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First-day road log from Las Cruces to Derry Hills and Mescal Canyon in the Caballo Mountains

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FIRST-DAY ROAD LOG FROM LAS CRUCES TO DERRY HILLS AND MESCAL CANYON IN THE CABALLO MOUNTAINS

GREG H. MACK, TIMOTHY F. LAWTON, and KATHERINE A. GILES

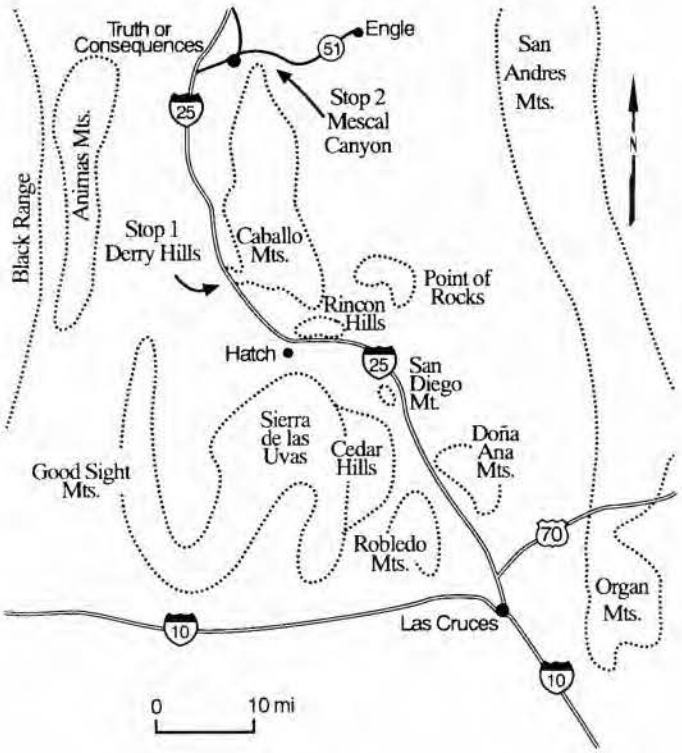
THURSDAY, NOVEMBER 5, 1998

Assembly point: Days Inn parking lot, corner of University Avenue and Main Street, Las Cruces. Take University Avenue east to I-25. Go north on I-25. Road log begins where I-25 crosses US-70 and is keyed to Interstate milepost signs.

Departure time: 8:00 a.m.

Distance: 153 mi

Stops: 2 with 10 foot-log stops



Summary

The first day of the field conference follows a route from Las Cruces to Truth or Consequences along I-25. The goal of the first day is to examine parts of the Paleozoic and Mesozoic sedimentary sections and discuss depositional environments and basin evolution. The first stop is in the Derry Hills, where the Pennsylvanian Magdalena Group and Permian Abo Formation are exposed in a late-rift (latest Miocene–Pliocene) fault block. We will examine the uppermost formation of the Magdalena Group, the Bar B Formation, whose mixed carbonate and siliciclastic facies will be placed in the context of sequence stratigraphy. At the end of the foot log traverse, the basal part of the nonmarine Abo Formation is exposed. The Magdalena Group and Abo Formation at this location were deposited on the western margin of the Orogrande Basin, one of the major north-trending basins of the Ancestral Rocky Mountains deformational belt. Dramatic thickness changes, intraformational unconformities, and the presence of conglomerates in the Magdalena and Abo provide important insight into the tectonic history of the basin.

The afternoon stop in Mescal Canyon, east of Truth or Consequences, is devoted to examination of Upper Cretaceous siliciclastic sedimentary rocks. These exposures, which represent the most complete Upper Cretaceous section in southern New Mexico, include the Dakota, Mancos, Tres Hermanos, D-Cross, Gallup, and Crevasse Canyon Formations. A variety of shallow marine, shoreline, and nonmarine depositional environments are represented and are arranged into two large-scale transgressive-regressive cycles, which will be placed in the context of sequence stratigraphy. The Mescal Canyon section will be compared to sections in the San



FIGURE 1.1. View westward from I-25 of Picacho Peak, an Oligocene flow-band rhyolite dome.



FIGURE 1.2. View eastward to the high peaks in southern part of the Doña Ana Mountains, which are composed of early Oligocene cauldron-fill ash-flow tuff intruded by quartz monzonite and quartz latite dikes.



FIGURE 1.3. View westward across the Mesilla Valley from I-25 of the southern part of the Robledo Mountains, where late Pleistocene alluvial fans are dissected by Holocene arroyos and the modern Rio Grande. Bedrock hills are composed of the Permian Hueco Formation.

Juan Basin and farther north and will be discussed in the context of the evolution of the Sevier fold and thrust belt and the complementary Western Interior foreland basin.

Mileage

0.0 I-25 passes beneath overpass of US-70. Proceed north on I-25. **2.0**

2.0 Milepost (MP) 8. At 9:00 across the Mesilla Valley is Picacho Peak, one of approximately two dozen flow-banded rhyolite domes that exist in the vicinity of Las Cruces (Fig. 1.1). Most of the domes are exposed west of Picacho Peak in a north-trending zone 16 mi long and 3 mi wide. A smaller group of domes exists at the southern end of the Doña Ana Mountains (Seager, 1975). A sanidine $^{40}Ar/^{39}Ar$ date of one dome in the Rough and Ready Hills indicates an age of 35.4 ± 0.21 Ma (D. Ware, W. McIntosh, and N. McMillan, personal commun., 1998). **3.0**

5.0 MP 11. At 2:00 are the Doña Ana Mountains, which are bordered on the east by the east-dipping Jornada normal fault and make up the hanging wall of the northern Mesilla half graben (Fig. 1.2). The bulk of the range is composed of early Oligocene cauldron-fill ash-flow tuffs, megabreccias, volcaniclastic rocks, and flow-banded rhyolites intruded by monzonite and latite porphyries (Seager et al., 1976). Single-crystal sanidine $^{40}Ar/^{39}Ar$ dates of the cauldron-fill tuffs give an age of 35.5 Ma (McIntosh et al., 1991). Also exposed in the Doña Ana Mountains are the late Eocene Palm Park Formation and Permian Hueco Formation. The Hueco is

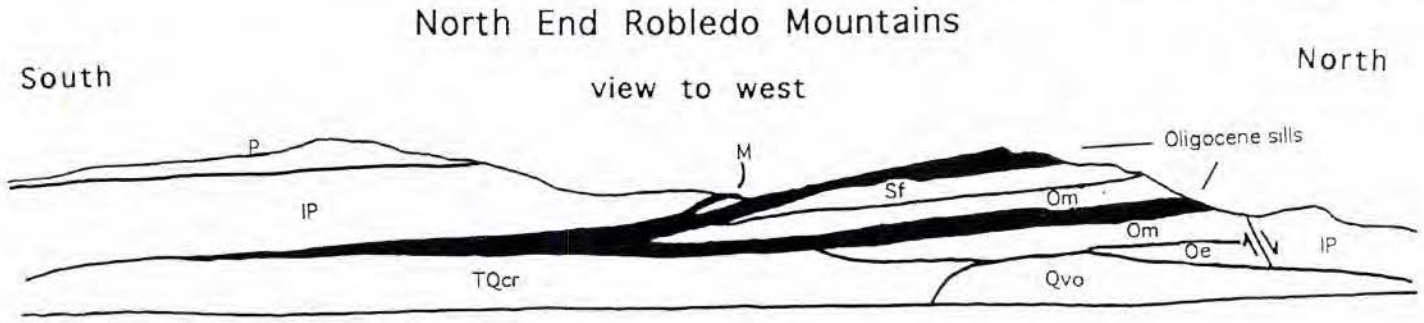




FIGURE 1.4. View westward across the Mesilla Valley of the northern end of the Robledo Mountains. Symbols on the corresponding cross section are: Oe = Ordovician El Paso Formation; Om = Ordovician Montoya Formation; Sf = Silurian Fusselman Dolomite; M = Mississippian rocks; IP = Pennsylvanian rocks; P = Permian Hueco Formation; TQcr = Pliocene–early Pleistocene Camp Rice Formation; Qvo = late Pleistocene alluvium inset against the Camp Rice Formation; black denotes Oligocene rhyolite sills.

deformed by folds and thrust faults in the northern part of the range (Seager et al., 1976). **2.0**

7.0 MP 13. At 9:00 across the Mesilla Valley are gently sloping geomorphic surfaces of late Pleistocene age representing the tops of alluvial fans inset against older alluvium (Fig. 1.3; Gile et al., 1981). The inset alluvium has been dissected by younger arroyos and by the modern Rio Grande. **3.0**

10.0 MP 16. At 9:00 are the Robledo Mountains (Fig. 1.4), a late-rift (latest Miocene–Pliocene) horst that constitutes the footwall of the northern Mesilla half graben (Seager et al., 1984; Mack and Seager, 1990). Exposed in the northern part of the range are Ordovician to Permian sedimentary rocks intruded by Oligocene rhyolite sills. The steep tan cliffs at the base of the mountains belong to the Plio–Pleistocene Camp Rice Formation and include alluvial-fan and axial-fluvial lithofacies. Also evident are inset geomorphic surfaces. **2.0**

12.0 MP 18. At 10:00 in the far distance is the Sierra de las Uvas; the lows hills in foreground are the Cedar Hills; at 11:00 are the low East Selden Hills. **3.0**

ROBLEDO MOUNTAINS, KEY OUTCROPS IN SOUTH-CENTRAL NEW MEXICO

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The Robledo Mountains and its prominent riverside terraces hug the west bank of the Rio Grande from Picacho Mountain at the south end, 4 mi west-northwest of Las Cruces, northward to Lookout Peak, 3 mi south of Radium Springs. The range is a wedge-shaped fault block of Paleozoic and Eocene rocks tilted to the south 10–14°, broadening southward from the northern apex. Late Pliocene and Pleistocene fan deposits and intertonguing ancestral Rio Grande fluvial sediments (Camp Rice Formation) overlap the southern part of the range near Picacho Mountain and form downfaulted blocks bordering the eastern and western sides. The East Robledo fault trends southeast from Lookout Peak to west of the town of Doña Ana, then swings to the south-southwest, continuing across La Mesa to a complex of faults near the Aden volcano. The West Robledo fault trends south-southwest and also continues across La Mesa to the center of the West Potrillo Mountains (Kottlowski, 1953, figs. 1-3 and 1-4; Seager et al., 1987).

Paleozoic strata exposed in the Robledos include 160 ft of upper El Paso Limestone, Montoya Dolomite (340 ft), Fusselman Dolomite (250 ft), Percha Shale (100–125 ft), Mississippian beds (100–200 ft), Atokan–Derryan (100 ft), Desmoinesian (225 ft), Missourian (170 ft), Virgilian (240 ft), Bursum (lowermost Wolfcampian) (180 ft), and Hueco Formation including a tongue of the Abo redbeds (1720 ft). The thin marine shelf facies of the Virgilian contrasts with the thick cyclic basin-filling Panther Seep Formation, composed of tidal-flat and clastics of the Orogrande Basin, a facies that crops out in the northwestern Doña Ana Mountains and in the San Andres Mountains farther east. The entire Pennsylvanian sequence in the Robledos was deposited on the Robledo Shelf, west of the Orogrande Basin.

The Hueco-Abo sequence is the westernmost outcrop of a thick Hueco section and the southernmost outcrop of a thick Abo tongue. The Hueco-Abo has been mapped (Seager and Kottlowski, unpubl. map, 1954, 1991) as a lower and middle Hueco (80 ft), Abo tongue (475 ft), and upper Hueco (355 ft), unconformably overlain by Eocene Love Ranch Formation fanglomerates and the upper Eocene–lower Oligocene Palm Park Formation. The Abo tongue (labeled Robledo Mountains Member by Lucas et al., 1995) crops out in the southern part of the range, and is actually an intertonguing of typical Hueco marine nodular to ledgy limestone and shale with Abo grayish-red micaceous sandstone and red siltstone. Thus, the unit is an intercalation of tidal-flat redbeds with shallow marine shelf limestones and calcareous shales (Mack and James, 1986; Mack et al., 1988; Lucas et al., 1995), and is close to the southern extent of the redbeds. Fusulinids, identified by M. L. Thompson and William E. King, date the lower and middle Hueco Members as Wolfcampian. Kues (1995) described the prolific marine fauna in the upper beds of the Abo tongue and LeMone et al. (1975) studied the upper Hueco Member, including phylloid-algal banks. These studies, although lacking fusulinid faunas, agree with Jordan's (1975) designation of late Wolfcampian age.

The abundant fossil tracks in the Abo tongue were extensively collected by J. MacDonald and coworkers (Lucas and Heckert, 1995). The bulk of the collections are exhibited and stored at the Natural History Museum in Albuquerque, and other specimens at the Las Cruces Natural History Museum, Carnegie Museum, Smithsonian, and Los Angeles County Natural History Museum.

In Apache Canyon, the second canyon north of Picacho Mountain, conglomerates of the Eocene Love Ranch Formation, about 100 ft thick, unconformably overlie and fill channels cut into the upper Hueco, and grade up into 240 ft of gypsum and redbeds. These strata underlie the main mass of the upper Eocene–lower Oligocene Palm Park Formation andesitic volcaniclastic rocks. From this south end of the range, the Love Ranch and Palm Park Formations truncate northward uppermost Hueco strata down to the Fusselman Dolomite (on the west side of Lookout Peak). This truncation is a major clue to the location of the northwest-trending Laramide Rio Grande uplift, whose Precambrian granite core is near San Diego Mountain 18 mi to the north (Seager et al., 1986, 1997).

At Highway Marker Mile 15 on I-25 (9 mi north of I-25-US-70 intersection), Robledo Mountain, altitude 4876 ft (1950 ft above Rio Grande) is at 9:00 (if northward bound) and Lookout Peak, altitude 5653 ft, is at 9:30, with bold outcrops exhibiting a thick Paleozoic section. Lookout Peak and the saddle to the south are capped by a 450-ft-thick high-potassium rhyolite sill (dated at 35.2 ± 1.3 Ma), containing large remnants of autochthonous Devonian and Mississippian strata. The prominent dark-colored, double cliff below the sill on Lookout Peak is the Fusselman Dolomite; below is the light-colored slope-forming Cutter Member of the Montoya Dolomite intruded by sills. The lower dark cliff consists of the cherty Aleman and Upham Members of the Montoya. Upper beds of the El Paso Limestone outcrop in the side canyons on the west side of the East Robledo fault.

Robledo Mountain is capped by 260 ft of the lower Hueco Member; the first thick limestones below the Hueco are of the Bursum strata, with a lower ledgy outcrop, 190 ft thick. The bold cliffs below are Virgilian limestones, 240 ft, underlain by slopes and ledges of the Missourian, 170 ft; then Desmoinesian ledges, 225 ft, and above the sill, slopes and ledges of Derryan–Atokan strata, 100 ft, but with variable amounts assimilated by the sill.

The light-brown cliffs of conglomerate near the base of Lookout Peak, east of the East Robledo fault, are mainly Camp Rice Formation fanglomerates, which overlap and intertongue with gray-tan fluvial sands of the Camp Rice. These upper Pliocene and Pleistocene sediments have been downdropped at least 300 ft by post-middle Pleistocene movement along the East Robledo fault (Hawley, et al., 1975).

The prominent series of terraces along the east foot of the Robledo Mountains, from Picacho Mountain northward, include two geomorphic-surface members: (1) Tortugas surface, a complex of older and higher surfaces graded to an ancient river base about 120 ft or more above the present floodplain level, and (2) Picacho



FIGURE 1.5. San Diego Mountain, looking westward from I-25. Highest mesa is underlain by latest Oligocene–early Miocene Hayner Ranch Formation, faulted against Precambrian metamorphic rocks. The mesa in the foreground consists of the Pliocene–early Pleistocene Camp Rice Formation. Small ridge on the right side is Camp Rice Formation on the footwall of the Jornada fault.

surface, graded to levels in the plus 70–90 ft range (Ruhe, 1967; Hawley and Kottlowski, 1969; Hawley, et al., 1975). Alluvium associated with these terraces record two older episodes of valley entrenchment followed by partial backfilling of river and arroyo valleys. The oldest fill, the Tortugas Alluvium of pre-Wisconsinan, late Pleistocene age, is as much as 100 ft thick, with coarse-grained piedmont sediments interfingering valleyward with tongues of river sand and gravel. The Picacho Alluvium of pre-late Wisconsinan age is as much as 50 ft thick with fluvial deposits intertongued with locally derived alluvial-fan alluvium. Lower, younger valley fill, the Fort Selden Alluvium of late Wisconsinan and Holocene age, forms the inner fill of the valleys of the Rio Grande and its arroyo tributaries, and is difficult to see from the highway. It has been subdivided into two members, the Leasburg of late Wisconsinan–early(?) Holocene age and the Fillmore, dated at less than 7500 yrs before present (Hawley, et al., 1975).

Robledo Mountain is named for Pedro Robledo, a senior member of Don Juan de Oñate's 1598 colonizing caravan, who died and was buried at El Paraje de Robledo, Robledo Campsite, just south of present day Radium Springs (Simmons, 1991)—400 yrs ago, as we observe Cuarto Centenario, the anniversary of the Spanish-Mexican entrada. This paraje was the last one before Camino Real de Tierra Adentro climbed northward out of the Mesilla Valley onto Jornada del Muerto.

15.0 MP 21. I-25 ascends axial-fluvial sands of the Plio–Pleistocene Camp Rice Formation. At the crest of the hill, the vista includes: at 10:00 the flat-topped hill of San Diego Mountain (also called Tonuco uplift); at 11:00 in the far distance are the Caballo Mountains; at 1:00 are low hills called Point of Rocks; at 3:00 are the San Andres Mountains. The highest point of the highway and the gentle plain to the north represent the La Mesa surface, the constructional top of the Camp Rice axial-fluvial facies. The surface is offset here approximately 80 ft by a west-trending segment of the Jornada fault that connects the Doña Ana Mountains and San Diego Mountain. This segment of the Jornada fault may have been active during Pliocene and early Pleistocene time, because the Camp Rice Formation has distinctly different sediment accumulation rates and facies on either side of the fault (Mack et al., 1994a). **5.0**

20.0 MP 26. Enter Border Check Station. **2.0**

22.0 MP 28. At 9:00 is San Diego Mountain, a late-rift (latest Miocene–Pliocene) fault block that came up near the center of a Miocene basin (Fig. 1.5; Seager et al., 1971; Mack et al., 1994b). The fault block has experienced post-early Pleistocene movement, because the constructional top of the Camp Rice Formation (La Mesa surface) is locally offset by about 60 ft. Despite its small size, San Diego Mountain contains a variety of geology, including about 5000 ft of latest Oligocene and Miocene basin-fill conglomerates, sandstones, and mudstones (Hayner Ranch and Rincon Valley Formations), and late Eocene andesitic volcanic rocks. A Laramide (latest Cretaceous–Eocene) north-vergent thrust fault brings Precambrian crystalline basement over lower Paleozoic sedimentary rocks. San Diego Mountain also contains Plio–Pleistocene alluvial-fan and axial-fluvial sand/sandstone and gravel/conglomerate of the Camp Rice Formation, and Holocene(?) geothermal tufas (Seager et al., 1971, 1986, 1997). **2.0**

24.0 MP 30. At 9:00 in the far distance is the Sierra de las Uvas, a rift fault-block that first began to rise in late Miocene time (Fig. 1.6; Mack et al., 1994b). The range is composed primarily of the Bell Top Formation and overlying Uvas Basaltic Andesite. The Bell Top Formation consists of several hundred feet of interbedded ash-flow tuff outflow sheets, basalt flows, tuffaceous sandstones that represent reworked fallout tephra, and epiclastic conglomerates (Clemons, 1975; Mack et al., 1994c). The Bell Top consists of six mappable ash-flow tuffs numbered 2 through 7, with $^{40}Ar/^{39}Ar$ ages of: AFT3 = 35.7 Ma, AFT4 = 35.0 Ma, AFT5 = 34.8 Ma, AFT6 = 33.6 Ma, and AFT7 = 28.6 Ma (McIntosh et al., 1991). The Uvas Basaltic Andesite has been dated at 28 Ma (Seager et al., 1984). Mack et al. (1994c) suggest that from at least 35 to 28.5 Ma the Bell Top Formation was deposited in an eastward-tilted half graben, which was subsequently inverted beginning in late Miocene time. **2.6**

26.6 Upham exit. Proceed north on I-25. **0.4**

27.0 MP 33. Road begins descent into Rincon Arroyo. The La Mesa surface, which represents the constructional top of the axial-fluvial lithofacies of the Plio–Pleistocene Camp Rice Formation is directly underlain by a stage V petrocalcic paleosol (Gile et al., 1981). The age of the La Mesa surface has been constrained by reversal magnetostratigraphy to be near or at the boundary between the Matuyama and Brunhes geopolarity chrons, 0.78 Ma (Mack et al., 1993, 1996). For



FIGURE 1.6. Mountains in the distance are the Sierra de las Uvas, consisting primarily of the Oligocene Bell Top Formation and Uvas Basaltic Andesite. View is westward from I-25.



FIGURE 1.7. Axial-fluvial lithofacies of the Pliocene–early Pleistocene Camp Rice Formation exposed in the I-25 roadcut due east of Rincon Arroyo.

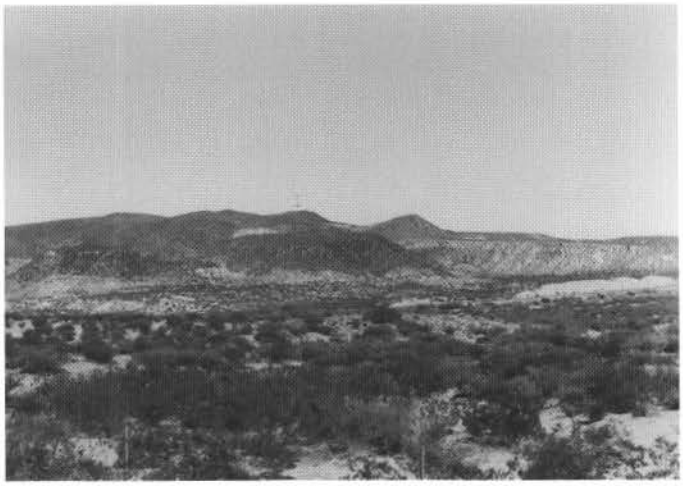


FIGURE 1.8. View northeastward toward the southeastern margin of the Rincon Hills, composed of latest Oligocene–Miocene Hayner Ranch and Rincon Valley Formations faulted against the Pliocene–early Pleistocene Camp Rice Formation.

the next 1.5 mi the roadcuts are in axial-fluvial facies of the Camp Rice Formation. Gray, pebbly sands deposited in the channels are interbedded with floodplain very fine sands and mudstones, some of which have superimposed calcic paleosols (Fig. 1.7). **2.0**

29.0 MP 35. At 2:00 is the Rincon Hills (Fig. 1.8), composed primarily of latest Oligocene and Miocene conglomerates, sandstones, and mudstones of the Hayner Ranch and Rincon Valley Formations deposited in early rift basins and uplifted in latest Miocene or Pliocene time. Also exposed in the northern part of the Rincon Hills are the Eocene Palm Park Formation, the Oligocene Bell Top Formation, the Uvas Basaltic Andesite, and Thurman Formation. **0.3**

29.3 Cross bridge over Rincon arroyo. **0.3**

29.6 Rincon exit. Proceed north on I-25. **0.4**

30.0 MP 36. The roadcuts for the next 3 mi are lacustrine mudstones and gypsums of the late Miocene Rincon Valley Formation (Fig. 1.9), overlain by light-colored axial-fluvial sand of the Plio–Pleistocene Camp Rice Formation. **3.0**

33.0 MP 39. At 9:00 are the Sierra de las Uvas; at 11:00 in the far distance is the sharp peak of the Cooke's Range; at 11:00 in the middle distance is a light-colored mesa that represents the La Mesa surface, the constructional top of the axial-fluvial lithofacies of the Plio–Pleistocene Camp Rice Formation; from 12:00 to 1:00 is the Black Range; at 3:00 the low dark hills in the middle distance are exposures of the Oligocene Uvas Basaltic Andesite and the higher mountain in the background is underlain by the Pennsylvanian Magdalena Group and represents the southern end of Red House Mountain. **2.2**

35.2 Hatch exit. Proceed north on 1-25. **2.8**

38.0 MP 44. At 2:00 is Red House Mountain (Fig. 1.10) composed of Ordovician through Pennsylvanian sedimentary rocks and uplifted during the earlier stage of extension of the Rio Grande rift, in latest Oligocene and early Miocene time (Mack et al., 1994b). **2.0**

41.0 MP 47. At 9:00 in the far distance is the Cooke's Range and in the middle distance is pyramid-shaped Nutt Mountain at the northern end of the Good Sight Mountains. At 10:00 to 12:00 in the far distance is the Black Range and in the middle distance are low hills of the Animas Mountains. The Black Range was the site of the early Oligocene Emory cauldron (Elston et al., 1975), which was subsequently dissected by normal faults during the early and late stages of the Rio Grande rift. The Animas Mountains represent a late-rift (latest Miocene–Pliocene) fault block that came up through an ancestral Palomas Basin, narrowing the basin to its present width (Mack et al., 1994b). **3.0**



FIGURE 1.9. South-facing roadcut of I-25 displaying a normal fault within the lacustrine gypsiferous mudstones of the late Miocene Rincon Valley Formation.

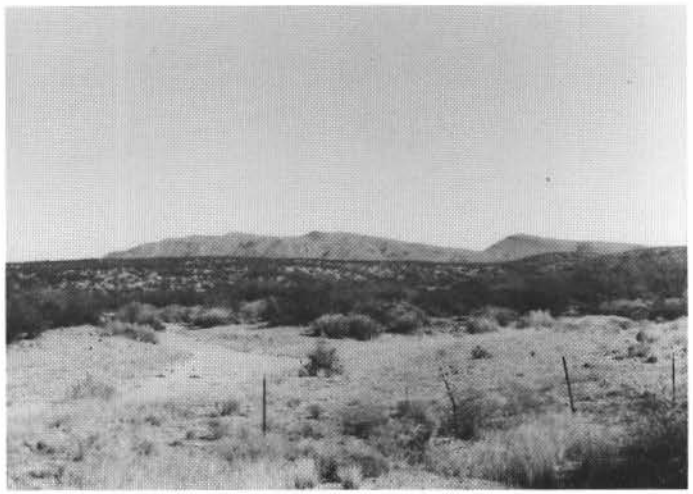


FIGURE 1.10. View to the east of Red House Mountain, a prominent normal-fault block composed of Paleozoic sedimentary rocks.

43.0 MP 49. For the next 2 mi the highway crosses well-developed late Pleistocene and Holocene inset surfaces (Fig. 1.11). In the background at 2:00 is Nakaye Mountain, a late-rift fault block of Paleozoic sedimentary rocks. **2.0**

BASIC PRINCIPLES OF SEQUENCE STRATIGRAPHY

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Sequence stratigraphy is a methodology for correlating and interpreting the three-dimensional architecture of marine and mixed marine-nonmarine sediment and sedimentary rocks. First developed in the 1970s by EXXON Production Research, the concepts of sequence stratigraphy were based on seismic reflection profiles and associated well-bore data from passive continental margins (see papers in Payton, 1977). Since that time, sequence stratigraphy has been applied to subsurface basins in other tectonic settings, as well as to outcrops of Precambrian and Phanerozoic rocks. The concepts of sequence stratigraphy have breathed new life into the study of regional stratigraphy and have become an important tool in hydrocarbon exploration. The goal here is to define the basic concepts of sequence stratigraphy so that they can be applied to Pennsylvanian and Upper Cretaceous sedimentary rocks examined during the first day of the New Mexico Geological Society 1998 Fall Field Conference. A more detailed treatment of the subject is presented in Van Wagoner et al. (1990).

FUNDAMENTAL PRINCIPLES

The fundamental unit of sequence stratigraphy is the **sequence**, which is a package of genetically related sediment or sedimentary rocks bounded above and below by regional unconformities, called the sequence boundaries, or by their correlative basinward conformities (Fig. 1.12). Sequence thickness varies depending upon the rate of sediment accumulation, the frequency and magnitude of sea-level change, and the depth of erosion beneath the sequence boundaries, but generally is measured on the scale of tens to hundreds of meters. The sequence boundaries and the architecture of the sediment within the sequence itself are related to relative rise and fall of sea level, as illustrated in the sinusoidal sea-level curve of Figure 1.12. Originally, EXXON workers assumed that sea-level cyclicity was entirely eustatic (global) in origin, but it is more likely that sea-level change in any given basin represents a combination of eustasy, basin subsidence rate, and sediment accumulation/production rate, the latter of which is strongly influenced by climate.



FIGURE 1.11. View northeastward from I-25 of Nakaye Mountain in the background and two levels of late Pleistocene inset alluvium in the foreground.

The **sequence boundary** is a regional unconformity cut during rapid drop in sea level (Fig. 1.12). As the shoreline regresses during sea level fall, base level of the streams is lowered and they incise the landward part of the basin, cutting the sequence boundary. The sedimentary record of this event are incised channels and valleys filled with fluvial or tidal/estuarine sediment. In seaward parts of the basin, the sequence boundary juxtaposes much shallower marine or nonmarine facies directly above deeper marine facies. In landward parts of the basin, however, the facies above and below the sequence boundary may be similar and the sequence boundary is recognized by deep erosion and/or evidence of protracted non-deposition, such as mature paleosols that developed on the interfluves between paleovalleys. In many basins, particularly those with a steep shelf break, the sequence boundary may not extend across the entire basin. Instead, on the seaward side of the basin, sediment is deposited as a **lowstand systems tract (LST)**, consisting either of deep-sea fans or shelf deposits (Fig. 1.12). It is important to note that the base of the LST is correlative with the sequence boundary unconformity.

As sea level begins to quickly rise, the LST and sequence boundary are onlapped by a package of sediment referred to as the **transgressive systems tract (TST)**, which displays a landward shift in facies and an overall upward-deepening of facies. Because rising sea level raises base level, streams tend to backfill, resulting in less siliciclastic sediment brought to the shoreline. Consequently, the marine parts of the TST may be unusually thin (condensed), because the shoreline and shelf are starved for sediment. In carbonate basins, this process may not apply, because the sediment is produced within the marine basin.

As the rate of sea-level rise begins to level off and gradually declines, corresponding to the crest of the sinusoidal curve in Figure 1.12, sediment progrades seaward. The resultant **highstand systems tract (HST)** is characterized by basinward offlap and seaward shift of facies. Overall, the HST displays an upward-shallowing succession of facies. Once sea level begins a more rapid fall, however, the upper sequence boundary is cut. In basins where the magnitude of sea-level fall is large, all or part of the HST may be removed by erosion from the landward side of the basin.

SEQUENCE STRATIGRAPHY IN OUTCROP

Applying sequence stratigraphy to outcrops presents special challenges and is in its formative stages. Only rarely is it possible to trace key stratal or unconformity surfaces for long distances laterally in outcrop and onlap and offlap stratal packages are commonly difficult to recognize. One advantage to outcrop analysis, however, is the ability to recognize vertical facies changes on a decimeter or meter scale, which is not possible in seismic reflection profiles. Such high-resolution facies analysis has led to several new concepts that are not as easily applied to subsurface data.

Parasequences

The basic building block of sequence stratigraphy in outcrop is the **parasequence**, which is a gradual, upward-shallowing succession of facies on a meter- to decimeter-scale (Van Wagoner et al., 1988). An example of a parasequence in Figure 1.12 is a vertical change from offshore shale, to hummocky stratified lower shoreface sandstone, to crossbedded upper shoreface sandstone, to horizontally laminated foreshore sandstone. Parasequences are bounded above by **flooding surfaces**, which record a substantial

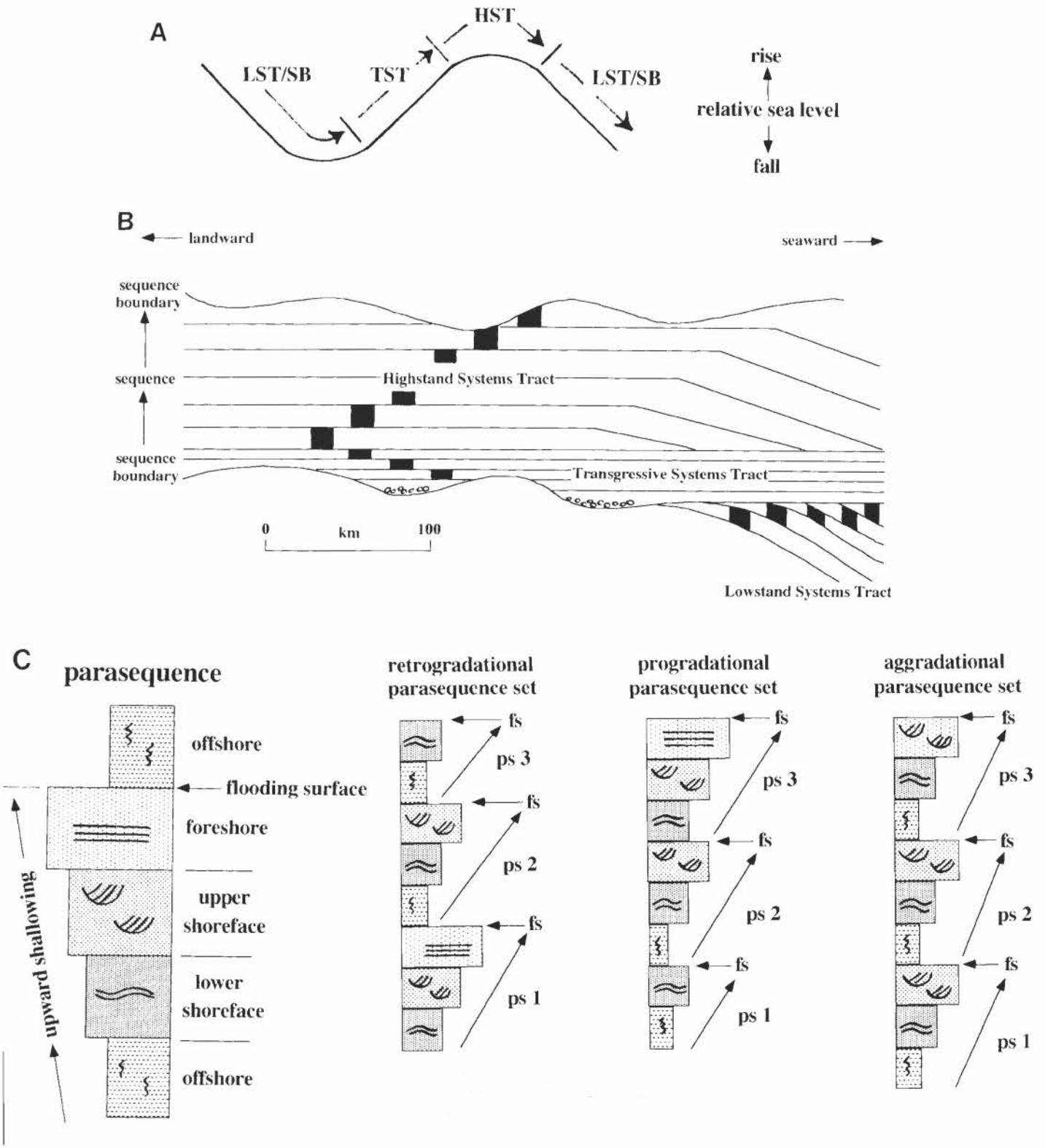


FIGURE 1.12. Fundamental principles of sequence stratigraphy. **A**, Sinusoidal sea-level curve and the sequence stratigraphic features produced by it. LST/SB = lowstand systems tract/sequence boundary; TST = transgressive systems tract; HST = highstand systems tract. **B**, Schematic cross section of a sedimentary basin showing unconformities and stratal packages and how they relate to sequence stratigraphy. Blackened areas represent a nearshore facies belt. **C**, Examples of parasequence and parasequence sets.

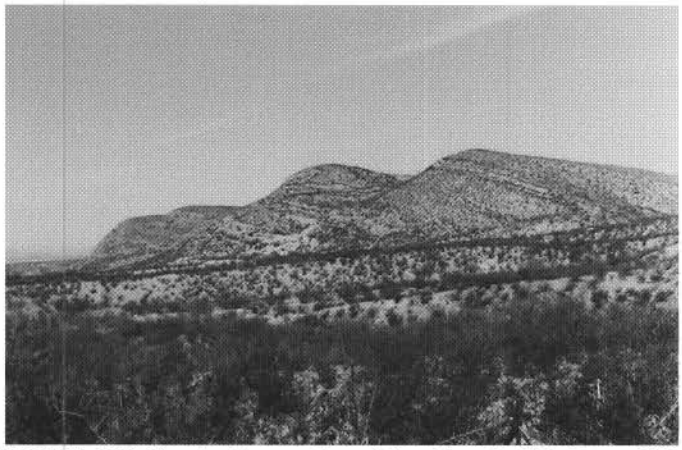


FIGURE 1.13. View looking northward from Stop 1 of the Derry Hills. Derry Hills are a late-rift fault block composed of Paleozoic sedimentary rocks.

increase in water depth and place substantially deeper water facies directly above shallower water facies. In the parasequence example of Figure 1.12, the horizontally laminated foreshore sandstone is directly overlain by offshore shale and that abrupt contact is a flooding surface. The flooding surface may also display erosion, referred to as a **ravinement**, with or without a thin lag of coarse sediment or fossils, referred to as a **transgressive lag**. Parasequences are applicable to rock sequences composed of marine facies or mixed marine and nonmarine facies. The concept is difficult, if not impossible, to apply to rock sequences composed entirely of nonmarine facies.

Parasequence sets and systems tracts

Parasequences are arranged into systematic vertical successions, called **parasequence sets** (Fig. 1.12; Van Wagoner et al., 1990). In a **retrogradational parasequence set**, successively younger parasequences are composed of more seaward facies, such that overall the set deepens upward. In a **progradational parasequence set**, successively younger parasequences are composed of more landward facies, delimiting an overall upward-shallowing trend. Stacked parasequences that display little or no change in water depth constitute a **aggradational parasequence set**. In outcrop, parasequence sets are used to define the systems tracts described above. A retrogradational parasequence set typifies the transgressive systems tract, whereas aggradational and progradational parasequence sets define the highstand systems tract. Lowstand systems tracts are commonly composed of progradational parasequence sets, but may contain aggradational parasequence sets as well (Nummedal, 1988).

APPLICATION TO PENNSYLVANIAN AND UPPER CRETACEOUS ROCKS OF SOUTHERN NEW MEXICO

The two stops on the first day of the 1998 New Mexico Geological Society Fall Field Conference are designed to examine Pennsylvanian and Upper Cretaceous mixed marine and nonmarine strata. At both stops an attempt has been made to relate the partial stratigraphic sections to sequence stratigraphy. Despite the limitations of applying sequence stratigraphy to single outcrops, it is a useful exercise, because (1) understanding the concepts of sequence stratigraphy is enhanced by application, (2) it promotes careful interpretation of facies and their vertical stacking, and (3) it forces us to think about the formations on a basin-wide scale. It should be noted, however, that a rigorous application of sequence stratigraphy requires litho- and biostratigraphic data from as many widely distributed outcrops and/or wells as are available

45.0 MP 51. **Exit I-25 at the Garfield exit (exit 51). Turn right at stop sign and park in the pullout. STOP 1.** Follow the foot log into the Derry Hills.

Derry Hills Foot Log

The Derry Hills (Fig. 1.13) are a late-rift fault block composed of Paleozoic sedimentary rocks. The eastern part of the hills contains several southwest-vergent folds and thrust faults presumably of Laramide age (latest Cretaceous–Eocene) (Fig. 1.14; Seager et al., 1986, 1997). We are primarily concerned with examining the Pennsylvanian Bar B Formation and overlying Permian Abo Formation, which were deposited on the western margin of the Orogrande Basin (Fig. 1.15).

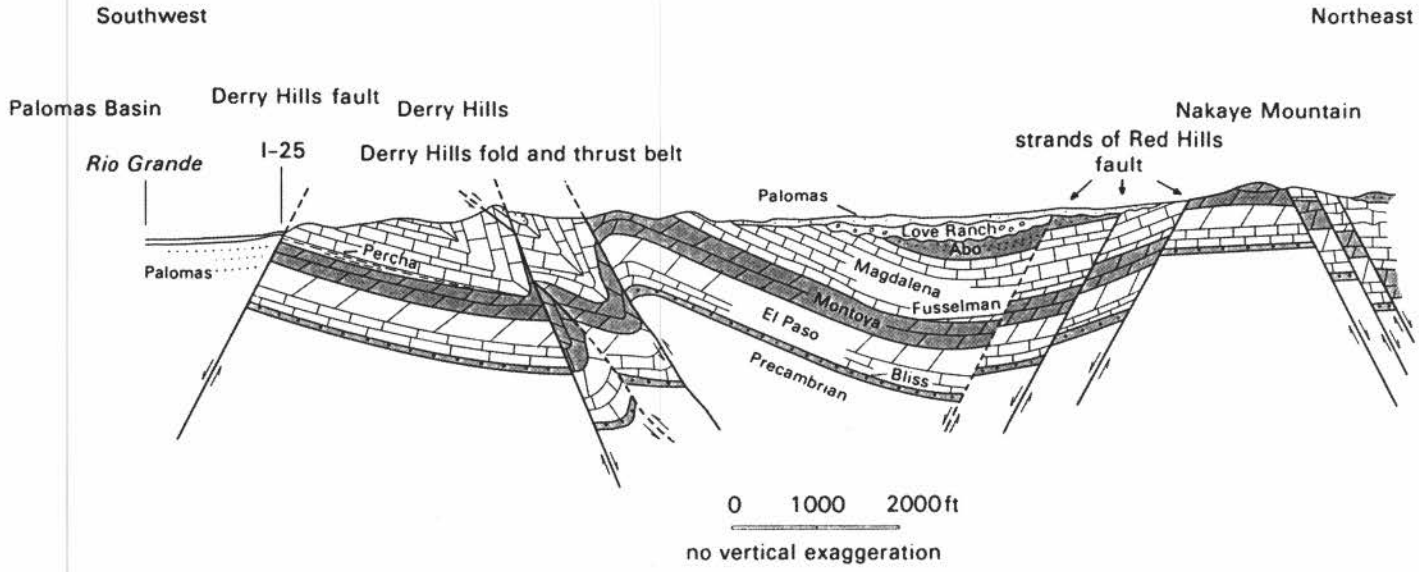


FIGURE 1.14. Northeast–southwest cross section of the Derry Hills and Nakaye Mountain, adapted from Seager and Mack (1991).

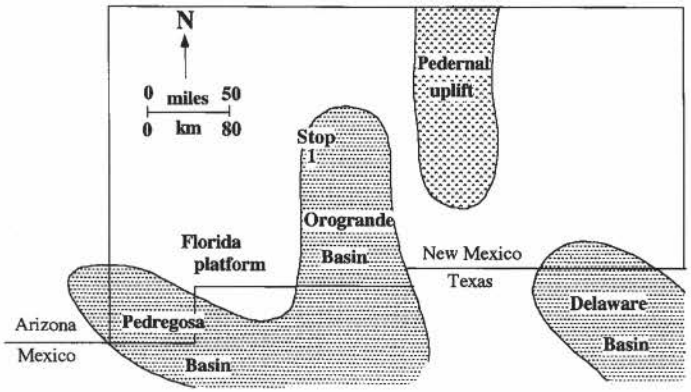


FIGURE 1.15. Generalized paleotectonic map of southern New Mexico in Permo–Pennsylvanian time. The Pennsylvanian Bar B and Permian Abo Formations, which will be examined at Stop 1, were deposited on the western margin of the Orogrande Basin.

Mileage

0 **Descend into the arroyo and proceed about 150 yds west-northwest** (Fig. 1.16). About 10 yds east of the culvert that passes beneath the interstate highway ramp, turn northeastward and ascend about 6 ft onto an abandoned road and follow it uphill (Fig. 1.17). After about 50 yds and below the crest of the hill, take a left fork onto another abandoned road leading to a quarry. Follow that road for 30 yds and descend onto another road that leads about 50 yds into the quarry (Fig. 1.18). **0.3**

0.3 **FOOT LOG STOP 1** Quarry. Caution: do not climb or stand near unstable quarry walls, particularly on the west side. The quarry is in an argillaceous limestone of the lower part of the Pennsylvanian Bar B Formation of the Magdalena Group (Kelley and Silver, 1952; Seager and Mack, 1991). The Bar B conformably overlies the Nakaye Formation of the Magdalena Group, which is characterized by thick, stair-stepped ledges of gray limestone. The Bar B contains more and thicker slope-forming shales between limestone beds and has distinctive tan-weathering limestones, such as are exposed in this quarry. Approximately 300 ft thick at this location, the Bar B thickens eastward along the east flank of the Caballo Mountains and into the adjacent Jornada del Muerto Basin. The upper part of the Bar B also contains distinctive conglomerates that will be viewed at Stop 3.

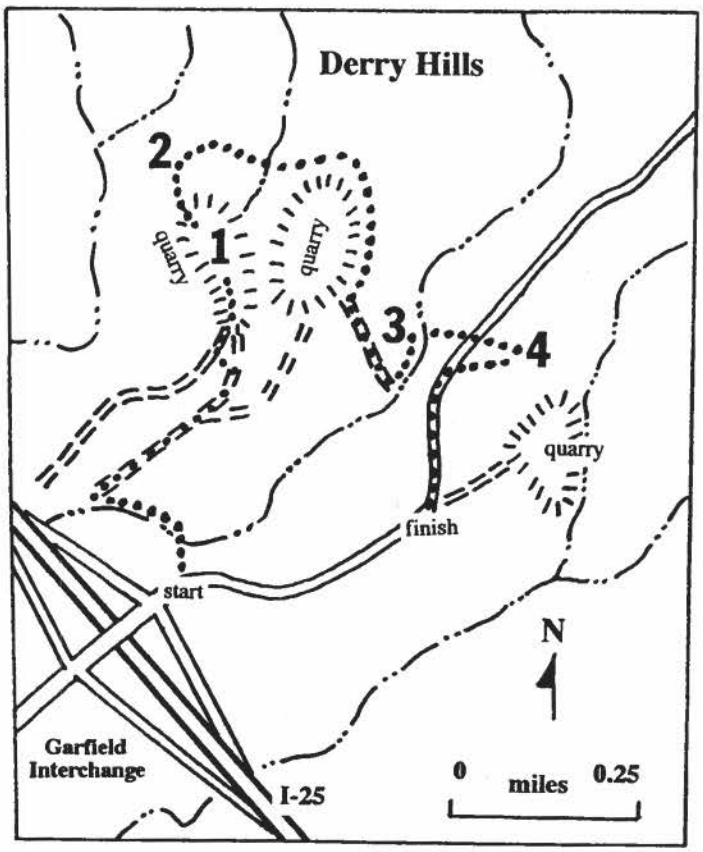


FIGURE 1.16. Traverse for Stop 1 in the Derry Hills. Double dashed lines are abandoned quarry roads; dots represent field trip route; numbers correspond to stop descriptions in the foot log.

According to the fusulinid data of Thompson (1991), the Bar B primarily belongs to the upper Desmoinesian and Missourian stages. No Virgilian fusulinids are present, although the uppermost part of the Bar B may be Wolfcampian, indicating an unconformity within the upper part of the formation. At the north end of the quarry are gray and tan mottled limestones exhibiting large horizontal and vertical burrows and whole spiriferid and productid brachiopods (Figs. 1.19 and 1.20). **0.1**

0.4 Climb out of the quarry at the northwestern side onto a ledge of limestone (Fig. 1.16). This ledge, the slope, and the ridge to the east constitute **FOOT LOG STOP 2** (Figs. 1.21



FIGURE 1.17. Abandoned quarry road leading to Stop 1 of the Derry Hills foot log.

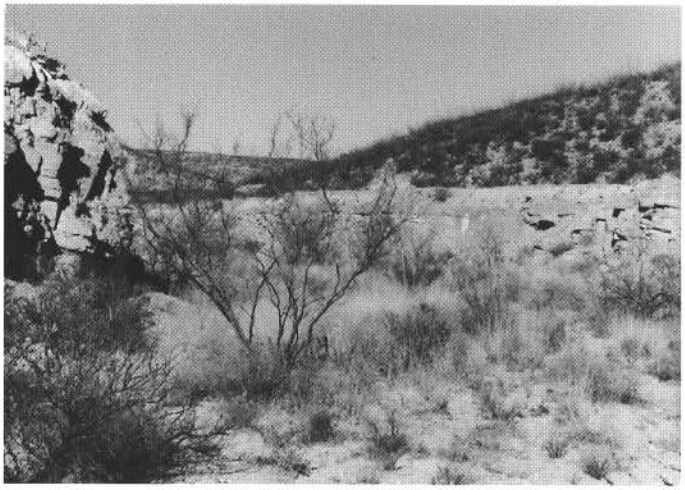


FIGURE 1.18. Quarry at Stop 1 of the Derry Hills foot log. Exposed are mottled limestones of the Pennsylvanian Bar B Formation.



FIGURE 1.19. Bedding plane view of mottled limestone of the Pennsylvanian Bar B Formation showing large burrows and a productid brachiopod.



FIGURE 1.20. Bedding plane view of mottled limestone of the Pennsylvanian Bar B Formation showing bioturbation and a spiriferid brachiopod.

and 1.22). From the crest of the ridge it is possible to view to the north-northwest in the middle distance an overturned syncline in Pennsylvanian rocks that is overridden by a southwest-vergent thrust fault with Ordovician rocks on the hanging wall. The trend and style of these structures suggest they are Laramide (latest Cretaceous–Eocene) (Seager et al., 1986, 1997).

The variety of carbonate and siliciclastic facies and the scale of their cyclic interbedding at Foot Log Stop 2 are typical of Pennsylvanian rocks deposited along the western margin of the Orogrande Basin (Fig. 1.22). The carbonate and shale facies were deposited in open-marine to restricted-marine environments (Figs. 1.23 and 1.24). Near the base of the section is a heterolithic conglomerate that represents marine reworked fluvial gravel and defines the lowest sequence boundary (Figs. 1.22 and 1.23). Above the conglomerate, the facies are arranged into a series of upward-shallowing cycles that range from 10 to 33 ft thick. Several cycles in the lower half of the section are bounded by thin, ferruginous, phosphatic sandstones that represent periods of transgressive reworking of underlying sediment and constitute flooding surfaces. The ferruginous sandstones may also represent sequence boundaries, because they are siliciclastic and they overlie siliciclastic-free carbonate facies, suggesting a basinward shift of facies. Cycles in the upper half of the section lack ferruginous sandstones, but still have evidence of upward-shallowing cycles bounded by flooding surfaces. Overall, the sequences are organized into a higher order transgressive-regressive cycle, in which the lower sequences are dominated by progressively deeper water facies, with the black fissile shale representing the deepest water, while the upper sequences demonstrate a progressive increase in shallower water facies. The apparent high frequency of sequences in this 148-ft-thick section can be attributed to a combination of slow subsidence of the western margin of the Orogrande Basin and high-frequency, large-magnitude glacial-eustatic sea-level fluctuations characteristic of Permo–Pennsylvanian time. **0.45**

0.75 From the crest of the ridge proceed east-southeast into the arroyo and onto a prominent bench on the adjacent ridge (Fig. 1.16). From this point move southward for about 50



FIGURE 1.21. View looking eastward of ridge of the Bar B Formation that constitutes Stop 2 of the Derry Hills foot log.

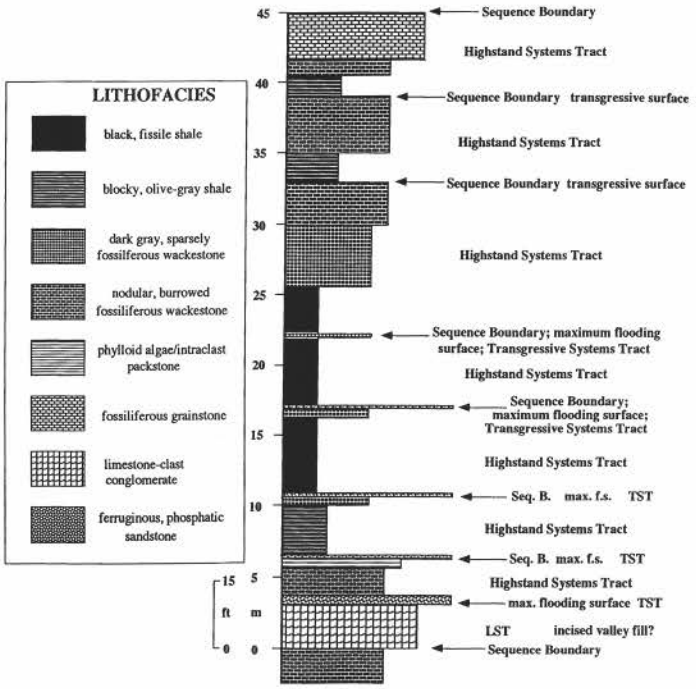


FIGURE 1.22. Measured section of the part of the Pennsylvanian Bar B Formation examined at Stop 2 of the Derry Hills foot log. TST = transgressive systems tract; LST = lowstand systems tract; max. f.s. = maximum flooding surface; Seq. B = sequence boundary.

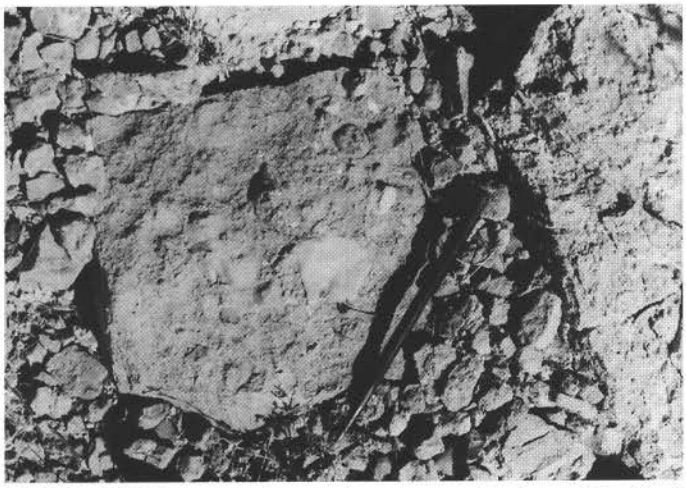


FIGURE 1.23. Limestone-clast conglomerate near the base of the Bar B section exposed at Stop 2 of the Derry Hills foot log.

yds before intersecting an abandoned quarry road. Follow the road southward toward the deep arroyo. Once in the arroyo bottom, proceed north-northwestward for about 50 yds to **FOOT LOG STOP 3**. Exposed on the east side of the arroyo are pebble and cobble conglomerates in the uppermost part of the Bar B Formation (Fig 1.25). These conglomerates contain clasts of Pennsylvanian and perhaps Mississippian limestones and are interpreted to be locally derived. **0.05**

0.8 Move due east from outcrops of Bar B conglomerates to the road, which roughly marks the contact between the Bar B Formation and redbeds of the Permian Abo Formation, the object of **FOOT LOG STOP 4**. The lower Abo consists of red mudstone that locally displays calcic Vertisol paleosols (Mack et al., 1991, 1995), thin (<2 ft) rip-up clast conglomerates composed of carbonate reworked from the calcic paleosols, and a 10 ft-thick ostracod-bearing limestone that may be lacustrine or marginal marine (Fig. 1.26). Above the limestone, thick, ledge-forming beds of siltstone or very fine-grain sandstone represent fluvial channels. **0.2**

1.0 Follow the road southward to the buses (Fig. 1.16).

End of Traverse. Continue with Interstate Road Log.

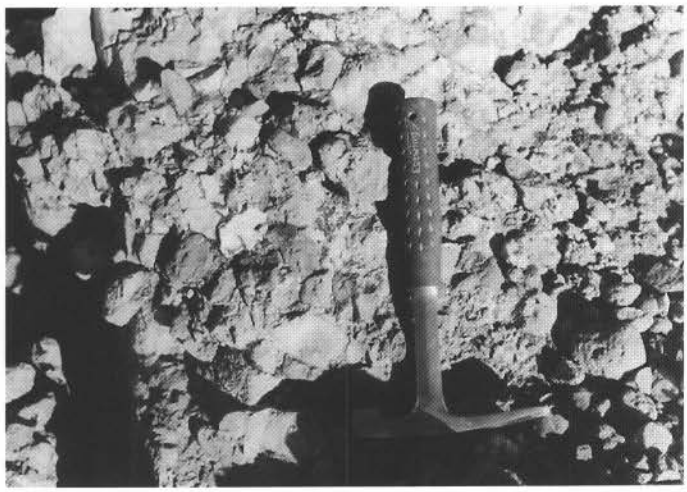


FIGURE 1.25. Limestone-clast conglomerate at the top of the Pennsylvanian Bar B Formation at Stop 3 of the Derry Hills foot log.

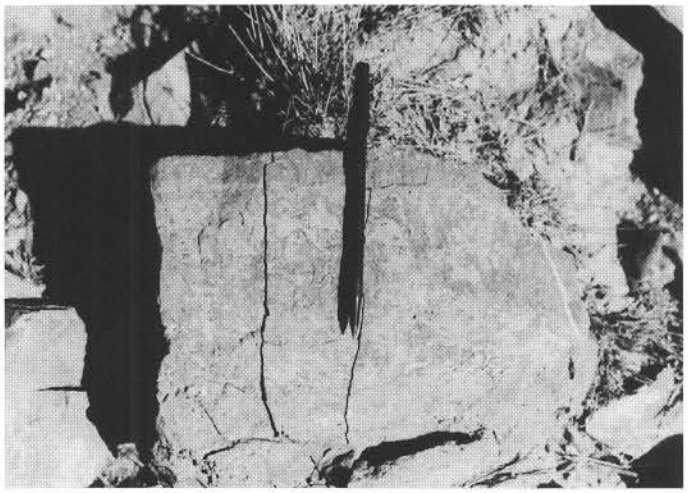


FIGURE 1.24. Phylloid algae-bearing limestone overlain by a thin rip-up clast conglomerate that represents the lag of a flooding surface; Stop 2 of the Derry Hills foot log.

KEY TO IDENTIFICATION OF TETRAPOD FOOTPRINTS FROM LOWER PERMIAN RED BEDS OF SOUTHERN NEW MEXICO

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In southern New Mexico, footprints of early tetrapods (amphibians and reptiles) are common ichnofossils in Lower Permian red beds of the Abo and Hueco Formations. These footprints are conservatively assigned to six ichnogenera (Lucas and Heckert, 1995). Here, we present an illustrated key to the identification of these footprints, which we hope will be of use to field geologists.

TO USE THE KEY

To use this key, you need to know some anatomical terms. The forefoot is the manus, the hind foot is the pes. Each finger (or toe) is a digit. A four-fingered hand (foot) is tetradactyl, a five-fingered foot (hand) is pentadactyl. The digit closest to the body midline ("thumb" or "big toe") is digit I, and the digits are numbered outward as I, II, III, IV, and V. To identify digit I, note that it often is



FIGURE 1.26. Exposure of the Permian Abo Formation at Stop 4 of the Derry Hills foot log. Ridge on the skyline is a limestone of lacustrine or marginal marine origin.

set apart (diverges from) the other digits, and that digit I usually is the shortest or the longest digit.

An undertrack is the impression of a hand or foot in strata below the substratum upon which the animal walked. Undertracks can look quite different from the actual track; a few are illustrated here (Fig. 1.27), but the key is a guide to tracks, not to undertracks.

KEY

1. Size very large (track longer than 80 mm)
   Dimetropus—large tracks with pes impression up to 250 mm long; manus and pes pentadactyl; length of digits increases from I to III/IV; in pes, digit V as long as digit II and set apart; in manus, digit V like digit I and not as set apart as in pes; pes has sole impression; digits are slender with strong, pointed claws (Fig. 1.27L–M).
2. Size moderate to very small (track shorter than 80 mm)
   2a. Size moderate (track length = 20 to 80 mm)
      2a.1. Digits long, thin and curved
         2a.1.1. Digits IV–V longest
            Hyloidichnus—small tracks (20 to 50 mm long); pentadactyl manus and pes; digit tips often bifurcated (Fig. 1.27G–H)
         2a.1.2. Digits increase dramatically in length from I through IV
            Dromopus—small to moderate tracks (pes is 10 to 80 mm long); pentadactyl manus and pes; strongly curved, long and slender digits with clawed tips; small sole pad (Fig. 1.27E–F)
      2a.2. Digits shorter, thicker and straighter
         2a.2.1. Manus tetradactyl, digits with rounded tips, small to moderate size
            Limnopus—small to moderate-sized tracks (length = 20 to 135 mm); pes pentadactyl and usually closely follows manus (Fig. 1.27D).
         2a.2.2. Manus pentadactyl, digits taper to pointed tips, small size
            Gilmoreichnus—small tracks (20 to 40 mm long); pes pentadactyl; digits increase in size from I to V, with V set back from the other digits (Fig. 1.27I–K)
   2b. Size very small (track length = 10–20 mm)

Batrachichnus-small tracks less than 20 mm long, usually 10 to 15 mm long; manus tetradactyl, pes pentadactyl; digit IV longest, and digits I–III closely grouped; may have tail drag; heel and palm impressions (Fig. 1.27A–C).

ACKNOWLEDGMENTS

H. Haubold, A. Heckert and J. MacDonald collaborated in the study of Lower Permian footprints from southern New Mexico. R. Pence drew Figure 1.27. O. Anderson and R. Sullivan provided helpful reviews of the manuscript.

46.0 MP 52. Roadcut at 3:00 consists of the Devonian Percha Shale at road level unconformably overlain by the Red House Formation of the Magdalena Group (Pennsylvanian). **1.0**

47.0 MP 53. Redbeds in roadcuts at 3:00 are the lower Permian Abo Formation. **3.0**

50.0 MP 56. At 9:00 in the far distance is the Black Range and in middle distance is the Animas Mountains, which together make up the hanging wall of the Palomas half-graben. The light-colored badlands represent distal hangingwall-derived alluvial-fan sediment of the Plio–Pleistocene Palomas Formation, which is coeval to the Camp Rice Formation (Lozinsky and Hawley, 1986a, b; Mack et al., 1993). At 1:00 in the far distance is the main block of the Caballo Mountains with the Red Hills fault block in the middle distance (Fig. 1.28). The Caballo Mountains first began to rise in latest Oligocene and early Miocene time, while the Red Hills fault block is late rift (latest Miocene–Pliocene) in origin and came up through the eastern edge of an ancestral Palomas Basin (Mack et al., 1994b). The Red Hills also contain a Laramide paleovalley consisting of several hundred feet of conglomerates and sandstones of the Eocene Love Ranch Formation unconformably above Precambrian crystalline basement in the deepest part of the paleovalley and progressively onlapping Paleozoic sedimentary rocks along the margins of the paleovalley (Fig. 1.29; Seager et al., 1986, 1997). **2.3**

52.3 I-25 crosses the Rio Grande. Bluffs on east side of river are interbedded alluvial-fan and axial-fluvial lithofacies of the Plio–Pleistocene Palomas Formation. **1.1**

53.4 Caballo Lake exit. Proceed north on I-25. **0.6**

54.0 MP 60. I-25 crosses Percha Creek. At 3:00 is the main block of the Caballo Mountains (Fig. 1.30), which consists, in ascending order, of Precambrian crystalline basement, Cambrian Bliss Formation, Ordovician El Paso and Montoya Formations, Silurian Fusselman Dolomite, Devonian Percha Shale (locally absent beneath sub-Pennsylvanian unconformity), and Pennsylvanian Magdalena Group. Trenching of the Caballo fault scarp suggests Holocene fault movement (Machette, 1987; Foley et al., 1988) **1.0**

55.0 MP 61. At 2:00 to 3:00 is Caballo Lake. **2.7**

57.7 Hillsboro exit. Proceed north on I-25. **0.3**

58.0 MP 64. The highway descends into Las Animas Creek. Roadcuts (Fig. 1.31) are distal, hanging wall-derived, alluvial-fan lithofacies of the Plio–Pleistocene Palomas Formation. Las Animas Creek is one of several arroyos, including Percha and Las Palomas Creeks, that head in the Black Range, cut narrow canyons through the Animas Mountains, and incise the Plio–Pleistocene Palomas Formation. **3.0**

61.0 MP 67. Rest area. Proceed north on I-25. **4.0**

65.0 MP 71. The highway begins descent into valley of Las Palomas Creek. At 9:00 are badlands developed in distal, hanging wall-derived, alluvial-fan sediment of the Plio–Pleistocene Palomas Formation (Fig. 1.32). At 12:00 are the Mud Springs Mountains. At 9:00 is Palomas Gap in the Caballo Mountains. **2.0**

67.0 MP 73. At 1:00 is a view of the town of Truth or Consequences with the Fra Cristobal Range in the background (Fig. 1.33). At 12:00 are the Mud Springs Mountains, composed of Precambrian crystalline basement and Paleozoic sedimentary rocks. **1.8**

68.8 **Take exit 75 into Williamsburg and Truth or Consequences. Proceed east toward town. 3.6**

72.4 **At stop light, turn right onto NM-51. 1.5**

73.9 Just before road descends onto floodplain of the Rio Grande there are fluvial gravels inset against brown conglomerates of the Palomas Formation. **0.7**

74.6 The highway crosses Cuchillo Creek. At 12:00 is the range boundary fault of the Caballo Mountains, placing Cretaceous sedimentary rocks against alluvial-fan conglomerates of the Palomas Formation. **0.8**

75.4 The highway crosses bridge across the Rio Grande. **Turn right onto dirt road at end of bridge. 1.1**

76.5 Follow road along river for 0.9 mi to **STOP 2**. Follow Mescal Canyon Foot Log. **0.9**

Mescal Canyon Foot Log

The section in Mescal Canyon represents the most complete and well-exposed Upper Cretaceous sedimentary section in southern New Mexico. These sedimentary rocks were deposited in and adjacent to the Western Interior Seaway (Fig. 1.34). The following traverse crosses the lower half of the 2000-ft-thick section and includes stops in the Dakota, Mancos, Tres Hermanos, D-Cross, Gallup, and basal Crevasse Canyon Formations (Fig. 1.35). The goals of the traverse are (1) to define the stratigraphic units, (2) to discuss depositional environments, (3) to place the formations in the context of sequence stratigraphy, and (4) to discuss the Western Interior foreland basin.

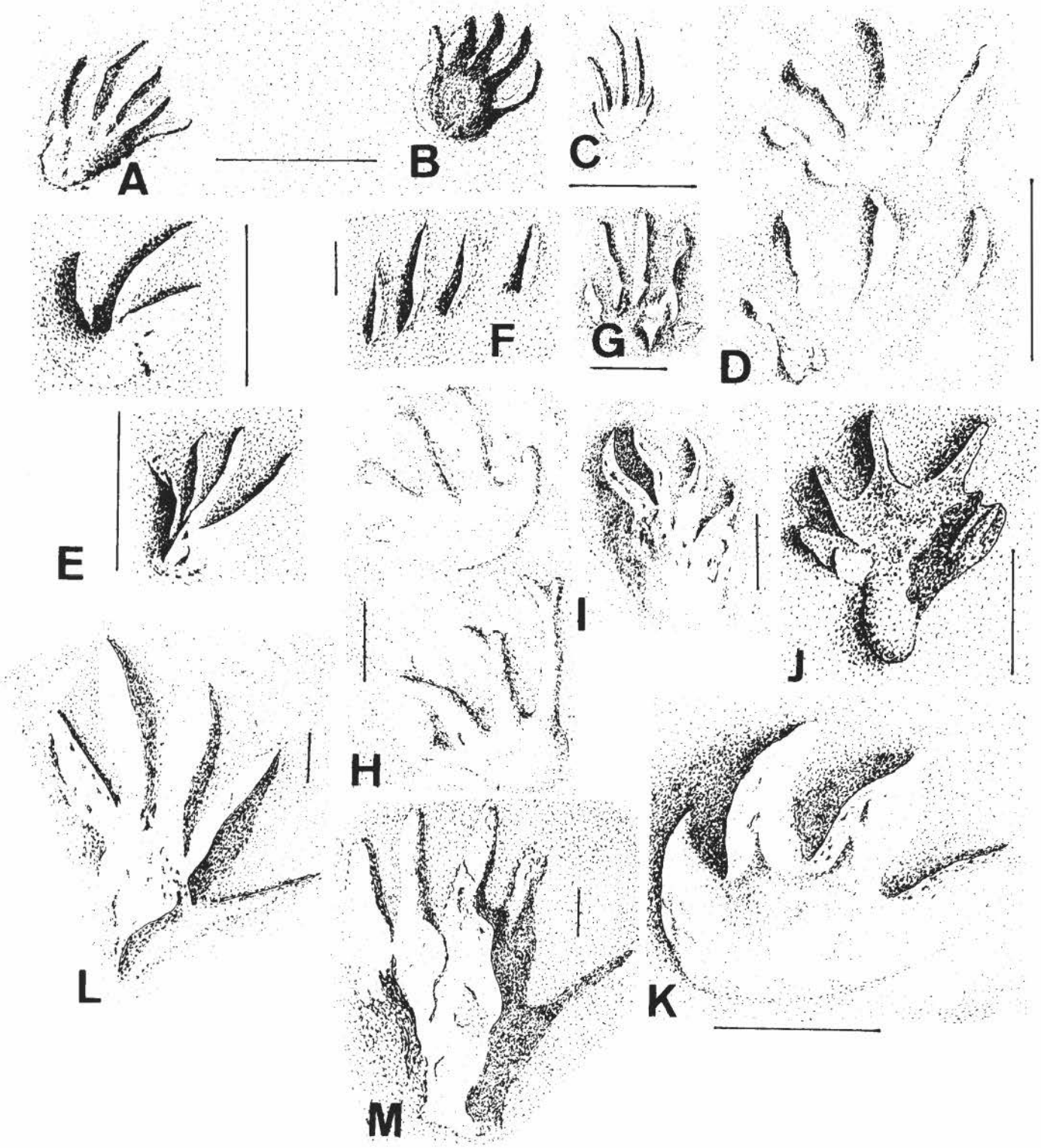


FIGURE 1.27. **A–C**, Batrachichnus delicatus, plantigrade pes tracks. **D**, Limnopus sp., undertracks of manus (above) and pes (below). **E–F**, Dromopus agilis, left and right manus tracks (**E**) and underprint (**F**) of pes digits 1–4. **G–H**, Hyloidichnus bifurcatus, undertrack (**G**) and pes track with forked digit tip (**H**). **I–K**, Gilmoreichnus hermitanus, undertrack (**I**), pes track with bulbous heel impression (**J**) and manus track (**K**). **L–M**, Dimetropus nicolasi, manus (**L**) and pes (**M**) tracks. All bar scales = 20 mm.



FIGURE 1.28. View northeastward from I-25 of the main fault block of the Caballo Mountains in the background and the Red Hills fault block in the middle distance. The Red Hills are underlain by Precambrian crystalline basement and Paleozoic sedimentary rocks. The low saddle in right-middle of photo corresponds to the Laramide paleovalley described in Figure 1.29.

Mileage

0.0 Parking lot. **0.2**

0.2 **From parking spot proceed about 100 yds westward into Mescal Canyon, turn south, and proceed up the arroyo approximately 0.2 mi** to **FOOT LOG STOP 1** (Fig. 1.36). Exposed along the west side of the main arroyo and extending up the side of the adjacent hill are several in.-thick bentonites in the lower half of the Mancos Shale (Figs. 1.37 and 1.38). Similar bentonites have been observed in the Mancos along the east-central flank of the Caballo Mountains in the Apache Gap quadrangle and in the Santa Rita quadrangle southeast of Silver City. The thicker bentonites also are recognizeable on geophysical logs from the Jornada del Muerto Basin. Also present here are complicated folds that may be related to Laramide deformation (latest Cretaceous–Eocene). **0.2**

0.4 Proceed up the arroyo to the south for about 0.2 mi to **FOOT LOG STOP 2,** located in a gully that cuts into the cliff face on the western side of the canyon (Fig. 1.36). This stop displays the upper half of the Dakota Sandstone, the basal formation of the Upper Cretaceous section in this region (Fig. 1.39). The Dakota is about 100 ft thick and consists of a lower nonmarine part and an upper marine part. Exposed at Foot Log Stop 2, in ascending order, are (1) the dip slope of a 3-ft-thick sandstone with ripple cross-laminae that is probably nonmarine in origin, (2) several feet of heavily bioturbated argillaceous sandstone that may represent a lagoon, (3) about 6 ft of ridge-forming, wavy-bedded sandstone with crossbeds and abundant Ophiomorpha burrows that may have been deposited as a flood-tidal delta or as a shoreline sand (Figs. 1.40 and 1.41), (4) a thin (1.5 ft), brown, granular sandstone deposited as a transgressive lag above a flooding surface, and (5) thin-bedded gray siltstones and brown very-fine sandstones of the basal Mancos Formation.

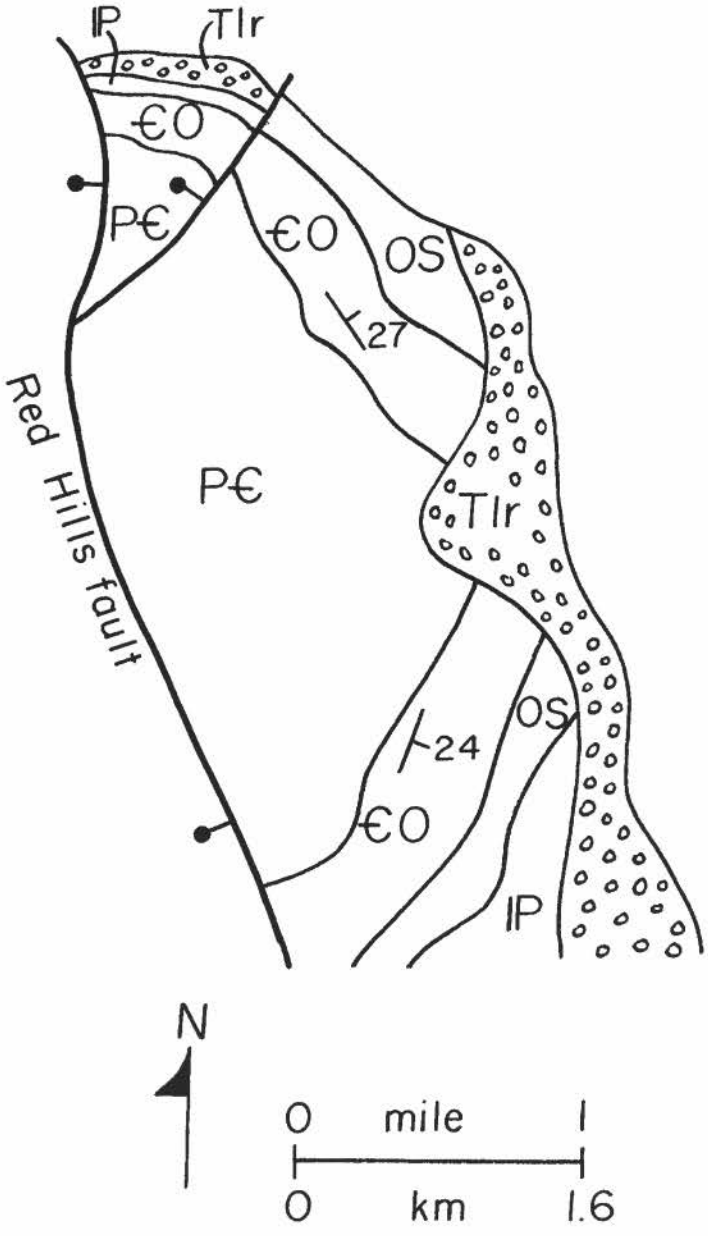


FIGURE 1.29. Geologic map and cross section of a part of the Red Hills showing the location of a Laramide paleovalley floored by the Paleocene–Eocene Love Ranch Formation. Adapted from Seager et al. (1986). P€ = Precambrian granite; €O = Cambrian–Ordovician Bliss and El Paso Formations; OS = Ordovician Montoya and Silurian Fusselman Formations; IP = Pennsylvanian Magdalena Group; Tlr = Tertiary Love Ranch Formation.



FIGURE 1.30. View to the east from I-25 of the Caballo Mountains. Precambrian metamorphic and granitic rocks are exposed in the low slopes, whereas the steep cliff is composed of Paleozoic sedimentary rocks (Bliss, El Paso, Montoya, Fusselman, Percha (locally), and Magdalena). In the foreground are heavily dissected Pliocene–early Pleistocene alluvial fans. The prominent canyon in the middle of the photo is Burbank Canyon.

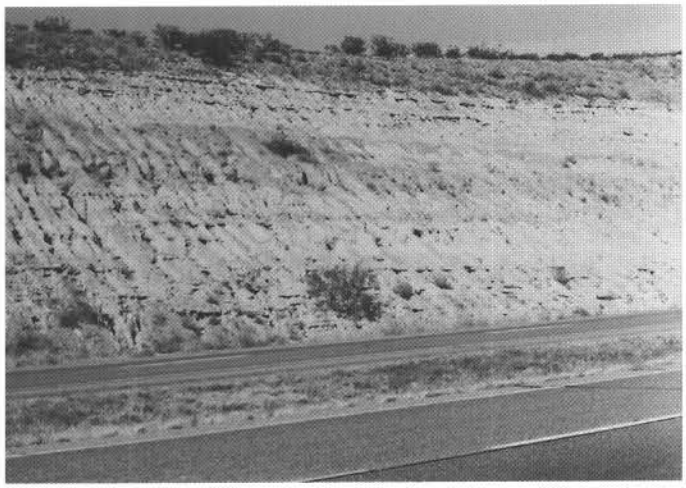


FIGURE 1.31. East-facing road cut in gravels, sands, and clays of the Pliocene–early Pleistocene Palomas Formation. These sediments were derived from the Black Range and Animas Mountains, which comprise the hanging wall of the Palomas half graben.

Overall, the Dakota Sandstone at this location records a transgressive systems tract. **0.3**

0.7 Go back to the main arroyo. Looking eastward, it is possible to see the middle and upper parts of the Mancos Shale and a prominent ledge in the middle of the ridge that marks the base of the Tres Hermanos Formation (Fig. 1.42). Proceed south for about 0.3 mi to where a major tributary arroyo enters the main arroyo from the east (Fig. 1.36). A prominent cliff face marks the confluence and is **FOOT LOG STOP 3** (Fig. 1.43). Exposed is the top of the Mancos Formation and the base of the Tres Hermanos Formation (Fig. 1.44). The upper Mancos represents delta-front environments and displays several parasequences characterized by upward-thickening sandstone beds. The Atarque is probably a shoreline sandstone that shows a vertical transition from wave-oscillation ripples (lower shoreface), to crossbeds (upper shoreface), to horizontal laminae (foreshore). The abrupt contact between the Mancos and Atarque is unusual for a normal progradational sequence and may suggest a



FIGURE 1.32. Badlands developed in the Pliocene–early Pleistocene Palomas Formation just south of Las Palomas Creek. These sediments were derived from the Black Range and Animas Mountains and deposited on the hanging wall dip slope of the Palomas half graben.



FIGURE 1.33. View to the north-northeast of the Mud Springs Mountains (12:00), the Fra Cristobal Range (1:00 far distance), the town of Truth or Consequences (1:00 middle distance), and the Rio Grande floodplain (2:00).

forced regression. The Atarque is immediately overlain by bioturbated, argillaceous fine-grained sandstones of probable lagoonal origin and rooted sandstones and coals deposited in swamps. The upper half of the Mancos and the basal and middle Tres Hermanos constitute a highstand systems tract. **0.2**

0.9 Follow bends in tributary arroyo for approximately 0.2 mi to where light-colored sandstones crop out across the arroyo at **FOOT LOG STOP 4** (Fig. 1.45). Between the previous stop and here the outcrops belong to the Carthage Member of the Tres Hermanos Formation, and were deposited in fluvial environments. At Foot Log Stop 4 evidence of marine transgression is in the form of dark gray shales with ammonites, heavily bioturbated, gray, fine sandstones, and the prominent light-colored sandstone ledges, which display hummocky cross stratification and Ophiomorpha burrows and probably represent a lower shoreface environment (Figs. 1.45 and 1.46). From a rock-stratigraphic perspective, the light-colored sandstones have been designated as the Fite Ranch Member of the Tres Hermanos Formation (Wallin, 1983). From the perspective of sequence stratigraphy, a sequence boundary is present within the Carthage Member and the marine units above it are part of the transgressive systems tract. **0.2**

1.05 Leave Foot Log Stop 4 and proceed up the arroyo. For the first 0.1 mi the arroyo is bordered on the west by a prominent dip slope of the Fite Ranch Member. Locally present on the dip slope is a thin (2 ft) brown sandstone containing pebbles and fossil debris; it probably represents a transgressive lag above a flooding surface. Exposed on the other side of the arroyo are dark gray marine shales of the D-Cross Tongue of the Mancos Shale. After a bend in the arroyo, the valley is oriented perpendicular to strike. Along the southern side of the arroyo is a small strike-slip fault with right-

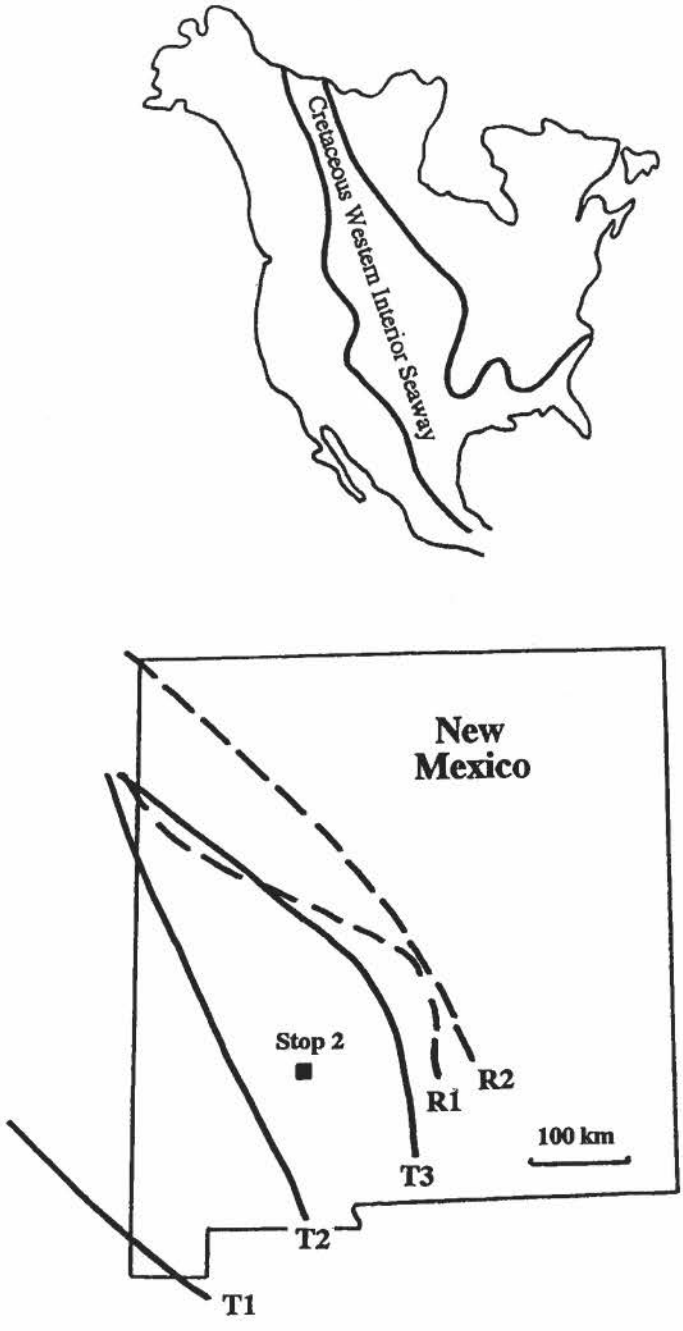


FIGURE 1.34. Top: map of North America showing the location of the Cretaceous Western Interior Seaway. Bottom: map of New Mexico displaying the inferred positions of maximum transgressions (T1, T2, T3) and regressions (R1, R2) during Late Cretaceous time, based on Molenaar (1983), as well as the location of Stop 2 (First-day Road Log) of the field trip. The transgressions and regressions are in chronologic order, with 1 being the oldest. Note that the area of Stop 2 experienced only the first two transgressions (T1, T2).

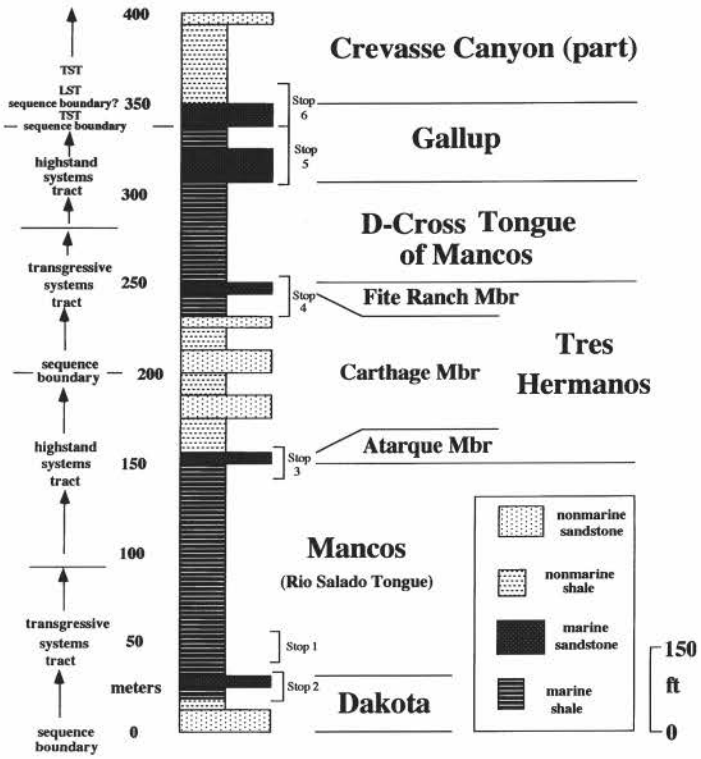
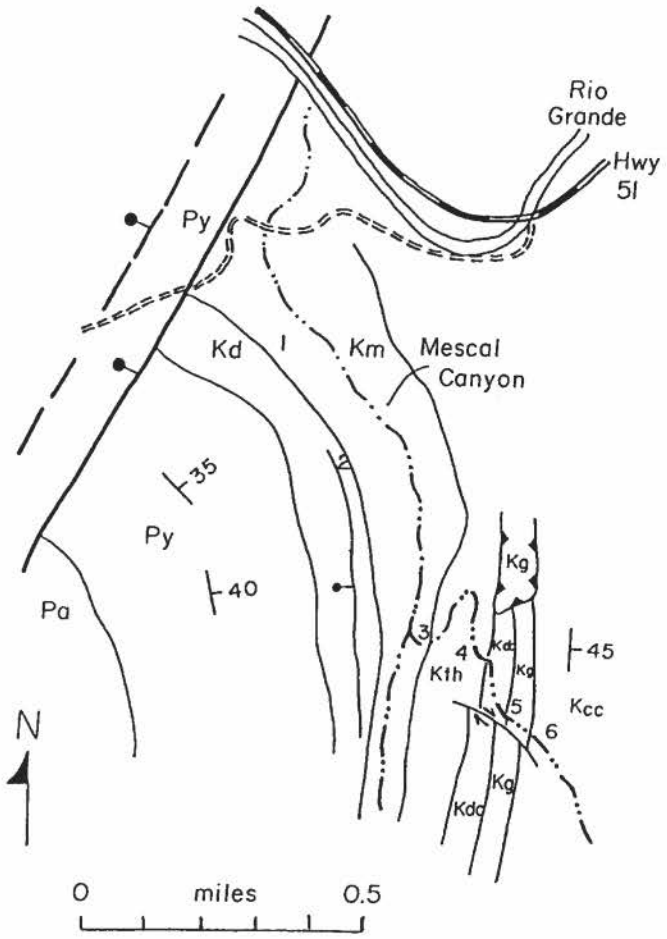


FIGURE 1.35. Generalized stratigraphy, depositional environments, and sequence stratigraphy of Upper Cretaceous sedimentary rocks exposed in Mescal Canyon. Approximate stratigraphic intervals of each of the foot log stops are also shown. LST = lowstand systems tract; TST = transgressive systems tract.

lateral displacement. After 0.1 mi the arroyo enters a narrow bedrock canyon, which is **FOOT LOG STOP 5** (Fig. 1.47). The cliff-forming sandstone in the narrows belongs to the Gallup Formation and exhibits several parasequences characterized by upward-thickening bedding sequences (Fig. 1.48). This lower half of the Gallup was deposited in the delta front and as distributary mouth bars. The dip slope of the uppermost distributary-mouth bar sandstone is covered with Ophiomorpha burrows. Just beyond the narrows, the distributary-mouth bar sandstone is overlain by heavily bioturbated, argillaceous sandstones with numerous whole oysters, which probably represent bays on the lower delta plain (Fig. 1.49). The section from the middle of the D-Cross



FIGURE 1.37. Stop 1 of the Mescal Canyon foot log, at which is exposed two light-colored bentonites in the lower half of the Mancos Shale.



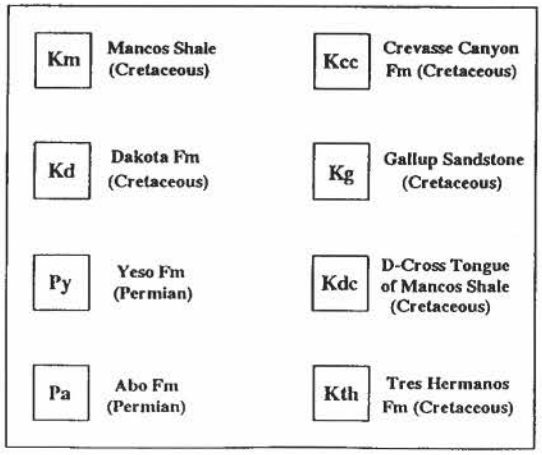


FIGURE 1.36. Generalized geologic map and foot log stops for Mescal Canyon, adapted from Lozinsky (1986).

Tongue to the oyster-bearing sandstones of the Gallup is part of a highstand systems tract. **0.05**

1.1 **FOOT LOG STOP 6** constitutes the stratigraphic interval immediately above the oyster-bearing sandstone, and includes the upper part of the Gallup and the base of the Crevasse Canyon Formation (Fig. 1.50). The oyster-bearing sandstone is truncated by a channel containing a bivalve-shell lag and crossbeds (Fig. 1.51). This channel may either represent a distributary channel on the lower delta plain, in which case it is part of the underlying highstand systems tract, or a tidal channel or estuary associated with a major

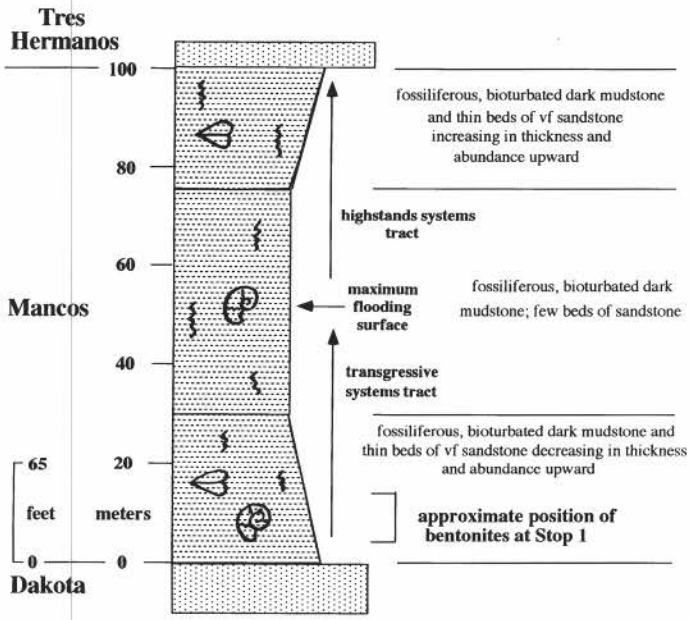


FIGURE 1.38. Generalized stratigraphy of the Mancos Shale exposed in Mescal Canyon. "vf" here and in subsequent figures means "very fine grained." Stop 1 here is Stop 1 of Mescal Canyon foot log.

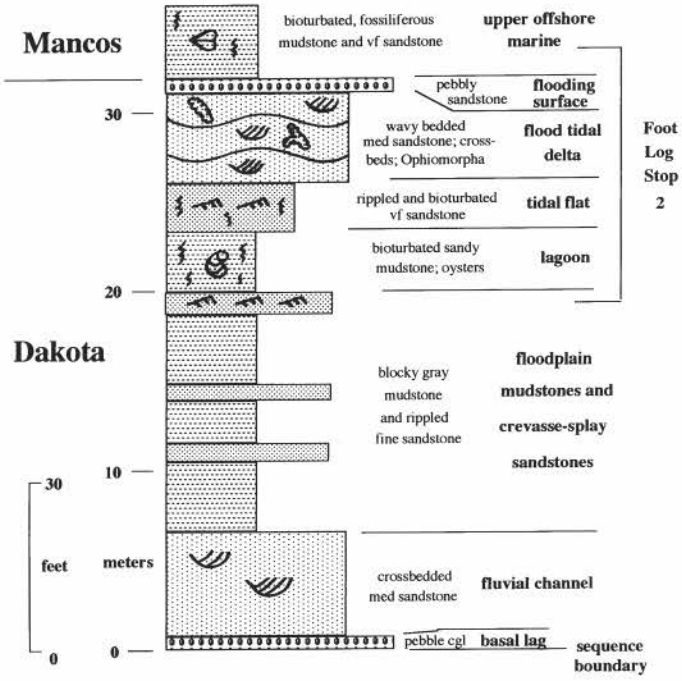


FIGURE 1.39. Stratigraphy of the Dakota Formation exposed in Mescal Canyon. Stop 2 of the Mescal Canyon foot log is in the upper part of the Dakota and base of the Mancos Shale, and defines a transgressive systems tract. "med" here and in subsequent figures means "medium grained."

drop in sea level, in which case the base of the channel is a sequence boundary and the channel itself is part of a lowstand systems tract. The latter interpretation is supported by the fact that the channel is overlain by bioturbated fine-grained sandstones of lower shoreface to upper offshore origin (Fig. 1.52), suggesting marine transgression (transgressive systems tract). Interbedded with the marine sandstones are flooding surfaces capped by in.-thick transgressive lags (Fig. 1.52). The uppermost sandstone was invaded by a paleosol characterized by dark gray color, blocky peds, and coaly root traces (Fig. 1.53). The occurrence of subaerial exposure indicates a basinward shift of facies, suggesting that a sequence boundary may exist beneath the paleosol. This type of paleosol is diagnostic of high water table, as is the coal above it, which may have existed as a result of lowstand or rising sea level. The paleosol and coal mark the base of the Crevasse Canyon Formation. Overlying the coal is a thin (2 ft) sandstone with wave-oscillation ripples that may be lacustrine (Fig. 1.54), and a thick sequence of olive-gray mudstones, some of which display root traces and blocky peds characteristic of a paleosol, and thin sandstones with ripple cross-laminae (Fig. 1.55). The mudstones are vertical accretion deposits of a floodplain and the thin sandstones represent crevasse splays. Several of the crevasse-splay sandstones contain plant fossils. The thick ledge at the top of the ridge has oyster fragments, suggesting it may be estuarine (Fig. 1.55), in which case the transgressive systems tract may have persisted to this level.

End of traverse. Retrace route to beginning of Foot Log. Board buses for return to starting point in Las Cruces. End of first-day road log.



FIGURE 1.40. Wavy bedded, bioturbated sandstones in the upper part of the Dakota Formation at Stop 2 of the Mescal Canyon foot log.

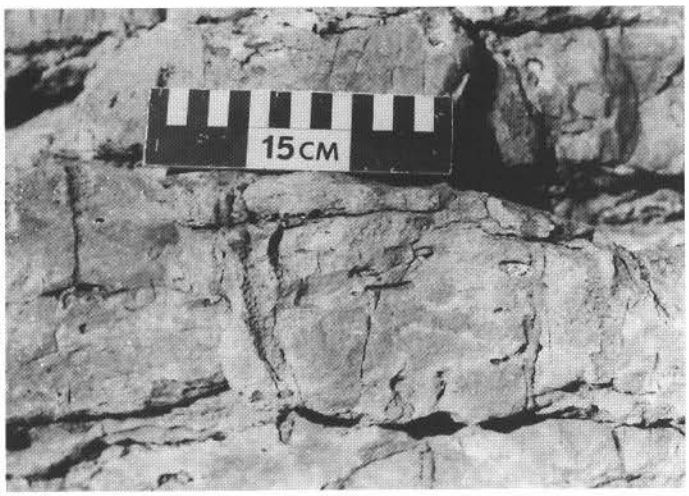


FIGURE 1.41. Close up of Ophiomorpha burrows in the sandstones shown in Figure 1.40.

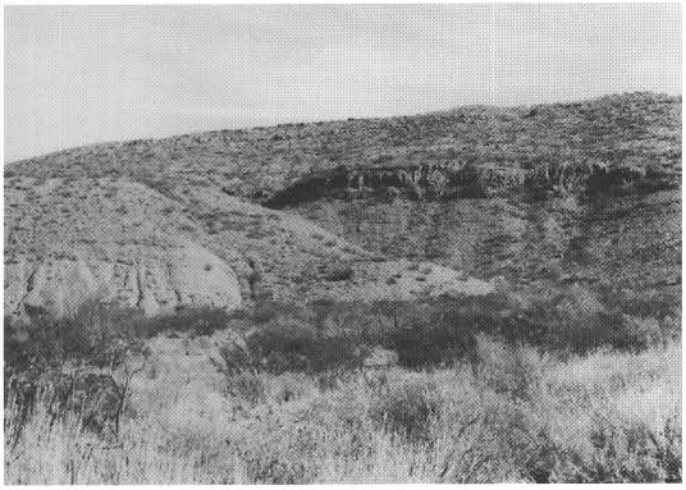


FIGURE 1.42. View eastward from Stop 2 of the middle and upper parts of the Mancos Shale and the base of the Tres Hermanos Formation. Prominent ledge in the middle of the ridge is the Atarque Member of the Tres Hermanos Formation.

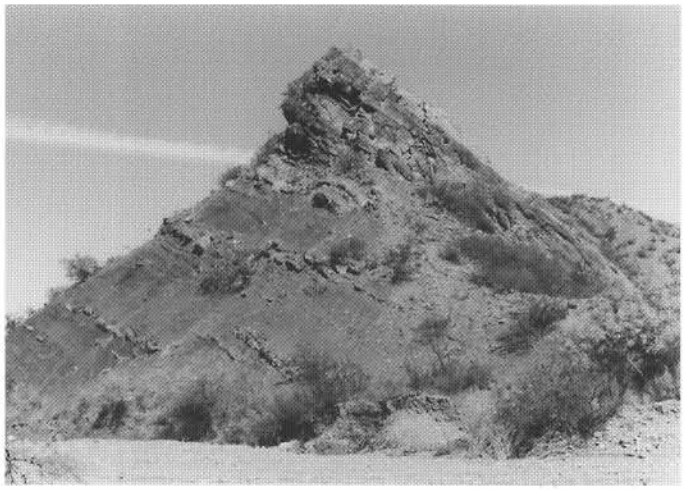


FIGURE 1.43. First outcrop constituting Stop 3 of the Mescal Canyon foot log. Exposed is the top of the Mancos Shale and the Atarque Member of the Tres Hermanos Formation.

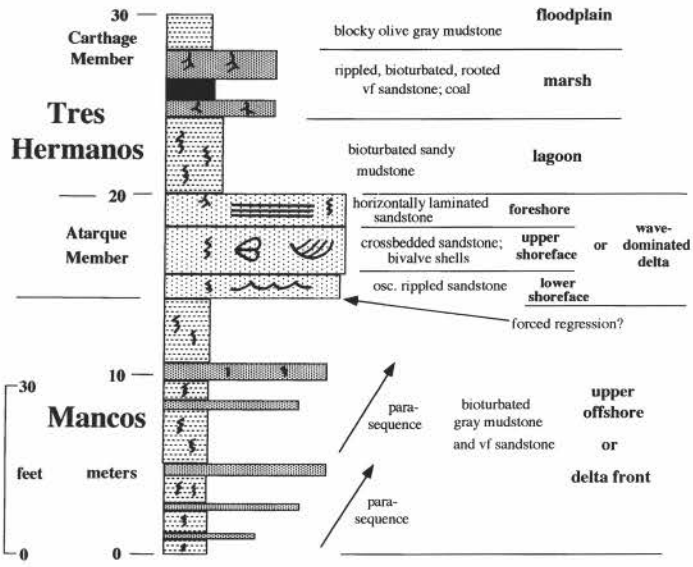


FIGURE 1.44. Stratigraphy, depositional environments, and sequence stratigraphy for Stop 3 of the Mescal Canyon foot log. This stratigraphic interval comprises part of a highstand systems tract.

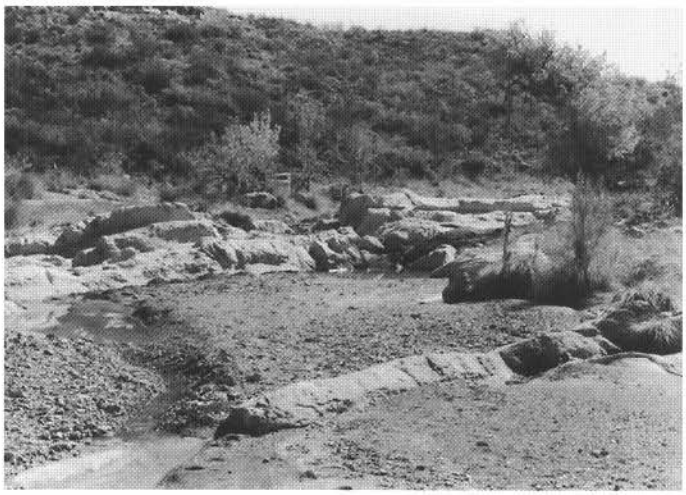


FIGURE 1.45. Exposure of the Fite Ranch Member of the Tres Hermanos Formation at Stop 4 of the Mescal Canyon foot log.

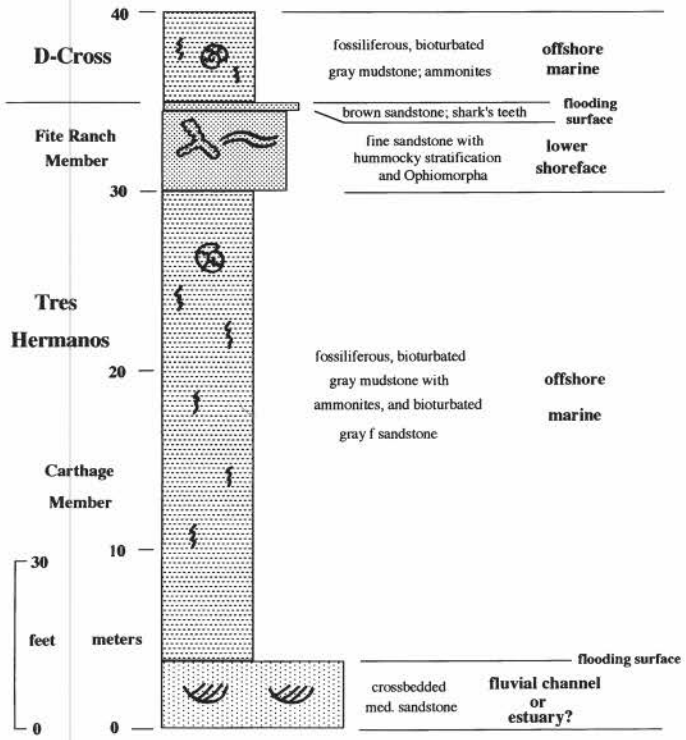


FIGURE 1.46. Stratigraphy, depositional environments, and sequence stratigraphy at Stop 4 of the Mescal Canyon foot log. The interval from the first appearance of marine sediment in the Carthage Member to the middle of the D-cross Tongue is a transgressive systems tract. "f" means "fine grained."

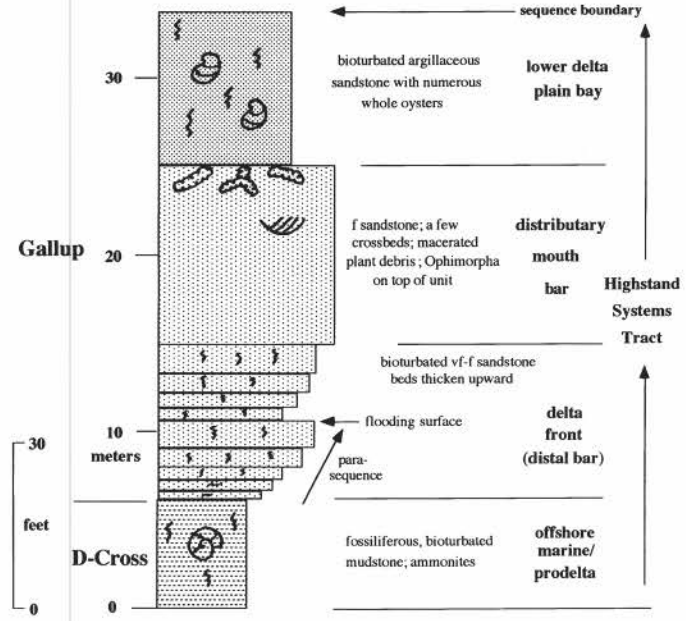


FIGURE 1.48. Stratigraphy, depositional environments, and sequence stratigraphy of Stop 5 of the Mescal Canyon foot log, corresponding to the upper D-Cross Tongue and lower Gallup Sandstone.

FIGURE 1.50. Stratigraphy, depositional environments, and sequence stratigraphy of Stop 6 of the Mescal Canyon foot log and a continuation of Stop 5, corresponding to the top of the Gallup and the base of the Crevasse Canyon Formations.

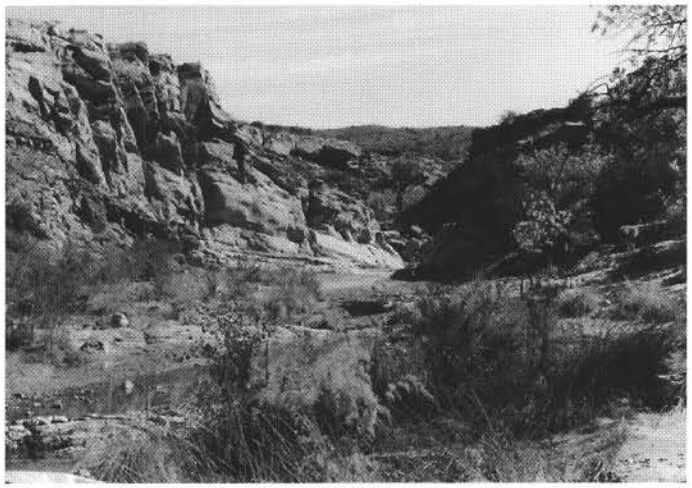


FIGURE 1.47. Exposure of the Gallup Sandstone at Stop 5 of the Mescal Canyon foot log.



FIGURE 1.49. Oysters in a bioturbated sandstone corresponding to the upper unit depicted in Figure 1.48.

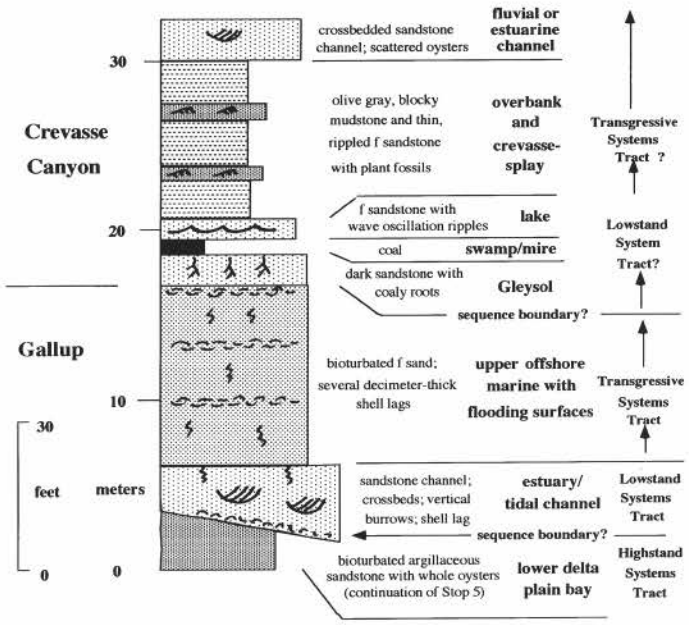




FIGURE 1.51. Tidal or estuarine sandstone channel in the middle of the Gallup Sandstone. Base of the channel has an in.-thick shell lag that is overlain by crossbeds. Channel is overlain by a thin flooding surface, whose base corresponds to the head of the hammer. This channel is significant because it may mark a sequence boundary.

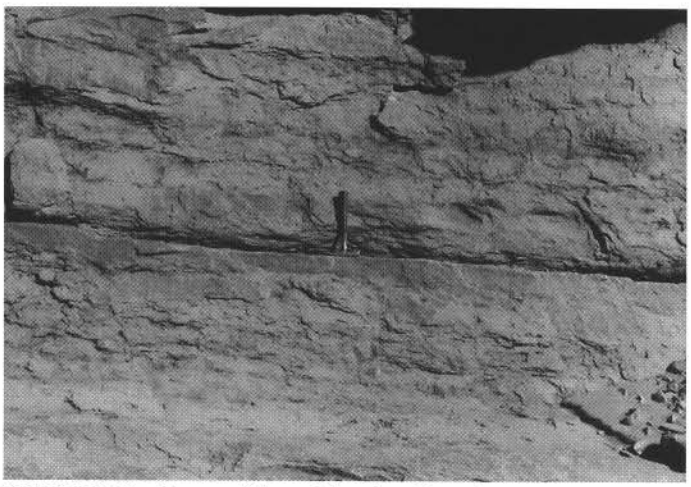


FIGURE 1.52. Upper offshore bioturbated sandstones representing a transgressive systems tract. Several shell lags corresponding to flooding surfaces are present, including one beneath the hammer.



FIGURE 1.53. Paleosol at the Gallup-Crevasse Canyon contact characterized by dark color, blocky peds, and coaly root traces (Mack, 1992).

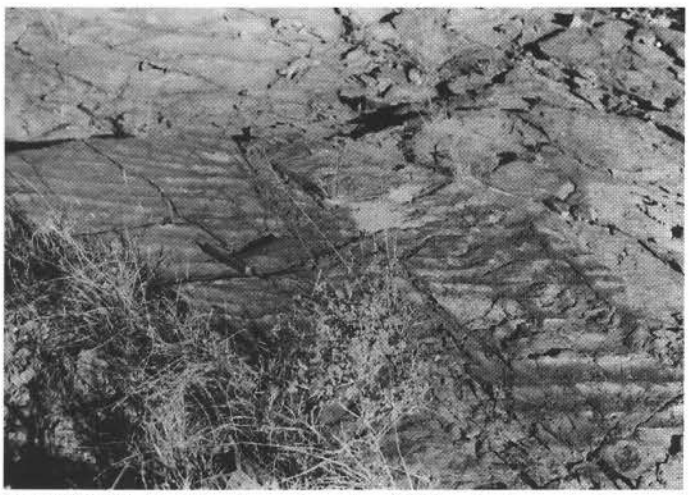


FIGURE 1.54. Bedding plane view of oscillation ripple marks in a sandstone near the base of the Crevasse Canyon Formation.



FIGURE 1.55. Overbank mudstones and crevasse-splay sandstones in the lower part of the Crevasse Canyon Formation. Cliff at top of photo is a fluvial or estuarine channel.



Near-vertical dike of Oligocene andesite exposed in Faulkner Canyon, west of the Robledo Mountains. Photograph by Greg Mack.