8).

We are parked near the middle of the Abo Formation (middle-upper Wolfcampian, Lower Permian). This is one of the few complete, unfaulted sections of the Abo in the Socorro area, measuring ~213 m thick (Fig. 8). We will begin by walking down section, to the south, to observe the lower Abo, Bursum, and upper Atrasado formations. To return, we will walk north, up section through the upper Abo to the transition with the overlying Yeso Group. These same strata will be seen tomorrow on Day 3, Stop 1.

Walk down the small canyon to the south a distance of 500-600 m, observing the geology in passing. The canyon is fenced and posted by the Four Hills Ranch; permission should be obtained before visiting Stop 2A. The other highlights of this site, Stops 2B, 2C, 2D, and 2E, are on government land and may be freely visited, detouring around fenced private property.

Stop 2A. Lower Abo Formation. This little canyon affords continuous exposures of the lower half of the formation. Immediately south of the road, we descend through ledges of reddish brown coarse siltstone to very fine sandstone. Bedding is somewhat lenticular, frequently showing shallow channel geometry. Planar and wavy lamination, cross lamination, and small-scale crossbedding are prevalent. Some channels display low-angel accretionary bedding indicative of meandering streams. Interbedded mudstone is mottled and veined with light greenish to bluish gray and contains only rare carbonate nodules.

Downward the lithology changes to 80-90% mudstone that is dark reddish brown, very silty, and massive to blocky. Irregular small nodules, inclined stringers, and vertical cylinders (rhizoliths) of limestone are abundant. Near the base of the Abo, some layers of carbonate nodules are intergrown to form semi-continuous beds (calcrete ledges). Within the mudstone are layers and lenses of siltstone and very fine sandstone. Some such layers are tabular, whereas others show channel geometry. Some siltstone and sandstone beds are massive to blocky and show paleosol features, whereas others have planar to wavy lamination and small-scale cross-lamination along with simple horizontal burrows and mud cracks. Fossil conifers, dominantly *Walchia*, are abundant in the upper part of a sandstone ledge 58 m above the base of the Abo (near the midpoint of the canyon traverse) (Fig. 9).

Two types of conglomerate occur in the lower Abo. Confined to the lower 15 m is coarse, pebbly sandstone containing clasts of quartz and fresh, pink feldspar. As with similar conglomerate in the Bursum, the Joyita uplift is the probable source. Intraformational conglomerate composed of carbonate nodules and siltstone or mudstone clasts in a silty to sandy matrix also occurs in the lower Abo, filling small bowl- or scoop-shaped channels. **At mouth of canyon, follow the larger arroyo about 300 m northeast to a cut bank on the northwest side of the arroyo.**

Stop 2B. Bursum Formation. Here is a good exposure of the upper 10 m of the formation, which consists of intercalated mudstone and bedded to nodular mudstone. Features to observe include root traces near the top, arkosic limestone about 1.5 m below the top, and the thick paleosol in the lower part of the exposure. Large slickensides, limestone nodules and stringers, and rhizoliths are developed in the variegated mudstone. The Bursum is much thinner here than at Carrizo Arroyo and lacks the thick intervals of laminated, fossiliferous shale and siltstone that characterize the latter locality. Evidently, the Cerros de Amado area underwent much slower subsidence than Carrizo Arroyo during Bursum deposition. The alternating marine limestone and claystone paleosols seen here are reminiscent of Kansas cyclothems of the same age (West et al., 2010). **Walk approximately 400 m south-southwest, entering a small canyon cutting through the ridge.**

Stop 2C. Upper Atrasado Formation. Seen here is a northwest-dipping succession similar to that viewed this morning at Stop 1. The Bursum Formation is largely eroded off the dip slope; basal beds may be found along both sides of the canyon exit and higher on the slope northeast of the canyon, where underground copper mining has taken place. Within the canyon, upper Atrasado strata comprise alternating limestone units that form small cliffs and diverse clastic rocks that erode to slopes. Despite close proximity to other measured Atrasado sections, the authors of this field guide do not agree on the identity of the members. These rocks may comprise the Story (oldest), Del Cuerto, and Moya Members or, alternatively, the Council Springs, Burrego, Story, and lower Del Cuerto Members, the upper Del Cuerto and Moya having been eroded prior to Bursum deposition.

At the upper (east) end of the canyon, we cross a fault zone that brings Abo Formation into contact with Atrasado (southeast side down). This is normal faulting, presumably related to Cenozoic rifting. **Walk northeast, climbing part way up the ridge to the abandoned open-pit mine. Beware of open shafts and, as always, watch out for snakes!**

Stop 2D. Minas del Chupadero. Small-scale mining of strata-bound copper took place here between 1958 and 1960, yielding about 2000 tons (1800 kg) of ore that averaged 2% copper (Jaworski, 1973). Low-grade ore, mainly malachite, is disseminated in gray sandstone, siltstone, and silty shale. Although Jaworski identified the host rock as Moya, we consider it to be basal Bursum Formation. Fossil plants (mostly fragmentary) collected at this site include *Odontopteris* and other ferns, *Walchia*, *Cordaites*, and *Calamites*. They suggest wetlands surrounding a lake or other small body of water.

Return to the vehicles.

Stop 2E. Upper Abo Formation and basal Yeso Group. If time permits, walk up the small canyon north of the vehicles, keeping to the left where the canyon forks and continuing to the head of the ravine. Approximately 400 m north of Quebradas Road, hikers will reach a more gently sloping hillside, where the U.S. Bureau of Land Management formerly allowed citizens to quarry flagstone. This area marks the transition from the Abo Formation to the overlying Yeso Group (Leonardian; Lower Permian). Characterizing the Yeso is an absence of mudstone (common in the Abo) and a change in color and character of sandstone. Whereas Abo sandstone is almost uniformly brick red, sandstone of the Yeso may be white, light gray, yellow, light red to orange, and bluish to greenish gray. The sand is fine grained, well sorted, quartzose, and cemented by calcite. Straight-crested and ladderback ripple marks are common, whereas crossbedding and lateral accretion are not developed. Sandstone layers are typically tabular rather than channel form. Fossils of any kind are exceedingly rare. These changes may reflect an increasingly arid climate, lack of flowing streams, and an increase in sediment transport by the wind. Also note that tetrapod tracks are the most common fossil remains of the Abo Formation in this section (Figs. 8, 10). Footprints have been found at six discrete stratigraphic levels corresponding to bed 2A, 11, 17, 24, 32 and 34 (Fig. 8).

The NMMNH (New Mexico Museum of Natural History) collection houses about 100 specimens of fossil footprints from this site attributed to *Batrachichnus*, *Limnopus*, *Amphisauropus* (Fig. 10C), *Dimetropus*, *Tambachichnium* (Fig. 10E), cf. *Varanopus* (Fig. 10F), cf. *Hyloidichnus* (Fig. 10G), and *Dromopus* (Fig. 10H). These tracks can be referred to small and large temnospondyls, seymouriamorphs, "pelycosaurs," "captorhinomorphs," and araeoscelids and are typical for the Abo red beds of central New Mexico (Lucas et al., 2013). *Batrachichnus*, *Limnopus* and *Dromopus* are remarkably abundant in the lower part of the section (bed 2A, 11, 12), whereas *Tambachichnium*, cf. *Varanopus* and cf. *Hyloidichnus* are known only from the upper part of the section (bed 17, 32, 34). This distribution may reflect the phylogeny and ecology of Early Permian terrestrial tetrapods considering the radiation of "captorhinomorphs" during the late Early Permian (Voigt et al., 2009) and potential habitat preferences of certain trackmakers (Voigt and Lucas, 2012). Also, a taphonomic bias cannot be excluded.

In general, fossil-plant-bearing deposits are rare in the Bursum Formation. In the area of Quebradas Road most of the exposed terrestrial deposits of the Bursum are paleosols. However, in the area of the former Chupadera copper mine, sandstones are exposed that contain a scrappy flora of conifers, pteridosperms and tree ferns. Although not stratigraphically diagnostic, or even sufficiently preserved to characterize a Bursum assemblage, this flora does indicate that the mixture of wetland and seasonally-dry substrate plants continued in this region into the latest Pennsylvanian. A much better representation of Bursum plants is preserved to the north in the area that will be examined on Day 3 of this field trip.

Plant fossils occur throughout the Abo Formation in the Quebradas Road area (Fig. 9). The Abo Formation is characterized here, as elsewhere, by an exceptionally low diversity flora dominated almost exclusively by conifers of several kinds and the peltasperm *Supaia thinnfeldioides*. The next most commonly encountered kind of plant, *Autunia* (formerly *Callipteris*) *conferta* occurs much less commonly. Of the other 25-30 species known from the Abo Formation throughout New Mexico, nearly all are very rare, though they may appear as dominants at any given collecting site. Plant fossils are most commonly found in siltstone/fine-sandstone sheet deposits, most often in upper parts of these fining upward benches where, thin coarser-grained beds are clay draped; this often results in platy debris aprons on slopes below these beds. The plant fossils occur in association with invertebrate and vertebrate trackways, mudcracks, raindrop imprints and fine sedimentary structures.

After the STOP, continue east on the Quebradas Road. 0.3

5.0 After crossing small valley, road bends to right. Note tilted Yeso Group strata to left in fault zone that has aspects of transtensional or pull-apart. Cresting ridge, looking south at a mosaic of tilted blocks of Yeso on lower slopes with cliff of Atrasado behind. Major fault (down to NW) crosses mid slope. **0.6**

5.6 Concrete ford, crossing fault just mentioned. The trace fossil site reported by Minter and Lucas (2009) is to the left. This NMMNH locality 6708, an outstanding occurrence of trace fossils in the Joyita Hills east of Socorro. Minter and Lucas (2009) described a diverse invertebrate ichnofauna from this site including *Cruziana problematica* (Fig. 10I), *Diplichnites gouldi*, *Diplichnites* isp., *Monomorphichnus* isp., *Palaeophycus tubularis*, *Rusophycus carbonarius*, and *Striatichnium* cf. *S. natalis*. The assemblage is dominated by striated bilobate traces that probably have been produced by crustaceans. Previously referred to floodplain deposits of the upper Abo Formation (Minter and Lucas, 2009) the traces have been recently reinterpreted as shallow marine ichnia situated in the upper part of the Arroyo de Alamillo Formation, about 34 m below the base of the Los Vallos Formation (Lucas et al., 2013). **0.2**

5.8 Climbing toward gap in ridge. There is a fault along the bottom of the gully to the east (left). Mesa to east has Bartolo Member capped by Amado Limestone, whereas younger Tinajas and Council Spring crop out on hillside to west. The Tinajas black shale deposit is also exposed to the right. **0.4**

6.2 Crest of ridge. Loma de las Cañas on skyline capped by San Andres over Yeso and older units. In middle distance are west dipping upper Atrasado strata. To right is Tinajas Member capped by Council Spring Member. **0.2**

6.4 **Bear right onto side road where Quebradas Road swings left, park. STOP 3.**

The area south of the Quebrada Road preserves one of the best stratigraphic and paleofloral successions of the Desmoinesian-Missourian transition in central New Mexico. Numerous fossiliferous shales and sandstones crop out in Arroyo de los Pinos and its tributaries. The plant-bearing deposits represent a variety of depositional environments, nearly all of which are allochthonous deposited in nearshore brackish to marine conditions or, more rarely in terrestrial channel deposits. Among these settings are two auto-chthonous assemblages that contrast strongly in the environ-

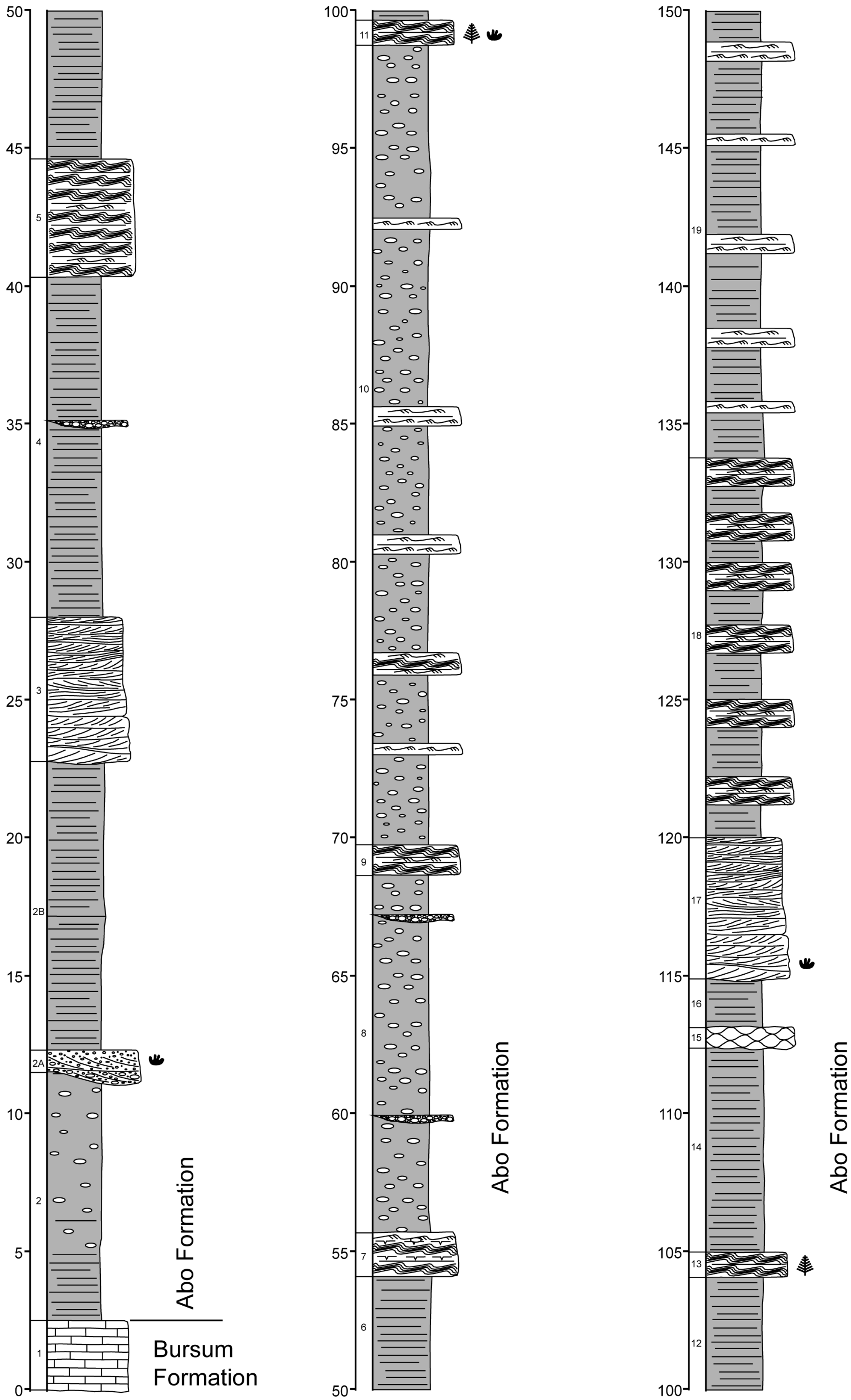


FIGURE 8. Measured stratigraphic section of the uppermost Bursum Formation, entire Abo Formation and lower part of the Yeso Group (lower part of Arroyo de Alamillo Formation) at Stop 2.

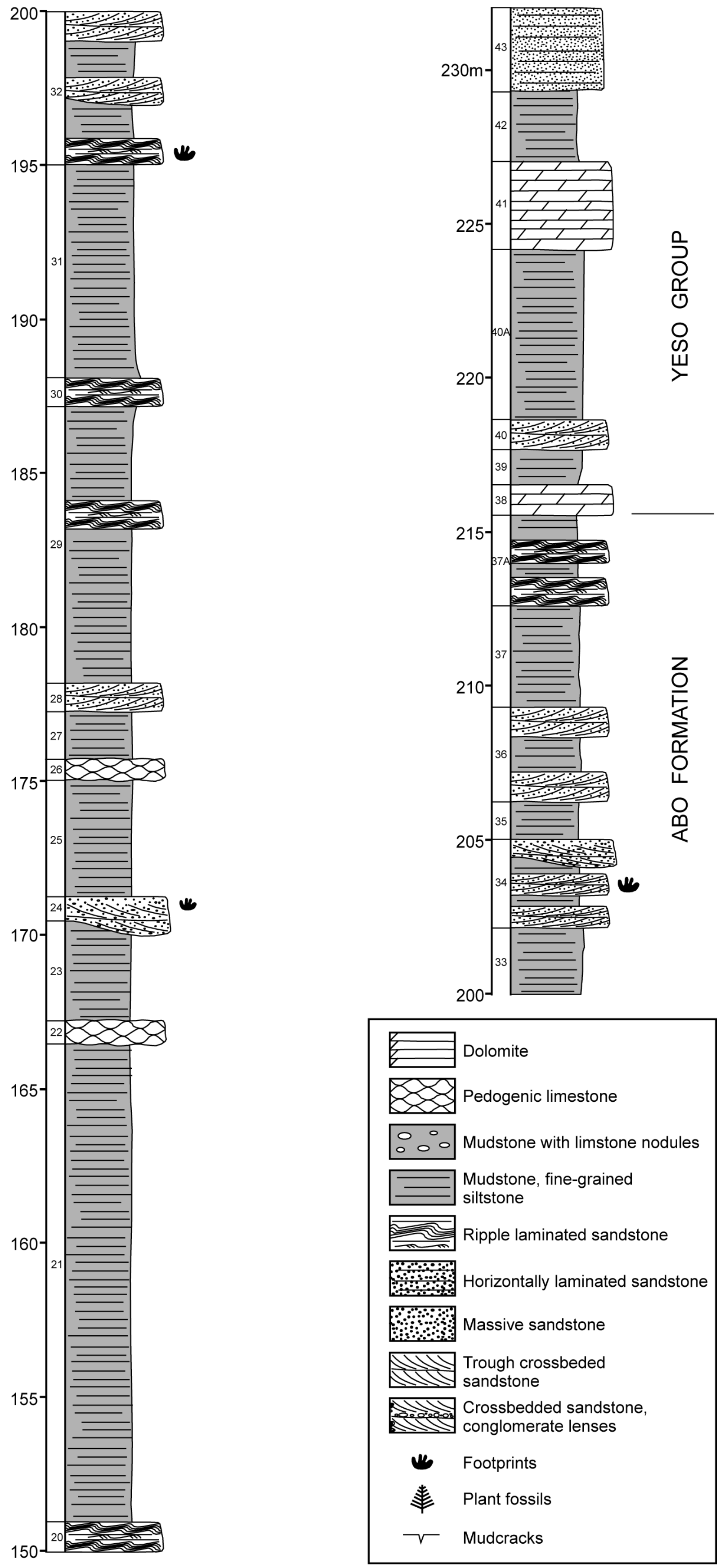


FIGURE 8. Continued. Measured stratigraphic section of the uppermost Bursum Formation, entire Abo Formation and lower part of the Yeso Group (lower part of Arroyo de Alamillo Formation) at Stop 2.

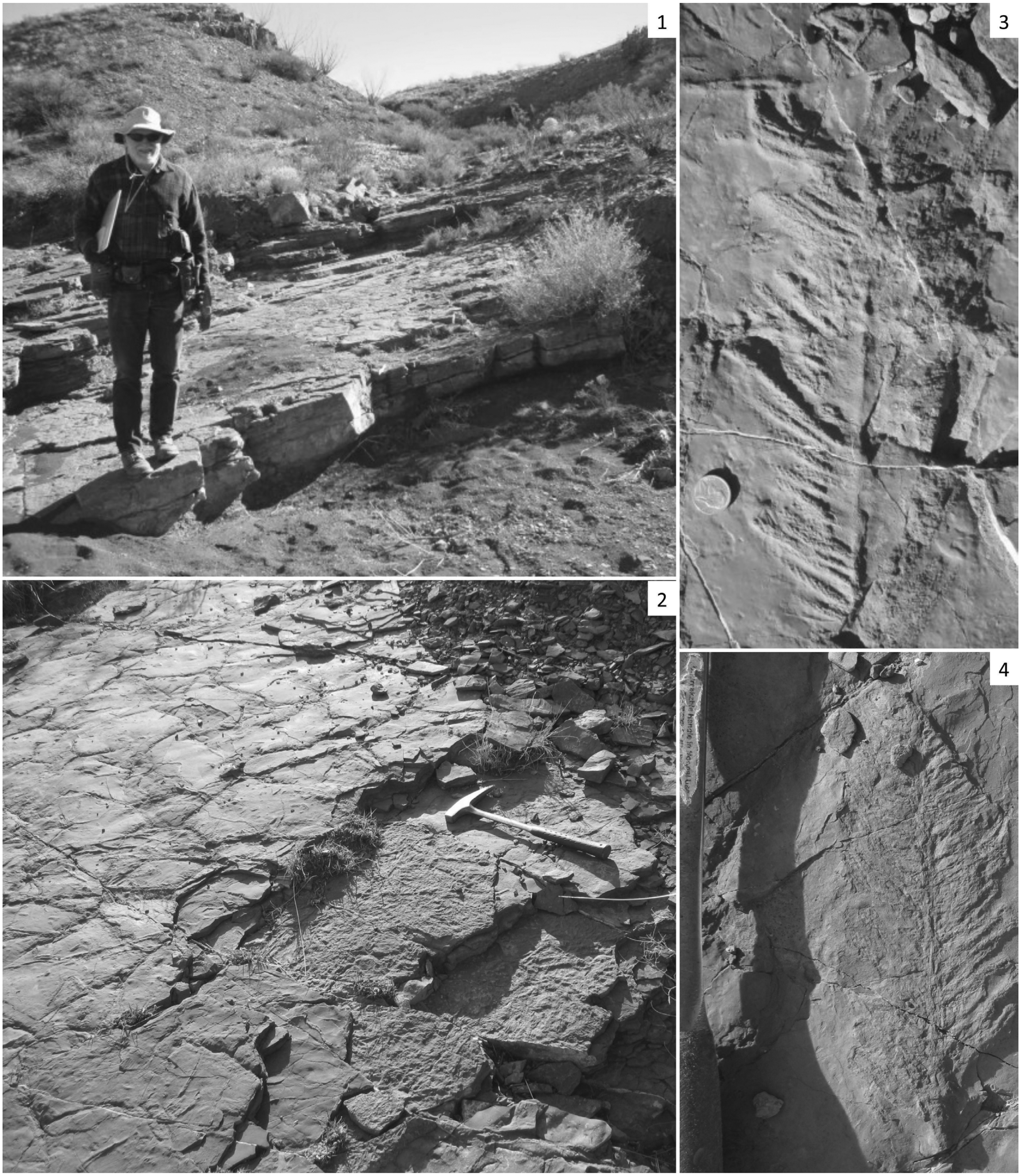


FIGURE 9. Abo Formation and flora in Quebradas Road Area. **1**, Outcrop of typical Abo Formation plant-bearing siltstone beds in ravine south of Quebradas Road. **2**, Plant-bearing siltstone beds south of Quebradas Road showing multiple bedding surfaces covered with conifer branch fragments. **3**, *Walchia* sp. branch fragment, field photograph. **4**, *Walchia* sp. branch fragment, field photograph.

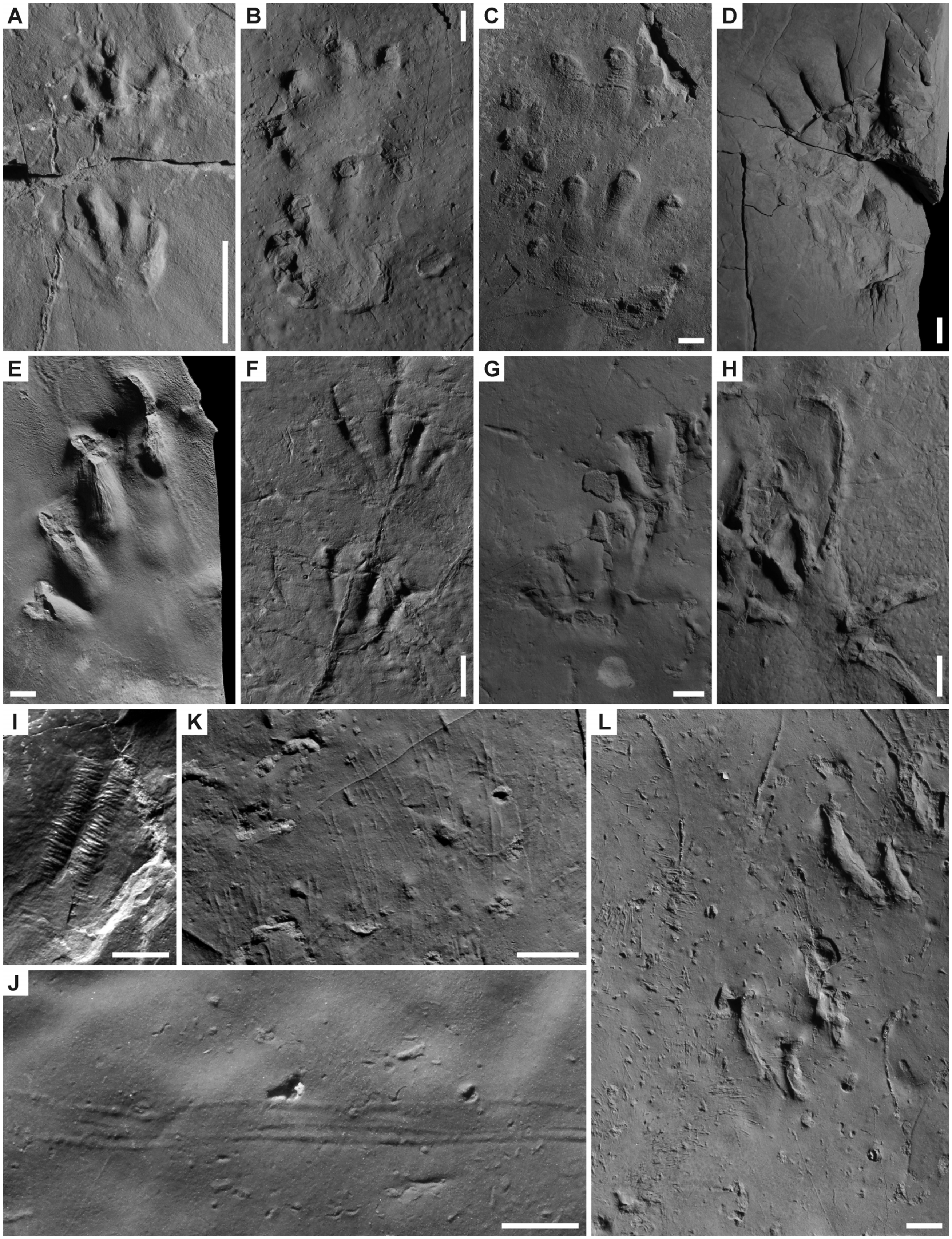


FIGURE 10. Invertebrate and vertebrate traces from the Abo (**A-H**) and Arroyo de Alamillo (**I-L**) formations in the Joyita Hills east of Socorro. **A**, *Batrachichnus salamandroides*. **B**, *Limnopus vagus*. **C**, *Amphisauropus kablikae*. **D**, *Dimetropus leisnerianus*. **E**, *Tambachichnium schmidti*. **F**, cf. *Varanopus* isp. **G**, cf. *Hyloidichnus bifurcates*. **H**, *Dromopus lacertoides*. **I**, *Cruziana problematica*. **J**, *Diplopodichnus biformis* with transition into *Diplichnites* isp. **K**, *Stiallia pillosa*. **L**, *Stiallia pillosa* and *Dromopus lacertoides*. Scale bars equal 1 cm.

mental settings: one, from the latest Desmoinesian is a coastal swamp deposit dominated by the seed fern *Neuropteris ovata*; the other, from the early Missourian is a sabkha deposit dominated by coniferous plants.

Fossil plants have been found from the lower part of the Atrasado Formation, in the Bartolo Member, beginning immediately above it contact with the Gray Mesa Formation, through the top of the overlying unit, the Tinajas Member, at its point of contact with the Council Springs Limestone (Figs. 11-15). This encompasses rocks of the uppermost Desmoinesian through the uppermost Missourian.

The Bartolo Member of the Atrasado Formation is of late Desmoinesian age. The following fossil-plant patterns are most notable in the Bartolo Member:

1. Basal Bartolo floras are rich in conifers and *Sphenopteridium*, both plants that have been linked to seasonally dry climatic conditions. Although allochthonous, these very fragmentary floras reveal that plants tolerant of seasonal moisture deficits were well established in the western parts of equatorial Pangea well back into the Pennsylvanian. In more central regions of Pangea, such as the coal basins of the eastern United States, such plants appear only as scraps, mainly during times of marine high-stand to regression (Falcon-Lang et al., 2009; Plotnick et al., 2009). Within the lower Bartolo flora are also highly fragmentary remains of wetland plants such as *Neuropteris*, calamitaleans, and pecopteroid tree ferns. This flora occurs intermixed with marine pectinoids and snails.

2. In the uppermost Bartolo, at three different sites, separated by more than a kilometer each, a flora is found that is dominated almost entirely by the pteridosperm *Neuropteris ovata*, a characteristic plant of wetland habitats. These accumulations are autochtonous, containing abundant stems and large fragments of fronds, along with laminate foliage. They occur several meters below the Amado Limestone, suggesting that they may be low-stand deposits, which climate models (Cecil et al., 2003; Peyser and Poulsen, 2007; Horton et al., 2012) and sequence stratigraphic studies (Eros et al., 2012) have identified as the most likely times of very wet conditions throughout the Pennsylvanian equatorial region

The Tinajas Member of the Atrasado Formation is of Missourian age. It is ltihologically complex and plants are preserved in a variety of different facies. The flora differs among these facies, but in general is much like that of the Bartolo Member, consisting of a mixture of wetland plants and those typical of more seasonally dry substrates. This mixture suggests that the background climate was seasonally dry and that wetland elements fringed coastal zones and riverine corridors under that same climate. The following plant patterns are most notable in the Tinajas Member of the Atrasado Formation:

1. Near the base of the Tinajas Member, a series of fossiliferous beds have been found that contain a conifer-dominated flora that appears to have grown in a coastal sabkha setting (Falcon-Lang et al., 2011). One of the most interesting exposures of this flora is a field of in situ, silicified stumps or tree bases of conifers or cordaitaleans rooted in a micritic limey mudstone, buried by dune deposits composed of calcium carbonate and gypsum grains (Fig. 13). The tree stumps may extend over a meter upward into these dune deposits, indicating tree burial during life or shortly after death. This deposit is widespread, also found north of the Quebradas Road, but is quite patchy in coverage, probably due to the rapidity

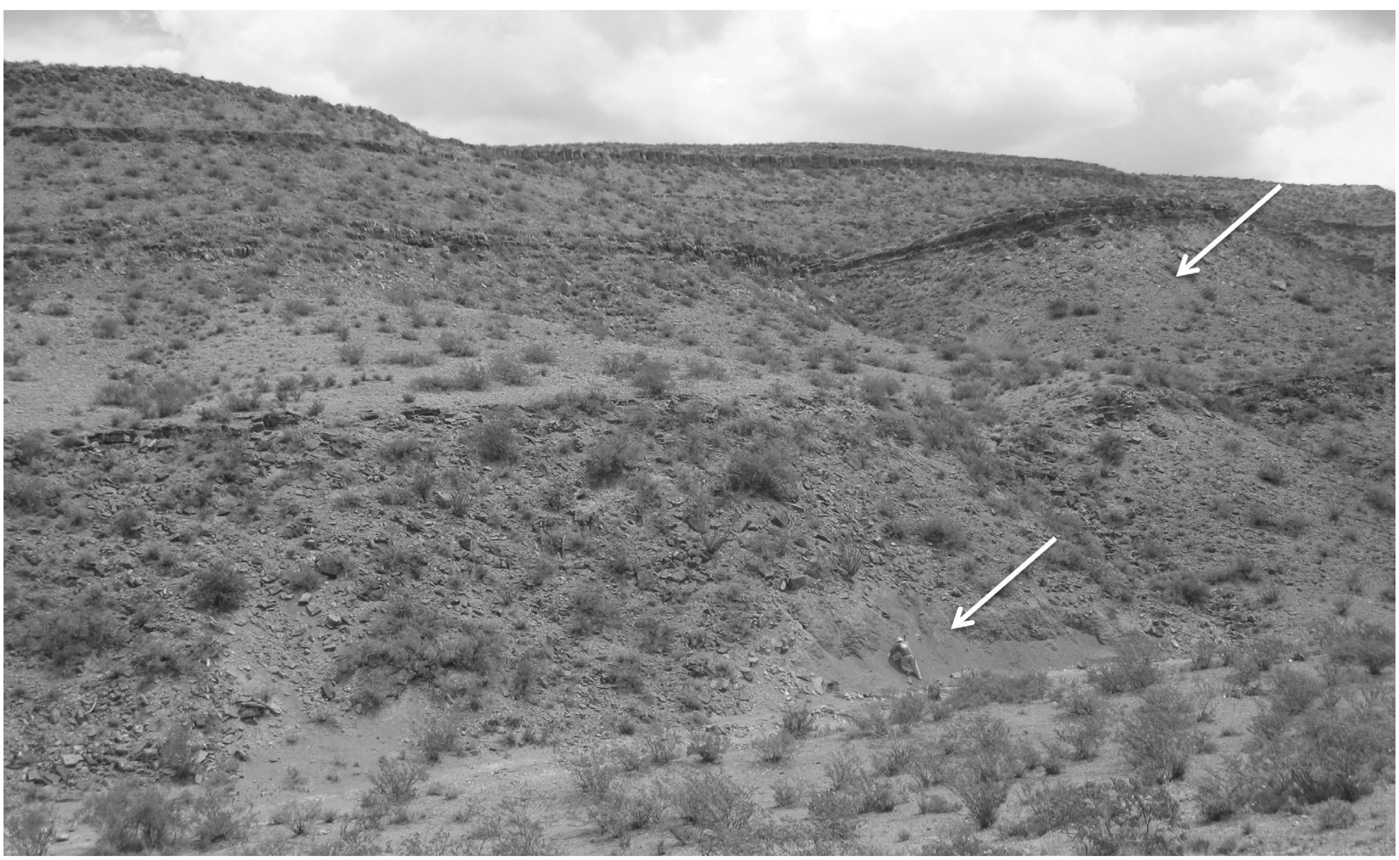


FIGURE 11. Bartolo Member, Fossiliferous Shales. This photograph illustrates two fossiliferous shale beds in the lower Bartolo Member of the Atrasado Formation (white arrows). The shales contain a sparse, allochthonous flora of mixed seasonally dry substrate and wetland elements.

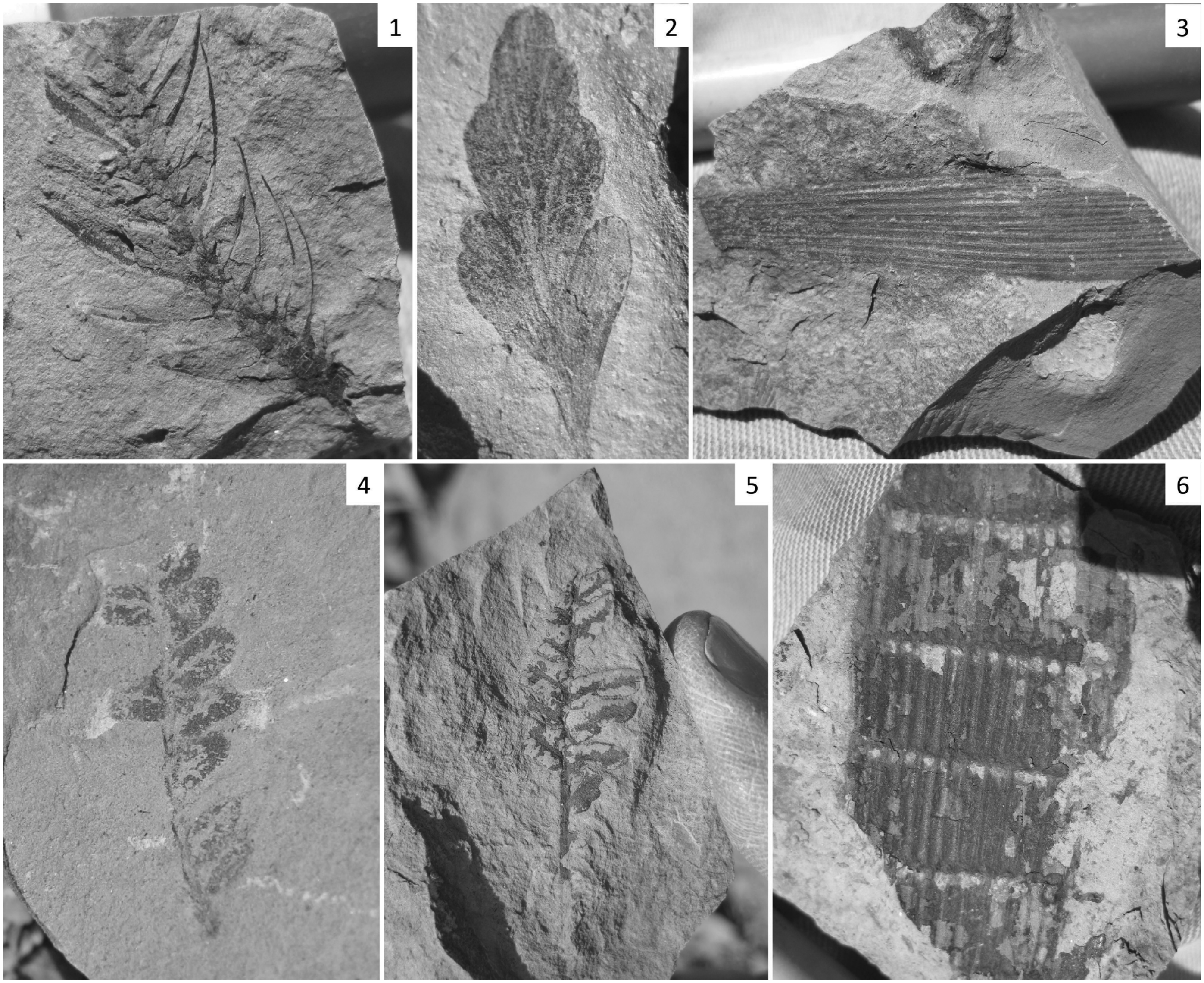


FIGURE 12. Bartolo Member, plant fossils from the lower part of the unit. **1**, Walchian conifer, field photograph. **2**, *Sphenopteridium* sp., field photograph. **3**, Unidentified parallel veined leaf lamina, cf. *Plagiozamites* sp., field photograph. **4**, Probable neuropterid pteridosperm foliage, field photograph. **5**, Pecopteroid fern foliage, field photograph. **6**, *Calamites* stem, field photograph.

with which it erodes. Tree stumps are larger in the more northerly exposures.

2. Above the sabkha deposit, in the middle Tinajas Member, a dark, organic-rich shale, containing distinctive "discus"-shaped siderite nodules, crops out throughout the area. This shale contains a sparse allochthonous flora of conifers, *Sphenopteridium*, the noeggerathialean *Charliea*, *Neuropteris ovata*, calamitalean foliage and tree fern foliage. Thus, again, the mixture of seasonally dry and wetland taxa is found, which characterizes both the Bartolo and Tinajas members.

3. A series of dark shales and olive shales crops out near the top of the Tinajas Member. The best exposed and most abundantly fossiliferous of these is the olive shale that crops out along Arroyo de los Pinos. This shale contains an allochthonous flora that, locally, is abundantly fossiliferous, and contains no evidence of brackish or marine conditions during deposition. The plants are scrappy but identifiable and, again, are the typically mixed seasonally dry and wetland floras, although wetland species are more common in this deposit than in the other plant-bearing Tinajas units.

4. Throughout the Tinajas Member, at various levels, there are silicified fossil logs that probably floated out into the near-shore environments that represent most of the Atrasado Formation in this area. Analyses of these woods have shown them to be primarily cordaitalean/coniferous (Tidwell et al., 2000).

The Atrasado Formation flora is significant because it occurs throughout a section that crosses the Desmoinesian-Missourian boundary. Across this boundary the flora shows little change, the same basic elements occurring both below and above the boundary, in particular conifers, the pteridosperm *Sphenopteridium* and various wetland pteridosperms and ferns. A few new, and significant taxa, such as *Charliea*, an element of the seasonally dry flora, appear in the Missourian. This pattern of little change across this boundary stands in marked contrast to patterns well documented in more easterly coal basins of the U.S., where a major floristic turnover occurred at this time. Wetlands, in particular, the history and composition

FIGURE 13. Tinajas Member, gypsum deposit with buried trees. **1**, Upright tree (U at arrow) surrounded by carbonate and gypsum bed. Gypsum deposit rests on a micritic limestone (M at arrow) and tufa bed (see 2). Jacob's Staff ruled in feet. **2**, Same upright stump as in 1, at hammer. Gypsum rests on a tufa (T at arrow) above a micritic limestone (M at arrow). Roots of trees are found in the micritic limestone. **3**, Large tree stump with roots extending down into the micritic limestone. Blocks of tufa can be seen scattered on the ground around the tree to the right.

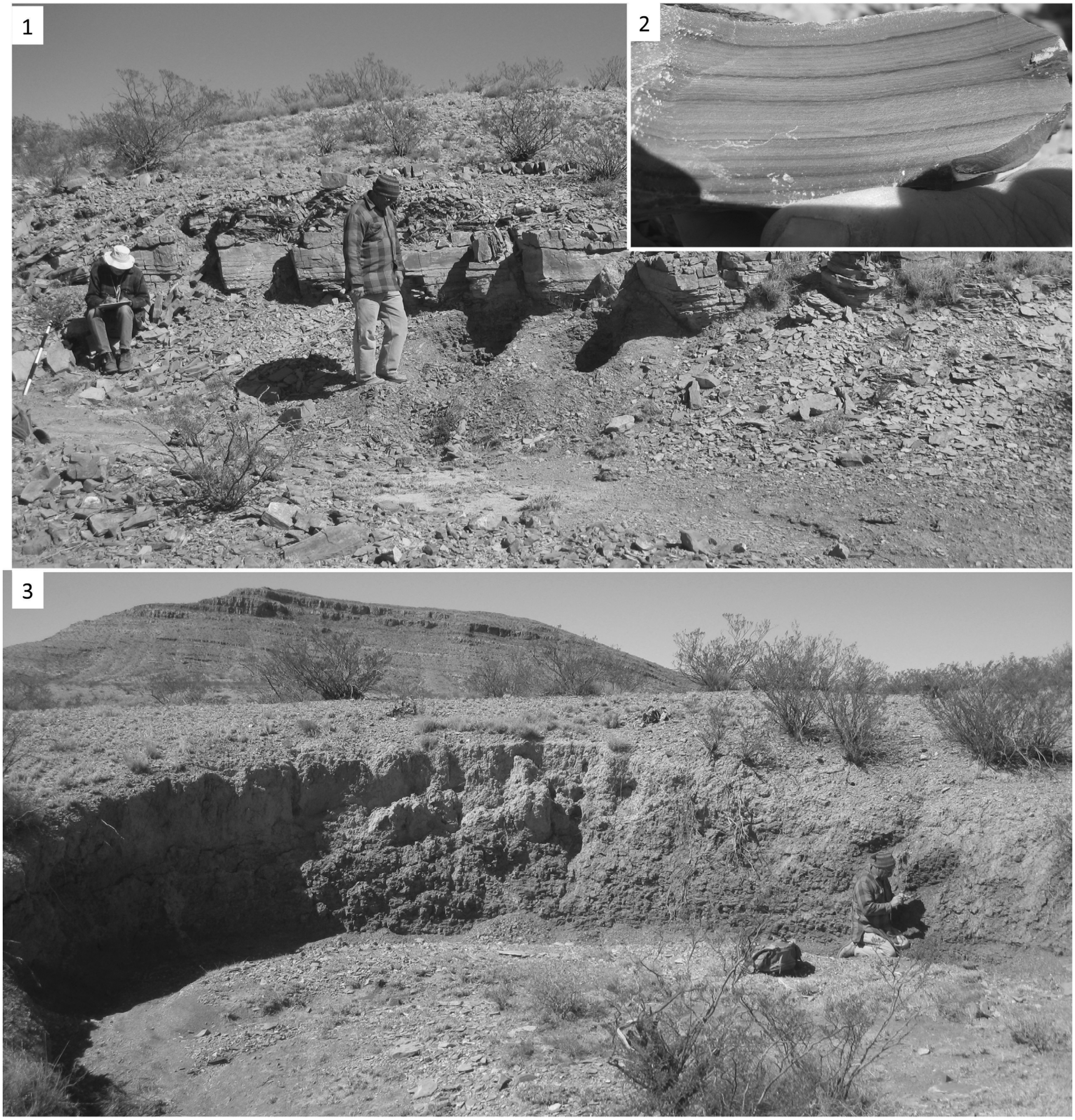


FIGURE 14. Middle Tinajas Member black, fossiliferous "discus" shale. This shale is widely traceable due to the distinctive "discus"-shaped siderite nodules it contains. It also contains a sparse but diverse, allochthonous flora and brackish water invertebrates. **1**, Outcrop exposure of shale. The unit is generally covered by talus. **2**, Detail of fine lamination of shale, indicative of accumulation in a quiet water setting, possibly lagoonal. **3**, Outcrop exposure of shale in small tributary of Arroyo de los Pinos.

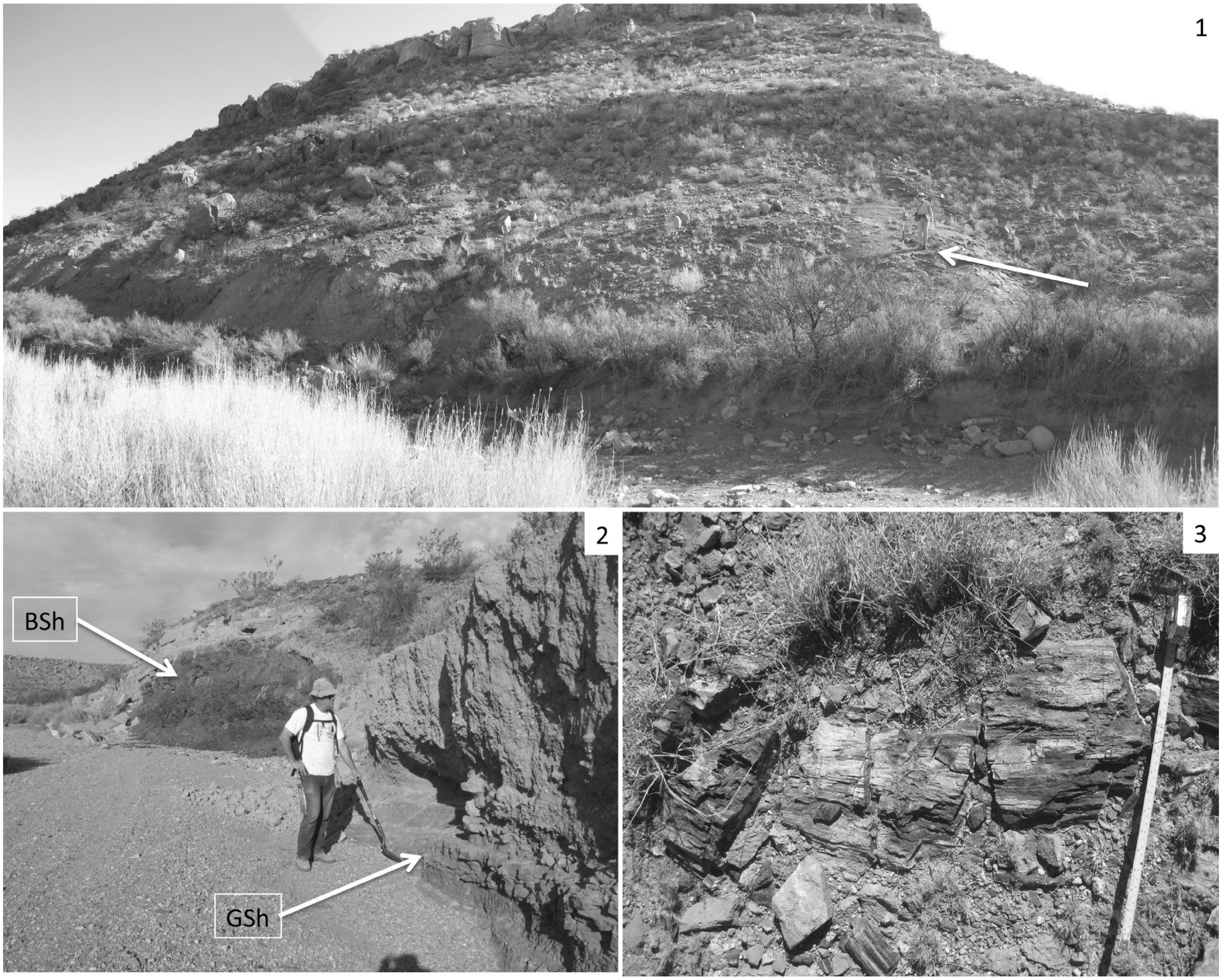


FIGURE 15. Tinajas Member, upper units and fossil log. **1**, Uppermost Tinajas Member, Atrasado Formation exposure on Arroyo de los Pinos. Arrow points to highly fossiliferous gray shale (person for scale, just above point of arrow). Council Spring Limestone at top of hill marks base of Virgilian. **2**, Exposure of fossiliferous gray (GSh at arrow) and organic, black (BSh at arrow) shales in Arroyo de los Pinos. The black shale contains both flora and fauna, which have been described by Lerner et al. (2009). **3**, Silicified fossil log from the Tinajas Member of the Atrasado Formation. Such logs crop out at several levels in shales of this unit. Tape measure ruled in inches and centimeters.

of which is much better known than that of seasonally dry assemblages, underwent a major vegetational turnover, with many lineages disappearing or being greatly reduced in importance, particularly lycopsid trees, and others rising greatly in importance, particularly tree ferns (Phillips et al., 1974). The turnover in wetlands appears to have taken place during one glacial-interglacial cycle and to have encompassed as much as a 2/3 species turnover (DiMichele and Phillips, 1996).

Proceed on foot down side road, then cross wash to south about 300 m south of parking place.

Stop 3A. Silicified wood in Atrasado Formation. Numerous masses of dark gray silicified wood can be found on the gently sloping pediment and adjacent gullies south of the main arroyo. Both stumps in growth position and prone logs have been observed in bedrock, which belongs to the lower part of the Tinajas Member of the Atrasado Formation (lower Missourian). Similar occurrences, including one described by Tidwell et al. (2000), have been encountered in the surrounding area, all from the same or closely similar stratigraphic horizons. Surprisingly, fossil wood is encased in gypsum, itself a rare rock type in the Atrasado. For trees to grow on a sabkha seems to be a contradiction, yet close inspection reveals that the trees were rooted in limestone or shale and afterwards covered by gypsum. Identity of the wood is uncertain; it may belong to cordaitaleans or (more likely) to conifers. Falcon-Lang et al. (2011), who investigated this site, measured a tree density of about 100 individuals per hectare, signifying “open woodland with large canopy gaps.” Setting of the fossils and presence of growth rings point to seasonal aridity in a coastal sabkha setting. Trees may have grown during an episode of increased rainfall or in sites where a perched water table was present (Falcon-Lang et al., 2011). **Proceed down the main arroyo approximately 600 m in a westerly direction, pausing at a cut bank that exposes shale and Stop 3B.**

Stop 3B. Lacustrine shale outcrop. Lerner et al. (2009) described the paleontology of this site in detail (Fig. 16). The cut bank exposes Tinajas Member strata slightly younger than those observed at the previous stop. The upper Tinajas Member, capped by light gray ledges of the Council Spring Limestone Member, is well displayed on the hillside immediately to the north. This is, in fact, the type locality of the Tinajas Member (Lucas et al., 2009).

The lower 5.6 m of the exposed Tinajas Member, units 1-5 below the black shale, are composed of greenish shale and micaceous siltstone to fine-grained sandstone. Silty shale contains fossil plants (seed ferns). Intercalated thin, nodular limestone beds are composed of fine-grained breccia containing subangular to rounded recrystallized micritic intraclasts floating in micritic matrix. The mudstone contains peloids and rare ostracods. Siltstone immediately below the black shale contains plant debris on bedding planes.

The siltstone is overlain by a 5.2 to 7 m thick interval of black shale which contains a few small carbonate nodules throughout the succession. The black shale is fissile in the lower part and laminated in the upper part and contains abundant conchostracans.

X-ray analysis of the black shale yielded calcite, quartz, kaolinite, ferroan phlogopite and clinochlor. In the shale abundant tubular structures occur within distinct horizons. Individual laminae are less than 0.1 mm thick and lense out laterally, locally the laminae may also be slightly folded.

The black shale is overlain by brownish-gray and greenish shale with a thin (3-5 cm) wavy limestone bed intercalated. The shale contains abundant *Dunbarella*. The thin limestone bed is composed of bioclastic wackestone containing few larger bioclasts. The most abundant fossils are brachiopod shell fragments and spines, subordinate crinoid fragments, ostracods and few smaller foraminifers. A few bioclasts are encrusted by cyanobacteria and *Palaeonubecularia*. The *Dunbarella*-bearing shale is overlain by two limestone beds (0.4 and 0.3 m thick), which are separated by a thin shale interval.

The thin fissile "paper shale" near the top of this unit contains abundant, densely packed, decalcified, complete valves of *Dunbarella*. The abnormally high density of the shells in this shale indicates that this may represent a mass-kill event, possibly from a sudden influx of marine water into the brackish environment in which these bivalves lived. The overlying thin bed of gray shale and profuse irregular encrusting algal growths containing a fauna which is dominated by the brachiopods *Derbyia* and *Crurithyris* marks the transition into marine conditions. Above follow 2 m of interbedded thin gray limestone and shale which contain a diverse, stenohaline fauna composed of abundant brachiopods *Hustedia* and *Hystriculina* and subordinate other brachiopods (*Juresania*, *Cancrinella*, *Rhipidomella*, *Composita*, *Punctospirifer*, *Beecheria*, *Cleiothyridina*, *Crurithyris*). The presence of the brachiopod *Chonetinella felmingi*, which is a widespread Missourian index species, indicates early to middle Missourian age. Limestone contains solitary rugose corals, fenestrate bryozoans and crinoid fragments, rarely molluscs and trilobites. The thin, sparsely fossiliferous gray limestone unit on top which contains a fauna essentially limited to solitary rugose corals, *Crurithyris* and crinoid debris, possibly represents a slightly hypersaline lagoon.

The lower limestone bed consists of bioclastic wackestone and locally of bindstone. The wackestone contains brachiopod shells and spines, crinoids, subordinate bryozoans, ostracods, rare smaller foraminifers (*Globivalvulina*, *Hemigordius*, *Planoendothyra*, *Syzranella*, *Tetrataxis*) and trilobite fragments. Locally abundant encrusting organisms are present (cyanobacteria and *Palaeonubecularia* transitional to

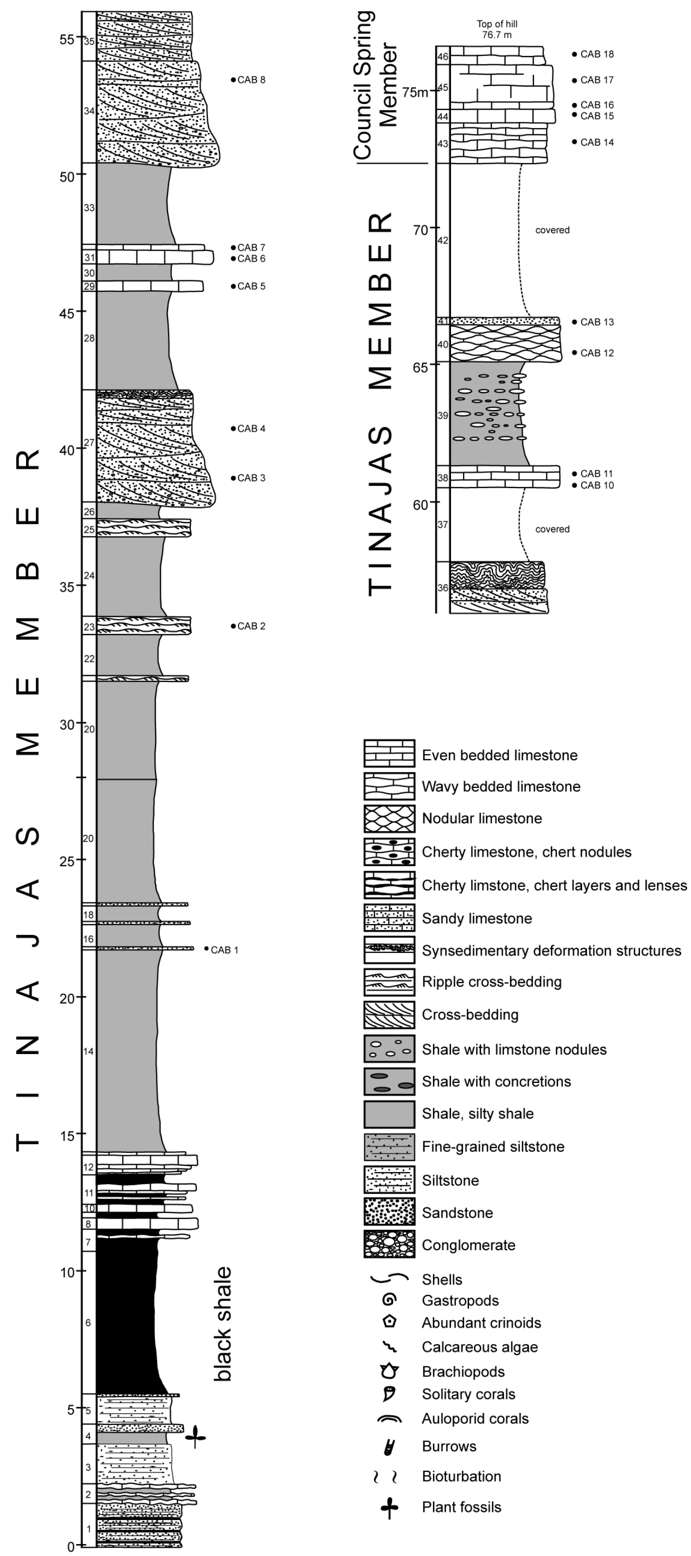


FIGURE 16. Measured stratigraphic section at the black-shale locality in the Tinajas Member (from Lucas et al., 2009).

Tubiphytes) forming patches of bindstone. The upper limestone bed is composed of coarse-grained crinoidal wackestone containing abundant crinoid stem fragments (mostly up to 2 mm, rarely up to 5 mm), subordinate brachiopod shells and spines and a few bryozoans, ostracods, rare trilobite fragments and very rare smaller foraminifers.

The limestone beds are overlain by a 1.1 m thick shale interval. Intercalated in the shale are abundant thin limestone lenses in the lower part and a 0.2 m thick limestone bed in the middle. The shale contains abundant brachiopods (*Dunbarella*).

The limestone is composed of bioclastic wackestone containing fragments of crinoids, brachiopods and bryozoans in varying amounts. Less abundant are small gastropods, ostracods, smaller foraminifers, bivalves and rare trilobite fragments. A few bioclasts are encrusted by cyanobacteria and *Palaeonubecularia*. This shale interval is overlain by dark gray, micritic, bedded limestone containing few solitary corals. Microfacies of this limestone is bioclastic and intraclast wackestone. The bioclastic wackestone contains few large and abundant small skeletons which float in micritic matrix. Common skeletons are crinoids, brachiopod shells and bryozoans subordinate are gastropods, ostracods, brachiopod spines, smaller foraminifers (*Calcitornella*, *Globivalvulina*, glomospiroid *Miliolata*, *Hemigordius*, *Spireitlina*, *Syzrania*), corals and trilobite fragments. Locally abundant spicules are present.. The intraclast wackestone contains abundant recrystallized intraclasts up to 10 mm, mostly up to 1 mm in diameter and skeletons of brachiopods, gastropods, ostracods, bryozoans, brachiopod spines and rare calcivertellid foraminifers.

The limestone is overlain by a thick succession of greenish, partly brownish shale to fine-grained siltstone, partly sandy in the upper part with ripple laminations and few 0.1 to 0.2 m thick fine-grained sandstone beds intercalated. The lowermost sandstone bed contains fossil plants (*Calamites*). In the upper part two fine-grained sandstone intervals with ripple lamination are intercalated, each 0.6 m thick.

Proceed downstream approximately 400 m, where shale and siltstone are exposed in the steep north bank.

Stop 3C. Plant-bearing siltstone exposures. The bank and hillside on the north side of the large arroyo reveals olive-gray silty shale and siltstone of the Tinajas Member, slightly younger than the black shale of the previous stop. Here and elsewhere in the vicinity, this unit has yielded a modest assemblage of fossil plants, together with uncommon bivalves and rare insect remains. At this exposure, the rock becomes finer-grained upward from stream level, reversing to upward coarsening in transition to the sandstone that forms broken ledges 12 to 15 m above the arroyo. Upward fining is atypical for a near-shore, bay-fill succession, such as this appears to be. Perhaps, this deposit developed in response to nearby tectonic uplift onshore or to offshore subsidence that outstripped sediment accumulation.

Stop 3D. Bartolo Member plant locality. A few hundred meters to the east, is an excellent example of an autochthonous accumulation of plants in the Bartolo Member (Fig. 17).

In this area, latest Desmoinesian conodonts occur in thin limestone beds of the upper part of the Bartolo Member and the basal bed of the overlying Amado Limestone Member of the Atrasado Formation at the Cerros de Amado A section (Fig. 17; Barrick et al., this volume). The Bartolo fauna is dominated by elements of *Adetognathus* and *Hindeodus*, but *Idiognathodus swadei*, *I. expansus*, *Neognathodus roundyi*, *N. expansus*, and *Swadelina* species occur. The latest Desmoinesian species *I. expansus* and *Swadelina nodocarinata* also occur in the basal limestone of the Amado Limestone Member. In the middle and upper parts of the Amado Limestone Member, a small number of early Missourian species of *Idiognathodus* occur in addition to the more common *Adetognathus* and *Hindeodus* elements: *I. swadei*, *I. harkeyi*, *I. eccentricus*, and in the upper part, *I. gemiformis*, *I. corrugatus*, and *I. turbatus*. These species indicate an age range extending from the basal Missourian *I. eccentricus* Zone up as high as possibly the *I. cancellosus* Zone. The base of the international Kasimovian Stage, which has been tentatively placed at the first occurrence of the *I. turbatus*, lies within the Amado Limestone Member.

The next highest conodont fauna occurs in the middle part of the Tinajas Member, in limestone beds that overlie the lacustrine black shale in the Cerros de Amado B section. This fauna contains abundant elements of *Idiognathodus eudoraensis* and *Streptognathodus firmus*, the co-occurrence of which is indicative of the middle Missourian *eudoraensis* Zone. Samples from higher in the Tinajas yielded small collections of *S. pawhuskaensis*, a species that ranges from the late Missourian into the early Virgilian.

The Council Spring Limestone Member at this section yielded sparse faunas with specimens of *Idiognathodus toretzianus* and *I. lobulatus*, the latter species of which occurs in Virgilian strata in North America, and above the base of the international Gzhelian Stage. In the overlying Borrego Member, P_1 elements of *Streptognathodus ruzhencevi* and *S. vitali* appear, which indicate the middle Virgilian *S. vitali* Zone. **Return to vehicles. End of Day 2 roadlog.**

THIRD-DAY ROAD LOG – FROM SOCORRO TO GALLINA WELL VIA THE ARROYO DE LA PARIDA AND THE CAÑONCITO DE LA UVA

Summary

The third day's trip crosses part of the Joyita Hills uplift to focus on Permian stratigraphy and sedimentation and on the locally complex structural deformation of the Pemian (and adjacent) strata, which could be the result of various tectonic events, ranging from the late Paleozoic Ancestral Rocky Mountain orogeny through the Cretaceous-Eocene Laramide orogeny to the late Cenozoic Rio Grande rift. There is also a component of large-scale, low-angle to horizontal detachment faulting, for which a variety of explanations have been proposed. These structures are particularly well developed in the gypsiferous portions of the Yeso Group.

From the Bosquecito road junction, the route continues north across the Arroyo de la Parida, one of the principal drainages on the west flank of the Joyita Hills uplift. The route then heads east, across the margin of the Rio Grande rift, into an extensive outcrop belt of Permian sedimentary rocks that are only mildly deformed, mostly by normal faulting. Stops 1 and 2, close to each other, include the type section of the Yeso Group. These stops allow us to observe the entire Permian section exposed in central New Mexico, more than 400 m thick here. We thus begin in the uppermost Pennsylvanian Bursum Formation and continue through the Lower Permian Abo Formation, Yeso Group (Arroyo de Alamillo and Los Vallos formations), Glorieta Sandstone and San Andres Formation. These rocks record the last pulses of the Ancestral Rocky Mountain orogeny as well as the final collapse of the late Paleozoic Gondwana ice sheets, and our examination of these strata focuses on how and what they record of these events. At Stop 3, we examine the Abo Formation at the Gallina Well vertebrate fossil site and the Bursum Formation nearby.

0.0 Bosquecito road junction; turn left and proceed north. 0.2

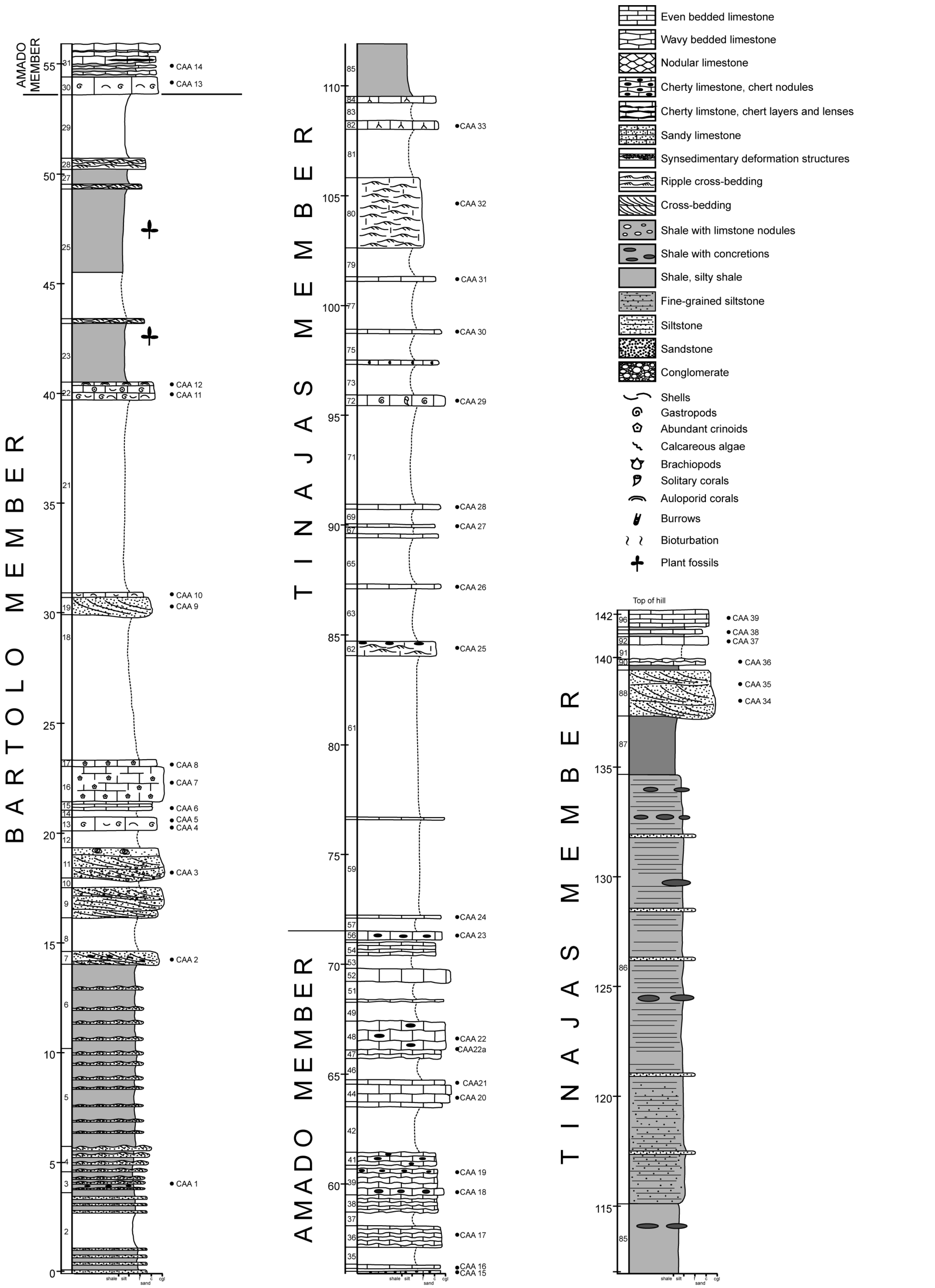


FIGURE 17. Measured section of part of the Atrasado Formation at the Cerros de Amado A section of Lucas et al. (2009). Note the plant localities in the upper part of the Bartolo Member.

0.2 Cattleguard, road forks, **bear right**. Johnson Hill is straight ahead. Note lower slopes are composed of tan and gray beds of the axial river facies of the ancestral Rio Grande. These beds are covered by reddish piedmont gravels. **0.7**

0.9 Crossing the Arroyo de la Parida. The Santa Fe Group forms red cliffs to the right. A fault that juxtaposes piedmont sediments against axial river facies of the ancestral Rio Grande is visible near the west end of the cliffs. **0.1**

1.0 Intersection with Johnson Mesa Road, **stay right**. **0.5**

1.5 Ascending the "real" Johnson Hill, road forks, **keep right**. Climbing Johnson Hill, our route approximates part of the Ocean-to-Ocean Highway, the first transcontinental automobile route in the United States, which opened in 1910 (Smith et al., 1983). **0.4**

1.9 To left, note redbeds of piedmont facies of Sierra Ladrones Formation of Santa Fe Group (mostly sedimentary conglomerates, breccias and sandstones). Color of these beds is imparted by clasts of Lower Permian Abo Formation and Yeso Group to the east, which have been stripped and transported by late Cenozoic alluvial fans to become the piedmont facies of the Sierra Ladrones Formation. **0.2**

2.1 Good exposure of piedmont facies in roadcuts on left. Note the abundant tabular clasts of Abo and Yeso sandstone and of Pennsylvanian limestone. East to west transport direction is indicated by west-facing clast imbrications. **0.6**

2.7 Crest of Johnson Hill, road to left, bear right. Road is still very narrow with blind curves and wash-outs. Roadcuts are still in piedmont red-bed facies of Sierra Ladrones Formation. Proceed cautiously. **0.5**

3.2 Road curves to left. Cerros de los Coyotes at 12:00 are a northeast-dipping hogback of Laramide origin. Looking to right, note excellent exposures of piedmont facies of Sierra Ladrones Formation in cut banks along Arroyo de la Parida. **0.9**

4.1 Crest hill. Road on uppermost piedmont surface of the Sierra Ladrones Formation that grades toward the Rio Grande. At 9:00-9:30, are west dipping hogbacks of Oligocene ash flow tuffs derived from the Socorro caldera complex. The skyline to the east consists of Paleozoic sedimentary rocks. Also in view are Mesa del Yeso at 11:30, type section of the Yeso Group; Sierra de la Cruz at 12:00, and La Cebolla at 1:00. We are driving eastward on the very eastern edge of the Socorro basin of the Rio Grande rift, about to cross the rift-bounding fault, which is buried by alluvium here. **0.5**

4.6 Cattleguard. **0.5**

5.1 Begin descent into the Valle del Ojo de la Parida. Cenozoic ash-flow tuff units at 11:00, Manzano Mountains at 12:00 with gasoline pipeline station in foreground, Los Pinos Mountains at 12:30–1:00, Mesa del Yeso at 1:00, Sierra de la Cruz at 2:00, and La Cebolla, a prominence of Sierra Larga, at 2:30. **0.3**

5.4 Driving on alluvium of Valle del Ojo de la Parida, road to pump station on left, continue straight. Low hill next to pump station is composed of middle Cenozoic volcanic Spears Formation. **0.3**

5.7 Fork in road, **bear right**. The road to left leads to the Palo Duro Canyon area of the Sevilleta National Wildlife Refuge. **0.6**

6.3 Road ascends hill of Los Vallos Formation of the Yeso Group (note characteristic salmon-colored siltstones/fine sandstones in roadcuts on left). **0.1**

6.4 Water tanks on hill at right. Good view of Mesa del Yeso at 12:00. **0.6**

7.0 Road sign on left. When the sign is flipped open, the road is closed for missile testing; as on rare occasions, missiles have escaped the bounds of the White Sands Missile Range to the south. Unnamed hills straight ahead are composed of Yeso Group strata. Mesa del Yeso at 10:30 is a west-dipping homocline. **0.2**

7.2 Intersection with road to right. Continue straight. **0.7**

7.9 Note Los Vallos Formation outcrops on both sides of road. **0.1**

8.0 Cattleguard. The Lower Permian Glorieta Sandstone forms cliffs that are overlain by limestone and dolomite of the Lower Permian San Andres Formation capping the hill at 11:30. Redbeds dipping northerly at 10:00 are lower part of Yeso Group (Arroyo de Alamillo Formation of Lucas et al., 2005). **0.6**

8.6 Crossing normal fault that juxtaposes Yeso Group (west side, hanging wall) against Abo Formation. **0.3**

8.9 Road curves right, pull to right for **STOP 1.** Faulted hill to the north is Yeso strata capped by Glorieta-San Andres. Sierra de la Cruz at 12:00 composed of Yeso Group. We are stopping very close to the base of the Yeso Group here, which is the base of the Arroyo de Alamillo Formation of Lucas et al. (2005). **We will walk from here approximately 1.5 km to the Bursum Formation outcrops exposed along the Cañoncito de la Uva to the south** (Fig. 18). We will then walk back through a complete, though faulted, Abo section (Fig. 19). Points of interest include:

1. The Bursum Formation is characteristically mixed marine and nonmarine strata in this area (Fig. 20) above the entirely marine upper part of the Atrasado Formation and below the entirely nonmarine Abo Formation. About 25 m thick here, conglomerates in the upper part of the Bursum Formation yield a pelycosaur-dominated vertebrate fossil assemblage. Finer grained strata yield a flora that includes cordaitaleans, conifers and peltasperms (Fig. 21).

2. The Abo Formation is relatively thin here, about 100 m thick (Figs. 19, 22), and its two members are readily recognized. Thus, the lower 42 m of the Abo are mudstone-dominated slopes with some trough-crossbedded sandstone and conglomerate beds, the Scholle Member of Lucas et al. (2005b). The overlying 58 m of the Abo contain numerous beds of ripple- and climbing-ripple laminated sandstone characteristic of the Cañon de Espinoso Member. This change in fluvial architecture within the Abo Formation can be explained by a stalling of subsidence or a change to a drier climate.

3. In the lower part of the Cañon de Espinoso Member we examine a tracksite with a conspicuous *Limnopus* trackway. It is NMMNH locality 5811 that predominantly yields footprints of *Batrachichnus* (Fig. 10A), *Limnopus* (Fig. 10B), *Dimetropus* (Fig. 10C), and *Dromopus*. These tracks can be referred to small and large temnospondyl, "pelycosaurian"-grade, and araeoscelid trackmakers. *Batrachichnus*, *Limnopus*, *Dimetropus*, and *Dromopus* are typical elements of Early Permian coastal plain tetrapod ichnofaunas (Lucas et al., 2011; Voigt et al., 2013) suggesting that this part of central New Mexico was a nearshore lowland environment during deposition of the Cañon de Espinoso Member.

4. As elsewhere in central New Mexico, Abo floras of both the Scholle and Cañon de Espinoso members in the Canoñcito de la Uva area (Fig. 22) are overwhelmingly dominated by conifers (primarily *Walchia*, *Otovicia* and *Culmitzschia*) and

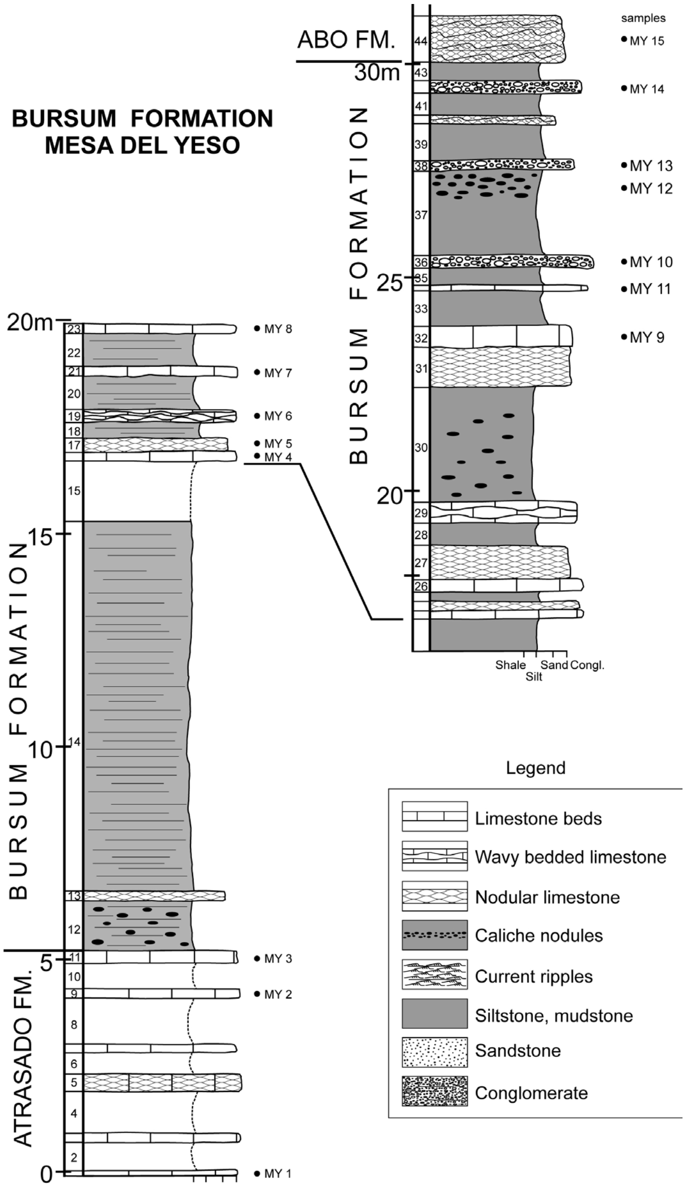


FIGURE 18. Measured section of the Burusm Formation at Cañoncito de la Uva.

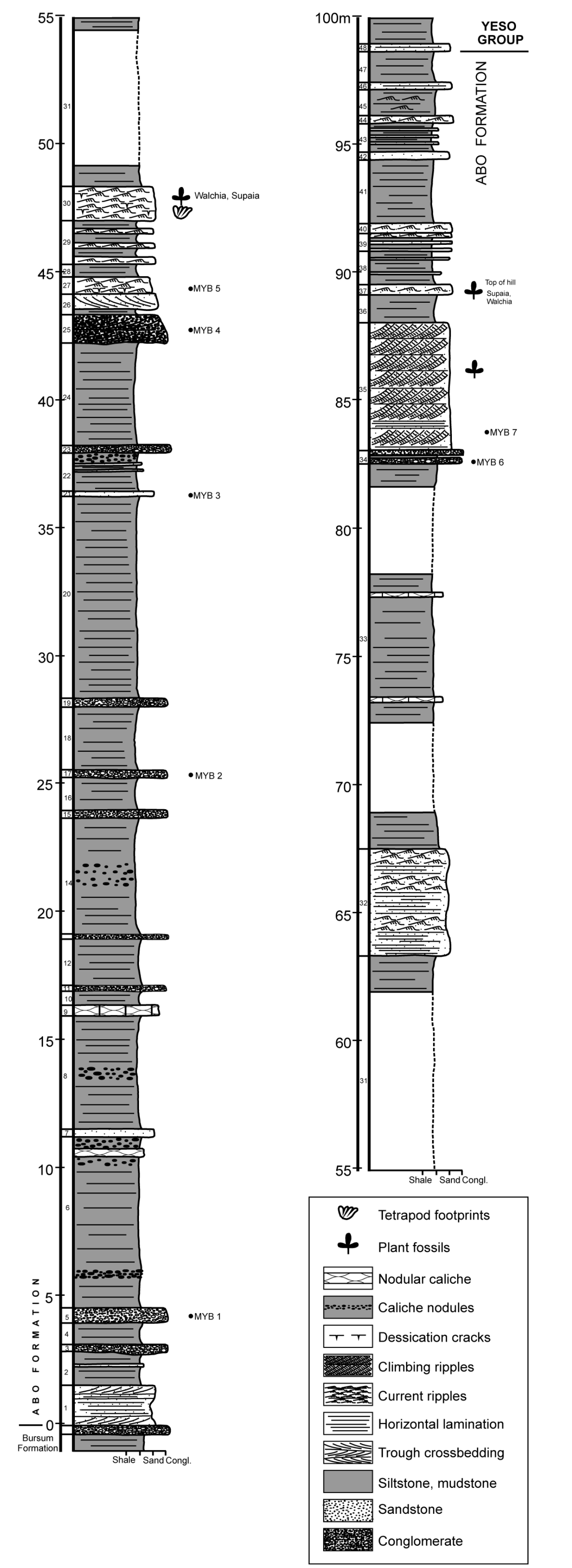


FIGURE 19. Measured section of the Abo Formation just north of Cañoncito de la Uva.

the peltasperm *Supaia thinnfeldioides*. Smaller numbers of occurrences have been noted of *Autunia* (*Calipteris*) *conferta*. In the Scholle Member, plants are often found disposed across bedding planes or in troughs, indicating transport and deposition in active, high energy channels. In both members, and almost exclusively so in the Cañon de Espinoso Member, the plants are found most commonly in the upper portions of sheet sandstone-siltstone tabular unites, where clay drapes and laminae are interbedded with coarser-grained siltstones. The plants often occur on surfaces that also contain trackways of vertebrates and invertebrates, mudcracks and other sedimentary features. The Abo Formation flora from Canoñcito de la Uva has been described in detail and illustrated by Hunt (1983) in one of the first full descriptions of an Abo flora, also placed in a larger context.

5. The Abo-Yeso contact (Fig. 23) is gradational (conformable) but can be picked out here as a distinct change in color and lithology from red-bed mudstone/siltstone and ripple-laminated/crossbedded sandstone of the Abo to mostly greenish

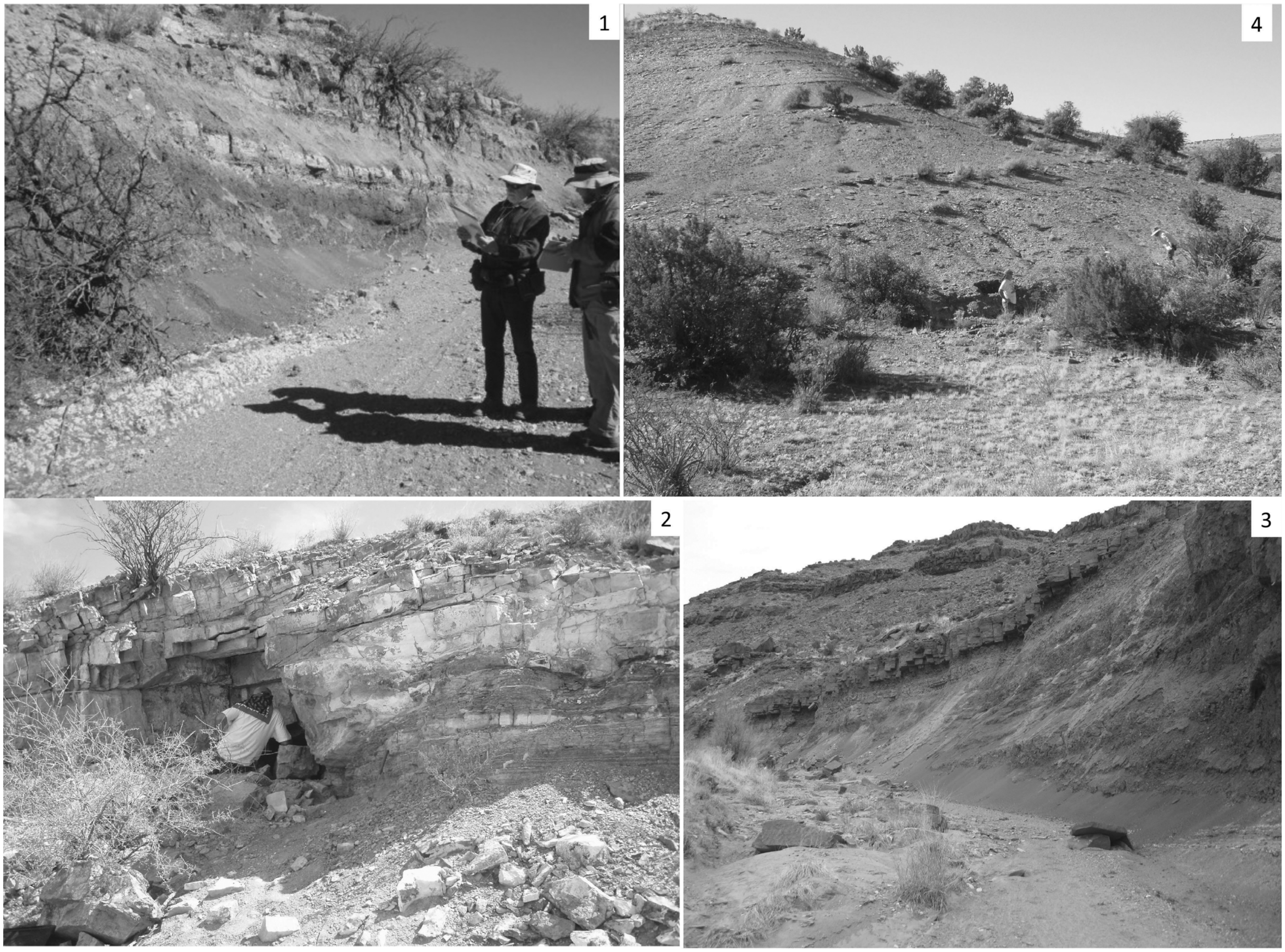


FIGURE 20. Bursum Formation outcrops. **1**, Typical Bursum Formation exposure. Terrestrial beds are represented primarily by paleosols, such as the one that crops out at the bottom of the exposure. Cerros de Amado area. **2**, Bursum Formation, Minas de Chupadera. Plant fossils come from the more finely bedded gray sandstones at the base of the exposure. **3**, Bursum Formation-Abo Formation contact, Carrizo Arroyo. The sharp contact shown in this image is typical of Bursum-Abo contact throughout the area of its exposure, including in the Socorro region. **4**, Fossiliferous Bursum Formation exposure. Thinly bedded to finely laminated gray siltstone and claystone, probable lagoonal environment. Plants at multiple levels, generally large and well preserved, indicated little transport prior to burial. Canoñcito de la Uva.

silty mudstone and siltstone with thin intercalations of sandy limestone and siltstone beds with abundant halite pseudomor phs at the Yeso base.

6. The halite pseudomorphs, siltstones, thin limestones and sandstones of the Arroyo de Alamillo Formation at the Yeso Group base are arid coastal plain deposits that formed seaward of the De Chelly erg of northwestern New Mexico and northeastern Arizona (Fig. 23).

After stop continue east on road through lower Yeso strata. 0.1

9.0 Road almost washed out to right, be careful. **0.6**

9.6 Road crosses arroyo, a tributary of Cañoncito de la Uva. **STOP 2 (pull off to left).** Approximate location of Abo-Yeso contact. Proceed up arroyo to view Yeso-Glorieta-San Andres section. To examine the type Yeso Group section (Fig. 23), we will walk through this outstanding type section, which was first described by Needham and Bates (1943) and later described in detail by Lucas et al. (2005). Along our traverse contemplate the obvious cycles and possible sequence boundaries present in the Yeso. Clearly, Yeso deposition here took place during a time of relatively little tectonism on the coastal plain northwest of the West Texas Permian basin (Fig. 24). In the Permian basin, Ross and Ross (1988) identified three major Leonardian-age transgressions that should be evident in the Yeso. Probably these equal the base of the Arroyo de Alamillo Formation, the base of the Los Vallos Formation and the thick limestone with oncoids near the top of the Torres Member.

The Yeso Group comprises two formations, the upper of which is divided into three members (Fig. 23). The lower formation, Arroyo del Alamillo, is about 107 m thick. The lower part of the formation is composed of massive to laminated mudstone and siltstone alternating with thin, tabular sandstone beds in a variety of colors. The upper part contains thicker and more numerous sandstone layers that are more uniformly reddish brown and exhibit larger scale bedforms, such as crossbedding. This upper portion can be mistaken for the Abo Formation when encountered in faulted areas.

The Los Vallos Formation, 225 m thick in the type section, contains the Torres Member (oldest), the Cañas Gypsum member, and the Joyita Member. The Torres, 156 thick, is

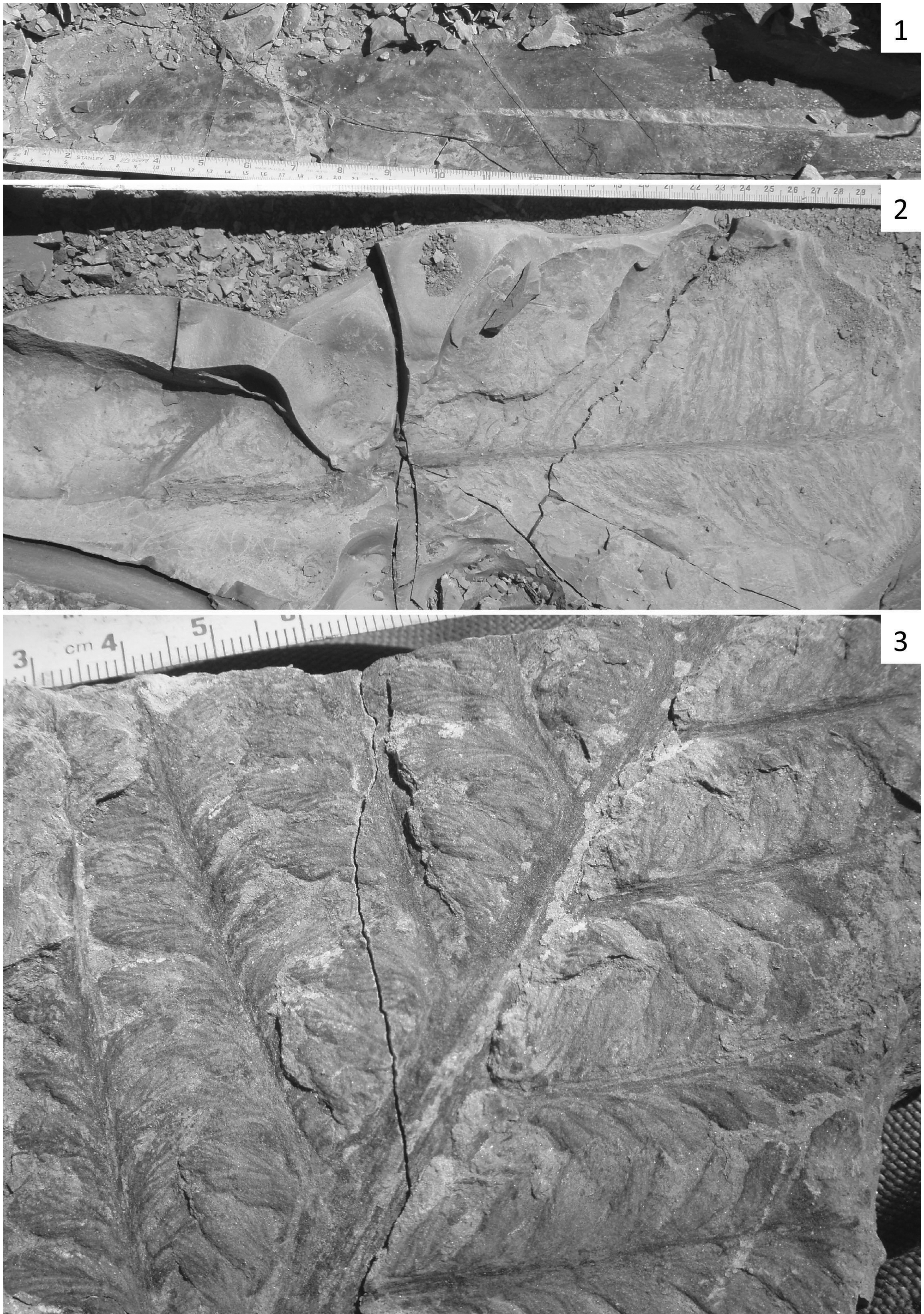


FIGURE 21. Bursum Formation plant fossils from Canoñcito de la Uva. **1**, *Cordaites* cordaitalean foliage showing tip of a large leaf. Field photograph. **2**, *Walchia* conifer branch, field photograph. **3**, *Rhachiphyllum*, a callipterid peltasperm, field photograph. Metric scales ruled in mm.

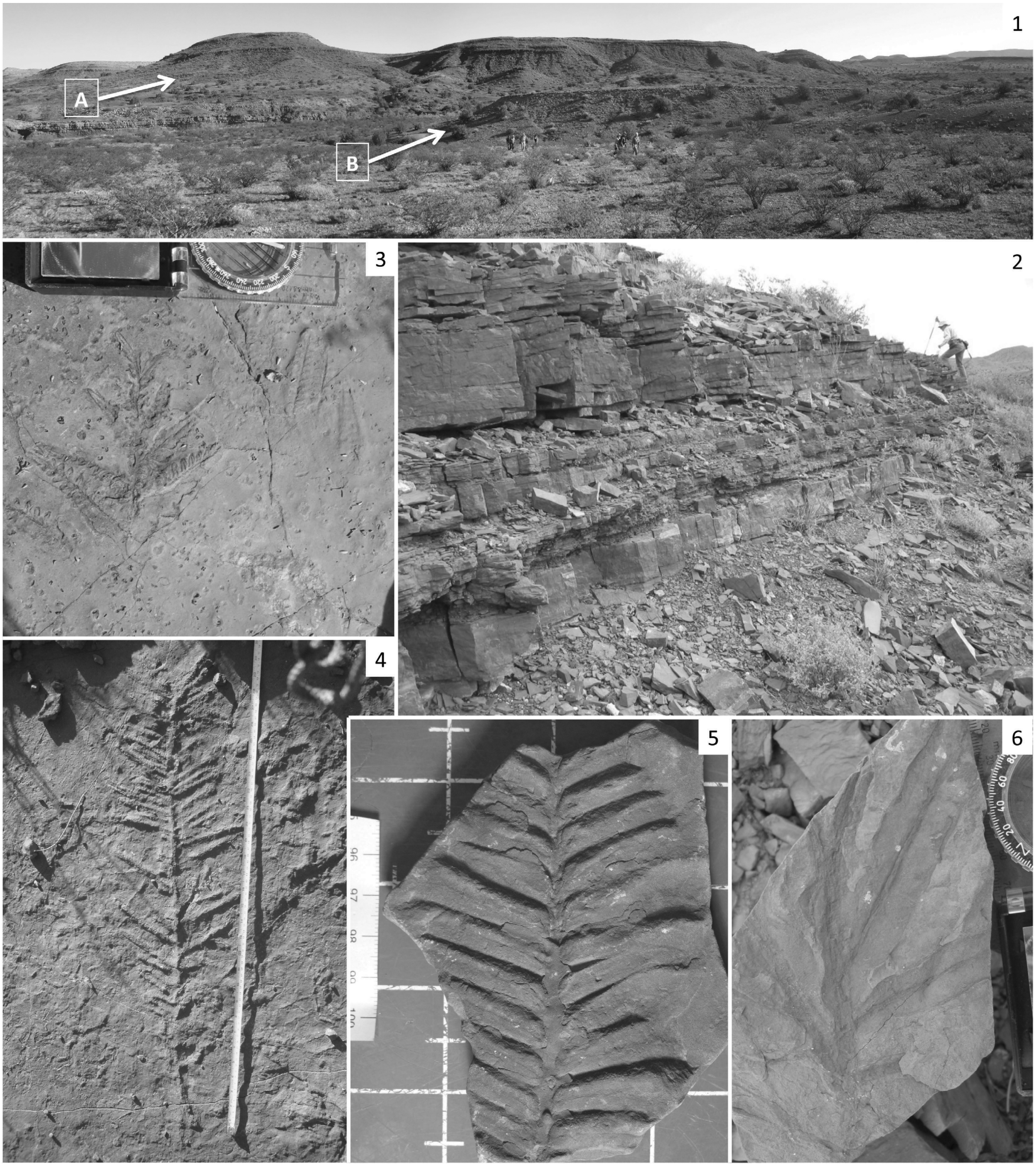


FIGURE 22. Abo Formation outcrops and flora in Cañoncito de la Uva. **1**, Bursum (B at arrow) and Abo (A at arrow) formation exposures in Cañoncito de la Uva looking south from the road. **2**, Abo Formation sheet-like siltstone-sandstone bed showing platy bedding in upper, fossiliferous portion. **3**, *Autunia conferta*, USNM specimen 543955. **4**, *Walchia* sp., entire branch, field photograph. **5**, *Supaia thinnfeldioides*, NMMNH specimen P-42811. **6**, *Supaia anomala*, field photograph.

composed of cyclically alternating layers of siltstone, bedded gypsum, and limestone or dolomite. Much of the siltstone is massive and may represent ancient loess, or wind-blown dust. Gypsum can be evenly laminated, wavy laminated, or nodular. The limestone and dolomite layers, which erode to ledges, are mostly carbonate mudstone and peloidal, oncoidal, and oolitic wackestone yielding a sparse fauna of ostracods, bivalves, and rare foraminifera. Overlying the Torres is the Cañas Gypsum, which is 66 m thick and composed of massive to bedded gypsum having interbeds of siltstone and dolomite. This material erodes to a "moonscape" that is practically devoid of vegetation and highly subject to karst development. The Joyita Member, at the top of the Yeso Group, is 12.3 m of reddish to greenish gray siltstone and sandstone that lacks gypsum and forms a reddish slope beneath the light gray cliffs of Glorieta Sandstone.

The more agile participants in the field trip will scramble up to the lower layers of the Glorieta Sandstone, the light-colored, crossbedded sandstone that forms prominent cliffs (Fig. 25). The Glorieta is largely an eolian deposit that is correlative with the Coconino Sandstone of the Grand Canyon, but toward the southeast, Glorieta sand underwent considerable reworking in shallow marine settings (Milner, 1978). Forming the top of the high knob is the youngest Permian formation in this area of New Mexico, the San Andres Formation. The San Andres is late Leonardian to early Guadalupian age and is composed largely of marine limestone and dolomite, with interbeds of gypsum, anhydrite, and sandstone in some localities. Access to the San Andres here is difficult and will not be attempted by the field party.

The outcrop area of the Arroyo de Alamillo Formation in this area, near Tomas Baca Well, also includes the stratigraphically highest record of terrestrial fossils of the Yeso Group in central New Mexico. Plant fossils, root traces, and invertebrate and vertebrate traces have been recently found at two sites (NMMNH localities 8715 and 8716) north of Tomas Baca Well in pale reddish to greenish-gray beds ~45–50 m above the base of the Arroyo de Alamillo Formation (Lucas et al., 2013). Plants are known from an *in situ* callipterid pteridosperm and various conifer remains. Abundant root traces indicate that plants must have been locally common during deposition of the Arroyo de Alamillo Formation. Invertebrate traces are remarkably diverse in siliciclastic strata of NMMNH locality 8715 and tentatively attributed to *Diplichnites*, *Diplopodichnus* (Fig. 10J), *Gordia*, *Helminthoidichnites*, *Scoyenia*, *Stiallia* (Fig. 10K, L), *Striatichnium*, and *Treptichnus*. According to this record aquatic to semiaquatic arthropods must have been an important element of the invertebrate fauna. The tetrapod ichnofauna consists of *Batrachichnus*, *Dromopus* (Fig. 10L) and undetermined "captorhinomorph" tracks. Taking the lenticular geometry of the fossil-bearing beds, the predominance of mud and the abundance of rain drop imprints and mudcracks into account, the strata most likely represent deposits of temporary pools.

Plant fossils are very rare in the Yeso Group, and where they occur, the depositional conditions appear very similar to those under which Abo Formation plants were deposited. Also, similarly to the Abo, Yeso floras are dominantly conifers and *Supaia*. At present, too few exposures are known to permit a definitive characterization of the Yeso flora and, thereby, to understand if there were any significant floristic compositional changes that accompanied the environmental transition from Abo to Yeso deposition.

After stop, continue east on all-weather road. 0.2

9.8 Prominent knob of Glorieta Sandstone at 10:30 on Yeso beds. Sierra de la Cruz at 2:00. Road is in lower Yeso strata. **0.3**

10.1 Cross tributary of Cañoncito de la Uva. Note lower Yeso strata exposed in arroyo banks. **0.2**

10.3 Cattleguard, Tomas Baca Well; road in Abo Formation. John Nelson's retirement home (not paid for yet!) on left. Note excellent view of Mesa del Yeso at 7:00. Arroyo crossing here is in lower Yeso strata. **0.2**

10.5 Cross arroyo; outcrops to left are very close to the Abo-Yeso contact. These are uppermost Abo red beds with rhizoliths in the siltstones and trough-crossbedded fluvial sandstone bodies. **0.5**

11.0 Cross arroyo (another tributary of Cañoncito de la Uva) floored by Abo red beds. Notice change in dip in the Abo Formation rocks here, east of the road dip east, west dip west. Apparently we are on a small anticlinal flexure. **0.2**

11.2 Crossed fault, rocks to right of road are interbedded siliclastic limestones and red beds of the Bursum Formation. **0.2**

11.4 Cross arroyo; note top of Bursum limestone to right; road is at Bursum-Abo contact here: dip slope on top of Bursum to right and Abo red beds to left. **0.4**

11.8 Cattleguard and brass cap for NE1/4 NE1/4 sec. 10 T02S R02E. The road here is on the upper part of the Bursum Formation. **0.1**

11.9 Small prospect on right. Many small prospects are found in the Bursum Formation in this area. Localized redbed copper deposits are common, together with small concentrations of uranium mineralization, though nothing large enough to be of economic significance. Road ascends hill along dip of limestone unit in upper part of the Bursum Formation. **0.2**

12.1 Crest hill, road now descends dipslope of upper Bursum strata. **0.2**

12.3 Cross arroyo, a tributary of the Cañoncito de la Uva. Outcrops near the road have been mapped as Bursum Formation. The road parallels a swarm of normal faults striking north-northwest (Colpitts, 1986). **0.1**

12.4 Road junction, keep left. Note larger mining prospect straight ahead. Road to right goes to Del Cuerto Ranch headquarters, 7 mi. Road to left (our route) to Creel Headquarters (18 mi.). **0.1**

12.5 Cross Cañoncito de la Uva. Gallina Well (windmill) to left. Note Bursum outcrop to left of and downstream of Gallina Well. **0.1**

12.6 Road(s) to left to Gallina Well, **continue straight on main road. 0.2**

12.8 Road enters arroyo floor and is driving in upper Bursum strata; note thick Abo section up hills to left. **0.1**

12.9 Road follows strike valley with some local faulting (note numerous slickensides in Abo rocks to right) along Bursum-lower Abo stratigraphic interval. **0.2**

13.1 Road climbs out of arroyo. Note low, conical hill of Abo Formation at 12:00; this is the Gallina Well vertebrate fossil locality. **STOP here.**

The Gallina Well vertebrate fossil locality. The Gallina Well locality is a Lower Permian vertebrate body and ichnofossil site located approximately 20 km northeast of Socorro, New Mexico in the Joyita uplift. The locality is situated

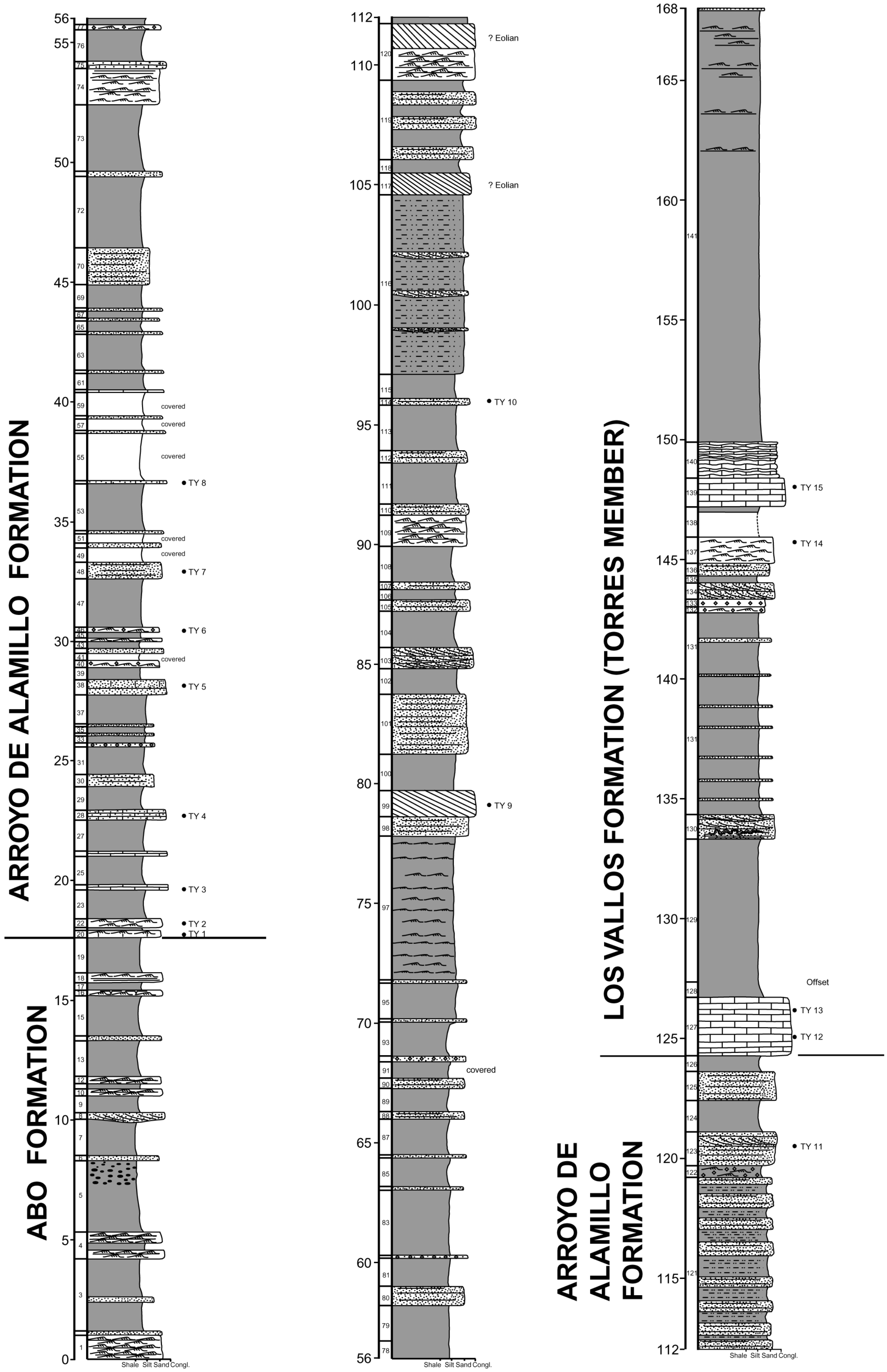


FIGURE 23. Type section of the Yeso Group (from Lucas et al., 2005).

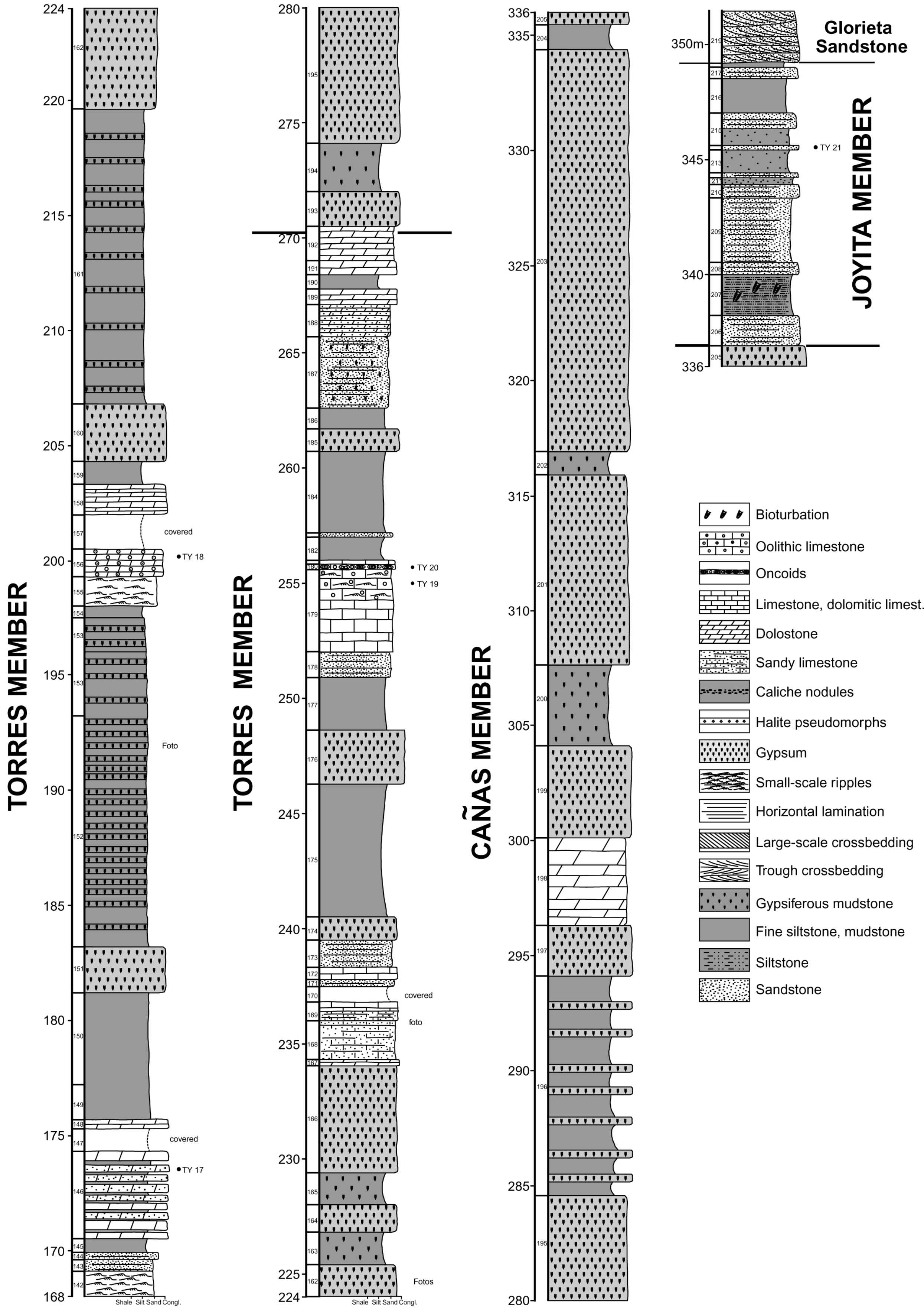


FIGURE 23. Continued. Type section of the Yeso Group (from Lucas et al., 2005).

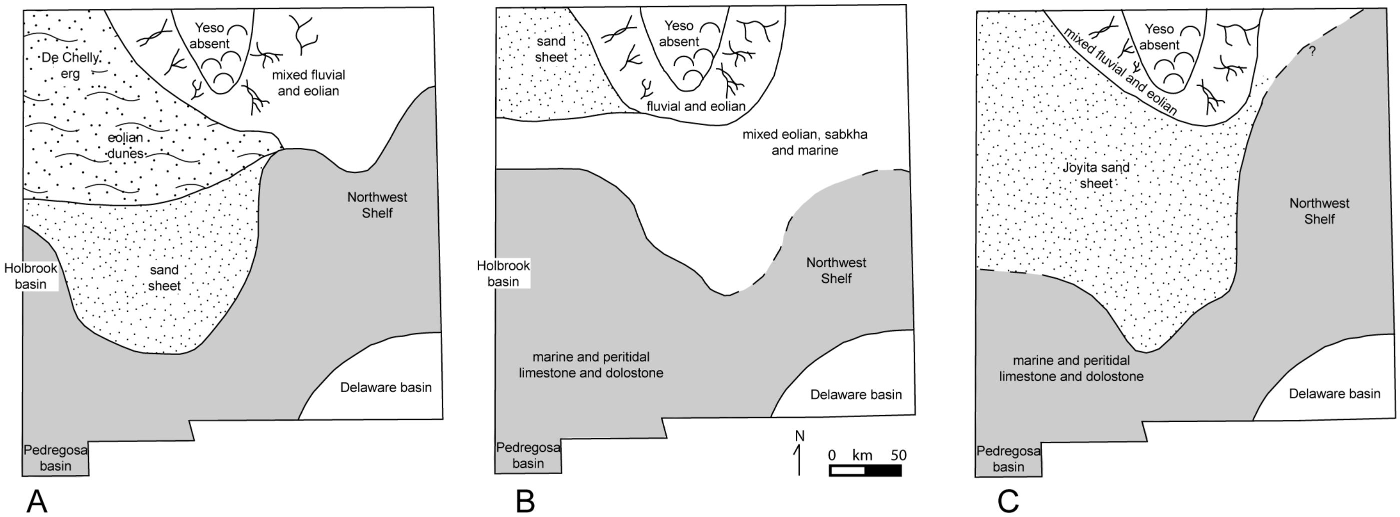


FIGURE 24. Yeso paleogeography (after Mack and Dinterman, 2002; Lucas et al., 2013). **A**, Early, **B**, middle and **C**, late Yeso deposition.

stratigraphically low in the Scholle Member of the Abo Formation and is Coyotean in age. The fossiliferous beds are reddish-brown, fluvially-deposited, calcrete-pebble conglomerates and mudrock. Vertebrate body fossils from the site include paleoniscoid fish; the temnospondyl amphibians *Eryops* sp., *Trimerorhachis* sp., *Platyhystrix* sp., and *Zatrachys* sp.; a skull fragment of the lepospondyl *Diplocaulus* sp.; postcrania of the diadectid *Diadectes* sp.; a captorhinid skull and postcranial skeleton; and specimens of the eupelycosaurs *Ophiacodon* sp., *Sphenacodon* sp. and *Dimetrodon* sp. The coprolite ichno-assemblage includes *Dakyronocopros arroyoensis*, *Alococopros triassicus*, *Heteropolacopros texaniensis* and amorphous coprolites. The Gallina Well locality yields the most diverse and extensive vertebrate body fossil and coprolite assemblage of Early Permian age known from southern New Mexico. Its basic composition differs little from the pelycosaur-dominated assemblages found to the north, indicating some uniformity of the Coyotean vertebrate fauna across New Mexico.

Not far to the northwest, we can examine an unusually thick section of the Burusm Formation.

Bursum Formation. The Bursum Formation here is 120 m thick and assigned to the Red Tanks Member (Fig. 26). The succession rests on nodular to wavy bedded fossiliferous limestone of the Atrasado Formation and is overlain by nonmarine red beds of the Abo Formation. The lower 45 m are composed of predominantly greenish gray and reddish mudstone-siltstone, some covered (?shale) intervals and intercalated conglomerate and sandstone beds. Three conglomerate beds are intercalated in the lower part between 6 and 14 m above the base (0.2-1 m thick). Conglomerate beds are poorly sorted, clast supported and composed of carbonate clasts with diameters up to 20 cm in the lowermost bed. Intercalated sandstone beds are up to 0.8 m thick. Thin sandstone beds (0.1-0.3 m) are massive, horizontally laminated or display ripples. Thicker sandstone beds display trough crossbedding and lense out laterally (channel fills). In the lower part one thin (0.3 m), dark gray micritic limestone bed is intercalated in shale about 35 m above the base.

The middle part of the Bursum Formation (45-65 m) is composed of greenish-gray and gray shale, some covered (?shale) intervals and many thin (mostly 5-20 cm, rarely up to 50 cm) micritic limestone beds (mudstone to wackestone). Some beds contain fossils such as brachiopods, gastropods, crinoidal debris and bryozoans (packstone). Two thin crossbedded sandstone beds are intercalated (0.2 and 0.4 m thick). At the top of this interval nodular limestone (0.6 m) is intercalated which contains brachiopods and bryozoans. A fault is observed about 50 m above the base, but does not appear to remove much of the section. Between approximately 65 and 80 m above the base several coarse-grained sandstone and conglomerate beds and one nodular calcrete horizon are intercalated in red mudstone which locally contains abundant small pedogenic limestone nodules. The conglomerate beds are up to 2.1 m thick, poorly sorted and composed of carbonate clasts and sandy arkosic matrix. The conglomerate beds are partly crossbedded, the clasts are subangular to subrounded; grain-size is mostly < 5 cm, rarely up to 20 cm. The upper part of the section (80-120 m) is composed of red and subordinately greenish-gray mudstone with intercalated carbonate conglomerate beds (0.3-0.6 m thick), crossbedded arkosic sandstone beds (0.4-1 m thick) and few fossiliferous, partly sandy limestone beds (3-30 cm), a nodular limestone (1.2 m) in the lower part and nodular calcrete horizons (0.6-2.8 m). Red mudstone locally contains small calcrete nodules. The uppermost conglomerate lacks arkosic material and contains bone fragments. A thin limestone bed in the lower part, approximately 90 m above the base contains crinoidal debris, bryozoans and brachiopods. The limestone bed approximately 104 m above the base is characterized by the occurrence of abundant echinoid spines, some of them up to 5 cm long. The thin limestone beds which are intercalated in pink shale near the top contain *Dunbarella* and represent the last marine horizon.

The lower part of the section is dominantly nonmarine, the middle part shallow marine and the upper part again dominantly nonmarine with few thin marine horizons represented by fossiliferous thin limestone beds.

The terrestrial deposits of the Bursum are primarily paleosols and plant fossils usually have been obliterated by pedogenesis. However, in the Canoñcito de la Uva area there are a number of plant-bearing deposits have been found in gray shales and occasionally sandy siltstones. These deposits occur in close association with syndepositional faulting and appear to represent lakes that were preserved by the creation of accommodation space allowing shorter-term burial. The floras of the Bursum are, for the most part, dominated by conifer branches and foliage cordaitalean foliage, and callipterids with other plants represented locally. This is the first unit in

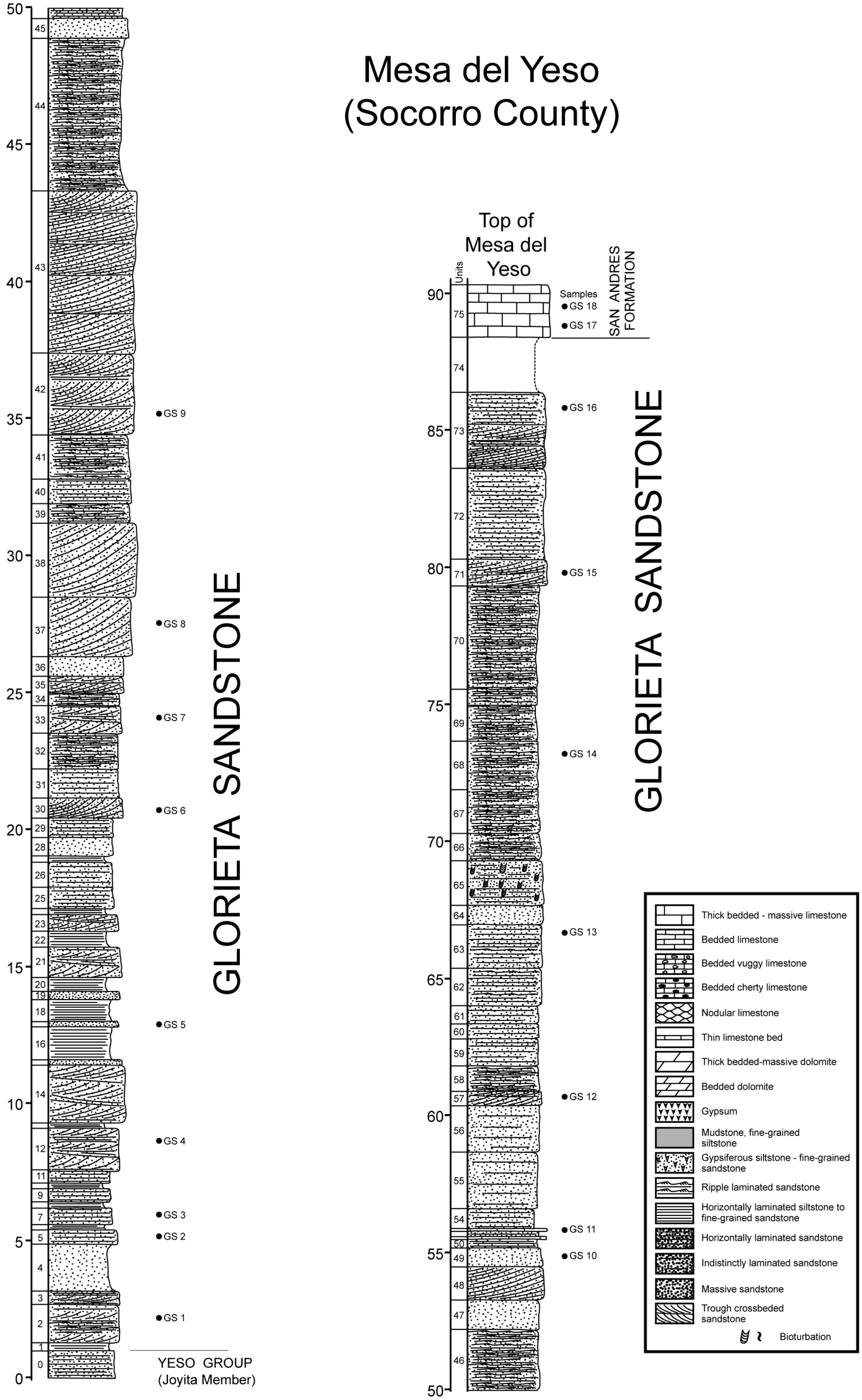


FIGURE 25. Measured stratigraphic section of the Glorieta Sandstone at Mesa del Yeso.

FIGURE 26. Bursum Formation section near Gallina Well.

the regional succession in which callipterid peltasperms are quantitatively important parts of the flora. The overall plant assemblage is indicative of seasonally dry climatic conditions. The wetland elements, typically found in the terrestrial facies of the Atrasado Formation, are mostly lacking or very rare in the Bursum Formation.

End of third-day road log.

ROAD-LOG REFERENCES

Barrick, J.E., Lucas, S.G. and Krainer, K., 2013, Conodonts of the Atrasado Formation (uppermost Middle to Upper Pennsylvanian), Cerros de Amado region, central New Mexico, U.S.A.: New Mexico Museum of Natural History and Science, Bulletin 59, this volume.

Cather, S.M. and Colpitts, R.M., Jr., 2005, Geologic map of the Loma de las Cañas 7.5-minute quadrangle: New Mexico Bureau of Geology and Mineral Resources, Open-File Map OF-GM 110, 1 sheet, scale 1:24,000.

Cecil, C.B., Dulong, F.T., West, R.R., Stamm, R., Wardlaw, B. and Edgar, N.T., 2003, Climate controls on the stratigraphy of a Middle Pennsylvanian cyclothem in North America; *in* Cecil, C.B. and Edgar, T.N., eds., Climate Controls on Stratigraphy: SEPM Special Publication, v. 77, p. 151–182.

Colpitts, R.M., Jr., 1986, Geology of the Sierra de la Cruz area, Socorro County, New Mexico: New Mexico Bureau of Mines and Mineral Resources, Open File Report 244, 166 p. and 3 plates.

DiMichele, W.A. and Phillips, T.L., 1996, Climate change, plant extinctions and vegetational recovery during the Middle–Late Pennsylvanian transition: The case of tropical peat-forming environments in North America, *in* Hart, M.B., ed., Biotic Recovery from Mass Extinction Events: Geological Society of London Special Publication, v. 102, p. 201–221.

Eros, J.M., Montañez, I.P., Osleger, D.A., Davydov, V.I., Nemyrovska, T.I., Poletaev, V.I. and Zhykalyak, M.V., 2012, Sequence stratigraphy and onlap history of the Donets Basin, Ukraine: Insight into Carboniferous icehouse dynamics: Palaeogeography, Palaeoclimatology, Palaeoecology, v. 313, p. 1-25.

Falcon-Lang, H.J., Nelson, W.J., Elrick, S., Looy, C.V., Ames, P.R. and DiMichele, W.A., 2009, Incised channel fills containing conifers indicate that seasonally dry vegetation dominated Pennsylvanian tropical lowlands: Geology, v. 37, p. 923–926.

Falcon-Lang, H.J., Jud, N.A., Nelson, W.J., DiMichele, W.A., Chaney, D.S. and Lucas, S.G., 2011, Pennsylvanian coniferopsid forests in sabkha facies reveal the nature of seasonal tropical biome: Geology, v. 39, no. 4, p. 371-374.

Hambleton, A.W., 1962, Carbonate-rock fabrics of three Missourian stratigraphic sections in Socorro County, New Mexico: Journal of Sedimentary Petrology, v. 32, no. 3, p. 579-601.

Herrick, C.L., 1904, A coal-measure forest near Socorro, New Mexico: Journal of Geology, v. 12, p. 237-251.

Horton, D.E., Poulsen, C.J., Montañez, I.P. and DiMichele, W.A., 2012, Eccentricity-paced late Paleozoic climate change: Palaeogeography, Palaeoclimatology, Palaeoecology, v. 331–332, p. 150–161.

Hunt, A., 1983, Plant fossils and lithostratigraphy of the Abo Formation (Lower Permian) in the Socorro area and plant biostratigraphy of Abo red beds in New Mexico: New Mexico Geological Society, Guidebook 34, p. 157-163.

Jaworski, M.J., 1973, Copper mineralization of the upper Moya Formation, Chupadero Mines area, Socorro County, New Mexico [M.S. thesis]: New Mexico Tech, Socorro, 102 p. and 5 plates.

Julyan, R., 1998, The place names of New Mexico: Albuquerque, University of New Mexico Press, 385 p.

Kottlowski, F.E. and Stewart, W.J., 1970, The Wolfcampian Joyita uplift in central New Mexico: New Mexico Bureau of Mines and Mineral Resources, Memoir 23, part 1, 31 p.

Krainer, K. and Lucas, S.G., 2004, The Upper Pennsylvanian Red Tanks Member of the Bursum Formation at Carrizo Arroyo, central New Mexico: Transition from shallow marine to nonmarine facies: New Mexico Museum of Natural History and Science, Bulletin 25, p. 53-69.

Krainer, K. and Lucas, S.G., 2009, Cyclic sedimentation of the Upper Pennsylvanian (lower Wolfcampian) Bursum Formation, central New Mexico: Tectonics versus glacioeustasy: New Mexico Geological Society, Guidebook 60, p. 167-182.

Lerner, A. J., Lucas, S.G., Spielmann, J. A., Krainer, K., DiMichele, W.A., Chaney, D.S., Schneider, J.W., Nelson, W.J. and Ivanov, A.B., 2009, The Biota and Paleoecology of the Upper Pennsylvanian (Missourian) Tinajas Locality, Socorro County, New Mexico: New Mexico Geological Society, Guidebook 60, p. 267-280.

Lucas, S.G., DiMichele, W.A., Chaney, D.S. and Nelson, J., 2003, Rediscovery of Herrick's "coal-measure forest" in the Pennsylvanian Sandia Formation, Socorro County, New Mexico: New Mexico Geology, v. 25, p. 43.

Lucas, S.G., Krainer, K. and Colpitts, R.M., Jr., 2005, Abo-Yeso (Lower Permian) stratigraphy in central New Mexico: New Mexico Museum of Natural History and Science, Bulletin 31, p. 101-117.

Lucas, S.G., Krainer, K. and Barrick, J.E., 2009, Pennsylvanian stratigraphy and conodont biostratigraphy in the Cerros de Amado, Socorro County, New Mexico: New Mexico Geological Society, Guidebook 60, p. 183-211.

Lucas, S.G., Voigt, S., Lerner, A.J., MacDonald, J.P. Spielmann, J.A. and Celeskey, M.D., 2011, The Prehistoric Trackways National Monument, Permian of southern New Mexico, U.S.A.: Ichnology Newsletter, v. 28, p. 10–14.

Lucas, S.G., Krainer, K. and Voigt, S., 2013, The Lower Permian Yeso Group in central New Mexico: New Mexico Museum of Natural History and Science, Bulletin 59, this volume.

Mack, G.H. and Dinterman, P.A., 2002, Depositional environments and paleogeography of the Lower Permian (Leonardian) Yeso and correlative formations in New Mexico: The Mountain Geologist, v. 39, p. 75-88.

Milner, S., 1978, Genesis, provenance, and petrography of the Glorieta Sandstone of eastern New Mexico: New Mexico Bureau of Mines and Mineral Resources, Circular 165, 25 p.

Minter, N.J. and Lucas, S.G., 2009, The arthropod trace fossil Cruziana and associated ichnotaxa from the Lower Permian Abo Formation, Socorro County, New Mexico: New Mexico Geological Society, Guidebook 60, p. 291–298.

Needham, C.E. and Bates, R.L., 1943, Permian type sections in central New Mexico: Geological Society of America Bulletin, v. 54, p. 1653-1668.

Peyser, C.E. and Poulsen, C.J., 2007, Controls on Permo-Carboniferous precipitation over tropical Pangaea: a GCM sensitivity study: Palaeogeography Palaeoclimatology Palaeoecology, v. 268, p. 181–192.

Phillips, T.L., Peppers, R.A., Avcin, M.J. and Laughnan, P.F., 1974, Fossil plants and coal: patterns of change in Pennsylvanian coal swamps of the Illinois Basin: Science, v. 184, p. 1367–1369.

Plotnick, R.E., Kenig, F., Scott, A., Glasspool, I., Eble, C.F. and Lang, W.J., 2009, Pennsylvanian paleokarst and cave fills from northern Illinois, USA: A window into late Carboniferous environments and landscapes: Palaios, v. 24, p. 627–637.

Ross, C.A. and Ross, J.R.P., 1988, Late Paleozoic transgressive-regressive deposition: SEPM Special Publication, no. 42, p. 227-247.

Smith, C.T. and 8 others, 1983, The Ocean-to-Ocean Highway: New Mexico Geological Society, Guidebook 34, p. 3-4.

Tidwell, W.D., Munzing, G.E. and Lucas, S.G., 2000, A new species of *Dadoxylon* from the Upper Pennsylvanian Atrasado Formation of central New Mexico: New Mexico Museum of Natural History and Science, Bulletin 16, p. 15-20.

Voigt, S. and Lucas, S.G., 2012, Late Paleozoic Diadectidae (Cotylosauria:

Diadectomorpha) of New Mexico and their potential preference for inland habitats: Geological Society of America, Rocky Mountains Section, Abstracts with Programs, 64th Annual Meeting, Albuquerque May 9–11, p. 90.

Voigt, S., Saber, H., Schneider, J., Hminna, A., Hmich, D. and Klein, H., 2009, Large imprints of *Hyloidichnus* Gilmore, 1927 from the Permian of Morocco in the light of captorhinid phylogeny and biogeography: Abstract Volume, First International Congress on North African Vertebrate Palaeontology, Marrakech, May 25-27, 2009, p. 22.

Voigt, S., Lucas, S.G. and Krainer, K., 2013, Coastal-plain origin of trace-fossil bearing red beds in the Early Permian of southern New Mexico, U.S.A.: Palaeogeography, Palaeoclimatology, Palaeoecology, v. 369, p. 323–334.

West, R.R., Miller, K.B. and Watney, W.L., 2010, The Permian System in Kansas: Kansas Geological Survey, Bulletin 257, 82 p.