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First-day road log: From Albuquerque to Mesita, Laguna, Acoma, McCartys and Grants

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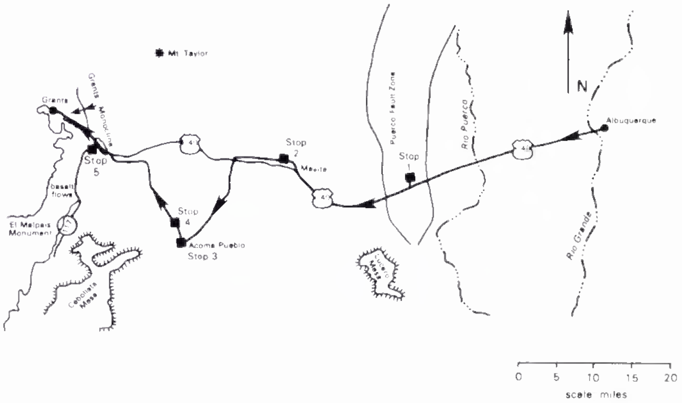
FIRST-DAY ROAD LOG, FROM ALBUQUERQUE TO MESITA, LAGUNA, ACOMA, McCARTYS AND GRANTS

CHARLES H. MAXWELL, ORIN J. ANDERSON, SPENCER G. LUCAS, RICHARD M. CHAMBERLIN and DAVID W. LOVE

FRIDAY, SEPTEMBER 29, 1989

Assembly point:	Parking lot of the New Mexico Museum of Natural History, 1801 Mountain Road NW, Albuquerque, New Mexico.
Departure time:	8:00 a.m.
Distance:	90.5 mi
Stops:	5



SUMMARY

The first day's tour covers Cenozoic deposits and volcanics of the Albuquerque basin, transitional structure between the Rio Grande trench and the southeastern Colorado Plateau, Mesozoic stratigraphy from the Rio Grande trench to the Grants area, Pliocene to Holocene basalts of the San Jose valley, Mount Taylor and El Malpais areas, and the structural and geomorphic evolution of the region.

The first stop is to examine the lithology and sedimentology of the Upper Cretaceous Gallup Sandstone, and to emphasize the southeastern Colorado Plateau as a zone of tectonic transition, where Laramide strike-slip faults and monoclinal uplifts have been modified or partially collapsed in response to late Cenozoic extension and magmatism. At the second stop we will examine the stratigraphy and some sandstone pipes in Jurassic units, and the Quaternary Laguna basalt flow, followed by a traverse through spectacular views of Jurassic and Cretaceous stratigraphy in the Rio San Jose and Acoma valleys. Stop 3 is at Sky City–Acoma Pueblo for unique shopping and photographic opportunities, and cultural enrichment. Stop 4 offers a spectacular view of the Acoma area and a chance to examine Jurassic and Cretaceous stratigraphic features. The last stop of the day includes more discussion of the tectonic transition zone around the Colorado Plateau, Laramide strike-slip faulting, local and regional stratigraphy and a view of the Holocene El Malpais tholeiitic basalt flow. For additional discussions on the region covered by day 1 and part of day 2, see the second-day road logs, in the NMGS 1982 Guidebook, Albuquerque Country II, pages 37–74.

Mileage

0.0 **Turn right** onto Mountain Road and **proceed west. 0.3**

0.3 Intersection and **stop light** at Rio Grande Blvd. **Turn right** and **proceed north. 0.1**

0.4 Sheraton Old Town Inn on right. **0.4**

0.8 I-40 underpass; **continue north** under bridge and **turn left** at light to enter I-40 westbound. **1.2**

2.0 Bridge over Rio Grande. Average annual flow past this point is 1,000,000 acre-ft. **0.1**

2.1 "Adobe Cliffs" to right are Middle Pleistocene Los Duranes Fm, well exposed here in a cut-bank where the Rio Grande lies at the western edge of its floodplain. **0.3**

2.4 Coors Road exit—continue west on I-40. **0.4**

2.8 Milepost 155. Note Albuquerque volcanoes on skyline at 2:00 (Fig. 1-2.8). the oldest of ten olivine basalt flows from these volcanoes has been dated 190,000 ± 40,000 years by Bachman et al. (1975; see discussion by Lambert et al., 1982). Geissman et al. (1989) obtained a weighted mean K-Ar age of 155 ± 47 ky for the flows. **1.1**

FIGURE 1-2.8. Looking northwest at Albuquerque volcanoes.

3.9 Unser Blvd., exit 154. **1.3**

5.2 98th Street, exit 153. I-40 now ascends "9-mile hill." **1.8**

7.0 Note erosion developed in the Santa Fe Group on right for next 0.5 mi. **0.1**

7.1 Cejita Blanca scarp (little white rim) from 1:00 to 3:00. Road crosses the County Dump fault (east side down) which is exposed in roadcut to right (Lambert, 1968). The following discussion was abstracted from the NMGS 1982 Guidebook Supplemental Road Log IIS, p. 102–104. The County Dump fault is a nearly vertical north-trending normal fault that is in line with the Albuquerque Volcanoes fissure. The fault is bounded on the east by a sequence of eolian deposits and locally derived alluvium and colluvium interbedded with calcic soils, and is bounded on the west by the Ceja Member of the Santa Fe (Kelley, 1977). The Ceja Mbr consists mainly of interbedded pinkish-gray sandy gravel and gravelly sand, and is generally equivalent to the uppermost part of Bryan and McCann's (1937) Upper Buff Mbr of the Santa Fe Fm. The sediments on the eastern downdropped side of the fault are derived mainly from, and displaced relative to, the Ceja Mbr and associated pedogenic caliche on the upthrown block. The sediments and buried soils in the downthrown block suggest that the fault has been intermittently active through middle to late Pleistocene time, with each displacement episode being followed by erosion of the scarp and rapid deposition of a wedge of sediment on the downthrown block, and surface stabilization and development of a calcic soil on the clastic wedge. Machette (1978, 1985) estimates that total displacement in the past 400,000 years is about 17 m; no displacement is apparent in the last 20,000 years.

An earthquake in the area on 4 January 1971 (Northrop, 1982), with an epicenter on the West Mesa north of I-40, appears to be related geographically to the County Dump fault and the fissures along which the Albuquerque Volcanoes erupted. The earthquake was felt over about 1600 km^2, and had a Modified Mercalli intensity VI at Albuquerque, where considerable minor damage was reported, principally in the west and northwest sections of the city.

The Cejita Blanca (little white rim) forms the eastern edge of the Llano de Albuquerque, which was an extensive upland plain prior to the middle-Pleistocene incision of the Rio Grande river-valley system. This complex surface, now preserved as a tableland between the Cejita Blanca and Ceja del Rio Puerco scarps, is about 105 km long and up to 13 km wide. **0.9**

8.0 Crest of "9-mile hill," exit 149 to airport and Central Ave. Note the partly stabilized dune field on both sides of I-40 for the next 0.5 mi. The dunes are greatly elongated, northeast-trending ridges of sand that may represent distended arms of migrating parabolic dunes (Lambert, 1974). **0.4**

8.4 Note Sierra Ladrones in distance (47 mi) at 11:00. Wind Mesa in mid-distance. **0.4**

8.8 Surface we are driving on is the Llano de Albuquerque. **0.6**

9.4 At 9:00–10:00 Los Lunas volcano in distance, Wind Mesa volcano in middle foreground. **1.0**

10.4 Mesa Lucero at 10:30 in distance, displays light-colored Permian strata (Yeso, Glorieta, San Andres fms) at its base, overlain by darker Triassic red beds (Moenkopi and Chinle fms) and is capped by Tertiary basalt. **2.4**

12.8 Crest of hill; elevation 5900 ft. Note pedogenic petrocalcic horizon in roadcut on right, view ahead is of Rio Puerco valley. **0.2**

13.0 Ceja del Rio Puerco (brow of the Rio Puerco). Begin descent into valley. The Rio Puerco originates about 60 mi to the north and drains an area of fine-grained Mesozoic rocks along the southeastern side of the San Juan Basin and thus carries a high suspended load. It enters the Rio Grande 45 mi to the south of here at Bernardo. **1.5**

14.5 Cerro Colorado 0.5 mi south of road at 10:00. It is part of a complex alkalic volcano with a funnel-shaped quartz latite dome intruded into the vent of a trachyte cone (Wright, 1943). Parts of the trachyte contain anomalous amounts of Th, Y, Zr and REE. A uranium prospect on the northeastern side of Cerro Colorado was described by Hilpert (1969) as "yellow and green uranium minerals in limonite stained fractures and brecciated pockets in a rhyolitic mass." **0.4**

14.9 Milepost 143. In the distance, Mesa Gigante at 1:00, Mt. Taylor at 2:00. **0.5**

15.4 Roadcut on right exposes thin-bedded Santa Fe Group. **0.5**

15.9 Milepost 142. La Mesita Negra on the right ahead, basalt flows on tilted middle Santa Fe red beds. **0.9**

16.8 Rio Puerco exit 140. Continue west on I-40. **0.6**

17.4 Highway crosses the muddy Rio Puerco. The Rio Puerco is an entrenched meandering river system with intermittent flow. It is known for its high suspended sediment load. For additional discussion of geomorphic processes along the Rio Puerco see Wells et al. (1982). The old overhead truss bridge on right was constructed in 1933 and served traffic on U.S. 66 for 35 years before I-40 was completed here in 1968. **1.3**

18.7 Outcrops of slightly carbonaceous facies of Crevasse Canyon Fm overlain by yellow fluvial channel sandstone on right ahead. The Crevasse Canyon is a coastal plain sequence of Coniacian and Santonian age deposited on the surface exposed during progradation of the Gallup Sandstone. **0.3**

19.0 The site of Shell No. 1 Laguna Wilson well is about 1000 ft south of the highway at this point (in sec. 8, T9N, R1W). Well was drilled in 1972, encountered granite at 11,103 ft after penetrating 2500 ft of Pennsylvanian section (courtesy NMBMMR petroleum records section). **0.1**

19.1 Crossing fault which bounds the eastern side of the Apache graben (Campbell, 1967) and entering southern part of Rio Puerco fault zone. Upper Santa Fe is downthrown to the west against mudstones and tan-brown sandstones of the Crevasse Canyon Fm. At 2:00 the white bed capping pinnacle in upper Santa Fe Group is 620,000-yr-old Lava Creek B volcanic ash (Fig. 1-19.1) from Yellowstone Caldera complex (Izett and Wilcox, 1982). **0.7**

19.8 Roadcut in frontage road on right displays fluvial sands and gravels of Santa Fe Group. **0.5**

20.3 Good view of Mesa Gigante from 1:00 to 2:00 with Mt. Taylor over right-hand side. I-40 now descends into the Apache graben. **0.7**

21.0 Bridge over Cañada de los Apaches, a major tributary

FIGURE 1-19.1. Lens of volcanic ash (middle Pleistocene Lava Creek B 620,000 yr) in upper Santa Fe Gr near eastern edge of Apache graben.

to the Rio Puerco. Outcrops of Santa Fe at 9:00 to 9:30. **1.4**

22.4 Folded and tilted Santa Fe Group strata in roadcuts signal the western edge of the Apache graben. Look for eastward dips in the gravel, thin sandstone and orange-brown mudstones with some westward dip at west end of roadcut on right. **3.5**

25.9 Milepost 132. Cibola County line; Suwanee Peak at 11:00. Bluff at 2:30 displays northeastward-dipping Gallup Sandstone. This bluff is site of Stop 1. **0.6**

26.5 **Leave I-40** at Cañoncito exit 131, proceed to stop sign. **0.2**

26.7 **Junction** with Arrowhead-56 at stop sign. **Turn right** and **proceed north.** Small mesa ahead on right is Stop 1 (Fig. 1-26.7). **0.75**

27.45 **STOP 1.** Leave buses and walk to examine outcrops of Gallup Sandstone in small mesa (elev. 5746 ft) 0.1 mi to east (Fig. 1-27.45a); mesa is nearly on the Bernalillo-Cibola County line; also for discussion of late Cenozoic extension and the associated faulting and structure, well displayed here along the western margin of the Rio Grande rift in the Santa Fe fault zone. For panoramic index see Figure 1-27.45b.

The Gallup Sandstone (early Coniacian) is a regressive, coastal barrier sandstone that prograded out into the Mancos sea. (See stratigraphic nomenclature chart for this area at beginning of road-log section.) Here, as far as we can determine, the Gallup consists of one relatively thick (up to 80 ft locally) sandstone unit. However, in the hogback east of Gallup where Sears (1925) first described it, the unit consists of "three massive sandstones and interbedded shale and coal." We will

FIGURE 1-26.7. Gallup Ss capping small mesa at Stop 1; looking N from I-40 exit.

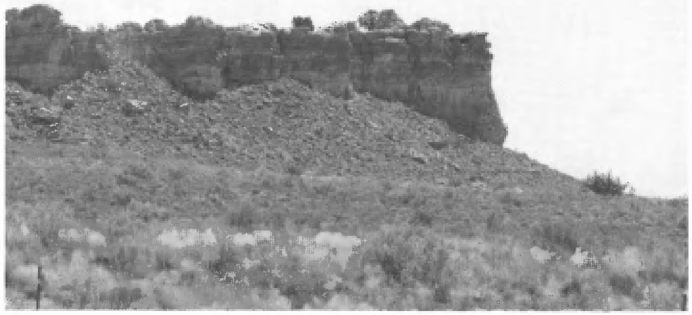


FIGURE 1-27.45a. Looking east at south end of mesa at Stop 1. *Inoceramus rotundatus* collected from base of Gallup Ss at right.

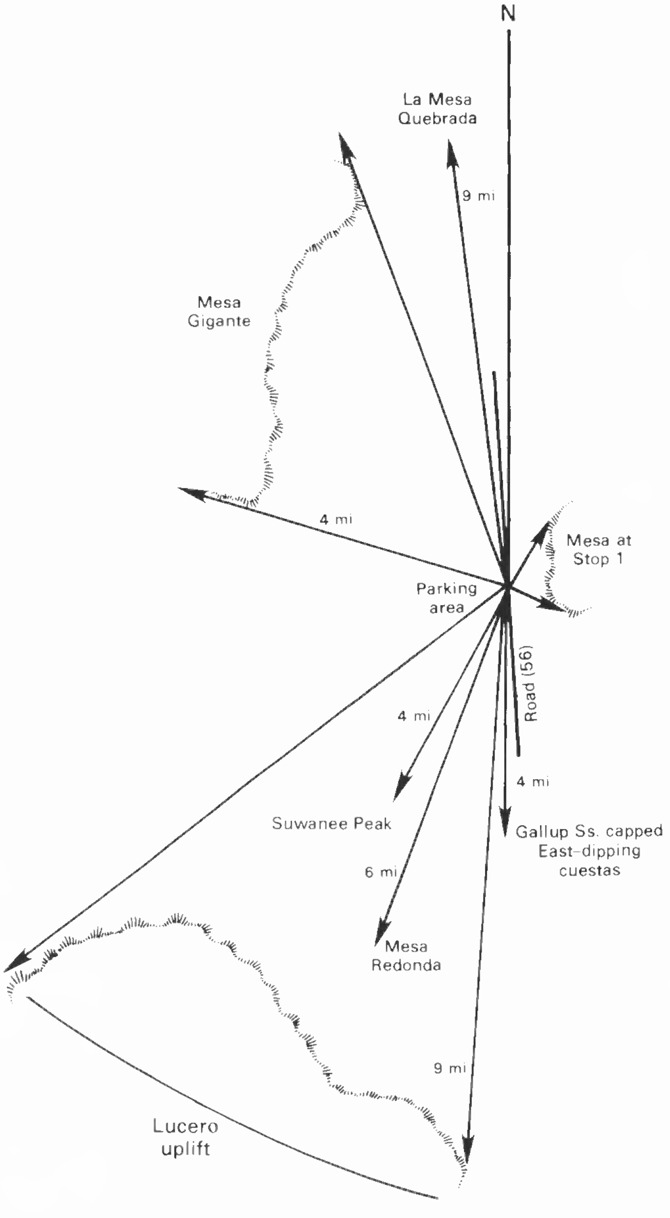


FIGURE 1-27.45b. Panoramic index for Stop 1 parking area.

see the hogback outcrop on the third day. The uppermost of Sears' three sandstones is an alluvial unit that is lithogenetically unrelated to the underlying sandstones, which are of marine origin. That problem does not confront us here as this sequence represents continuous deposition in, first, a lower shoreface and, later, an upper shoreface environment. The lower shoreface sequence was deposited below wave base and seaward from the stronger longshore currents (Molenaar, 1973), is very fine grained and tends to display flat bedding (Fig. 1-27.45c). The upper shoreface sequence, in contrast, is upper fine grained to lower medium grained, highly crossbedded and represents deposition in much shallower water where longshore and/or rip currents reworked all incoming sediment. Both facies are well displayed at this stop. In addition, the lower shoreface sequence shows many biogenic sedimentary structures (burrows, tubes and trails) indicating an extensive infauna (Fig. 1-27.45d). *Inoceramus rotundatus* Fiege, an early Coniacian bivalve (Fig. 1-27.45e), was collected from the base of the Gallup Sandstone at this stop (identification by William Cobban of the USGS). *I. rotundatus* Fiege occurs in the upper part of the *I. waltersdorfensis* zone, which in turn occurs in the Fort Hays Limestone Mbr of the Niobrara Fm in the offshore sequence. Thus, the Gallup Sandstone at this stop is roughly the age equivalent of the Fort Hays Mbr in northeastern New Mexico and adjacent parts of Colorado.

FIGURE 1-27.45d. Vertical burrows in lower flat-bedded portion of Gallup Ss.

FIGURE 1-27.45e. Specimen of *Inoceramus rotundatus* Fiege collected at Stop 1 (scale in mm).

FIGURE 1-27.45c. Flat-bedded, very fine-grained, basal Gallup Ss grades up into upper fine-grained, crossbedded sequence at top.

Our first stop as we walk up the mesa will be to examine the base of the Gallup and look for the fossiliferous bed. From that point we will proceed northward to look at a small, down-to-east normal fault on our way to the top for a discussion of local structure.

Most of the structure (exemplified by the generally broken-up landscape) seen from the vantage point of the small mesa is associated with the southern part of the Rio Puerco fault zone, more specifically called the "en echelon fault belt" by Slack and Campbell (1976). The Rio Puerco fault zone is a major structural element along the western margin of the Rio Grande rift (Fig. 1-27.45f)

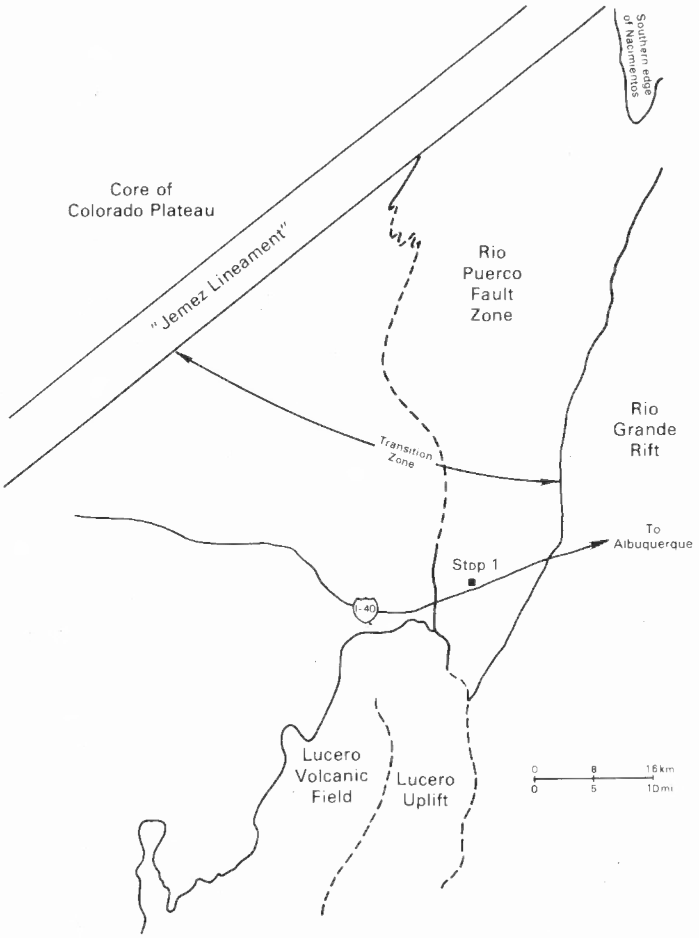


FIGURE 1-27.45f. Generalized map of the Rio Puerco fault zone, showing the relationship to the Rio Grande rift, the Lucero uplift, the Nacimiento uplift and the "Jemez lineament."

between the Nacimiento uplift on the north and the Lucero uplift to the south. It was recognized by Hawley (1982 NMGS Field Conference Guidebook, p. 71) as a "downdropped transition zone" between the southeastern margin of the Colorado Plateau and the Rio Grande rift. The Rio Puerco fault zone in this area is characterized by northeast-trending, moderate displacement, down-to-the-west normal faults considered by Slack and Campbell (1976) to have originated in a region of divergent wrench faulting during the late Laramide. The cross section (Fig. 1-27.45g) shows the contrast in style and sense of movement with the faulting that defines the western margin of the rift. The faults within the rift proper are down-to-the-east, although low displacement, and truncate the Rio Puerco fault zone.

Immediately to the east is the Albuquerque basin, one of four major axial basins that define the Rio Grande rift between Socorro, NM and Leadville, CO (Chapin, 1988). The basins to the north are, in order, the Española, the San Luis and the Upper Arkansas. As are most of the rift basins, the Albuquerque basin is asymmetric, with the major fault boundary on the east side. On the east side, the Sandia Mountains form an eastward or outward tilted prominent shoulder with a total of 40,000 ft of structural relief (Black, 1982). Along the west side, strata are, in contrast, tilted inward and downwarped toward the rift, so that we have a modified half-graben here, in its overall configuration. To the west is the Colorado Plateau, characterized by relatively flat-lying Mesozoic rocks. Thus, the Rio Puerco fault zone upon which we are standing is part of the transition zone between the Rio Grande rift and the Colorado Plateau, although a good case can be made for extending the transition zone northwestward to the "Jemez lineament." This "lineament" is a N52°E-trending alignment of Late Cenozoic volcanism, and extends from the Springerville volcanic field, through Mt. Taylor and the Jemez Mountains (Fig. 1-27.45f).

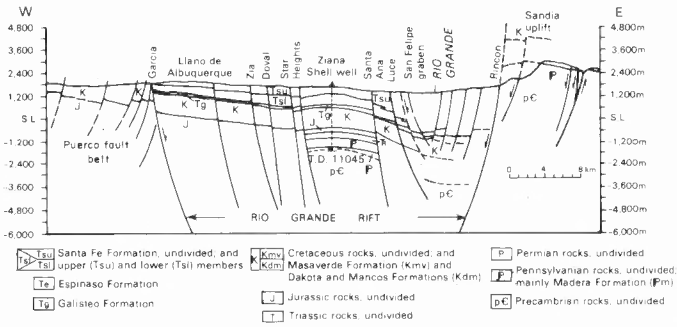


FIGURE 1-27.45g. Cross section from Sandia Crest westward, contrasting the dip direction and sense of movement on faults in the Rio Grande rift and in the Puerco fault zone (after Hawley and Kottlowski, 1978).

TECTONICS AND TIMING OF RIFTING

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The Colorado Plateau and the Southern Rocky Mountains provinces attained their present outlines and general characteristics during the Laramide orogeny (80–40 my), although they have undergone deformation since, as noted by Woodward (1982). The Rio Grande rift, on the other hand, is a late Cenozoic feature created by extensional tectonics. The rift, however, did exist as a major crustal flaw long before the onset of rifting. Chapin and Cather (1981) have presented evidence that the present rift was the site of late Laramide wrench faulting during which the Colorado Plateau was translated as much as 100 km northward with respect to the High Plains. Along this major wrench fault were zones of divergent and convergent block movement. Two nearby structures, the Ignacio monocline to the north and the Lucero uplift to the south, are Laramide related structures. The north-trending Ignacio monocline, with 500 m of structural relief, has been attributed by Slack and Campbell (1976) to late Laramide (Eocene) vertical uplift; late Laramide was specified primarily because they interpreted the southern part of the Rio Puerco fault zone to be in a divergent wrench fault zone earlier in the Laramide (Paleocene). They called upon the numerous northeast-trending, small displacement, northwest-dipping normal faults in the area to support that interpretation. The northern part of the Rio Puerco fault zone was described by Slack and Campbell (1976) to be a region of convergent wrenching extending northward to the Nacimiento uplift. This is consistent with Chapin and Cather (1981), in that the latter authors also have the major wrench faulting occurring during the late Laramide when the axis of horizontal compression had shifted to a more northerly direction.

The Lucero uplift to the south provides an uplifted, outward (westward) tilted shoulder to the western margin of the Albuquerque basin and thus provides some degree of symmetry to the rift. Primarily for that reason, Chapin (1988) places that portion of the basin in a different domain. The east-facing Lucero monocline defines the eastern margin of the Lucero uplift. The monocline plunges to the north and was considered by Callender and Zilinski (1976) to be structurally contiguous with the Ignacio monocline. They concluded that "vertical tectonics in an overall Laramide compressional stress field produced the monocline folding."

It is thus readily apparent that there are structural features along the western margin of the rift that are inconsistent with normal faulting related to rift development. Late Cenozoic extension merely reactivated many of the Laramide wrench or high-angle reverse faults with the onset of rifting. Chapin (1988) has summarized the evidence for the timing and onset of rifting. Precise ^{40}Ar/^{39}Ar dating methods now available have provided age dates on four major ash-flow sheets that crossed the southern end of what is now the Albuquerque basin just prior to the onset of major rifting. Dates on these voluminous flows of 28.8 to 27.4 my (McIntosh et al., 1986), as well as other work by Baldridge et al. (1980) in the Española basin and Machette (1978) in the Albuquerque basin, provide the most important evidence for the onset of rifting, now accepted as late Oligocene.

The synrift sedimentary deposits and relatively minor volcanic rocks of the Rio Grande rift are collectively known as the Santa Fe Group. Early sedimentary fill accumulated in closed basins, and for obvious reasons is not well exposed. The lower part of the Santa Fe is called the Popotosa Formation in the southern Albuquerque basin and Zia Sand Formation in this area. The establishment of an integrated drainage system to form the ancestral Rio Grande occurred about 4.5 my (Chapin, 1988). The axial river deposits and the associated intertonguing piedmont facies that were subsequently laid down are known as the Sierra Ladrones Formation in most of the Albuquerque basin. For additional discussion of the Albuquerque basin, see Lozinsky (this guidebook).

After stop, **return to I-40.** **0.75**

28.2 **Turn right** on westbound ramp to I-40 (**do not cross bridge!**). To the southwest is view of Mesa Redonda with conical Suwanee Peak to the right in middle distance (Fig. 1-28.2). **0.5**

28.7 Gallup Ss in roadcut on right. Base of the Gallup Ss is visible at bottom of roadcut at far end. **0.4**

29.1 View to south of eastward-dipping Mancos Sh in gullies. Cuestas at 9:00 to 10:30 capped by basal Dakota Ss over Morrison Fm and Zuni Ss. Suwanee Peak in middle ground at 10:00 has travertine cap underlain by Dakota. The mesa to the south beyond the valley of Rio San Jose is Lucero Mesa, at the northern end of the Lucero uplift. The mesa is capped by the Lucero cone and basalt flows of Pliocene age, and extensive travertine deposits, overlying the San Andres Fm, Glorieta Ss and Yeso Fm. The isolated butte in the valley is Mesa Redonda (partially hidden by Suwanee Peak) which exposes a faulted syncline on its north face and a cap of Pliocene basalt. Both Morrison and Dakota are exposed on its flanks; a cross section in Darton (1928) is a northward view (Fig. 1-29.1) of Mesa Redonda and its position relative to the Puerco fault zone on the east. Also note that Darton's cross section indicated a Cretaceous age for the Morrison! (See following mini-paper.) **0.3**

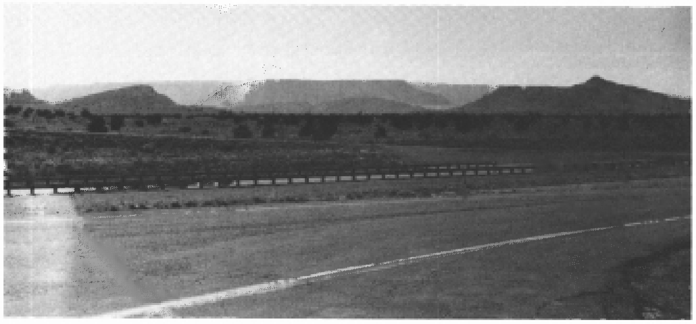

FIGURE 1-28.2. Looking southwest from I-40 on-ramp toward Mesa Redonda and Suwanee Peak (at right); Mesa Lucero in background; Gallup Ss capped cuestas at left.

JURASSIC-CRETACEOUS BOUNDARY IN WEST-CENTRAL NEW MEXICO

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For many years, geologists working in west-central New Mexico have placed the Jurassic-Cretaceous boundary between the Morrison and Dakota formations. Thus placed, the boundary coincides with a profound unconformity (K unconformity of Pipiringos and O'Sullivan, 1978) between the supposed Upper Jurassic (Tithonian) Morrison and the "middle Cretaceous" (Cenomanian or latest Albian) Dakota. However, recent radiometric ages as well as magnetostratigraphy suggest that part of the Morrison Formation is of Cretaceous age, necessitating a revised placement of the Jurassic-Cretaceous boundary in much of the Western Interior.

The Jurassic-Cretaceous boundary is the boundary between the Tithonian (latest Jurassic) and Berriasian (earliest Cretaceous) marine stage-ages. Recent geochronometry calibrates this boundary at 135 my (Hallam et al., 1985) or 144 my (Kent and Gradstein, 1985). In terms of geomagnetic reversals, the Jurassic-Cretaceous boundary is between M17 and M19 of the M-sequence of geomagnetic reversals (Ogg and Lowrie, 1986).

Fission-track ages of bentonite beds in the Brushy Basin Member of the Morrison in southeastern Utah indicate a Cretaceous age (younger than 135 my) for much of the Brushy Basin Member (Kowallis and Heaton, 1987). Similar ages have also been obtained from the Morrison in western Colorado (Kowallis, 1986). K-Ar ages at Dinosaur National Monument in eastern Utah indicate a Cretaceous age for the upper part of the Brushy Basin Member as well (Bowman et al., 1986). Magnetostratigraphy in the Bighorn basin of northern Wyoming suggests that the upper part of the Morrison is much younger than M17, and thus of Cretaceous age (Douglass and Johnson, 1984). In west-central New Mexico, Rb-Sr age determinations suggest a minimum age of deposition for the Jackpile Sandstone Member of the Morrison of 139 ± 9.5 my, consistent with a Cretaceous age assignment (Lee and Brookins, 1978; Brookins, 1980).

The biochronological evidence of a Jurassic age for the entire Morrison Formation has always been weak. Indeed, it largely hinges on Simpson (1926), who argued that the Morrison dinosaurs are the same age as a supposed Jurassic dinosaur fauna from Tendagaru in East Africa. The new geochronometric and magnetostratigraphic evidence for a Cretaceous age for the upper part of the Morrison should override the previous, imprecise age assignment based on dinosaurs. Thus, the Jurassic-Cretaceous boundary in west-central New Mexico is almost

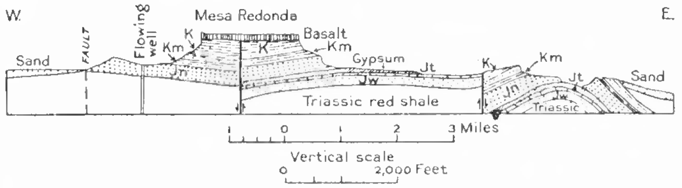

FIGURE 1-29.1. Section through Mesa Redonda, south of Suwanee, looking north. K, Dakota(?) and overlying Cretaceous sandstones and shales; Km, Morrison Formation; Jn, Navajo sandstone; Jt, Todilto Formation, including gypsum member at top; Jw, Wingate Sandstone (from Darton, 1928).

certainly within the Morrison Formation. Our common use of "JM" to refer to the Morrison in map legends will have to give way to "JKM," and the geologists of the past (e.g., Sears, 1925; Darton, 1928), who considered part or all of the Morrison to be Cretaceous, have turned out to be right (although for the wrong reasons).

29.4 Milepost 130; crossing major north-trending, down-to-the-east normal faults that drop the Gallup Ss down against the Entrada Ss and Todilto Ls, a vertical displacement of more than 1000 ft. This marks the western edge of Rio Puerco fault zone. **1.1**

30.5 At 3:00, Petrified Forest Mbr of Chinle Fm and Correo Ss bed (Upper Triassic) on right ahead; behind to north is pink Entrada Ss with bleached upper zone underlying the thin darker band of Todilto Ls (Middle Jurassic). Bold grayish red cliffs near road for the next several miles are Correo Sandstone bed overlying mudrocks of Petrified Forest Mbr of Chinle Fm. Good views just ahead of Mesa Gigante 4 mi off to the right. Units exposed on the south side of Mesa Gigante are, in ascending order: the Entrada Ss, a small ledge of Todilto Ls overlain by the grayish hummocky rounded slopes of the Todilto gypsum; reddish-brown to pale orange mudstone and sandstone of the Beclabito Mbr of Wanakah (formerly Summerville Fm) forming slopes and ledges; reddish-brown, cliff-forming Horse Mesa Ss Mbr (formerly the Bluff Ss), with light colored upper zone called an eolian facies of the Recapture Mbr of Morrison Fm (Condon, this guidebook) or correlative with the Zuni Ss of Maxwell (1976a, 1982a); greenish-gray variegated mudstone and sandstone of the Morrison Fm, forming talus covered slopes and ledges (top of Jurassic sequence); and basal Dakota Ss (Cretaceous) capping the cliffs and forming the mesa rim. The Dakota/Morrison contact is an unconformity which is angular on a regional scale; pre-Cretaceous units were tilted gently northward and beveled by erosion before the Dakota Ss was deposited. To the south, the Dakota overlies progressively older strata, truncating all of the Jurassic units and part of the Triassic (Silver, 1948; Maxwell, 1982a). **1.0**

31.5 Blocks of Correo Ss on right must be relatively old (mid-Pleistocene) slumps. Mesa Gigante visible at 2:00. **1.1**

32.6 Underpass and exit 126 for NM Highway 6 to Los Lunas. Note type section of Correo Ss bed at 2:00. Stewart et al. (1972a) and Lucas et al. (1987) redefined Kelley's and Wood's (1946) Correo Ss Mbr of the Chinle Fm as a bed within the Petrified Forest Mbr (Fig. 1-32.6a). Behind the Correo at 2:30, note light gray Todilto Ls and Gypsum mbrs overlain by reddish brown Wanakah Fm (red bluff), and, on the skyline, the slope-forming Morrison Fm and Dakota Ss capping Mesa Gigante. **0.8**

33.4 Milepost 126. Above the Correo Ss bed which caps mesa on right, note light colored Todilto and Wanakah fms in a sequence which is dipping gently away from viewer. **0.7**

34.1 Correo Ss Bed on right side of highway, capping mesa (Fig. 1-34.1). **0.6**

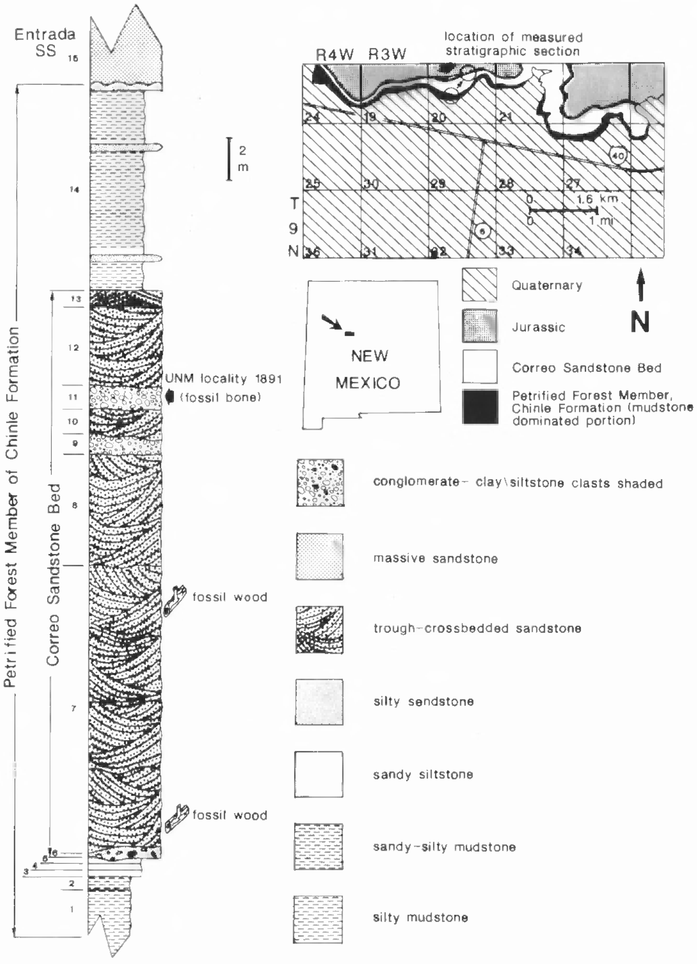

FIGURE 1-32.6a. Type section of Correo Ss Bed (from Lucas et al., 1987).

FIGURE 1-34.1. View northward from I-40 of Correo Ss Bed of Petrified Forest Mbr of Chinle Fm. Photo by S. G. Lucas.

34.7 View from 8:00 to 11:00, across the valley of Rio San Jose and up the broad flat valley of Arroyo Colorado cut into Chinle Fm includes the Lucero volcanic field. Scanning clockwise from 8:00 is Mesa Lucero, Mesa Gallina and Chicken Mtn, lava-capped mesas of the Lucero uplift; Cerro Verde volcano, source of basalt flow down San Jose valley; Mesa del Oro and Victorino Mesa, capped by basalt and surrounded by huge toreva–block landslides, and East Mesa on skyline at 10:00 to 11:00 with vertical cliffs of Jurassic sandstones. The East Mesa quadrangle was mapped by Maxwell (1979) as were the adjacent Acoma Pueblo (1976a) and Marmon Ranch quadrangles (1988b). **0.3**

THE LUCERO VOLCANIC FIELD

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The Lucero volcanic field on the southeastern margin of the Colorado Plateau has been studied in detail by Baldridge et al. (1987). They described it as an area characterized by extensional features, including large, asymmetric horst and graben (or half-graben) blocks, and thinned lithosphere that constitutes part of a broad transition zone concentric about the southeastern and southern margins of the Colorado Plateau (Fig. 1-27.45f). This transition zone (in an expanded sense) is bounded on the northwest by the "Jemez lineament" that demarcates the less deformed core of the plateau which lies to the west and north. A glance at the State Geologic Map (Dane and Bachman, 1965) illustrates how the outcrop pattern changes at the "Jemez lineament" to reflect the relatively flatter-lying rocks and diminished volcanism within the core of the plateau. Forming the eastern margin of the transition area is the Lucero uplift (or volcanic field) which trends more northerly than the "Jemez lineament"; thus, the two converge northward on the Rio Puerco fault zone to lend a triangular shape to the transition area (Fig. 1-27.45f).

The pattern of volcanism in the Lucero field does not suggest strong relationship to linear crustal flaws or a pervasive basement fracture pattern. The vents and flows are scattered somewhat arbitrarily along the western flank of the Lucero uplift and are a manifestation of randomly fragmented and irregularly thinned lithosphere. The fragmentation could be as old as the Laramide. The lithospheric thinning may have been a relatively recent and dynamic process (within the last 8 my) based upon changes in composition of rocks associated with each successive pulse of volcanism (Baldridge et al., 1987). The age of the three main pulses were defined by these authors as 8.3–6.2, 4.3–3.3 and 1.10–0 my. Total volume of volcanic rock in the Lucero field was estimated at 1.7 mi^3.

TRIASSIC STRATIGRAPHY AND PALEONTOLOGY, MESA DEL ORO, VALENCIA COUNTY, NEW MEXICO

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Triassic strata exposed in the Mesa del Oro area have been assigned to various units. Kelley and Wood (1946) recognized three Triassic units in the Lucero uplift north of Mesa del Oro: (1) their basal, "Shinarump Conglomerate," which is actually Middle Triassic Moenkopi Formation (Hayden and Lucas, 1988a); (2) the "red shale member" of the Chinle which, at "1000+ ft," must represent most of the Chinle Formation; and (3) their Correo Sandstone Member (now considered a bed in the Petrified Forest Member of the Chinle Formation: Lucas et al., 1987).

Jicha (1958, p. 19, pl. 1), in his geologic study and map of the Mesa del Oro 15-minute quadrangle, followed Tonking in recognizing a fourfold division of Triassic strata: (1) a "lower sandstone unit," the "Shinarump" of Kelley and Wood (1946), now recognized as Moenkopi; (2) above that, a "lower siltstone-shale unit," the unit from which we report fossils here, and we believe to represent the lower portion of the Petrified Forest Member of the Chinle Formation; (3) an "upper sandstone unit" which is the Sonsela Sandstone Bed of the Chinle Formation, and (4) an "upper siltstone-shale unit" which is the upper portion of the Petrified Forest Member of the Chinle.

Most recently, Maxwell (1979, 1988a, b), in mapping near Mesa del Oro, only recognized two informal Chinle units. These are upper and lower parts dominated by mudstone and siltstone, although the lower part is somewhat sandier than the upper (we are, however, skeptical of Maxwell's identification of some sandstones in the lower part as "eolian").

Unlike previous workers, and as indicated above, we see the Triassic section at Mesa del Oro as little different from that described by Akers et al. (1958; also see Cooley, 1957) at Fort Wingate and Thoreau in McKinley County, New Mexico. Thus, above the Middle Triassic Moenkopi Formation, strata of the Upper Triassic Chinle Formation can be divided into the lower and upper portions of the Petrified Forest Member split by the Sonsela Sandstone Bed. Whether or not a "lower red member" of the Chinle between the Moenkopi and lower Petrified Forest Member can be recognized at Mesa del Oro will require further study.

The fossils described below were recovered from two localities in the lower portion of the Petrified Forest Member of the Chinle Formation (note that the Sonsela Sandstone Bed crops out stratigraphically above the fossiliferous strata in the SE$^1/_4$ sec. 10, T5N, R5W). NMMNH (New Mexico Museum of Natural History) locality 248 is a unionid-clam locality in slightly calcareous red-purple (5 R 4/2) and grayish red-purple (5 RP 4/2) sandy mudstone in the NE$^1/_4$ SW$^1/_4$ SW$^1/_4$ SE$^1/_4$ sec. 11, T5N, R5W. The second locality, NMMNH locality 249, is about 16 m lower stratigraphically than locality 248. Here, bone occurs in dark yellowish brown (10 YR 4/2) calcrete nodules in non-calcareous, very dusky red-purple (5 RP 2/2) silty mudstone in the NE$^1/_4$ SE$^1/_4$ SW$^1/_4$ SW$^1/_4$ sec. 15, T5N, R5W. The fauna from the lower Petrified Forest Member consists of unionid bivalves, the preservation of which varies from good to badly recrystallized, and disarticulated and fragmented vertebrate remains. NMMNH P- refers to specimens in the collection of NMMNH.

The *Unio* specimens are typified by P-3655 (Fig. 1-34.7A–B), which has metric ratios similar to *U. arizonensis* (e.g., height/length = 0.52, width/length = 0.30; cf. Kues, 1985, table 1), but lacks the conspicuously concave ventral margin of that species (Henderson, 1934; Kues, 1985). Hence, NMMNH P-3655 is referred to *Unio* sp., as are all other unionid specimens from these localities.

NMMNH P-3659 represents a dorsal-lateral skull fragment of a large labyrinthodont amphibian (Fig. 1-34.7C). This specimen is probably assignable to *Metoposaurus*, the common genus in the lower Chinle Formation. In contrast, NMMNH P-3657 (Fig. 1-34.7D–E) represents fragments of a very small metoposaur, probably a new taxon (*Anaschisma* n. sp. of Gregory, 1980; *Dictyocephalus* sp. of Davidow-Henry, 1987).

The heavily armored aetosaurian reptiles are represented by a lateral scute (P-3658; Fig. 1-34.7F–G) and a fragment of a paramedian scute (P-3663; Fig. 1-34.7H) of *Calyptosuchus wellesi* (cf. Long and Ballew, 1985; figs. 13–16).

The remains of phytosaurian reptiles constitute the majority of the collected specimens. NMMNH P-3656 is a rostral fragment of a phytosaur (Fig. 1-34.7J) with a v-shaped dorsal cross section. None of the phytosaur material is generically determinate.

A number of vertebrate coprolites (P-3660) are present in the NMMNH collection, including longitudinally striated forms (Fig. 1-34.7K; type B coprolite of Lucas et al., 1985) and nonstriated forms (type A coprolites of Lucas et al., 1985).

Unio sp. and indeterminate vertebrate material are present at NMMNH locality 248 and *Unio* sp., *Calyptosuchus wellesi*, *Metoposaurus* sp., "*Anaschisma* n. sp." and Phytosauridae at NMMNH locality 249. The presence of *Calyptosuchus* and common *Metoposaurus* material supports a correlation of the faunas of NMMNH 248 and 249 with the fauna of the lower Petrified Forest Member of the Chinle Formation in northeastern Arizona (Long and Ballew, 1985; R. Long, oral commun., 1988), thus supporting the stratigraphic assignments outlined above.

35.0 Windmill at 2:00, Mt. Taylor at 1:00. **0.5**

35.5 Good view of south end of Mesa Gigante on right (Fig. 1-35.5). The yellow sandstone above the red-brown cliff-forming Wanakah Fm visible at about 3:00 on Mesa Gigante is the Zuni Ss (of Maxwell, 1976a, 1979); however, Condon (this guidebook) would assign it to the Bluff Ss Mbr of the Morrison Fm, which in this area is merely an eolian facies of the Recapture Mbr. **1.0**

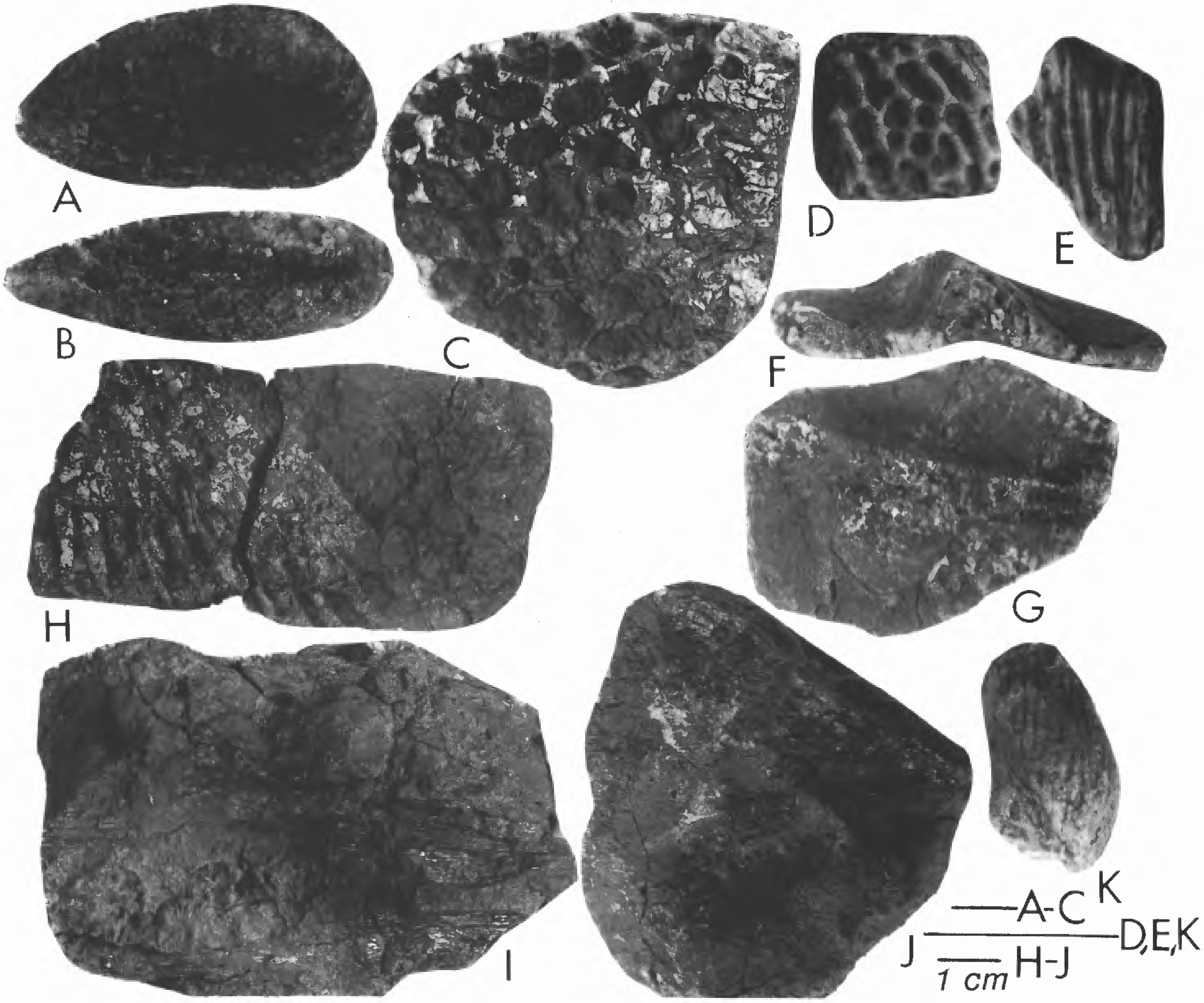

FIGURE 1-34.7. Fossils from the Lower Petrified Forest Member of the Chinle Formation (NMMNH localities 248 and 249), Mesa del Oro, New Mexico: A–B, Left lateral (A) and dorsal (B) views of *Unio* sp. (P-3655); C, Dorsal view of cranial fragment of *Metoposaurus* sp. (P-3659); D–E, Fragments of "*Anaschisma* n. sp." (P-3657); F–G, Posterior (F) and dorsal (G) views of lateral scute of *Calyptosuchus* sp. (P-3658); H, Dorsal view of paramedian scute fragment of *Calyptosuchus* sp. (P-3663); I–J, Ventral (I) and ?anterior (J) views of phytosaurian rostral fragment (P-3656); K, Vertebrate coprolite (P-3660).

36.5 Milepost 123; southwest edge of Mesa Gigante at 3:00 exposes sequence of Entrada through Dakota. **1.1**

37.6 Bridge over Santa Fe Railroad tracks. Broad, flat valley ahead is that of Rio San Jose, a tributary to the Rio Puerco. **1.6**

39.2 Bridge across Rio San Jose. At 2:00, Todilto Ls and Gypsum mbrs overlain by Beclabito and Horse Mesa mbrs of the Wanakah. **0.3**

39.5 Milepost 120; note Petrified Forest Mbr of Chinle Fm in small outcrops at 9:00 and just ahead on right. At 2:00 to 3:00, good exposure of Todilto Ls and Beclabito Mbr of Wanakah Fm overlain by the more massive red cliff of the Horse Mesa Mbr of Wanakah. Mt. Taylor is at 1:00, elevation 11,301 ft. **0.6**

40.1 Underpass. Chinle in roadcut on right. **1.5**

41.6 **Leave I-40** by bearing right onto exit 117 for Mesita. **0.2**

FIGURE 1-35.5. View of south end of Mesa Gigante from near mile 35.5. Most of the light-colored slope former is Morrison Fm capped by Dakota Ss. Basal part of slope former is an eolian unit that correlates with Zuni Ss of Maxwell (1976).

41.8 **Stop sign. Turn right.** Good view ahead of the thick Todilto Gypsum Mbr. A photo of this area appeared in Darton (1915), "Western U.S., the Santa Fe Route." The modern Laguna Indian village of Mesita is on the southern tip of the Laguna basalt flow. The Laguna flow caps relatively fine grained valley-fill alluvium of the Rio San Jose. **0.1**

41.9 **Cattleguard. Turn sharply left** onto frontage road and **proceed west** parallel to I-40 (on old US 66). **0.8**

42.7 Sandstone capping cliff to left is the Horse Mesa Mbr of Wanakah Fm which overlies the thin-bedded sandstone and mudstone of the Beclabito Mbr of the Wanakah (formerly Summerville). Note the gray-green diabase dike/sill/dike combination vaguely visible in cliffs of Wanakah Fm at 2:30 across Rio San Jose. At 3:00 to 4:00 is view of Todilto gypsum facies overlain by Wanakah Fm (Fig. 1-42.7). Sandstone pipes and collapse features are easily visible in cliffs and slopes from 11:00 to 12:30. Schlee and Moench (1963) mapped 58 pipes in less than 0.5 mi^2 locally. **0.3**

43.0 Note sandstone pipes from 10:00 to 2:00; major "collapse feature" at 11:30 (Fig. 1-43.0) is more of a spring vent than a well-defined pipe. **0.4**

43.4 Roadcut at left ahead on I-40 through Wanakah Fm. Contact about $^2/_3$ way up the cut is between thin bedded Beclabito below and more massive overlying Horse Mesa Mbr. Note "drag" along margins of the sandstone pipes. **0.2**

43.6 Basalt flow in the Rio San Jose visible ahead and to right. **0.1**

43.7 Diabasic sill in roadcut domes up highly fractured Wanakah siltstones and sandstones (Fig. 1-43.7). Note contact of Beclabito and Horse Mesa mbrs of Wanakah Fm on hill slope to left, and sandstone pipes crossing the contact. **0.5**

44.2 Color-banded Wanakah Fm forms cliffs along left side of road. **0.6**

44.8 **STOP 2.** Leave buses and cross road (watch for traffic!) and gather near cliffs to south. Here we will examine several well-developed sandstone pipes (Fig. 1-44.8a) in the Horse Mesa Mbr of Wanakah Fm.

The pipes are generally more resistant to weathering than the surrounding rock, and stand out on cliff faces or form isolated pillars on slopes or on valley floors. The collapse structures have numerous small faults that displace the bedding downward, and generally weather to form re-entrants or tributary canyons along the cliffs. The pipes cut across bedding with a sharp contact and generally leave no vestige of the original bedding. Most of them are homogenous, but a few show sheaths of differentiation in size or cementation that appear in outcrop as vertical "layering" or as concentric rings of


FIGURE 1-42.7. View to north from near mile 42.7 of Todilto gypsum facies at base of mesa overlain by Beclabito (talus-covered) and Horse Mesa mbrs of Wanakah Fm.


FIGURE 1-43.0. Pipes and a large collapse feature (spring vent) in Beclabito Mbr of Wanakah Fm on south side of I-40 near Mesita.

FIGURE 1-43.7. Diabase sill with overlying highly fractured Wanakah Fm, north side of I-40 frontage road.


FIGURE 1-44.8a. Sandstone pipe in Beclabito Mbr at Stop 2. Note three local hunters for scale. Photo by R. M. Chamberlin.

differential weathering. Some of the rings have concentrations of organic material or of pyrite weathered to goethite. The following quotation from Moench and Schlee (1967, p. 44) gives a possible explanation of these features:

> We suggest that the pipes formed (in Jurassic time) by foundering of sand into spring vents during compaction and dewatering of the sediment. At some stage in the accumulation of sand on top of water-saturated mud, the area was deformed. This deformation produced north- and east-trending synclines. The structurally low areas received more sediments than the higher areas; and the resulting greater weight of sediment in the synclines, coupled with spring activity aligned along the folds, permitted foundering of sand into spring vents. As the process continued, the sand moved downward and mixed with materials derived from the sides of the vents. The total amount of room required to accommodate the sand was probably considerably less than the volume of the pipe, because the pipes are composed of materials derived from the sides as well as from the top. Room for the sand was probably created by compaction and dewatering of the finer sediment. Where spring activity extended in depth to the Todilto, solution of gypsum unquestionably enhanced formation of the pipes.

The 380,000 year old Laguna basalt flows lie immediately north (right) of road. These flows followed the course of the ancestral Rio San Jose.

GEOMORPHIC DEVELOPMENT OF THE RIO SAN JOSE VALLEY

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Episodic entrenchment of streams is common worldwide and is attributed in the long term ($>10^5$ yr) to various tectonic, climatic and geomorphic-sedimentologic-response factors. In northern and central New Mexico, streams have entrenched their present valleys during Plio-Pleistocene time and have left numerous levels of deposits as terraces along their valley margins. While many New Mexican streams have deepened their valleys episodically and presently are flowing at levels near their bedrock valley floors, some streams such as the Rio San Jose cut their valleys to their maximum much earlier and are presently flowing on thick alluvium that partially fills the former valleys. If the Rio San Jose were the only stream to show such behavior, it could be explained by the disruptive effects of lava flows which form barriers to short-term (10^4 to 10^5 yr) erosion. But adjacent drainages without lava flows exhibit similar deep valleys with thick alluvial fills. Therefore, dating the development of the Rio San Jose valley may suggest when and why adjacent drainages cut and extensively backfilled their valleys.

The Rio San Jose drains 3745 mi^2 eastward from the Continental Divide in the Zuni Mountains to the Rio Puerco and Rio Grande (Wright, 1946; Love, 1986). Modern base level for the Rio San Jose is the Rio Puerco at an elevation of 5060 ft. According to U.S. Geological Survey records, present average discharge at the stream gage near Correo is 11.8 ft^3/s, and flow occurs only 41% of the year (148 days). The largest measured flood was 11,000 ft^3/s on 21 August 1935. Large areas of the drainage (roughly one-third) are underlain by basalt flows, which yield minimal surface runoff. Springs near the termini of some of the basalt flows contribute to the flow of the Rio San Jose. Evidence for the development of the Rio San Jose is preserved beneath numerous basalt flows in the drainage basin, in discontinuous stream terraces along the valley margins and in tributaries, in thick valley-fill alluvium and in the fill of the Albuquerque basin.

The Rio San Jose drainage basin probably developed in late Oligocene time in response to initial subsidence of the Albuquerque basin along the Rio Grande rift to the east. Basin subsidence has continued, while episodic uplift of the Colorado Plateau may have punctuated erosion upstream. Former southern and eastern tributaries have been cut off from the drainage by tectonism along the plateau margin and by stream capture. Although the initial drainage may have developed eastward on top of a volcaniclastic alluvial apron from Datil volcanics to the south, the present valley is cut through nearly flat-lying Mesozoic strata. The stream crosses most older structures at nearly right angles and only locally follows structurally weak zones. Major valley segments commonly follow strike of easily erodable units.

North of the Rio San Jose Valley between Grants and Laguna, an irregular surface that slopes southward with a gradient of 80 ft/mi is preserved 920–1215 ft above the present valley (Fig. 1-44.8b) by Pliocene basalts of the Mount Taylor field (3.3–2.6 my; Moench and

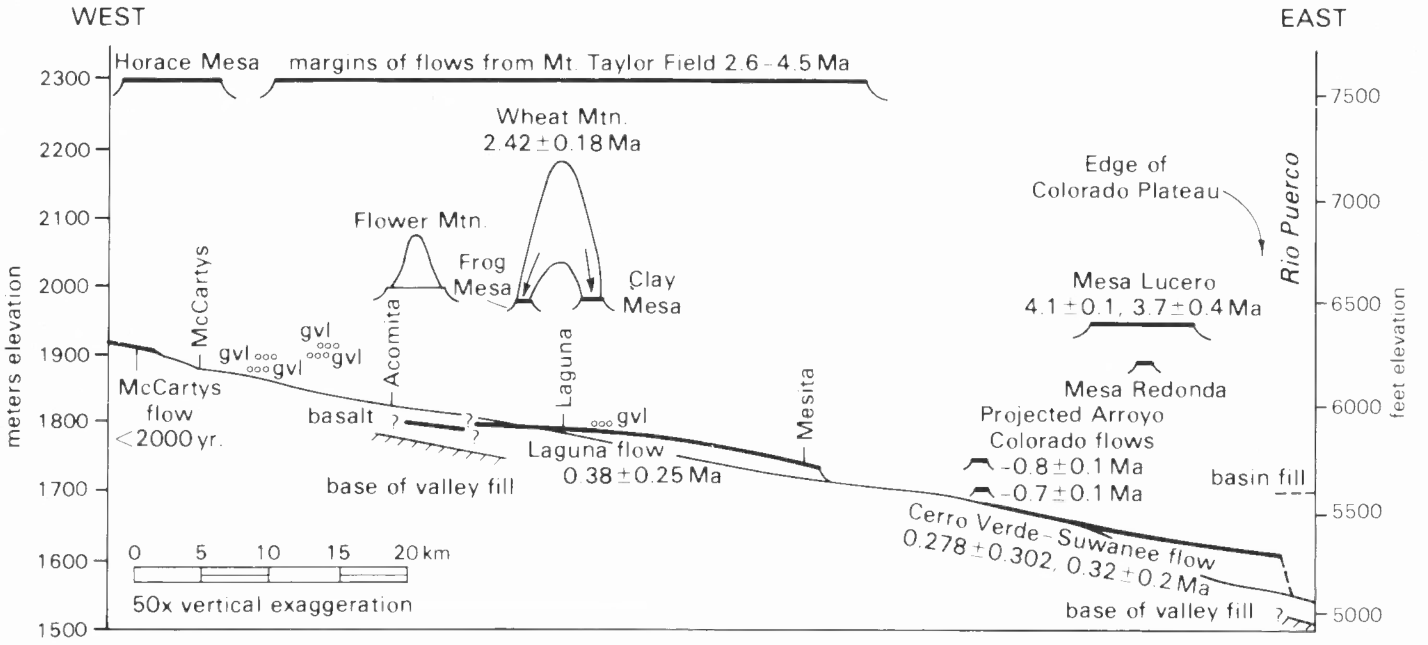


FIGURE 1-44.8b. Longitudinal profile of the Rio San Jose from the distal end of McCartys flow to the confluence with the Rio Puerco. Elevations of geomorphic surfaces, terrace deposits and basalt flows are projected onto the profile from the valley margins as mesa symbols. Wheat Mountain and its two flow lobes projecting toward the valley form the arrow-shape above Laguna, and the profile of Flower Mountain is projected above Acomita. Small circles with gvl indicate levels of gravel-terrace remnants. Dashed horizontal line on eastern edge is maximum fill of the Albuquerque basin adjacent to the present mouth of the Rio San Jose.

Schlee, 1967; Bachman and Mehnert, 1978; Lipman and Mehnert, 1980; Grimm, 1985). South of the Rio San Jose valley, basaltic lavas, erupted between 3 and 4 my ago near the margin of the Colorado Plateau (Bachman and Mehnert, 1978; Baldridge et al., 1987), are presently 1050 ft above the Rio San Jose at an elevation of 6230 ft, while correlative sediments near the mouth of the Rio San Jose and along the Rio Puerco in the Albuquerque structural basin 6 mi to the east are thought to be buried at elevations less than 4900 ft (Love, 1986). These relative differences in elevation suggest Pliocene and Early Pleistocene tectonic displacements between the Colorado Plateau and the Rio Grande rift. However, the western part of the Albuquerque basin may have continued to aggrade until less than 1 my (Love, 1986), so base level of the Rio San Jose may have risen to about 5600 ft until after incision of the Rio Puerco began. This base level would have affected incision/aggradation of the lower Rio San Jose to the vicinity of Mesita (Fig. 1-44.8b).

The Rio San Jose had entrenched 160–470 ft below the basalt-capped upper surface when the Wheat Mountain volcanic center erupted near Laguna 2.42 ± 0.18 my ago (Lipman and Mehnert, 1980). The level of the base of the flows is currently 440 ft above the present stream (Grimm, 1985).

Scattered gravel from the ancestral Rio San Jose occurs in bedrock-defended positions 220–245 ft above the present valley floor (Fig. 1-44.8b; Maxwell, 1977), whereas the highest remnant geomorphic surfaces in tributaries range from 130 to 250 ft above the current drainages (Grimm, 1985). For example, basalt flows in Arroyo Colorado, tributary to the Rio San Jose, mark erosional levels 230 ft above the valley at 0.8 ± 0.1 my and 150 ft above the valley 0.7 ± 0.1 my ago (Baldridge et al., 1987; cf. Wright, 1946). Lower gravelly terraces occur as remnants along the Rio San Jose and its tributaries at 100 ft, 60–80 ft and 20 ft above present valley floors (Maxwell, 1977; Grimm, 1985).

At present, the Rio San Jose crosses at least five basalt flows that form temporary base levels. The stream has been unable to entrench through the most recent flow (<2000-yr-old McCartys basalt; Nichols, 1946; Maxwell, 1982b, 1986) but has cut canyons through older flows. At the margin of the Colorado Plateau, the Rio San Jose cut a canyon 8 mi long and more than 130 ft deep below the 320,000 ± 200,000-yr-old Suwanee basalt flow (Wright, 1946; Bachman and Mehnert, 1978; Baldridge et al., 1987; flow also dated 278,000 ± 302,000 yr by Leavy and Shafiqullah, 1987). The Suwanee flow crosses the Rio Puerco fault zone and is not offset by it, so there has been no tectonic displacement along the boundary of the Colorado Plateau after the flow was emplaced. However, the Rio Puerco and the Rio Grande have determined a lower base level for the lower Rio San Jose, incising more than 230 ft since the flow, and subsequently aggrading as much as 140 ft. The Rio San Jose cut a smaller canyon 9 mi long and 40–65 ft deep along the 380,000 ± 250,000-yr-old Laguna basalt flow (Lipman and Mehnert, 1980), upstream from the Suwanee flow (Fig. 1-44.8b).

Wells drilled in the San Jose valley upstream from Laguna indicate that the valley was formerly entrenched in a canyon as much as 160 ft below the present surface (Fig. 1-44.8b; Risser and Lyford, 1983). The canyon has been filled with gravelly and finer alluvium and at least two basalt flows (Risser and Lyford, 1983). The upper basalt flow (at a depth of 20 ft) may be the Laguna flow which is exposed along the canyon near Laguna 4 mi downstream. This flow does not extend farther upstream and is not correlated with El Calderon flows west of McCartys flow near Grants (Maxwell, 1986) as was suggested by Nichols (1946). A controversial date of 1.57 ± 0.26 my (Laughlin et al., 1979) and a much younger unpublished date (W. Laughlin, personal commun., 1987) on the El Calderon flow near Grants also indicate that the two flows are separate. The lower basalt flow near Laguna (at a depth of 60 ft) probably has no surface exposures.

The valley of a former major tributary of the Rio San Jose between the east end of the Zuni Mountains and Cebollita Mesa has been inundated by basalt flows of the El Malpais and North Plains numerous times, so that there is no integrated surface runoff and no name for the stream valley. One rancher at the upper end of the valley reported drilling 900 ft through basalt flows before reaching gravel overlying bedrock along the valley floor (C. Maxwell, personal commun., 1988). Kelly and Reynolds (this guidebook) show 600 ft of fill at the lower end of the same valley. Flows exposed in this valley have dates ranging from 3.8 ± 0.40 my to <2000 yr (Laughlin et al., 1982). The older dates appear to be questionable because the valley cannot have eroded before the basalt of Horace Mesa were emplaced 2.5–2.9 my ago (Lipman and Mehnert, 1980), and the possibly correlative basalts that flowed northward and later formed resistant caps of Cebollita Mesa and Mesa Negra (Maxwell, 1986). Two younger flows apparently date about 1.5 my (Laughlin et al., 1982) and may indicate that the valley reached maximum entrenchment prior to that time. Maxwell (1986) and Kelly and Reynolds (this guidebook) show a young fault along the southeastern margin of the valley. Even if the valley floor has subsided due to tectonic movement, it is unlikely that the 3.8 my basalts could have been displaced thousands of ft relative to old basalts on Cebollita Mesa to form the valley.

Valley margins along the Laguna, Suwanee and El Calderon flows have not been eroded back appreciably since the flows. Numerous landslides, talus cones and colluvial-alluvial aprons apparently grade to the present valley. The lack of extensive backwearing suggests that masswastage processes also take place episodically and, on the average, rather slowly over long periods of time.

In summary, the Rio San Jose had undergone erosion of Mesozoic strata prior to the eruption of the Mount Taylor–Mesa Chivato volcanic field 2.6 to 3.4 my ago. The valley of the Rio San Jose had cut 160–440 ft below the level of the early basalts by 2.4 my. The maximum incision of the valley had taken place perhaps as early as 1.5 my ago, and most certainly prior to 380,000 years ago. The valley has backfilled upstream from local basalt flows since then and has entrenched the distal ends of the flows. The presence of the buried canyon and buried basalt flows indicates that even the lowest exposed gravel terraces must be much older than the 380,000-yr-old Laguna basalt. These relationships between maximum valley incision, alluvial fill and likely ages of exposed gravel terraces suggest caution in interpreting the Quaternary histories of adjacent drainages that have similar terrace remnants and valley fills.

Present discharge is inadequate to flush stored sediment out of the valley. Episodes of prolonged higher discharge are necessary to flush sediment and erode the major valleys. Such episodes must have occurred between 2.6 and 2.4 my, between 2.4 and possibly 1.5 my and possibly prior to 380,000 years ago. Large-scale incision prior to 1.5 my is evident along the Rio Grande adjacent to White Rock Canyon (Smith et al., 1970; Aubele, 1978), Los Lunas Volcano (Kelley and Kudo, 1978) and at San Antonio (Cather, 1988). More recent episodic incision and aggradation by the Rio Puerco–Rio Grande has not affected more than the lowest 6-mi reach of the Rio San Jose. Also, valleys have not widened appreciably since the El Calderon, Laguna and Suwanee flows were emplaced. Thus, even though the Rio San Jose has more radiometric dates documenting its behavior during the past 3–4 my than any New Mexican drainage except the Rio Grande, the data remain inadequate to reconstruct a detailed erosion/sedimentation and paleodischarge record; the drainage appears to be largely insensitive to less than long-term discharge/climate fluctuations.

After the stop, **continue west** on frontage road. Note the isolated sandstone pipe at 12:00. **0.3**

45.1 Highway now climbs through upper part of Wanakah Fm (Horse Member Mbr). Note pipe just below road level on right. **0.3**

45.4 Diabasic dike at 11:00 to 11:30 cuts through the hill and is exposed in roadcut along I-40. Recent sand dunes visible at 10:30. **1.0**

46.4 Enter greater **Laguna.** At 11:00–2:30, light colored massive eolian sandstone is Zuni Ss of Maxwell (1976a), Recapture Mbr of Condon (this guidebook). At 11:00 note Old Laguna Pueblo. **0.2**

46.6 **Stop sign; turn right** and **proceed west** on old U.S. 66. **0.3**

46.9 Cross Rio San Jose, note basalt under bridge abutment; enter Laguna Pueblo. **Laguna** (Spanish "lake") is a pueblo of Keresan people who were given a land grant by the King of Spain in 1689. The original lake from which the pueblo takes its name is now a dry meadow. **0.2**

47.1 Sandstone in roadcut on right is Zuni Ss of Maxwell (1976a), eolian facies of Recapture Mbr of Condon (this guidebook). **0.7**

47.8 Gravel cap is Pleistocene lag; note gravel deposits in railroad cut to right. Cross bridge over Santa Fe Railroad tracks; bluffs at 1:00–2:00 are basalt flows capping Clay Mesa and overlying (from top down) the Cubero Tongue and Oak Canyon mbrs of Dakota Ss and basal nonmarine Encinal Canyon Ss Mbr of the Dakota. The Brushy Basin Mbr of Morrison forms the lower slopes, here mostly covered by colluvium and landslide blocks. **0.2**

48.0 Highway at right goes to Jackpile uranium mine, and the villages of Paguate, Bibo and Seboyeta. **0.3**

48.3 Zuni Ss (of Maxwell, 1976a) in roaduct on right just ahead, overlain by landslide debris composed mostly of Brushy Basin Mbr of Morrison Fm. **0.3**

48.6 Road at left goes to New Laguna; continue straight ahead. Large canyon to right divides Frog Mesa (W) from Clay Mesa (E). **0.2**

48.8 Frog Mesa at 1:00–3:00; from top down: basalt flows from Wheat Mountain cone overlying Clay Mesa Tongue of Mancos Sh, light colored Cubero Tongue of Dakota Ss, paludal shale of Oak Canyon Mbr of Dakota and dark gray sandstone ledge of Encinal Canyon Mbr of Dakota. Landslide-debris covers the mudstone-dominated Brushy Basin Mbr of the Morrison Fm. The surface below the basalt flows on Clay and Frog mesas, the Wheat Mountain surface of Moench and Schlee (1967), represents an early stage of valley entrenchment about 200 ft below the highest basalt capped erosion surfaces on the flanks of Mount Taylor. The youngest flow on Frog Mesa has a K-Ar age of 2.42 my (Lipman and Mehnert, 1980). **0.7**

49.5 Casa Blanca Mesa at 10:00 is capped by the Cubero Tongue and Oak Canyon Mbr of the Dakota Ss. Slopes are mantled with extensive colluvial and landslide deposits that veneer Morrison Fm and Zuni Ss. A portion of New Laguna on left. **0.4**

49.9 Milepost 22; New Laguna Post Office on right. **0.7**

50.6 Encinal Canyon to right, type area for Encinal Canyon Ss Mbr of the Dakota (Aubrey, 1986); East Paraje Mesa to the west. At 2:00, note white sandstone of Jackpile Mbr of Morrison under dark gray Encinal Canyon Ss Mbr. **0.2**

50.8 Lower slopes of mesas in this area are developed on greenish-gray claystone and siltstones of Brushy Basin Mbr of Morrison but are generally talus covered. **0.3**

51.1 Laguna-Acoma High School on right. A well near here penetrated 160 ft of alluvium (Risser and Lyford, 1983). **0.8**

51.9 Toreva block of Brushy Basin Mbr on right. On mesa above note dark band of Encinal Canyon Mbr forming basal Dakota Ss, and overlying the much lighter colored Jackpile Mbr of the Morrison (Fig. 1-51.9). **0.8**

52.7 Enter **Paraje** (Spanish "place or residence"); it is a Laguna Indian village based on the irrigation of crops in the valley of San Jose Creek. **Turn left** at intersection, and **proceed south** on paved road. **0.3**

53.0 **Bridge** across Rio San Jose; road jogs sharply to left. **0.2**

53.2 Metropolis of **Casa Blanca** (Spanish "white house"). **0.2**

53.4 **Stop, look and listen!** Cross mainline Santa Fe Railroad tracks. Road is on alluvial valley floor of Rio San Jose. **0.8**

54.2 Cross I-40 on overpass, continue straight ahead. **0.1**

54.3 "New" Casa Blanca. Behind village on right, mesa is capped by Cubero Tongue of Dakota; below is Oak Canyon Mbr, Encinal Canyon Mbr(?) and slopes of Brushy Basin Mbr of Morrison (Fig. 1-54.3). The upper part of the Oak Canyon Mbr in this area is marine, and the lower half is paludal or paralic; the two facies are separated by a transgressive disconformity marked by a zone of siderite and calcite oolites (Maxwell, 1976a). The lower part consists of interbedded sandstone lenses and dark-gray siltstone and claystone with abundant carbonaceous debris, and very thin lenticular coal beds (1–4″); the upper part is fossiliferous, very fine-grained sandstone and shaley siltstone. Note extensive landslides

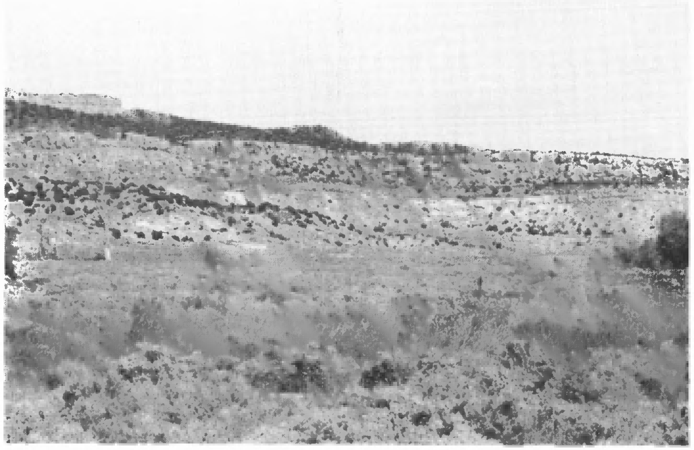


FIGURE 1-51.9. Encinal Canyon Mbr of Dakota on light-colored Jackpile Ss Mbr of Morrison north of road between mile 51.9 and 52.7.

FIGURE 1-54.3. "New" Casa Blanca; mesa is capped by Cubero Tongue of Dakota Ss.

which conceal the Brushy Basin Mbr on the right side of road for next 2 mi. **0.8**

55.1 Laguna Rainbow Corporation on left. **0.5**

55.6 Near base of mesa at 9:00, the lowest exposures are yellow, crossbedded Zuni Ss (of Maxwell, 1976a), Recapture Mbr (of Condon, this guidebook) overlain by light-greenish gray Westwater Canyon Mbr, in turn overlain by slope-forming, talus-covered Brushy Basin Mbr, and capped by Oak Canyon Mbr and Cubero Tongue of Dakota Ss. Also note good exposures of yellow Zuni (or Recapture) at 2:00. **0.6**

56.2 Entering a broad, gentle, structural dome; doming apparently affects only pre-Cretaceous rocks. Good outcrops of Wanakah Fm from 11:30 to 2:00. **1.0**

57.2 Remnant of butte at 2:30 (ribs and spines) is Wanakah Fm cut by a NW-trending dike that has weathered out to form a notch (Fig. 1-57.2); notch can be seen just ahead. Lower talus slopes on mesa to the west is Beclabito Mbr of Wanakah Fm; cliff above is Horse Mesa Mbr, and overlying moderate slope-former is the friable, eolian Zuni (or Recapture Mbr of Condon, this guidebook). The greenish, talus-covered slope is Brushy Basin, capped by Dakota Sandstone. Note the thinning of the Brushy Basin Mbr of the Morrison under the Dakota (Fig. 1.57.2). This thinning might be related to the pre-Cretaceous doming in the area, mentioned at mile 56.2. Note also that the Horse Mesa Mbr is light tan instead of reddish as it is near Mesita. The change is consistent from here to the south and west, where the Horse Mesa and the Zuni become indistinguishable and are mapped as a single unit.

In the area from north of Laguna to here, and on to the west, the base of the Brushy Basin Mbr of the Morrison Fm is marked by lenticular conglomerate beds, crossbedded, with irregular tops and bottoms, and variable in thickness, locally interfingering with the green siltstone and claystone. The conglomerate beds are poorly sorted, composed of granules to large pebbles of angular to rounded rock fragments of chert, limestone, quartzite, gneiss, schist, sandstone, shale chips and clay balls. The conglomerate rests unconformably on a fossil soil zone at the top of the Zuni Ss (Recapture Mbr of Condon, this guidebook). Locally, the conglomerate rests directly on or channels down into unweathered Zuni (Maxwell, 1976a). The gneiss, schist and quartzite pebbles appear to be Precambrian; sufficient evidence exists to suggest a major regional unconformity. **0.7**

57.9 At 10:30 is Castle Rock; note the small natural window (la ventana). At 4:00, note north-trending dike weathered out to form notch in the isolated rib of the Wanakah Fm (Fig. 1-57.9). **0.7**

58.6 Bleached Entrada Sandstone capped by Todilto Limestone in low benches on left side of road. The Gypsum Mbr of the Todilto pinches out a few mi to the east and is not present in this area. The Todilto Ls is thinning progressively southward and pinches out 9 mi SSW of this point (Maxwell, 1979). **0.2**

58.8 At 3:00, note southward thickening of Brushy Basin Mbr on mesa slope (Fig. 1-58.8). Entrada and Todilto present on left side of road. **0.1**

58.9 Curve, Enchanted Mesa at 12:00. **0.2**

59.1 Last outcrops of Todilto Ls on left. **0.2**

59.3 Castle Rock at 9:30 exposes both the Beclabito and Horse Mesa mbrs of the Wanakah Fm; note that only a few thin beds of the red mudstone are left in the formation. The red beds pinch out a few mi to the south, and from that point on the Wanakah Fm and Zuni Ss (of Maxwell, 1976a) are the same tan-white color. **0.3**

59.6 Dirt road to left. Castle Rock at 9:00 (Fig. 1-59.6). Jar Butte at 10:30; Wanakah Fm at base with numerous sandstone pipes, overlain by rounded Zuni Ss (Recapture

FIGURE 1-57.9. View of notch in Wanakah Fm formed by weathered-out dike. Photo by O. J. Anderson.

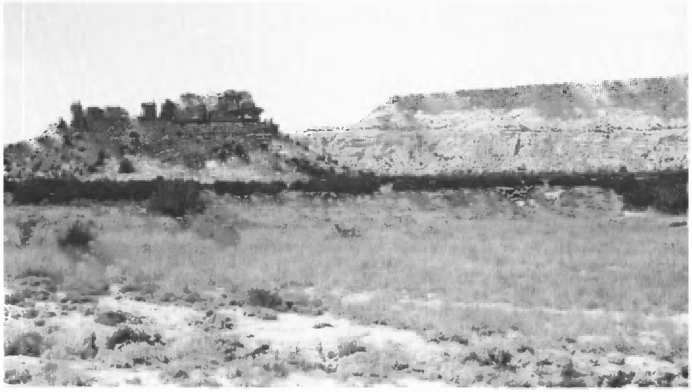


FIGURE 1-57.2. Remnant of butte in foreground contains north-trending dike. Mesa in background is capped by Dakota, which overlies a southward-thinning Brushy Basin Mbr of the Morrison, which rests on a white, friable eolian sandstone (the Zuni of Maxwell; the Recapture Mbr of Condon). Cliff-former at base is Wanakah Fm.

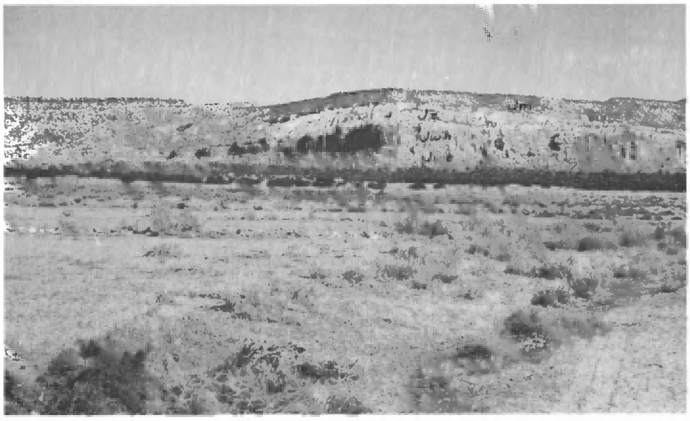


FIGURE 1-58.8. Brushy Basin Mbr of Morrison (Jm) thickening to south at expanse of underlying Zuni (Jz). The Jz is equivalent to Condon's (this guidebook) Recapture Mbr. Jwb = Beclabito Mbr, Jwh = Horse Mesa Mbr of Wanakah Fm. Photo by C. H. Maxwell.

Mbr of Condon, this guidebook) with generally northeast-dipping crossbeds and a thin Brushy Basin Mbr capped by Dakota Ss. The Brushy Basin is truncated by pre-Dakota erosion on the mesa behind Jar Butte. We are now on the Acoma Pueblo Quadrangle, mapped by Maxwell (1976a). **0.6**

60.2 Rabbit Butte (a miniature enchanted mesa) in valley at 3:00, exposing Wanakah Fm. **0.6**

60.8 Enchanted Mesa at 12:00; lowermost part is Wanakah, largely covered by talus. Lower part of the vertical cliffs is Wanakah Fm; most of cliff is Zuni Ss; the darker cap is basal Dakota Ss. **1.9**

62.7 Boundary of Acoma Reservation. Enchanted Mesa at 11:00 (Fig. 1-62.7a). Darton (1915) ventured far enough off the railroad to photograph the mesa. **0.6**

63.3 Dirt road to left goes 1/2 mile to Enchanted Mesa picnic grounds. **0.4**

63.7 Acoma Pueblo, Sky City, at 11:00; mesa behind Enchanted Mesa, from 8:00 to 10:00, is South Plaza. **1.7**

65.4 Sky City at 10:00, on mesa of Zuni Ss (Maxwell, 1976a) capped by thin Encinal(?) Canyon Mbr of Dakota Ss (Fig. 1-65.4). **0.5**

65.9 **STOP 3. Turn right** into museum parking lot (Fig. 1-65.9a). Stay within museum-visitor center area until we begin the hike to Sky City. Shuttle vans will be available for those who prefer to ride to the top of Sky City. The following was excerpted from Hawley et al. (1982).

Old Acoma–Sky City is situated on top of a 200-ft-high mesa of Zuni Ss (Maxwell, 1976a) capped by a thin Dakota Ss. The settlement was mentioned as early as 1539 by Fray Marcos de Niza. Hernando de Alvarado, of Coronado's army, visited the site in 1540. Acoma vies with the Hopi village of Oraibi for the title of oldest continually occupied city in the United States. The people of Acoma are members of the western group of Keresan linguistic stock, and the language is still widely spoken. Acoma is from the Keresan "ako" meaing "white rock" and "ma," "people." Espejo first used the present spelling in 1583. The mission (Fig. 1-65.9b), dedicated to Saint Stephen, was established in 1629 and is the largest of early New Mexico churches. The capture of Acoma, in a siege lasting from 21–23 January 1599, is reported by Gaspar Perez de Villagra in his *History of New Mexico* (1610). The original Spanish land grant to the pueblo was made in 1689. The Reservation area is about 245,700 acres.

After tour, **leave parking area via west exist, turn right** and **proceed north** on Arrowhead 38. **0.3**

FIGURE 1-59.6. Castle Rock; window is developed in Zuni Ss of Maxwell, Recapture Mbr of Condon. Photo by R. M. Chamberlin.

FIGURE 1-62.7a. Enchanted Mesa on Acoma Indian Reservation.

FIGURE 1-65.4. Sky City at Pueblo de Acoma. Cliffs are of Zuni Ss (Maxwell, 1976) with a thin capping of Dakota Ss. Acoma was mentioned as early as 1539 by Spanish explorers.

FIGURE 1-65.9a. Museum parking lot at Acoma Pueblo.

FIGURE 1-65.9b. Old mission church on mesa top at Sky City was established in 1629. Photo by R. M. Chamberlin.

66.2 Pillars of Zuni Ss next 1 mi. **1.3**

67.5 Dark red-brown bed just above valley floor at 11:30 is fossil–soil zone developed at top of light greenish-gray Zuni Ss, a horizon that is also marked by a basal conglomerate of the Morrison Fm. Dark gray to black paludal shale and thin sandstone of Oak Canyon Mbr of Dakota Ss exposed in roadcut (Fig. 1-67.5) overlie Brushy Basin Mbr of Morrison Fm. The Morrison is truncated by pre-Dakota erosion in re-entrant at 10:30; however, talus masks the details. **1.2**

68.7 Road curves to right; note landslide debris on both sides as road ascends mesa. **0.1**

68.8 Curve with guard rails; visible to right is the fossil–soil zone developed on the Zuni Ss, the thin lenses of purple sandy shale above the soil zone and the light-colored bold outcrops of the basal conglomerate in the Brushy Basin; most of the Brushy Basin Mbr above the conglomerate is covered by landslides. **0.3**

69.1 Note black carbonaceous shale and fluvial sandstone of Oak Canyon Mbr of Dakota overlying Brushy Basin Mbr of Morrison on right. The thick conglomeratic sandstone that caps Enchanted Mesa and Sky City is not present here and to the north. The sandstone at the top of the roadcut is a local lens within the Oak Canyon Mbr. **0.2**

69.3 **STOP 4.** Deadman's Rock. **Pull off to left** in parking area; watch out for traffic on this dangerous curve!

This stop offers a spectacular view of the Acoma Pueblo area (Fig. 1-69.3a). To the east is Acoma valley, traversed earlier today, and most of the features seen along the route earlier are visible from here. The high mesa behind Enchanted Mesa and Sky City is South Plaza, with the red-brown upper member of the Entrada Ss at the base of the mesa, bleached at the top, just under the thin dark line of Todilto Ls; above the Todilto is a talus-covered slope of the lower Wanakah, cliffs of upper Wanakah (Horse Mesa), then the lighter colored Zuni (Maxwell, 1976a), with the sequence capped by the Dakota Ss. Beyond Sky City, which is S23°E, and extending to the right, is East Mesa and Paradise Canyon, exposing the same stratigraphic units as on South Plaza. The Todilto Ls pinches out southward in East Mesa, about in line with Sky City. The higher bench to the right is capped by the Twowells Tongue of Dakota; the small mesa beyond is Blue Mesa (S5°W), capped by Gallup Ss (Moore, 1989). The distant mesa on the skyline is the basalt-capped Cebolleta Mesa. The low mesa to the west is Crow Point, capped by Twowells Tongue of Dakota.

Directly north of the parking area is Deadman's Rock, which is capped by the Cubero Tongue of the Dakota Ss (Fig. 1-69.3b). The Cubero is about 20 ft thick and composed of grayish orange, upper fine-grained sandstone; burrows and minor bioturbated zones are common. The underlying sequence down to nearly road level is the upper, marine portion of the Oak Canyon Mbr (Fig. 1-69.3c). The break between the marine and un-

FIGURE 1-67.5. View to north of Stop 4 area (upper left of photo) from a point just north of mile 67.5. The Cubero Tongue of the Dakota Ss caps the mesa and Deadman's Rock at upper left. It overlies a slightly-carbonaceous Oak Canyon Mbr of Dakota well exposed in roadcut at center of photo. Extensive landslide debris and colluvium covers the underlying Morrison Fm.

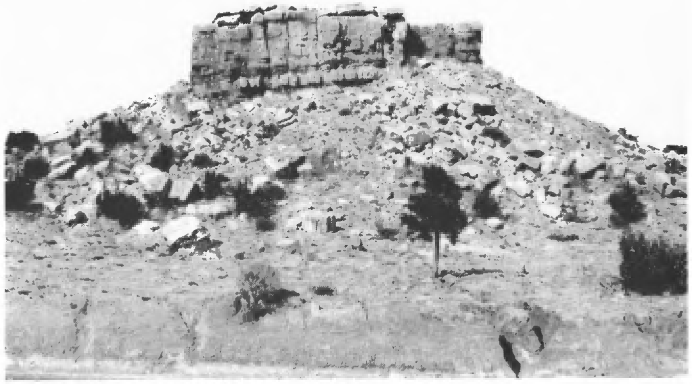


FIGURE 1-69.3b. Deadman's Rock, capped by Cubero Tongue of Dakota Ss.

FIGURE 1-69.3a. View to the south-southeast from Stop 4 into Acoma valley. Sky City is compact mesa below skyline just to right of center of photo. Photo by O. J. Anderson.

FIGURE 1-69.3c. View eastward from parking area of Stop 4. Sandstone at top of roadcut on left is near middle of Oak Canyon Mbr (Kdo); just above this sandstone is the transgressive unconformity that marks the marine-nonmarine break in the Oak Canyon Mbr. Jm = Morrison Fm; Kdc = Cubero Tongue.

derlying nonmarine parts is approximately 15 ft above the sandstone at the top of the roadcut and is commonly marked by siderite(?) and calcite oolites; Maxwell (1976a) called it a transgressive unconformity. Above the unconformity are numerous brown weathering ferruginous ss concretions or lenticular beds containing abundant fossils diagnostic of the Thatcher fauna (named from the Thatcher Ls Mbr of the Graneros Sh in NE New Mexico). These fossils include *Exogyra columbella* Meek, *Pinna petrina* White, *Camptonectes* sp., *Turritella* sp. and *Plicatula arenaria* (Landis et al., 1973; Maxwell, 1976a) (Fig. 1-69.3d). Cobban (1977) described a specimen of *Conlinoceros tarrantense* collected from the upper part of the Oak Canyon at this locality (Fig. 1-69.3e). *C. tarrantense* is of middle Cenomanian age. The marine fauna we see here records the initial transgression of the Western Interior seaway into this area.

At the base of the Oak Canyon Mbr, below a thick (50 ft) slightly carbonaceous paludal/floodplain section, is a 4.5-ft-thick fluvial channel ss (Fig. 1-69.3f). With the presence of the basal sandstone, thin as it is, we have the typical tripartite nature of the Dakota displayed before us. This informal nomenclature system recognizes the widespread existence of: (1) a basal fluvial sandstone or "braided alluvial" unit; (2) a medial shale—commonly carbonaceous with interbedded sandstone and siltstone; and (3) an upper marine–sandstone interval. These lithostratigraphic units have been given formal names (Kues and Lucas, 1987; Lucas and Kisucky, 1988) as part of the Dakota Group in northeastern New Mexico. In ascending order they are Mesa Rica Ss, Pajarito Sh and Romeroville Ss. The age of the Romeroville is not known with certainty but is apparently earliest Cenomanian, possibly latest Albian. The Romeroville Sandstone marks the onset of the transgressive phase of the Greenhorn cycle. Inasmuch as the sea transgressed from east to west, in a general way, it would be expected that the basal marine sand associated with the Greenhorn cycle would be time transgressive and become younger

FIGURE 1-69.3d. Slab of fossiliferous brown-weathering ss from base of marine portion of Oak Canyon Mbr. This assemblage is diagnostic of the Thatcher fauna and includes *Turritella* cf. *T. schuleri*, *Plicatula arenaria*, *Exogyra columbella* and *Pinna petrina*.

FIGURE 1-69.3e. Middle Cenomanian ammonite *Conlinoceros tarrantense* (from Cobban, 1977).

FIGURE 1-69.3f. Close up of base of Oak Canyon Mbr (Kdo) at Stop 4. Note the thin (4.5 ft) sandstone bed at base of carbonaceous section just above the Morrison Fm (Jm). Cubero Tongue (Kdc) caps the mesa.

to the west. The middle Cenomanian age of the upper Oak Canyon and Cubero tongues at this locality compared with an earliest Cenomanian age for the Romeroville in NE New Mexico demonstrates the time transgressive nature of basal Greenhorn cycle sediments. The three Dakota units we see here are homotaxial equivalents of the three units formalized as the Dakota Group by Lucas and Kisucky (1988) in NE New Mexico. (See also discussion of Dakota at Stop 5.)

After the stop **continue north** on Arrowhead-38. **0.2**

69.5 **Cattleguard. 0.1**

69.6 Roadcut through thick-bedded Cubero Tongue. **0.3**

69.9 At top of Woods Mesa. Horace Mesa at 12:00, Canipa Mesa at 12:30; Mt. Taylor at 1:00; cliffs of Twowells Tongue on left are underlain by Whitewater Arroyo Tongue of Mancos Sh. **0.9**

70.8 Surface on Twowells Tongue at 10:00 on skyline is stepped down to the east (toward the viewer) by the Crow Point Fault, a northern extension of the Red Lake Fault, a fault zone more than 50 mi long. Highway continues on Woods Mesa formed on Cubero Tongue. **1.2**

72.0 Road intersection, continue straight ahead. Road to left, up into notch, follows the Crow Point fault line and leads to Cebollita Mesa; road to right goes to Acomita and Tribal headquarters. **0.2**

72.2 Canipa Mesa at 12:00, capped by Twowells Tongue (Fig. 1-72.2). **0.8**

73.0 Twowells Tongue capping Canipa Mesa on right. Slopes below mesa top expose Whitewater Arroyo Tongue of Mancos Sh. **0.3**

73.3 Across canyon at 10:00–11:00 at base of slope is the intertongued Dakota-Mancos sequence capped by the Twowells Tongue. The high basalt-capped mesa beyond is Mesa Negra (Putney Mesa); below the basalt is the Crevasse Canyon Fm, Gallup Ss, Mancos Sh and at the base of the mesa, some very seaward facies of the Tres Hermanos Fm. **0.6**

73.9 Road is on bench developed in basal Whitewater Arroyo Tongue of Mancos Sh, exposed in roadcuts. At 12:30, southern pinchout of Paguate Tongue of Dakota near base of mesa. Note how quickly it thickens as we go north. Cubero Tongue immediately below road at 10:00 to 11:00. **0.2**

74.1 Good exposures of gradational base of Twowells at 2:00 to 3:00 (Fig. 1-74.1). The darker-colored, coarser-grained unit at the top of the Twowells has been suggested as resting on a transgressive unconformity which Nummedal et al. (1988) recognized as a sequence boundary. Road is now on the Clay Mesa Tongue of the Mancos. **0.7**

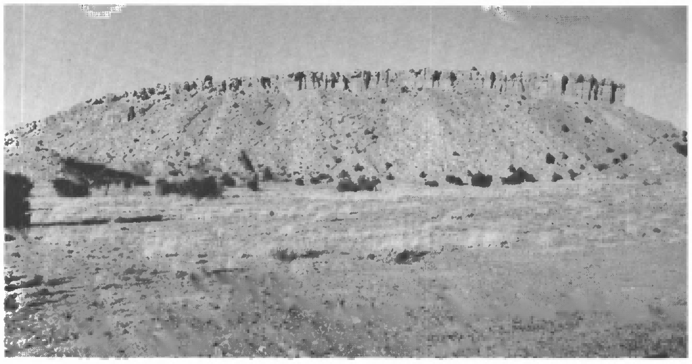


FIGURE 1-72.1. Canipa Mesa; Twowells Tongue of Dakota forms cap overlying a talus-covered Whitewater Arroyo Shale Tongue.

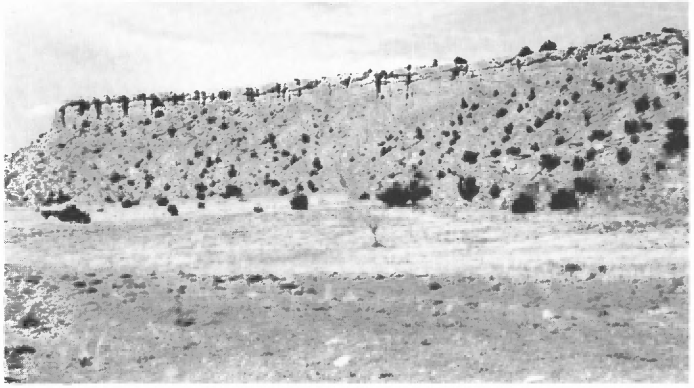


FIGURE 1-74.1. Twowells Tongue of Dakota capping mesa near mile 74.1. Gradational base may be seen clearly just to right and above center. Coarser unit at top (darker color) may rest on a transgressive unconformity.

74.8 The upper part of the intertongued Dakota-Mancos sequence—Paguate, Whitewater Arroyo and Twowells—well exposed just above road level both to right and left for next 0.7 mi. **0.5**

75.3 Thick Paguate Tongue on right with Twowells at higher level; Paguate also on left at 10:00; road is on Clay Mesa Tongue. **0.2**

75.5 Descending through Cubero Tongue in roadcut. Mt. Taylor at 12:30, Horace Mesa at 11:30, Mesa Chivato visible at 2:00. The low ridge across the valley in middle distance at 1:00–2:00 is a NNW-trending diabase dike that can be traced for 16.5 mi, from near Acoma Pueblo to a point where it is truncated by the basalt on Horace Mesa. The dike has an age of 29.9 my (Laughlin et al., 1983) and was apparently emplaced in a stress-field similar to the one indicated by the Pietown–Fence Lake dike swarm near our second-day route.

A small, very steep dome is visible just beyond the edge of the high mesa on the southwestern side of Mt. Taylor. It is about 1 mi in diameter, with beds of Crevasse Canyon Fm dipping steeply away on all sides, and returning to nearly horizontal attitudes in a very short distance. A hole drilled near the center of the dome encountered a mafic intrusive just below the surface. **1.1**

76.6 Paguate Tongue overlying Clay Mesa Tongue caps small mesa on left side of road. **0.6**

77.2 Bridge over arroyo. On slope ahead and to left, in ascending order: at road level Cubero Tongue of Dakota, Clay Mesa Tongue of Mancos Sh (covered), Paguate Tongue (light tan main cliff), Whitewater Arroyo Tongue (covered) and Twowells Tongue of Dakota (cap). **1.0**

78.2 Note deltaic facies(?) of light-colored Paguate Tongue on left overlain by talus-covered Whitewater Arroyo Tongue. **0.2**

78.4 Stop sign; turn left onto frontage road and proceed west. **0.1**

78.5 Deltaic facies of Paguate Tongue on left at road level. **0.7**

79.2 Mission church of Santa Maria de Acoma at left is built on Clay Mesa Tongue of Mancos. The modern church is a half-size replica of the church at Acoma. **0.2**

79.4 **Cross canal bridge;** road enters highway from right. **0.4**

79.8 **Stop sign; turn left** and **proceed west** on frontage road. Across valley and I-40 to northeast in railroad cut, note clean, talus-free outcrop of Whitewater Arroyo Tongue overlain sharply by the Twowells Tongue of Dakota (Fig. 1-79.8). **0.7**

80.5 Distal end of McCartys basalt flow in Rio San Jose valley across I-40. **0.2**

80.7 Roadcuts are in basalt of the McCartys flow. Note pressure ridges. **1.0**

81.7 Bridge; Horace Mesa at 2:00–3:30 is capped by columnar jointed basalts. The slopes below the Pliocene basalt have a nearly continuous cover of landslides and colluvial deposits, covering Crevasse Canyon Fm, Gallup Ss and the intertongued Dakota-Mancos sequence. **0.8**

82.5 Road parallels I-40; note landslide blocks on flanks of Horace Mesa north of I-40. **1.5**

84.0 Sharp "S" curve, road passes under I-40, **turn left** on north frontage road. Horace Mesa on north side of road. Also along north side of road are a series of springs and seeps along and within the McCartys flow. **1.3**

85.3 **Stop sign;** the store and facilities are at the intersection of NM Highway 117 and I-40 exit 89. **Turn left** and **proceed southward** across I-40 overpass to parking area on west side of NM-117 just over crest of hill. **0.3**

85.6 **STOP 5.** Leave buses, watch for traffic, stay on west side of NM-117, and walk to good exposure of the lower part of the Dakota Ss and the underlying Jurassic Morrison Fm (Fig. 1-85.6a). Following a general discussion attention will turn to: (1) Dakota Ss stratigraphy and depositional patterns in the area; (2) Morrison stratigraphy (are there really three members of the Morrison Fm represented here?); and (3) Laramide strike-slip faults that we see in the immediate area.

This stop, approximately 4 mi SE of Grants, NM, is on the north end of Las Ventanas ridge, on the eastern edge of the eastward-dipping Grants monocline. Dakota Ss caps Las Ventanas ridge to the south and the low ridge at El Cañoncito of the Rio San Jose to the north. Across the valley to the north-northeast, the ridge at the base of the west edge of Horace Mesa shows the upturned Cretaceous strata along a better developed (or preserved) segment of the monocline.

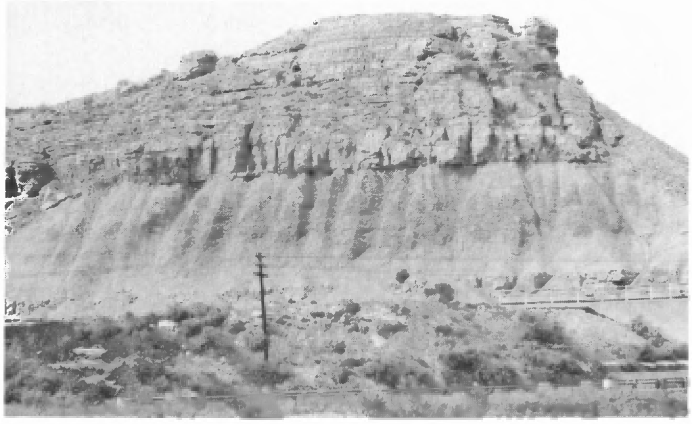


FIGURE 1-79.8. View to north at mile 79.8; thick sandstone is Twowells Tongue of Dakota overlying Whitewater Arroyo Tongue of Mancos.

FIGURE 1-85.6a. View northward at Stop 5 of basal Dakota Ss (Oak Canyon Mbr Kdc) on Morrison Fm (Jm). ENE-trending fault trace shown in photo has horizontal slickensides on near vertical surfaces. Horace Mesa in right background.

The Horace Mesa escarpment has a nearly continuous cover of landslides and colluvial deposits below the basalt cap of Pliocene age. The Crevasse Canyon Fm forms slopes and ledges below the basalt, and is separated into upper and lower parts by the Mulatto Tongue of the Mancos Sh. The upper part is very poorly exposed and locally removed by erosion. It includes the basal Dalton Ss and the upper Gibson Coal Mbr. The lower part comprises the basal Dilco Coal Mbr and the informal stray ss. Coal beds in this area are sparse and thin. Coal resources of the Mt. Taylor area are described in Sears (1934) and Shomaker et al. (1971). The prominent sandstone ledges in patchy outcrops below the Crevasse Canyon are tongues of Gallup Ss, separated by tongues of Mancos Sh. The slope below the Gallup is almost totally covered by landslides which conceal the Mancos and the intertongued Mancos-Dakota sequence. The south end of Horace Mesa is cut by several northeast-trending faults (Maxwell, 1986).

The broad lava-covered plains in the El Malpais to the west are cut primarily in mudstone and shale of the Triassic Chinle Fm. The Zuni Mountains to the west have been a positive area subject to periodic uplift during much of Phanerozoic time. The Precambrian core of the mountains is overlain by clastic and carbonate rocks of the Permian Abo, Yeso, Glorieta and San Andres fms; Pennsylvanian rocks in the subsurface lap onto the uplift. The San Andres Ls forms much of the dip slope visible to the west, dipping east-northeastward under the Triassic Moenkopi and Chinle fms.

Dakota Sandstone

The Dakota Ss sequence is different from that seen at Stop 4. The primary difference is that at this locality most of the Oak Canyon Mbr is missing. The Cubero Tongue overlies the Oak Canyon and caps the small butte 0.5 mi to the southeast. A short hike to the top of the gently northeastward dipping (4–5°) sequence immediately north of the parking area offers a good look at all these relationships, including the unconformity at the base of the Dakota.

The basal Dakota is a highly burrowed and bioturbated sandstone deposited in a shallow marine environment. The trace fossil assemblage includes *Skolithos*, *Thalassinoides* and *Ophiomorpha*—the ones with the pelleted or textured walls. These are all dwelling burrows. Molluscan fossils have not been found in the limited search of the Dakota at this site. The Cubero, however, occurs in or near the top of the stratigraphic range of the Thatcher fauna, which is in the middle Cenomanian ammonite zone of *Conlinoceras tarrantense*. The next youngest ammonite zone of *Acanthoceras amphibolum*, also of middle Cenomanian age, is diagnostic of the overlying Clay Mesa Tongue of the Mancos Sh (Cobban, 1984). Thus the age of the Cubero Tongue is well constrained.

The Thatcher fauna, named from the fossilferous Thatcher Ls Mbr of the Granero Sh in northeastern New Mexico and southeastern Colorado, is the oldest unquestioned Cenomanian megafossil zone in the Western Interior (Cobban, 1961). It records the initial transgression of the epeiric sea into the western New Mexico area. Also of interest is that the Oak Canyon and Cubero are older than basal Upper Cretaceous rocks to the north or south and thus provide evidence that the seaway transgressed into this area more rapidly. This realization led to the concept of Seboyeta Bay (Fig. 1-85.6b) set forth by Hook and Cobban (1980). This particular site, however, apparently was a slight but persistent positive area for part of early and middle Cenomanian time because not only is part of the Oak Canyon Mbr missing and Cubero Tongue thinned, but the Jackpile Ss (Upper Jurassic or lowermost Cretaceous) is missing as well.

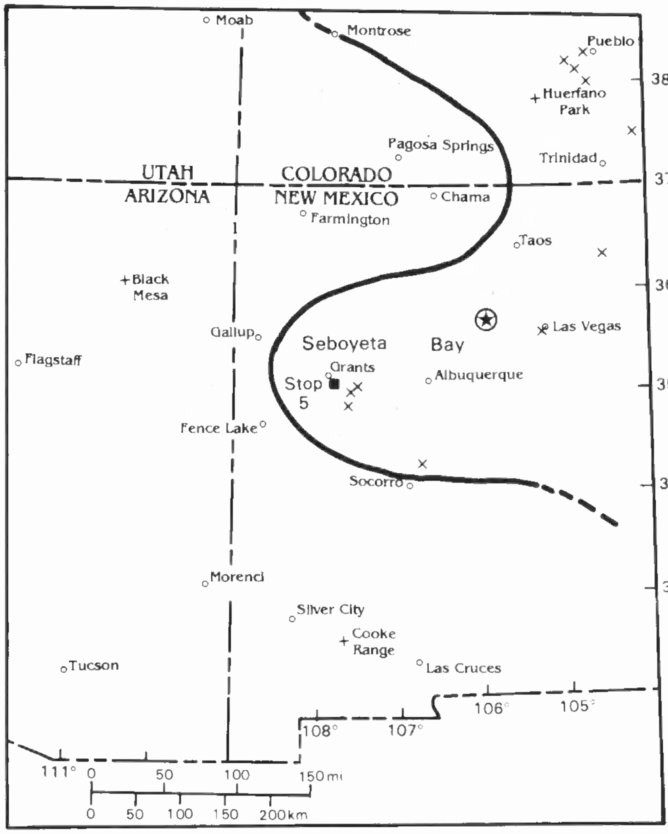


FIGURE 1-85.6b. Map of New Mexico and adjacent areas showing general position of the shoreline during Middle Cenomanian time and Seboyeta bay. Localities where *Conlinoceras tarrantense* have been collected are shown by (x). Stop 5 is indicated. Modified from Cobban and Hook (1984).

Morrison Formation

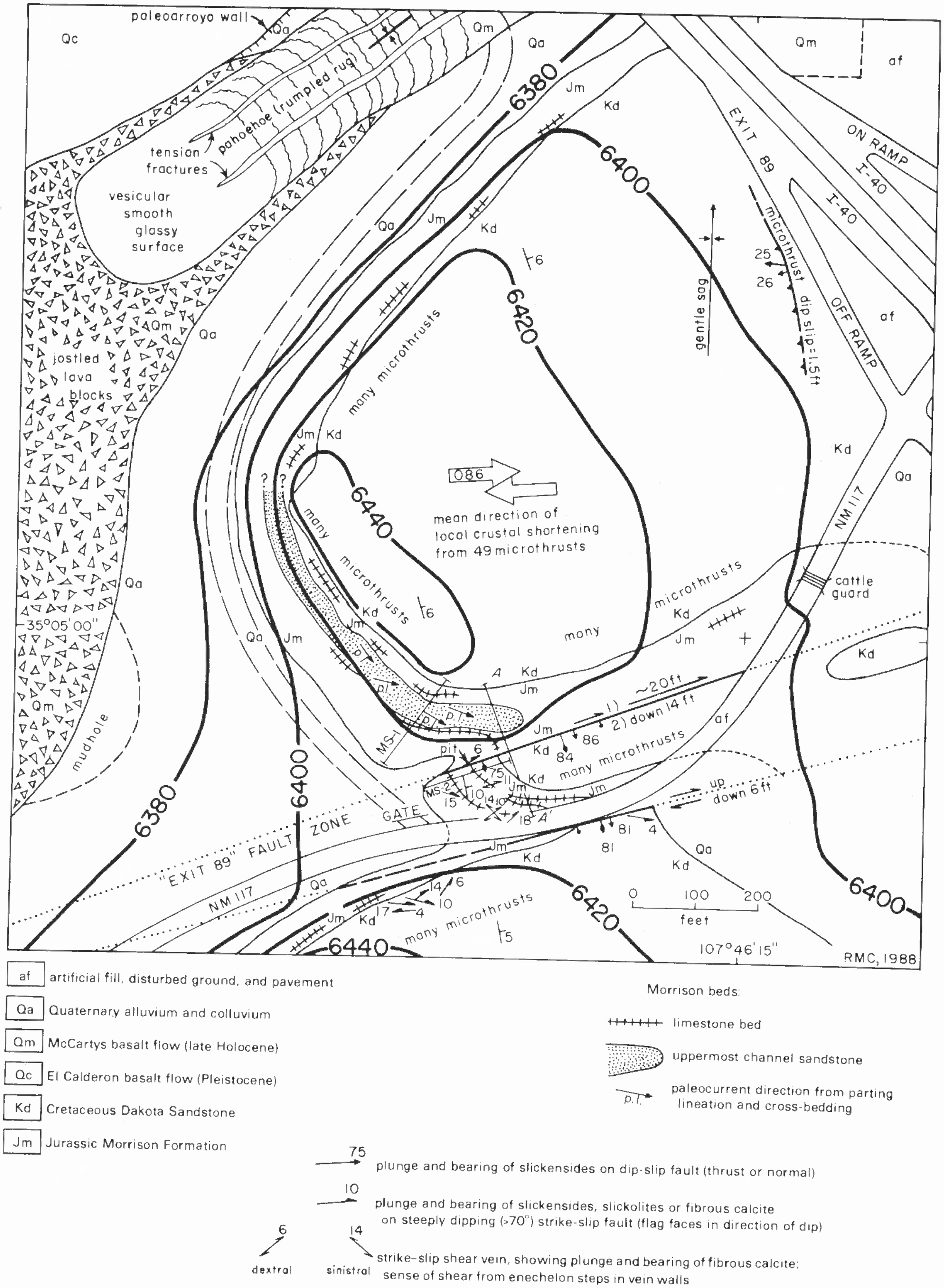
This site was Stop 3 of the Geological Society of America field trip led by Huffman et al. (1984). Those authors suggested that all three local members of the Morrison Fm (Recapture, Westwater Canyon and Brushy Basin) were present and thinned simultaneously in this area, with the truncation line being just a few miles to the south. A grayish-red to maroon (with some grayish-green mottling) zone 6 to 10 ft thick is well exposed at the top of the Zuni Ss (of Maxwell) about 0.1 mi to the south, just east of the highway right-of-way fence. The grayish red zone was considered to be the Recapture Mbr sharply overlain by a crossbedded conglomeratic sandstone designated as the Westwater Canyon Mbr by Thaden et al. (1967). However, this grayish red unit could be merely a weathering zone and related to the J-5 unconformity, the widespread unconformity at the base of the Morrison. It is thin enough here for the paleosol explanation to apply; the lithology is a sandy siltstone, which is not inconsistent with derivation from the underlying Zuni, plus some minor eolian contributions. Elsewhere, such as along the western side of the San Juan Basin, the basal reddish (oxidized) part of the Morrison is much thicker, is commonly mottled, and contains mudstone beds that suggest it is a depositional sequence distinct from the Westwater Canyon Mbr. Here, however, the lithology, thickness and simultaneous thinning of all three members southward toward the Morrison truncation line are evidence that we are looking at just one depositional unit.

Structure

A primary objective of this stop is to present tangible evidence for Laramide strike-slip displacement, most likely minor dextral shear, along an ENE-striking fault zone that has been previously mapped as a down-to-the-south zone of normal faults (Thaden et al., 1967; Maxwell, 1986). Although both of these maps show hypothetical dextral shear on concealed faults in the area, little or no evidence has been presented to support this interpretation.

The most obvious indications of lateral shearing along the Exit 89 fault zone, as depicted on a detailed map of the area (Fig. 1-85.6c), are numerous subhorizontal slickensides, fibrous shear veins and slickolites (linear stylolites) exposed on steeply dipping (>70°) microfaults between the two mappable normal faults; and also on the Dakota Sandstone rim just south of the fault zone. Several of these strike-slip microfaults are well exposed in the roadcuts north and south of NM-117.

A general mismatch of Morrison Fm beds across the northernmost normal fault, as documented in Figure 1-85.6d, implies some strike-slip motion on this fault. Parting-step lineations and crossbedding in the uppermost Morrison channel sandstone (Fig. 1-85.6c) indicate an average paleoflow direction to the ESE (110°). This local channel orientation is in good agreement with the regional ESE trend of Westwater Canyon sandstones, which has been determined from numerous uranium ex-



af	artificial fill, disturbed ground, and pavement
Qa	Quaternary alluvium and colluvium
Qm	McCartys basalt flow (late Holocene)
Qc	El Calderon basalt flow (Pleistocene)
Kd	Cretaceous Dakota Sandstone
Jm	Jurassic Morrison Formation

Morrison beds:

- limestone bed
- uppermost channel sandstone
- p.l. paleocurrent direction from parting lineation and cross-bedding

75 plunge and bearing of slickensides on dip-slip fault (thrust or normal)

10 plunge and bearing of slickensides, slickolites or fibrous calcite on steeply dipping (>70°) strike-slip fault (flag faces in direction of dip)

6 dextral, 14 sinistral: strike-slip shear vein, showing plunge and bearing of fibrous calcite; sense of shear from enechelon steps in vein walls

FIGURE 1-85.6c. Geologic map of the Exit 89 area, on the south side of the I-40, NM-117 interchange. General geology from Thaden et al. (1967) and Maxwell (1986); stratigraphic and structural details mapped by R. M. Chamberlin and O. J. Anderson, 1988. MS = measured section; A-A' = line of cross section (Fig. 1-85.6d).

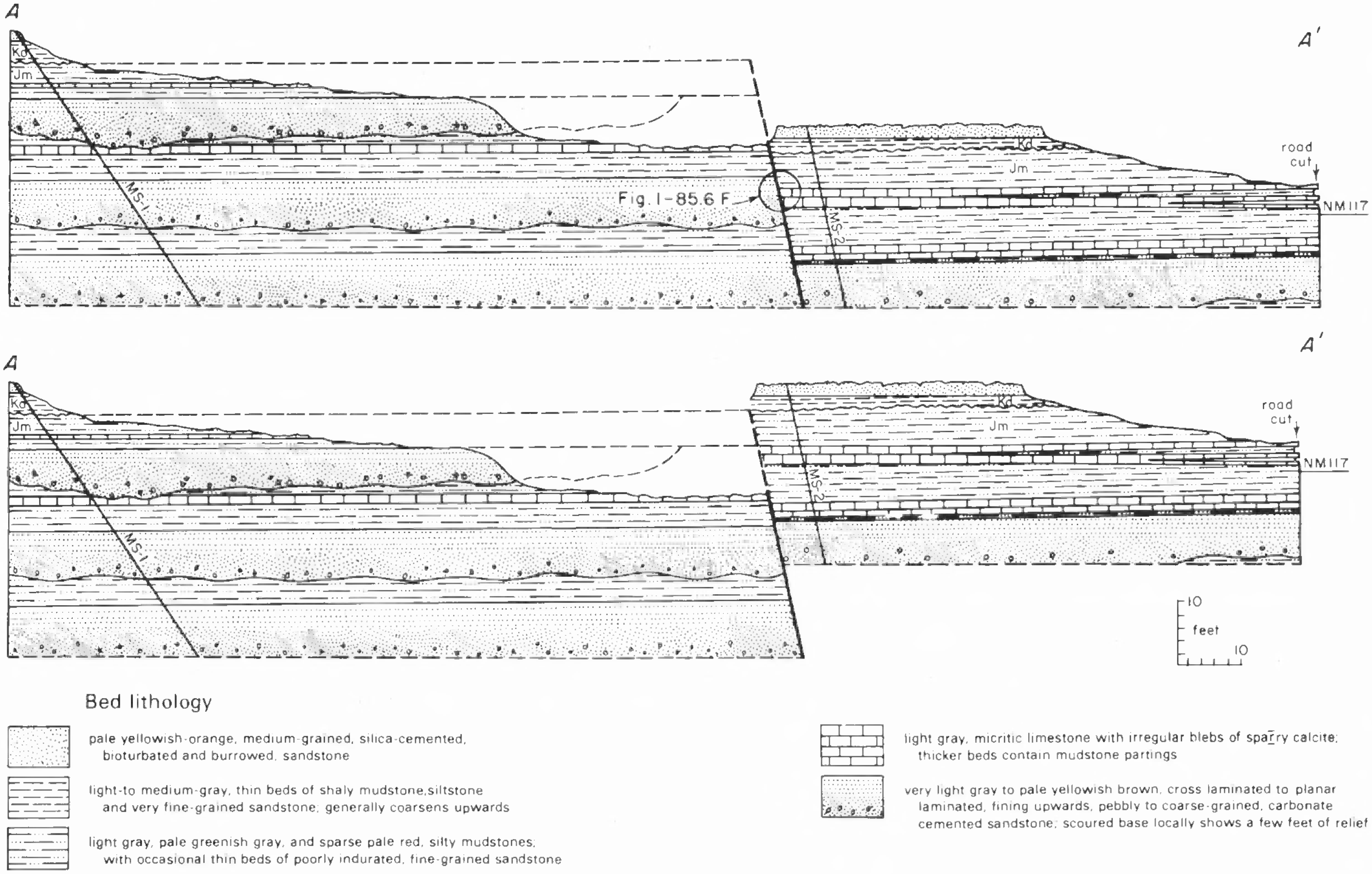


FIGURE 1-85.6d. Detailed stratigraphic and structural cross section across the northern fault of the Exit 89 fault zone; location of section A-A′ shown on Figure 1-85.6c. Stratigraphic details based on measured sections by O. J. Anderson (MS-1) and R. M. Chamberlin (MS-2). Section 1 shows present configuration, with 14 ft of normal, dip-slip offset of the Cretaceous-Jurassic unconformity. Section 2 shows configuration of fault with dip-slip event removed by restoring the Cretaceous-Jurassic unconformity to original continuity. The abrupt change in thickness of limestone beds, truncation of the uppermost channel sandstone bed and the general mismatch of Morrison beds argue strongly for significant strike-slip displacement on this fault.

ploration holes in the Grants area (see Galloway, 1980, fig. 1). As shown on the geologic map (Fig. 1-85.6c), the uppermost channel sandstone is truncated by erosion about 50 ft north of the mapped normal fault. Here, the conglomeratic sandstone visibly trends to the east and appears to dip under a higher mudstone at the northeastern end of the exposure. The relationships suggest the channel sandstone abruptly changed trend here, which may explain its absence on the downthrown block. However, differences in thickness of mudstone intervals and general thickening of limestone beds apparently represent a stratigraphic mismatch caused by strike-slip movement on this fault. Thaden et al. (1967) accurately portrayed this stratigraphic relationship as an abrupt thickening of their Brushy Basin Mbr on the south side of the fault trace.

As part of the 1988 mapping, a shallow pit was dug on the northern fault trace of the Exit 89 zone (Fig. 1-85.6e). With luck, this pit revealed compelling evidence of a composite origin for this fault (Fig. 1-85.6f). Fibrous calcite veins along the fault demonstrate one stage of slip essentially parallel to strike and another stage of slip essentially perpendicular to strike, the latter unquestionably representing dip-slip normal faulting. It seems unlikely that these slip vectors, nearly orthogonal

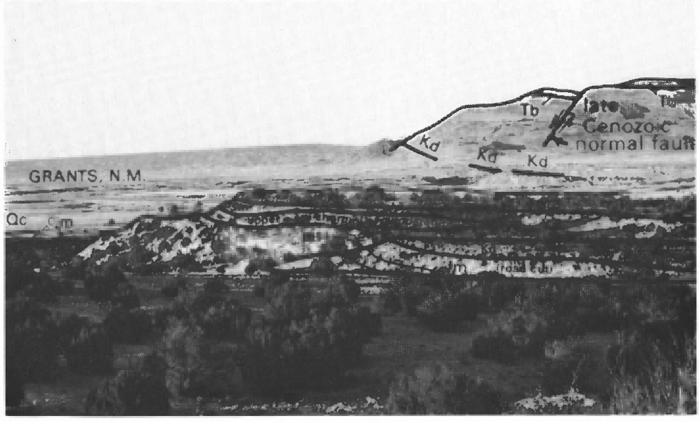


FIGURE 1-85.6e. View to NNW along ENE-dipping cuestas of Dakota Ss (Kd) that delineate the Grants monocline. Note the progressive northward increase in dip of the Dakota, from about 6° to 23°. This perspective provides a longitudinal view of the Exit 89 fault zone in the foreground and clearly shows the abrupt termination of the uppermost channel sandstone by inferred right-lateral slip along the fault. A normal fault, which displaces the Pliocene basalt cap (Tb) of Horace Mesa (Thaden et al., 1967), is but one of many late Cenozoic normal faults (Maxwell, 1976, fig. 1) that demonstrate incipient crustal extension in the Grants region of the Colorado Plateau.

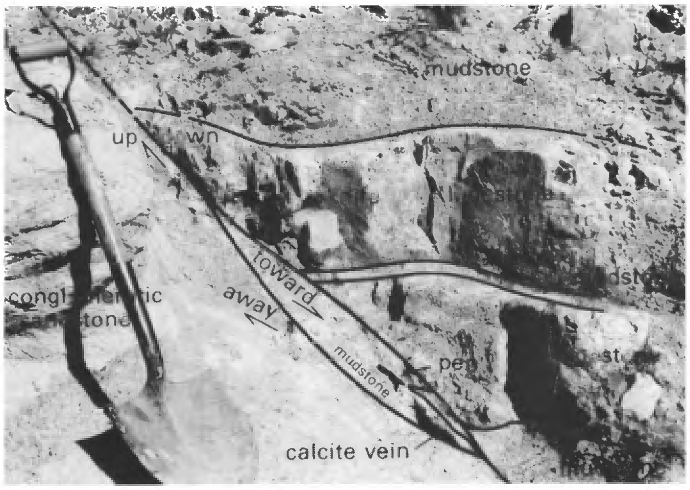


FIGURE 1-85.6f. Shallow pit along northern fault of the Exit 89 fault zone, about 100 ft NE of gate shown in Figure 1-85.6c. The fault juxtaposes lacustrine limestone beds of the Morrison Fm against a conglomeratic channel sandstone, also in the Morrison Fm. Shear veins filled with fibrous calcite indicate two distinctly different directions of slip on the fault. Calcite fibers below the pen plunge at 6° to the ENE, essentially parallel to bedding and the strike of the fault; whereas calcite fibers adjacent to the knife plunge at 75°, to the SSE, nearly perpendicular to bedding and the strike of the fault. Low technology data gathering tool on left is about 1 m long.

FIGURE 1-85.6g. Subhorizontal slickolites (grooved limestone) and fibrous calcite shear vein in Morrison limestone bed exposed in roadcut on north side of NM-117 about 120 ft NE of gate (Fig. 1-85.6c). Vein is near vertical and strikes to 060°; left en echelon steps in the vein walls suggest dextral shear.

FIGURE 1-85.6h. Microthrust fault cutting sandstone and mudstone of the Dakota Ss (Oak Canyon Mbr) in roadcut adjacent to eastbound I-40 Exit 89 off-ramp. Medial mudstone has been thrust about 1.5 ft eastward (to the left) over the base of the upper sandstone. The thrust apparently flattens downward into the medial mudstone.

to one another, could have formed contemporaneously in a uniform regional stress field. Additional observations at other localities suggest that the dip-slip normal faults are generally younger than the strike-slip faults. Strike-slip slickensides are often masked by microcrystalline calcite coatings formed after apparently recent dilation of the near vertical shears. An example of white calcite masking strike-slip slickensides is present on the eastern end of the southern roadcut here at Exit 89. Similar calcite masks are present at the NM-117 borrow pit (Stop 2, Day 2, this guidebook). There you will also see that the dip-slip normal slickensides are much fresher, and more highly polished, than the strike-slip slickensides.

Additional lines of evidence suggest a dextral sense of shear on the Exit 89 fault zone. First, some fibrous calcite shear veins, which are exposed in roadcuts on the north side of 117 (Fig. 1-85.6g), exhibit small en echelon steps in their walls. The en echelon steps are similar to those described by Ramsay and Huber (1983, fig. 13.22), and indicate dextral shear on ENE-striking veins and sinistral shear on NW-striking veins. Also, numerous microthrusts, which are exposed as a myriad of moderately plunging dip-slip slickensides, occur all around the cuesta rims of Dakota Ss at Exit 89. The largest of these microthrusts is documented in Figure 1-85.6h. A stereographic plot of 49 observations on microthrust slip directions shows that the mean direction of crustal shortening at Exit 89 is 086 ± 15°. These conjugate sets of microthrusts and strike-slip microfaults locally form a complexly interlocking set of shears (SW corner, Fig. 1-85.6c) and display mutually crosscutting relationships suggesting that they formed penecontemporaneously. Sinistral shear on the ENE-striking Exit 89 zone would *not* be compatible with the apparently contemporaneous easterly-directed local crustal shortening. Thus, dextral shear is the most likely sense of strike-slip displacement on the Exit 89 fault zone. However, several ESE-trending (090–110) strike-slip shears in the Dakota Ss SE of the highway do show evidence of sinistral shear. Short Reidel shears similar to those described by Angelier et al. (1985) demonstrate the sinistral sense of shear. The total amount of lateral slip on the northern Exit 89 fault is estimated to be about 20 ft.

The Exit 89 fault zone is obviously not a major strike-slip fault zone, but it does demonstrate a composite origin for this fault zone. The tectonic studies of Chapin and Cather (1981) and Aldrich et al. (1986) provide a temporal and spatial framework that is generally compatible with a composite origin for the Exit 89 fault zone. Dextral shear and local easterly crustal shortening would fit with Chapin and Cather's model of *early* Laramide (80–55 my) crowding of the Colorado Plateau against the craton due to west-southwest convergence of the Farallon and North American plates. Alternatively, the Exit 89 zone could be interpreted as a secondary Reidel shear zone formed during NNE-translation of the Colorado Plateau in late Laramide time (55–40 my, op cit). In the latter case the observed microfaults would be third-order features. The Exit 89 dextral shears were probably reactivated as normal faults sometime after 17 my, when the general direction of regional extension shifted from WSW to WNW (Aldrich et al., 1986, fig. 5).

Volcanic geology

For friends of volcanic geology, this stop allows one to examine an interesting pattern in the surface morphology of the McCartys basalt flow that was not mentioned by Nichols (1946) in his classic description. The abrupt change from blocky aa lava to a smooth vesicular surface as mapped (Fig. 1-85.6c) at the constriction, is interpreted as a flow-unit boundary. Presumably the chilled and crumbled front of the northward advancing flow was temporarily dammed at a low drainage divide, which connected with the valley of the Rio San Jose a few hundred yards farther to the northeast. Molten lava then pooled below the broken upper crust until it was able to top the drainage divide. At this time a new flow broke through, and rafted away the old crust to form a younger flow unit. The narrow transition from a smooth glassy surface to the "rumpled rug" (pahoehoe) structure (Fig. 1-85.6i) reflects the rapid increase in viscosity of the new flow surface associated with the change from subterranean to subaerial flow. Longitudinal tension cracks and sagging along the crest of the flow suggest the presence of an evacuated lava tube here. Could there be another "Ice Cave" under Interstate 40?

Return to buses and **retrace route to I-40** westbound on-ramp. **0.3**

85.9 **Turn left** onto westbound I-40. Ahead on the left note the narrow, domed McCartys basalt flow, funneled between the older El Calderon flow to the west and Las Ventanas ridge on the east. **0.6**

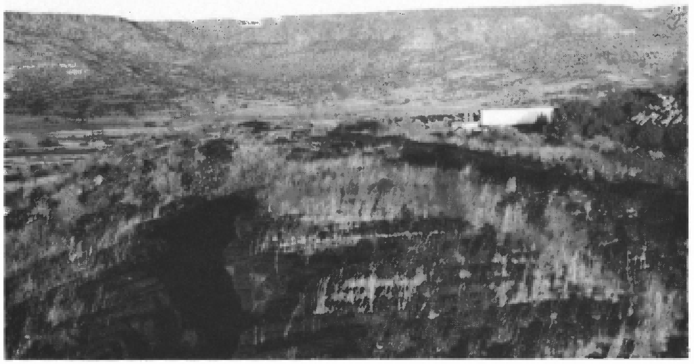


FIGURE 1-85.6i. Looking NE along the welled-up crest of the McCartys basalt flow at its narrowest point, just south of I-40. Note parallel strips of grass growing in furrows of a rumpled rug, pahoehoe surface. Longitudinal tension fractures and gentle sagging of the crest suggest subsidence above an evacuated lava tube.

86.5 Low ridge at 2:30 is Dakota Ss. **0.4**

86.9 Note upturned Cretaceous strata exposed at 2:00 on limb of Grants monocline. **3.0**

89.9 **Bear right** and **leave I-40** via exit 85 to Grants. Originally a coaling station for the AT&SF Railroad, Grants was named for the Grant brothers (Angus, Lewis and John) who were contractors for the construction of the railroad. Grants boomed with the expanding uranium industry in the 1950's and 60's and witnessed a growth reversal in the 80's because of the collapse of uranium prices (see Chenoweth, this guidebook). The city has now stabilized due to the economic activity created by the nearby Lee Ranch coal mine, the Plains Electric generating station 20 mi NW of town and the fact that it is now the seat of Cibola County. **0.7**

90.5 **Turn left** into parking lot at The Inn in Grants.

End of First-Day Road Log.