First-day road log: From Albuquerque to Placitas, Hagan Basin, and Espinaso Ridge

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FIRST-DAY ROAD LOG, FROM ALBUQUERQUE TO PLACITAS, HAGAN BASIN, AND ESPINASO RIDGE

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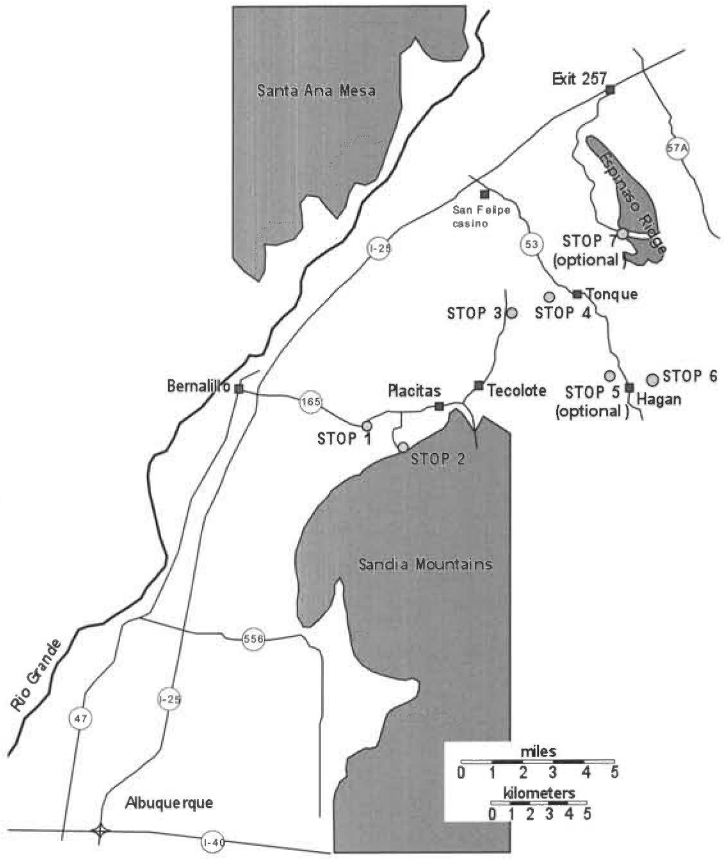
THURSDAY, SEPTEMBER 23, 1999

Assembly point: South end of parking lot of Hilton Hotel, Menaul and University, Albuquerque.
Departure time: 7:30 a.m.
Distance: 82.7 mi
Stops: 7; 2 optional stops



Summary

The purpose of the first day field trip is to reconstruct the geologic, structural, geomorphic, and paleoclimatic history of north-central New Mexico as expressed in the rocks and landscapes of the Hagan basin. We wish to focus on several contemporary controversies that should generate stimulating discussions. These controversies include the role the basement structure has played in shaping later tectonic events (Karlstrom); the enigmatic ancestral Rocky Mountain orogeny (Woodward and Lucas); a tale of two Laramides (Cather and Erslev); footwall uplifts and the Rio Grande rift (Karlstrom, Woodward, Hawley, and Pazzaglia); regional significance of the Tuerto gravel and Ortiz pediment (Connell and Pazzaglia); and contemporary hydro-environmental issues (Johnson, Connell, and Hawley).

Mileage

0.0 Load buses on south side of Hilton Hotel. **Turn left** on University Blvd. (heading north). Gravels underlying the intersection of Menaul and University are mapped as Edith and Menaul gravel (likely middle to late Pleistocene age) with an intervening bed of piedmont-derived alluvial fan deposits (Lambert, 1968). The broad constructional surface south and east of the Menaul-University intersection is underlain by a large alluvial fan lobe of a middle Pleistocene paleo-Tijeras Arroyo. **0.5**

0.5 Get into middle lane before traffic light at Candelaria Blvd. **0.1**

0.6 **Merge left onto I-25 heading North** (to Santa Fe). You are in the middle of the Albuquerque basin, one of the major Neogene rift basins that collectively define the north–south-trending Rio Grande rift. The Albuquerque basin is filled with up to 21,000 ft of syn-rift sediment, collectively called the Santa Fe Group, derived primarily from the north. To your east (right) are the Sandia Mountains, the rift-flank footwall uplift on the eastern side of the Albuquerque basin. To your west (left) is the West Mesa, geomorphically referred to as the Llano de Albuquerque. The Llano de Albuquerque is a complex, time-transgressive geomorphic surface that preserves both the constructional top of Santa Fe Group basin fill and younger, fluvially inset surfaces. Geology for the Albuquerque West quadrangle is provided by Connell and Hawley (1998).

An eolian mantle of variable thickness blankets the West Mesa. Entrenchment of the Rio Grande into its present valley initiated approximately 1 Ma, although sedimentation may have ceased in parts of the western rift flank as early as 3 Ma. The dark-colored basalt flows are sourced from the small spatter cones clearly visible to your left (see paper by Smith et al., this volume). One basalt flow has yielded a single $^{238}U/^{230}Th$ date of 156 ± 29 ka (Peate et al., 1996), and all flows exhibit identical paleomagnetic characteristics (Geissman et al., 1990), suggesting that they were extruded over a short period of time. At one location, a basalt flow is interbedded with the Los Duranes Formation (Lambert, 1968), which underlies the Segundo Alto terrace tread. The Segundo Alto terrace tread is elsewhere underlain by Edith

Formation gravel, and the Los Duranes Formation is thought to be just a fine-grained facies of the Edith Formation. If this is the case, the Albuquerque basalts constrain the age of Edith Formation deposition to the late-middle Pleistocene, or during oxygen isotope stage 6 (late Illinoian). Fossil mammals from the Edith Formation indicate a Rancholabrean age (Lucas et al., 1988), which is consistent with (but not demonstrative of) a late Illinoian age. **1.4**

2.1 Continue north on I-25, passing under Montaño Road at bridge. Note gravel-quarrying operations of Albuquerque Gravel Products on left. The gravel (Edith Formation of Lambert, 1968) quarried at this pit yields fossil mammals of Rancholabrean age (middle–late Pleistocene, about 400–10 ka), especially mammoth, bison, horse, and ground sloth (Lucas et al., 1988). Particularly significant is the record of *Bison*, an immigrant from Eurasia whose first appearance datum in North America marks the beginning of the Rancholabrean land-mammal "age." The Edith gravel represents an important building material for the Albuquerque–Santa Fe corridor. **1.1**

3.2 Jefferson overpass. **0.6**

3.8 Continue north on I-25, passing the Osuna/San Mateo exit (Exit 230). From this vantage point, you can easily view the Sandia Mountain front, Rincon Ridge, and the northeast heights of Albuquerque. Expansion of Albuquerque into the northeast heights has been facilitated by a large, productive aquifer in the upper Santa Fe Group. Clean, well-sorted axial stream gravel of the ancestral Rio Grande define this aquifer situated roughly between Eubank and Carlisle blvds. Wells may produce as much as 800–1000 gpm, lifting water from as deep as 1000 ft, and then distributing that water by gravity feed to the rest of the city. The Sandia piedmont, sometimes referred to as the "Llano de Sandia," is underlain by a thin veneer (~100–130 ft) of Quaternary alluvial fans that bury a fluvially-cut pediment. That pediment, presumably cut during the late Pliocene and early Pleistocene, bevels granite east of Tramway Blvd. (approximately 7 mi to the east) and upper Santa Fe Group west of Tramway Blvd. **0.6**

4.4 Continue north on I-25, passing the San Antonio exit (Exit 231). The Budgetel hotel at this exit has been affected by structural damage attributed to hydro-collapsible soils. The distal portions of alluvial fans mantling the Sandia piedmont are underlain by silty sands susceptible to compaction when they receive large amounts of moisture, typically associated with development and landscaping irrigation. **1.2**

5.6 Pass under bridge of Paseo del Norte Blvd. **0.8**

6.4 Alameda overpass. Note here that the distal portions of Sandia piedmont Holocene alluvial fans overlie the Edith Formation. **1.0**

7.4 Continue north on I-25, passing Tramway exit (Exit 234). Note panoramic view: Nacimiento uplift at 10:30, Jemez Mountains and basalts of Santa Ana Mesa at 11:00, and Sandia uplift at 2:30. The cliff face of the Sandia Mountains consists of the 1.44-Ga Sandia Granite nonconformably overlain by the Pennsylvanian Sandia and Madera formations, with remnants of Mississippian Arroyo Peñasco Group locally preserved along the nonconformity. The Sandia Mountain front exhibits erosion landforms suggestive of the mountain's uplift history. From this vantage point, you can easily see triangular-shaped facets, particularly between the Juan Tabo and La Cueva drainages (Kelley and Northrop, 1975). The apices of these facets define a concordant bench, coincident with the top of Rincon Ridge that slopes to the south parallel with the range crest into the Pino embayment. Two pulses of rift-flank uplift—the first produced the upper half of the Sandia Mountain front, the second produced the facets and Rincon Ridge—are consistent with the observed landforms. Fission-track thermochronology indicates primarily latest Oligocene–middle Miocene exhumation of the range (Kelley et al., 1992), but does not clearly resolve individual uplift events. **0.4**

7.8 The highway continues to follow the Edith Formation, which here is overlain by the distal portions of middle Pleistocene alluvial fans. In contrast to the stratigraphic relationships at Mile 6.4, here the Holocene alluvial fans are inset into the Edith Formation. This geomorphic relation and subtle changes in the dip of the underlying Santa Fe Group sediments are used to locate a broad north-trending, west-dipping flexure in the basin called the Alameda monocline (Plate S). An alternative explanation for the inset nature of the Holocene fans may be attributed to their proximity to valley base level controlled here by the Rio Grande, which takes a broad swing to the east. **1.0**

8.7 Milepost 235. **0.7**

9.4 Cross an arroyo incised in Holocene valley-fill deposits. **1.3**

10.7 Milepost 237. Gravel of the Edith Formation is well exposed on the eastern side of the highway. These exposures of the Edith Formation clearly illustrate its relationship to the older Santa Fe Group. The Edith Formation underlies an inset terrace tread and was produced during a short period of valley-bottom widening and aggradation during the overall long-term fluvial excavation of the Rio Grande Valley. At 9:00, on the western side of the river, is Loma Colorado de Abajo (site of Rio Rancho High School) that exposes red-colored sediments of the middle portion of the Santa Fe Group (Loma Barbon Member of the Arroyo Ojito Formation). Fossil mammals from these red beds indicate a Pliocene (Blancan) age (see Morgan and Lucas, this volume). **0.7**

11.4 Cross a Holocene alluvial fan, graded to the flood plain of the Rio Grande. Rincon Ridge to your right is underlain by 1.6–1.7-Ga metamorphic rocks, cut by conspicuous leucrocratic pegmatite dikes that form part of the contact aureole of the Sandia Granite. Rincon Ridge is likely the most active segment of the Sandia uplift, as fault scarps of late Pleistocene age are well exposed at its base (Connell, 1995). Uplift of the ridge has influenced the flow of the two major west-flowing drainages, Juan Tabo in the south and del Agua in the north, which have been diverted to the south and north, respectively, in their effort to get around the ridge. A prominent notch in Rincon Ridge at 3:00 may be a windgap, centered on the La Cueva structure of Kelley and Northrop (1975), of the paleo-Juan Tabo drainage that was defeated at this location prior to establishing itself across the ridge further to the south in the present location of Juan Tabo canyon.

0.8

12.2 Continue north on I-25, crossing a bridge. Note, on right, the Edith Formation as the highway climbs onto the Segundo Alto terrace. The Edith Formation is one of three or four inset fills composed primarily of extrabasinal, axial-stream gravel. The base of the Edith terrace represents the paleovalley bottom of the Rio Grande that most recently preceded the formation of the modern valley bottom. Underlying the Rio Grande flood plain to your left are several yards of vertically accreted overbank silt and mud, underlain by approximately 100 ft of coarse gravel virtually identical to the Edith Formation exposed here. Cut-and-fill cycles of the Rio Grande to produce gravel deposits like the Edith terrace, accomplished during long-term (10^6 years) incision of the basin, are likely driven by 10^5-year glacial–interglacial climatic and hydrologic cycles. **0.9**

13.1 Diatomite (white beds) in fine-grained facies of the Edith Formation to your right. **0.4**

13.5 Bernalillo fault is exposed to your right (Fig. 1.1). The down-to-the-west fault strikes 012° and dips approximately 80° NW. This fault offsets the base of the Edith Formation approximately 16 ft and as such can be classified as having one of the most recent rupture histories of all faults within the Albuquerque basin. **0.4**

13.9 Diatomite in Edith Formation to your right. **0.4**

14.3 Continue north on I-25, passing first Bernalillo exit (Exit 240). **0.9**

15.2 Good outcrops of the Edith Formation overlying Loma Barbon Member or reddish Sierra Ladrones Formation on right. Nomenclature and understanding of the Santa Fe Group changed little over five decades between Kirk Bryan's original descriptions (Bryan and McCann, 1937; Bryan, 1938) and Vin Kelley's synopsis (Kelley, 1977). Traditionally, the Santa Fe Group in the Albuquerque basin (originally the Santa Fe Formation of Darton [1922]) was subdivided into lower gray, middle red, and upper buff members. Over the past decade, increased pressure to understand the various aquifers of the Albuquerque basin has driven an explosion of new data and understanding of the basin-fill stratigraphy (e.g., Hawley and Haase, 1992). A provisional redefinition of the Santa Fe Group includes the lower Miocene Zia Formation, the middle Miocene Cerro Conejo Formation, and the late Miocene–Quaternary Sierra Ladrones and Arroyo Ojito formations (Connell et al., this volume). These formations preserve a record of basin filling, first by primarily eolian deposits (Zia Formation), followed by large, perennial sand-bed streams (Cerro Conejo Formation), and then by coarse sand–gravel bed streams (Sierra Ladrones and Arroyo Ojito formations). Detailed descriptions of these formations and their various members are featured in Day 2, Trip 2, of this conference. **0.5**

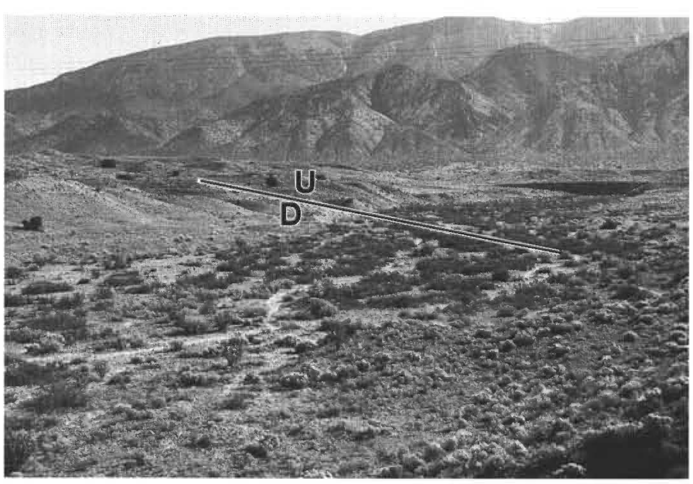


FIGURE 1.1. Annotated photograph of Bernalillo Fault.

15.7 Note good exposure of the strata (base) of the Edith Formation unconformably overlying the reddish-colored Santa Fe Group. **0.1**

15.8 **Leave I-25 taking NM-44/165 exit,** (Exit 242 for Rio Rancho and Placitas) to right. **0.4**

16.2 On exit ramp bear toward right lane. At traffic light, **turn right,** going east on NM-165. **0.1**

16.3 Note flood control dam to your right. **0.5**

16.8 Continue east on NM-165, note that the road ascends Quaternary surface Qf7a of Connell (1995). Small faults exposed along road cuts in the subdivision to your right offset the upper Santa Fe Group and Edith Formation. **0.5**

17.3 Entering greater Placitas. The rapid development of this community is tempered by the availability of ground water resources. Here, in the hanging wall of the rift-bounding faults, the community can generally find ground water resources within the Santa Fe Group. Ahead of you on the uplifted footwall block of the rift-bounding faults, there are no thick sections of Santa Fe Group, and ground water resources are more scarce. **0.4**

17.7 Good exposures of Loma Barbon Member of the Arroyo Ojito Formation at 9:00. Clasts of the lower Bandelier Tuff (1.5 Ma) occur about 30 m up section in these exposures. **0.4**

18.1 Note good view of Rincon ridge at 2:00. **0.2**

18.3 Milepost 2. Ridge ahead is the uplifted footwall of the Valley View fault. Quaternary pediment gravel of Qp2 are offset by this fault (Connell, 1995). **0.5**

18.8 Escarpment of the Valley View fault extends from 9:00 to 12:00 ahead of you. To your right is a good view of Rincon Ridge and geomorphic features related to uplift of the rift flank (Fig 1.2). At 3:00, note the distinct break in topographic ruggedness about halfway up Rincon Ridge. The lower, smooth slopes suggest recent exposure along an active range front fault. The break in topographic ruggedness can be traced to the north to the hill in the middle foreground ahead of you that is capped by Qp1, which suggests Quaternary movement on the fault. **0.4**

19.2 Road to right is U.S. Forest Service loop road (FS-445). **0.3**

19.5 Road to right is other end of FS-445. The geology of this portion of Rincon Ridge is described in the NMGS 1982 guidebook and in the Albuquerque Geological Society-AAPG-SEPM-EMD 1989 guidebook. Excellent examples of a metamorphic contact aureole related to emplacement of the Sandia Granite into the Cibola Gneiss can be viewed along this portion of Rincon Ridge. There are also some exposures of orbicular granite. Cross the Valley View fault and note the coarse grav-

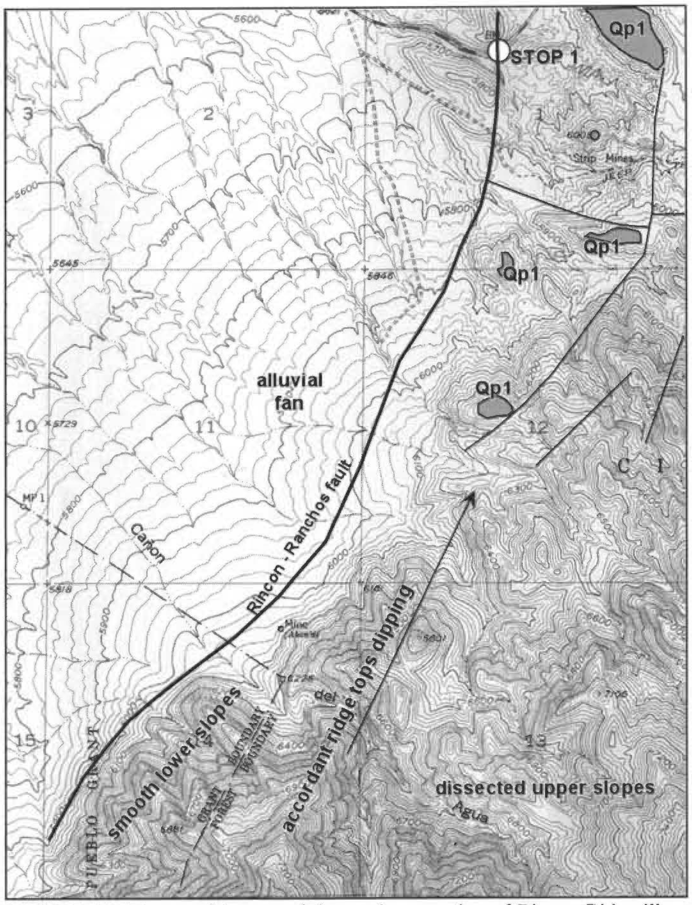


FIGURE 1.2. Topographic map of the northern portion of Rincon Ridge illustrating features discussed in the road log text.

elly facies of the Santa Fe Group. **0.2**

19.7 Ridge tops ahead of you are capped by Qf3 (middle Pleistocene alluvial fan deposits). **0.3**

20.0 **Pull off road** at Las Placitas historical marker on right for **STOP 1**—Rincon-Ranchos fault. The purpose of this stop is to begin the Hagan basin geologic story at the structural boundary between the Albuquerque basin (Rio Grande rift) and the older rocks preserved in the rift flank. The Rincon-Ranchos fault exposed in the road outcrop places Cretaceous Mancos Formation in the footwall (east side) against upper Santa Fe Group in the hanging wall (west side; Fig. 1.3). Several small fault splays synthetic and antithetic to the main fault are visible, including one in the swale approximately 165 ft to the west of the main fault splay. The main fault splay dips about 25° NW and apparently moved at this low angle based on the shallow (<10°) dip of bedding in the Santa Fe Group. We follow the interpretation of Kelly and Northrop (1975), Menne (1989), and Woodward and Menne (1995) by locating the main fault at the contact between the Santa Fe Group and Mancos Formation. We favor this interpretation because this contact contains clear kinematic indicators of fault movement and distinctly lacks sedimentary rip-ups of the Mancos Formation within the Santa Fe Group. It is important to point out that alternative interpretations (Woodward, 1977; May et al., 1994) locate the main fault in the swale to the west of the Santa Fe Group-Mancos Formation contact.

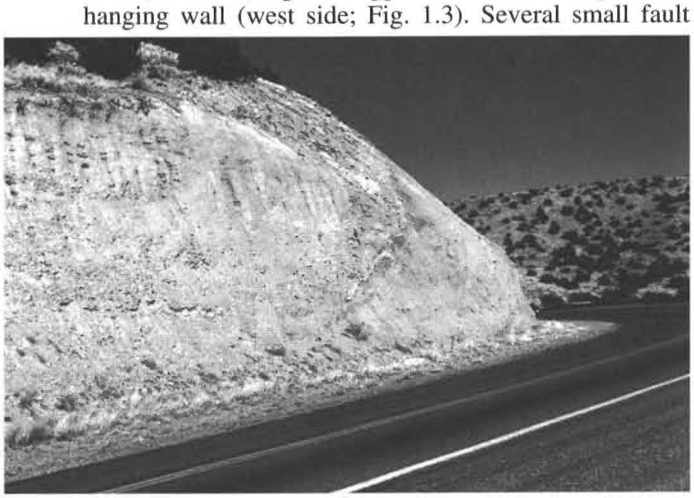


FIGURE 1.3. Photograph of the Rincon-Ranchos fault at Stop 1.

The Rincon fault is one of several north- to northeast-striking faults that decrease in displacement to the north and collectively define a north-dipping ramp that transfers the rift margin to the east at the northern end of the Sandia uplift (Menne, 1989; Woodward and Menne, 1995). Upper Paleozoic and Mesozoic rocks are preserved in this ramp structure, which is bounded by this fault and the east–northeast-trending Placitas fault to the southeast. Did the Placitas fault, the main one of this family of transfer faults, have a Laramide as well as Neogene movement history? The Placitas fault (and related structures) dips steeply (about 70°) northwest, suggesting it may be kinematically distinct from the Rincon fault (see below). The transfer faults are exposed in upper Paleozoic and Mesozoic strata that form a ramp or faulted north-plunging anticline (Kelley and Northrop, 1975; Woodward and Menne, 1995; see controversy below and in Karlstrom et al., this volume).

The upper Paleozoic and Mesozoic strata exposed around Placitas are much better exposed in the Hagan basin to the north (Menne, 1989; Lucas and Heckert, 1995; Lucas et al., 1995). Redbeds (Upper Triassic outcrops) seen from this stop are just the upper portion of the Petrified Forest Formation of the Chinle Group in fault contact with the Jurassic Morrison Formation and Cretaceous Dakota Formation. Most of the Cretaceous section from the Dakota Formation through the lower Menefee Formation is exposed here, but only the Mancos Formation is exposed in the road outcrops. The topographic high knobs to both the south and north are capped by Qp3, and the higher topographic surface to the east is underlain by Qp1 (Connell, 1995). After Stop return to buses and continue east on NM-165. **0.3**

20.3 Milepost 4. Note Cretaceous Mancos Formation on right. Proceed past Puesta del Sol Road. The footwall of the Valley View fault is visible at 9:00. From 10:00 to 11:00 note the ridge of Lomos Altos. This ridge is underlain by a coarse-grained facies of the Santa Fe Group that records an unroofing of the Sandia block to your south. The base of the exposed Santa Fe Group contains numerous angular clasts of the Permian section including clasts from the Abo, San Andres, and Glorieta formations. These poorly sorted deposits suggest deposition on alluvial fans proximal to the Ranchos, Placitas, and San

Francisco faults. The deposits become much better stratified and well sorted further up section, where they are dominated by clasts of Madera Group limestones and Sandia Granite. Menne (1989) reports minor (<1%) amounts of reworked Oligocene volcaniclastic (Espinaso Formation) clasts in the base of the Lomos Altos deposits. If substantiated, the presence of reworked Espinaso clasts here would suggest that the Sandia block would have had to be low-standing following the Laramide, a conclusion consistent with the fission-track data (Kelley et al., 1992), but in contrast to structural data we will review at Stop 2. At 9:30 pebbly reddish-brown sediments are exposed that were originally mapped as Eocene Galisteo Formation by Stearns (1953a). **0.2**

20.5 Juniper Road to your left. Middle Pleistocene alluvial fan surface Qp2 is visible at 11:00, with Qp3 visible further south. **0.2**

20.7 Note a broad Quaternary alluvial fan surface (Qp2) overlying Mesozoic sediments at 2:00. A left turn here into the Ranchos de Placitas subdivision will proceed to the blue water tank and an optional stop of the 1982 NMGS field conference. **0.5**

21.2 Windmill to your left. **0.1**

21.3 **Turn right** at Tunnel Springs Road (FS-231). **0.5**

21.8 Descend riser of Qp3. Go straight (continue on FS-231). **0.3**

22.1 Continue straight. **0.3**

22.4 Road cuts on right are in Triassic Chinle Group litharenitic sandstone. Ascend the Qp2 surface. **0.4**

22.8 **Stop at turn-around** (parking lot) for **STOP 2**—Tunnel Spring (Fig. 1.4). The purpose of this stop is to get an overview of the Hagan basin, observe the oldest rocks exposed in central New Mexico, here represented by the Sandia Granite and upper Paleozoic clastic and carbonate rocks, and discuss controversial ideas regarding the Laramide history of the Sandia Mountains.

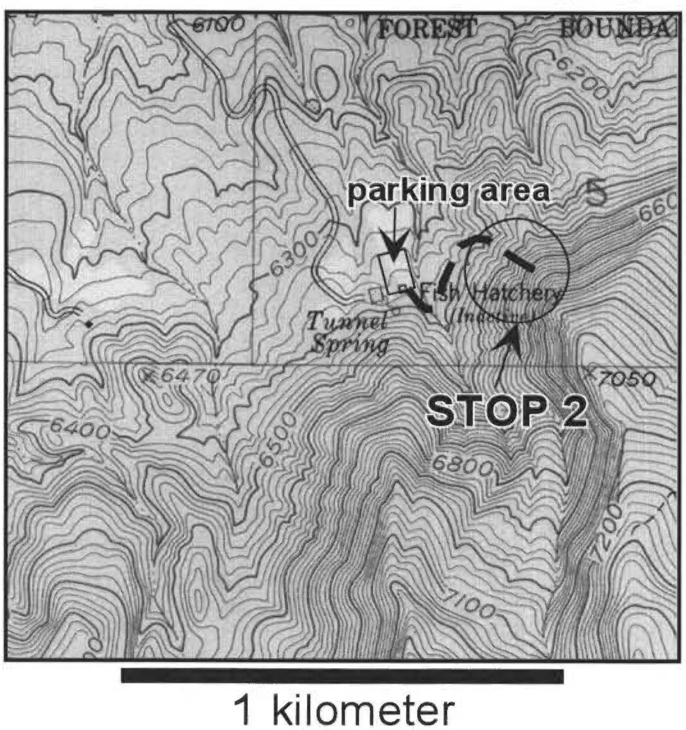


FIGURE 1.4. Annotated topographic map of Stop 2 showing trail to exposures of Mississippian and Pennsylvanian rocks.

Tunnel Spring, a flooded mine adit, maintains a perennial flow as it issues from the Madera Group near a splay of the down-to-the-west Pomecerro fault near its intersection of the Placitas fault zone (Plate S). This stop affords an outstanding overview of the north-dipping structural ramp at the northern end of the Sandia Mountains. The rift-bounding structures here step to the east, preserving the Mesozoic rocks between the Rincon-Ranchos fault to your west and the San Francisco fault to your east. The nearly east–west-striking Placitas fault juxtaposes the Mesozoic rocks against the Paleozoic and Precambrian rocks immediately to our south (behind us).

The view to the far north and northeast displays the northern portion of the Albuquerque basin and the numerous faults across Santa Ana Mesa that represent the structural boundary between the Albuquerque and Santo Domingo basins (both are rift basins: Smith and Kuhle, 1998). The Hagan basin (a Mesozoic–early Cenozoic basin: Gorham and Ingersoll, 1979; Cather, 1992) lies to the east of the Rio Grande rift and is represented by the northeast-dipping cuestas. The structural boundary between the Hagan and Albuquerque basins is the San Francisco fault. We will travel along the strike of this fault for our approach to Stop 3, which is located at approximately 1:30.

The Hagan basin, a locus for Mesozoic and early Cenozoic accumulation of fluvial and marine sediments (Stearns, 1953a), now lies on the uplifted and incised eastern flank of the Rio Grande rift. As the San Francisco fault strikes north, more-or-less oblique to the strike of beds in the Hagan basin, the former western portion has been down dropped and is now buried by rift sediments. Mesozoic and early Cenozoic rocks are locally exposed in horst blocks to the west across the rift, and then are well exposed on the Colorado Plateau. These structural relationships argue for a more or less continuous cover of pre-Neogene rocks from the Colorado Plateau to the Hagan basin prior to crustal thinning and rift development in the mid and late Tertiary.

To observe the stratigraphy exposed at this stop, follow the forest service trail to the south and then west to a large rock cairn, then proceed up the hillslope (Fig. 1.4). The 1.44-Ga-old Sandia Granite is exposed in the footwall of the Pomecerro fault. The Great Unconformity is well exposed between the granite and the overlying Mississippian Arroyo Peñasco Group (Armstrong and Mamet, 1974). Typical of the Great Unconformity in central New Mexico, the Sandia Granite is deeply weathered beneath the Arroyo Peñasco Group, suggestive of a protracted period of exposure prior to submergence beneath Mississippian seas. The Arroyo Peñasco Group here is 0–82-ft thick and is dominated by dark gray, locally white-banded, massive limestone with lesser amounts of gray shale and white, pebbly, quartzose sandstone. A coarse pebbly base is locally preserved at the basal unconformity, whereas a local red siltstone top, called the Log Springs Formation, may represent subaerial exposure and weathering (Fig. 1.5). Unconformably overlying the Arroyo Peñasco Group is 10–165 ft of dark shale and brownish pebbly sandstone of the Pennsylvanian Sandia Formation. The Sandia Formation

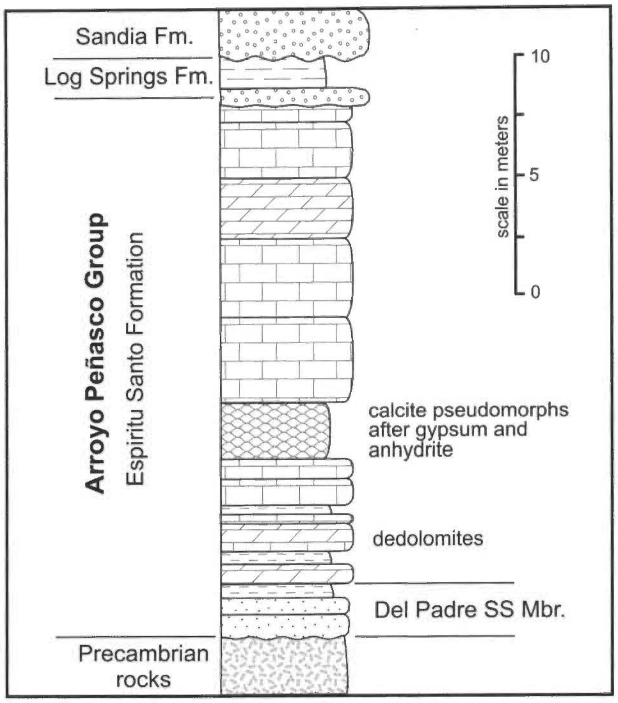


FIGURE 1.5. Measured stratigraphic section of Mississippian strata at Placitas (from Armstrong et al., 1979). Although measured about 3 mi. northeast of Stop 1, the Mississippian section at Stop 1 is essentially the same as shown here.

is conformably overlain by a 1300-ft-thick sequence of gray carbonates, interbedded with lesser amounts of tan sandstone and carbonaceous shale of Madera Group (Wiberg and Smith, 1993). The rocks exposed at this stop represent fluvial and marine deposition in central New Mexico on a passive margin/shallow basin setting associated with the ancestral Rocky Mountain orogeny.

During the Mississippian, New Mexico was essentially at the paleoequator (Plate F). In Mississippian time, a subequatorial Tethys Sea separated Gondwana from Laurussia, and global sea level was relatively high. Warm, shallow seas covered much of the continents, and in these low-latitudes climates were warm and moist. In New Mexico (Fig. 1.6), Mississippian seas covered the southwestern and northwestern parts of the state, generally separated by a northwest–southeast peninsula of land (Johnson, 1974). In north-central New Mexico, where we are now, an early Mississippian transgression of the epicontinental seas flooded this area, and a warm-water carbonate platform developed in a tectonically quiescent setting (Armstrong et al., 1979; Fig. 1.6). The end of Early Mississippian time in New Mexico was marked by marine regression and regional uplift. Locally, on the north end of the Sandia uplift, a thin, nonmarine interval of siliciclastic red-beds and conglomerates composed of clasts of basement and recycled Mississippian carbonates is of probable Late Mississippian age. These strata, the Log Springs Formation, are regolith and syntectonic sediments that were washed into small basins around tectonically active highlands.

Please see papers in this guidebook on the detailed stratigraphy and tectonic setting related to this stop. Note small mine prospects at several places on the hillslope as we traverse the Sandia Granite through Sandia Formation.

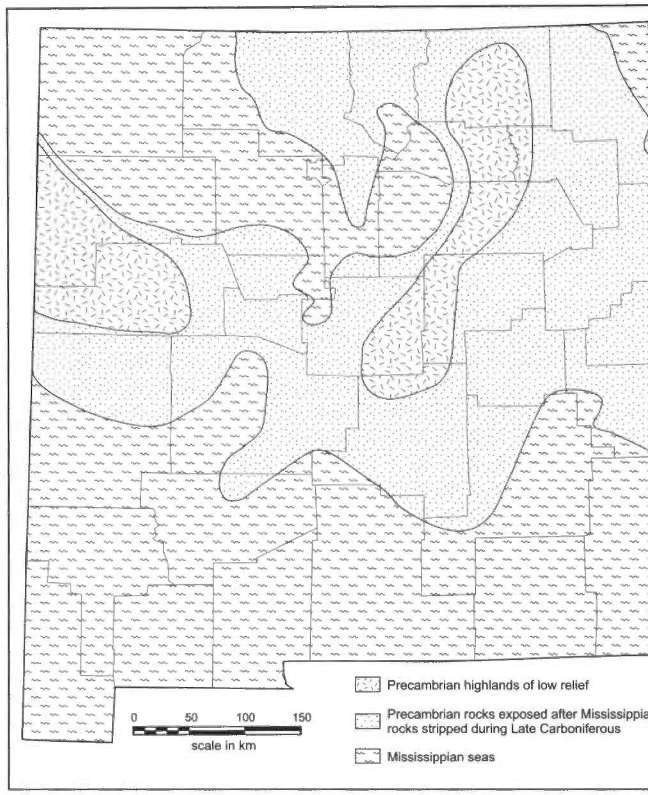


FIGURE 1.6. Paleogeography of New Mexico during the Early Mississippian (modified from Armstrong et al., 1979).

CONTROVERSY REGARDING SANDIA MOUNTAIN UPLIFT HISTORY

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The Sandia Mountains form the east flank of the Rio Grande rift and have long been viewed as a classic example of a rift-flank uplift, where rock uplift was and continues to be driven by isostatic unloading of the footwall in response to crustal thinning (May et al., 1994; Roy et al., this volume). However, these mountains are also part of the eastern Front Range of the southern Rocky Mountain uplift that extends from Wyoming to New Mexico. They lie between ranges to the north (the Sangre de Cristo Mountains) and the south (Manzano Mountains) that exhibit clear evidence for Laramide compressional structures (Woodward, 1984) and exhumation (Kelley et al., 1992). For the Sandia Mountains, like the Rocky Mountains themselves, there is uncertainty whether uplift of rocks from sea level (at the end of the Cretaceous) to their high current elevations occurred mainly in the Laramide (Cretaceous–Eocene) (Gregory and Chase, 1992; Wolfe et al., 1998), mainly in the Neogene (Love, 1970; Eaton, 1987) or both (Pazzaglia and Kelly, 1998). The origin of the "ramp" structure of Paleozoic and Mesozoic strata at the north end of the Sandia Mountains carries a similar uncertainty. Kelley and Northrop (1975) proposed that it was late Cenozoic in age and formed as a relay ramp that acts to transfer extensional slip from the Rincon to San Francisco faults. This is a viable hypothesis and it seems consistent with the interpretation of the low-angle nature of transfer faults (Woodward and Menne, 1985), the usual interpretation of the Neogene cooling ages for apatite-fission tracks (Kelley et al., 1992), and evidence for Espinaso Formation unroofed from the Sandia block during late Santa Fe Group time (Menne, 1989).

A second model is also examined by Karlstrom et al. (this volume) and Roy et al. (this volume) involving multiple periods of uplift. In these models, the ramp represents a preserved part of a Laramide structure that was possibly analogous to the northern Nacimiento

Mountains. NE-trending Placitas (and related) faults are interpreted to initially have been right-steps (extensional jogs) in a Laramide right-lateral strike-slip system at the north end of this Montosa uplift. Paleomagnetic data from a ~30.9-Ma dike in the Placitas area, although not entirely conclusive, seem to suggest that northward tilts of bedding in the ramp formed in two stages. Thirty degrees of tilt took place after 30 Ma but before deposition of the Santa Fe Group strata (Miocene?), and another 30º took place during and after Santa Fe Group deposition. Fission-track ages (30–15 Ma) in the Sandia Mountains record exhumation of the crystalline rocks from beneath at least 3 km of Paleozoic and Mesozoic sedimentary rocks. Thus, it seems reasonable that some uplift of the Sandia block took place in the Laramide, then again around 30–20 Ma, as well as finally in the past 10–15 m.y. To resolve the relative importance of each component of uplift, we need to further understand the pre-Laramide geologic and tectonic setting, obtain better evidence for origin and timing of movement on faults, and reconstruct the original thickness, configuration, syntectonic(?) histories, and denudation histories of the sedimentary basins that are now only preserved as remnants in the Hagan, San Juan, and related syn-Laramide basins.

The oldest rocks in central New Mexico are 1.7–1.6-Ga metasedimentary and metavolcanic rocks like those exposed on Rincon Ridge, in the western aureole of the Sandia Granite (Bowering and Condie, 1982; Brookins and Majumdar, 1989). Aureole rocks (metarhyolites) are also exposed within view to the northeast, in a small outcrop of basement rocks in an inverted Laramide monocline along the East Las Huertas fault (Plate S; see below). These Paleoproterozoic metasedimentary and metavolcanic rocks were involved in the 1.65-Ga Manzanita thrust belt (Brown et al., this volume) and tectonically buried to depths of about 8 km. At 1.44 Ga, they were intruded by the Sandia Granite, which makes up most of the Sandia uplift. Sandia Granite is well exposed near Tunnel Springs, in the hanging wall of the Pomecerro fault and as the unit beneath the Great Unconformity in much of the range. This granite is one of the so-called "anorogenic" granites that perforated the Paleoproterozoic crust of the Southwest some 200 Ma after crustal assembly (Karlstrom and Bowring, 1993). However, recent work in the Sandias and other areas indicate that penetrative deformation and regional metamorphism were associated with pluton emplacement (Kirby et al., 1995; Andronicos et al., in press). We now view this event as an intracratonic response to accretion of arc terranes (in Texas) to North America involving input of mantle basalts with consequent lower crustal anhydrous melting and production of A-type granites (Karlstrom and Humphreys, 1998).

The Paleozoic record in New Mexico records a history of cratonic sedimentation interrupted by the late Paleozoic ancestral Rockies tectonic event. Cambrian through Devonian sediments, if they ever were deposited in the Sandia region, were eroded during the ancestral Rockies orogeny. As with the better-known Laramide history of movement on faults, ancestral Rockies fault movements need to be better understood to evaluate the total uplift history of the Sandias. Regional sediment patterns suggest the Sandias were west of the Pedernal uplift and not a tectonically active area in the Late Paleozoic. In fact, sequence stratigraphy of the Madera Group (Wiberg and Smith, 1993; see Day 2, Trip 1 road log) clearly shows the overwhelming influence of glacioeustatic fluctuations rather than tectonic activity. The controversy continues over the origin and nature of ancestral Rocky Mountain deformation. Evidence for the orogeny is best preserved in thick, clastic sedimentary packages, whereas evidence for basin bounding highlands and associated structures is scarce. The very fact that syn-ancestral Rocky Mountain sediments are well exposed attests to the fact that later Laramide deformation did not everywhere simply reactivate ancestral Rocky Mountain highlands. Clearly, deep ancestral Rocky Mountain basins were structurally inverted in Laramide time. At least three major hypotheses have been proposed to explain this late Paleozoic orogeny: (1) deformation was driven from the southeast by hinterland shortening, arching, and left-lateral strike-slip faulting related to Ouchita (Alleghenian) continent–continent convergence (Kluth, 1986; Kluth and Coney, 1981; Kluth et al., 1998); (2) the deformation was driven from the southwest by a subduction-related fold-and-thrust belt and associated right-lateral strike-slip faulting (Ye et al., 1996); and (3) the deformation was driven primarily by wrench faults (Baars and Stevenson, 1982) in response to plate-margin tectonics of (1), (2), or both.

Following ancestral Rocky Mountain deformation, the Sandias persisted as a topographic low throughout the Mesozoic as sediments of those ages were deposited as a more-or-less continuous blanket across central New Mexico. Sedimentation in the Late Cretaceous was focused in specific basins, such as the Hagan basin, in response to foreland subsidence east of approaching Sevier orogeny thrust sheets as well as subsidence driven by dynamic mantle topography (Burgess et al., 1997). Beginning in the latest Cretaceous and continuing through the Eocene, the foreland itself was deformed by shortening and basement-involved thrust faults. This orogeny, called the Laramide orogeny, uplifted several ranges in New Mexico, including the Nacimiento, Brazos, Sangre de Cristo, Zuni, and Manzano Mountains. Detritus shed from the ranges was deposited in basins proximal to the uplifts (Lucas and Ingersoll, 1981; Smith et al., 1985). The Laramide Galisteo basin (coincident with the Hagan basin), a northwest-trending Paleogene basin, formed in response to north-down deformation along the Tijeras-Cañoncito fault system (Cather, 1992). In most other parts of the Rio Grande rift, the pre-Miocene Phanerozoic section is absent or thinned due to the effects of erosion on Laramide uplifts that were subsequently structurally inverted to form rift basins. There is some documented Laramide deformation in the Sandias along the Las Huertas and Tijeras faults (Fergusen et al., 1998), but paleoflow directions in syn-Laramide sediments of the Hagan basin (Galisteo Formation) suggest a Sangre de Cristo rather than Sandia source. Laramide shortening was accompanied by a certain degree of right-lateral strike-slip faulting (Karlstrom and Daniel, 1993; Woodward et al., 1997; Cather, in press), which may have played a major role in the development of the ramp at the northern end of the Sandia Mountains. Dextral offset was associated with the north and eastward translation of the Colorado Plateau, producing a high-standing welt against the Wyoming Province in the north, and stable craton to the east. The total amount of mean elevation created by the Laramide orogeny in the western United States is aggressively debated, with the current consensus swinging in the direction of 2–2.5 km, or near the modern mean elevation, based on paleoflora data (Wolfe et al., 1998). Syn- and immediate post-Laramide volcanism in central New Mexico produced the Ortiz Mountains and their associated volcaniclastic apron, the Espinaso Formation.

The traditional view that Laramide-related deformation of the western U.S. ceased in the late Eocene to be followed by a period of tectonic quiescence prior to active extension has been recently challenged (Erslev, this volume). In fact, the transition from Laramide compression and Basin-and-Range-style extension in central and northern New Mexico has always been blurred by the presence of thick accumulations of late Eocene and Oligocene volcaniclastic and volcaniclastic-derived sediments in structural basins. These deposits include the Espinaso Formation (Stop 7 of this field trip), the volcaniclastic unit of Shell Isleta well No. 2 (Lozinsky, 1994), and Abiquiu Formation of northern New Mexico. In any event, by the late Oligocene, Cenozoic extension in central New Mexico and elsewhere in the western United States ensued as the overthickened Laramide lithosphere, combined with changes in far-field tectonic forces at the western margin of North America, drove collapse of the high-standing topography (Sonder et al., 1987). As the Basin and Range extended, the Colorado Plateau was rotated away from the High Plains, separating along the former Laramide welt. Crustal thinning first destroyed high-standing paleo-Laramide topography, and then proceeded to produce a narrow north–south-oriented line of extensional basins that we recognize as the Rio Grande rift. Rift extension during the latest Oligocene and early Miocene was broad and relatively shallow, followed by deeper, more-narrow basins forming in the middle Miocene through the Pliocene (Chapin and Cather, 1994). The Albuquerque basin is decidedly asymmetric, with most of the fault offset occurring along its eastern margin. Exposures of early syn-rift sediments along the western margin of the rift, and thick accumulations of paleo-Rio Grande axial-stream facies against the Sandias support this model of basin asymmetry and progressive narrowing. The polarity of basin asymmetry flips at accommodation zones in the Rio Grande rift. Most of the fault offset in the Española basin to our north occurs along its western margin. The transfer of down-to-the-east offset in the Albuquerque basin to down-to-the-west offset in the Española basin is accomplished by the numerous visible faults striking across Santa Ana Mesa.

PALEOMAGNETISM OF THE EARLY OLIGOCENE MAFIC DIKE EXPOSED IN PLACITAS, NORTHERN TERMINATION OF THE SANDIA MOUNTAINS

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Exposed north of Placitas, a single aphanitic mafic dike, up to 8 m in width, cuts strata of the Cretaceous Mancos Shale, Point Lookout Sandstone, and Menefee Formation. The host strata dip about 70° to the north-northeast (Kelley, 1975; Connell et al., 1995). The dike and host strata are unconformably overlain by upper Tertiary strata of the Santa Fe Group that dip 20–25° in a similar direction, to the north-northeast. An early Oligocene age for the dike is based on a whole-rock $^{40}Ar/^{39}Ar$ age determination of 30.9 ± 0.5 Ma (Connell et al., 1995). We have obtained paleomagnetic data from the mafic dike at two sites, one at the road cut on the west side of the paved road leading north from town, and the other as a surface exposure east of the road, collected as low as absolutely possible, to evaluate the magnitude of post-early Oligocene tilting of the dike and host Cretaceous strata. We collected a total of 12 oriented block samples from each of these sites. Block samples were prepared into standard right cylinders for paleomagnetic measurement. At the time of this writing, a total of 15 of the 24 samples were prepared for measurement. Natural remanant magnetization (NRM) intensities for most samples are typically between 1 and 5 A/m, leading us to infer that most of the sampled part of the dike has not been substantially affected by lightning strikes. Some samples, however, have NRM intensities exceeding 10 A/m and, on the basis of their demagnetization behavior, are believed to be partially to substantially contaminated by a lightning-induced isothermal remanant magnetization (IRM). Alternating field demagnetization to about 100 mT randomizes at least 90% of the natural remanant magnetization (NRM) and adequately isolated all components of the NRM (Fig. 1.7 A–D). Those samples with the lowest NRM intensities responded in a similar manner in AF demagnetization, in that a moderate inclination, north-directed magnetization is removed by about 20 mT of demagnetization; at higher peak fields, a magnetization of northeast declination and moderate negative inclination is isolated (Fig. 1.7A, E). For these samples, the method of Kirschvink (1980) was used to determine the direction of the magnetization isolated over high peak fields and the quality of the determination. For strongly magnetized samples, demagnetization rarely defined a stable endpoint linearly decaying to the origin, and the demagnetization data were fit to great circles. Using the less strongly magnetized samples with well-defined stable endpoints, the grand mean paleomagnetic direction for the dike is Declination = 60.4°, Inclination = 47.4°, α_{95} = 6.7°, k = 40.0 , N = 15 independent samples. In comparison, if we combine stable endpoints and great circles, following Kirschvink's (1980) method two, then the grand mean is Declination = 60.5°, Inclination = 50.5°, $\alpha_{95 3-1}$ = 6.4°, $\alpha_{95 3-2}$ = 8.9°.

In comparison to an expected normal polarity early Oligocene reference direction based on an approximately 30-Ma paleomagnetic pole position for North America, (Van der Voo, 1993; Diehl et al., 1983), the in situ magnetization is exceedingly distinct. One possible explanation of this discrepancy is that the dike acquired an unusual magnetization direction during a high-amplitude excursion or transitional part of a field reversal. Alternatively, assuming that the characteristic magnetization of the dike is representative of either a normal or reversed polarity mid-Tertiary field, with typical paleosecular variation (PSV) defined by virtual geomagnetic pole angular standard deviation of some 16–18°, then the discrepancy between the observed in situ magnetization direction and the expected field direction must be explained by post-dike-emplacement tilting. If the dike acquired a normal polarity remanence, then the discrepancy is explained by a large-magnitude (>100°) east-side-down tilt about a north–south-trending axis. If, on the other hand, the dike acquired a reverse polarity remanence, then the discrepancy could be explained by a northeast-side-down tilt, of about 70°, about a northwest–southeast-trending tilt axis (Fig. 1.7E, open arrow). The latter structural explanation is at least consistent with field relations. In addition, the interpretation that the dike acquired a reverse polarity magnetization is not inconsistent with the geomagnetic polarity time scale (Cande and Kent, 1995), where chron C12r, of unusually long duration, lasts between about 33.06 and 30.94 Ma. A plausible, yet by no means robust, interpretation of the available paleomagnetic data is that the dike has been tilted to the northeast by a large magnitude and that the tilt of the host Cretaceous strata occurred after dike intrusion at about 30 Ma. If this interpretation is realistic, then a considerable component of deformation along the northern termination of the Sandia

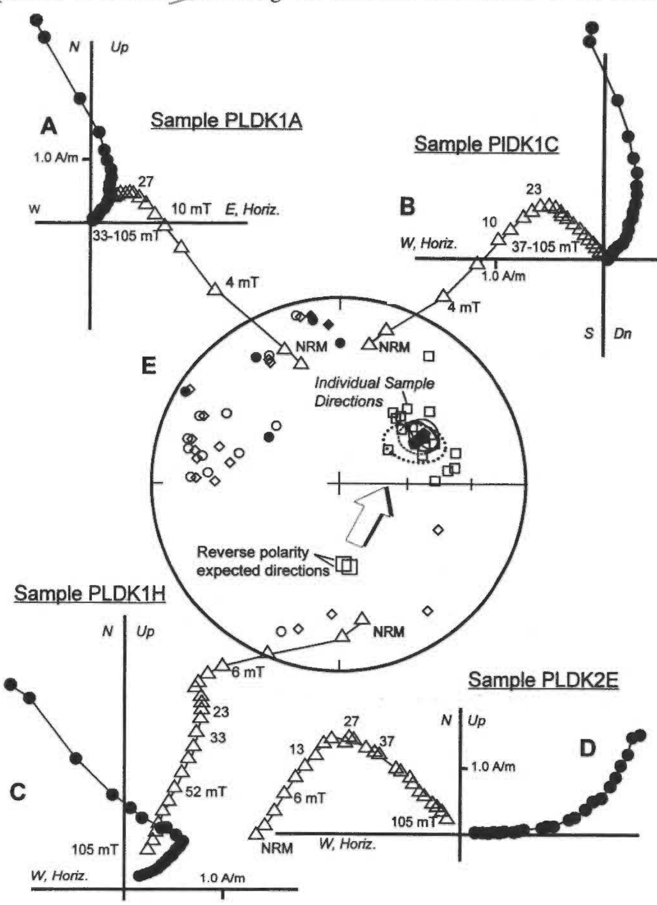

FIGURE 1.7. **A–D**, Orthogonal demagnetization diagrams showing the response by representative samples from the Placitas dike to progressive alternating field demagnetization. The endpoint of the magnetization vector is simultaneously projected onto the horizontal plane (closed circles) and true vertical plane (open triangles). Peak alternating field demagnetizing steps are indicated beside the vertical projections. **E**, Equal area projection of paleomagnetic data from the Placitas dike. Open (closed) symbols refer to upper (lower) hemisphere projections. Small squares are sample directions (one specimen demagnetized per sample) based on stable endpoint demagnetization behavior over a range of high peak demagnetizing fields. Large squares are expected reverse polarity field directions for early Oligocene (ca. 30 Ma) time. Circles and diamonds are normals to planes (small circles) and great circles defined by demagnetization data between about 6 mT and 60–70 mT in progressive demagnetization. The first magnetization isolated may be of lightning-related origin. Pentagons are different estimates of the mean direction for populations of remanence data, all of which are statistically indistinguishable.

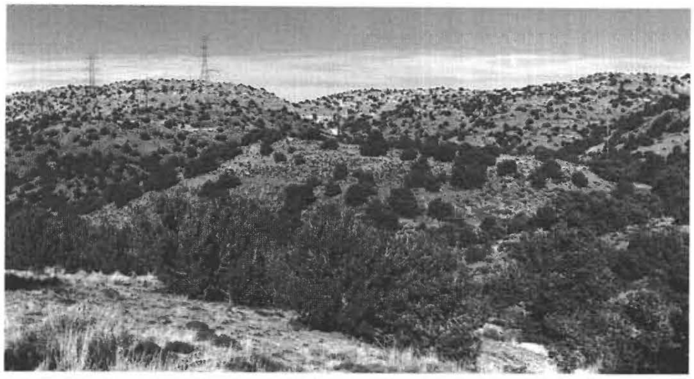

FIGURE 1.8. View of the Upper Pennsylvanian–Permian section at about Mile 29.3. Dark Abo red beds in the foreground dip northeasterly under lighter-colored Yeso slopes with Glorieta–San Andres strata capping ridges in distance.

Mountains, involving motion along the Placitas fault system (Karlstrom et al., this volume), must be younger than about 30 Ma.

After stop, return to buses, turn around and retrace route out to NM-165. **1.5**

24.3 **Turn right** at intersection with NM-165. **0.2**

24.5 Entrance to Overlook Road and the Lomos Altos exposures to your left. **0.8**

25.3 Enter Placitas; note Jurassic Morrison outcrops. Placitas, Spanish for "little plaza," is a name derived from the fact that original Spanish settlements in New Mexico were built around plazas. Gradually, the word "plaza" came to signify most villages because the plazas acted as an assembly place for protection as the outer walls of the buildings that circled it constituted a rampart. Thus, "placitas" came to signify a small cluster of houses. In Sandoval County, the village of Placitas was built over an ancient Native American Pueblo, with a post office first established in 1901.

Greater Placitas has experienced exponential residential development in the last 15 years, with corresponding pressure placed on development of the area's ground-water resources. From 1985 through 1995, ground-water withdrawals from community drinking water systems increased from approximately 10 million gallons per year (Mgpy) to over 40 Mgpy (Groffman et al., unpubl. report for the Office of Planning, Sandoval County, New Mexico, 1997). Most of these withdrawals were from aquifers within the Santa Fe Group, west of the Valley View fault, but a significant increase in withdrawals has also occurred from small community systems and individual wells completed in Mesozoic and Paleozoic formations. During the 1996–1997 drought, many such shallow, individual wells went dry, spring discharge decreased to 20–30% of normal, and seasonal stream discharge was nonexistent (Johnson, this volume). The areas most severely affected were those developments dependent on Paleozoic and Mesozoic aquifers.

In traversing the Paleozoic and Mesozoic units around Placitas, one can appreciate the extreme variability in aquifer properties between, for example, the Mancos Shale, various sandstones within the Morrison Formation, and the Madera Group limestones. Ground water in this stratigraphically and structurally complex setting exists in a compartmentalized aquifer system that is recharged through a combination of surface water and preferential ground-water-flow paths originating in the Sandia Mountains to the south. Hydrogeologic and geochemical data indicate the existence of an assortment of confined and unconfined aquifers with a wide range of water quality and productivity, varying degrees of hydraulic interconnection, and ground-water residence times that vary from annual to tens of thousands of years (Johnson, this volume). **0.1**

25.4 Note green claystone of Brushy Basin Member of Jurassic Morrison Formation on right and left. **0.8**

26.2 High ridge to the left is underlain by the upper Cretaceous Mancos through Menefee formations, Eocene Galisteo Formation, and upper Santa Fe Group, all dipping to the northeast. **0.2**

26.4 Cross the San Francisco fault and pass into red beds of the Permian Abo Formation in the footwall. **0.1**

26.5 **Turn left** onto paved road. Note the inverted crown of this road, which leads to it being frequently washed out during storms. **0.2**

26.7 Abo Formation red beds in roadcuts. Cross a small, down-to-the-north fault, and pass through the Permian San Andres Formation, Middle Triassic Moenkopi Formation, and Upper Triassic Agua Zarca Formation. **0.5**

27.2 Jurassic Morrison Formation (Brushy Basin Member) in roadcuts. **0.2**

27.4 Cross Las Huertas Creek. Note gravel of a low terrace exposed to the right. Las Huertas Creek maintains a perennial flow through this reach, being maintained by a stable base flow recharged in the Sandia Mountains to your south. The water table is shallow throughout this entire valley of Las Huertas Creek south and east of the San Francisco fault. Numerous springs, marked by dense stands of willow and other phreatophytes occur along this road, which more or less follows the San Francisco fault. The high-standing ridge to your right, the Crest of Montezuma, exposes an excellent section of Pennsylvanian Madera Group. **0.1**

27.5 Roadcut to left is in Cretaceous Hosta-Dalton Sandstone in the Mancos Shale; **stay right** on Camino del San Francisco. **0.1**

27.6 **Stay left. 0.4**

28.0 Small fault blocks of the Jurassic Todilto and Morrison formations are exposed in roadcuts on right. **0.1**

28.1 **Do not follow the access road to the pipeline facility.** The main road here follows exactly the strike of the San Francisco fault, placing Miocene(?) Santa Fe Group in the hanging wall to your left against Pennsylvanian Madera Group in the footwall to your right. You now cross an important ground-water and topographic divide between flow associated with Las Huertas canyon behind you, and a smaller, more local recharge-discharge system controlled by the Cuchilla de San Francisco to your right and San Francisco fault to your immediate left, respectively. **1.2**

29.3 San Francisco Hills Road to left, continue straight. View ahead of Cuchilla de San Francisco, which exposes a north–northeast dipping Permian section (Fig. 1.8). **0.1**

29.4 This is the upper valley of the Arroyo de San Francisco, which has a perennial flow through this reach, fed by a large spring. **0.1**

29.5 Note large spring at 9:00. **0.2**

29.7 Road is on cuesta of upper part of Madera Group lime-

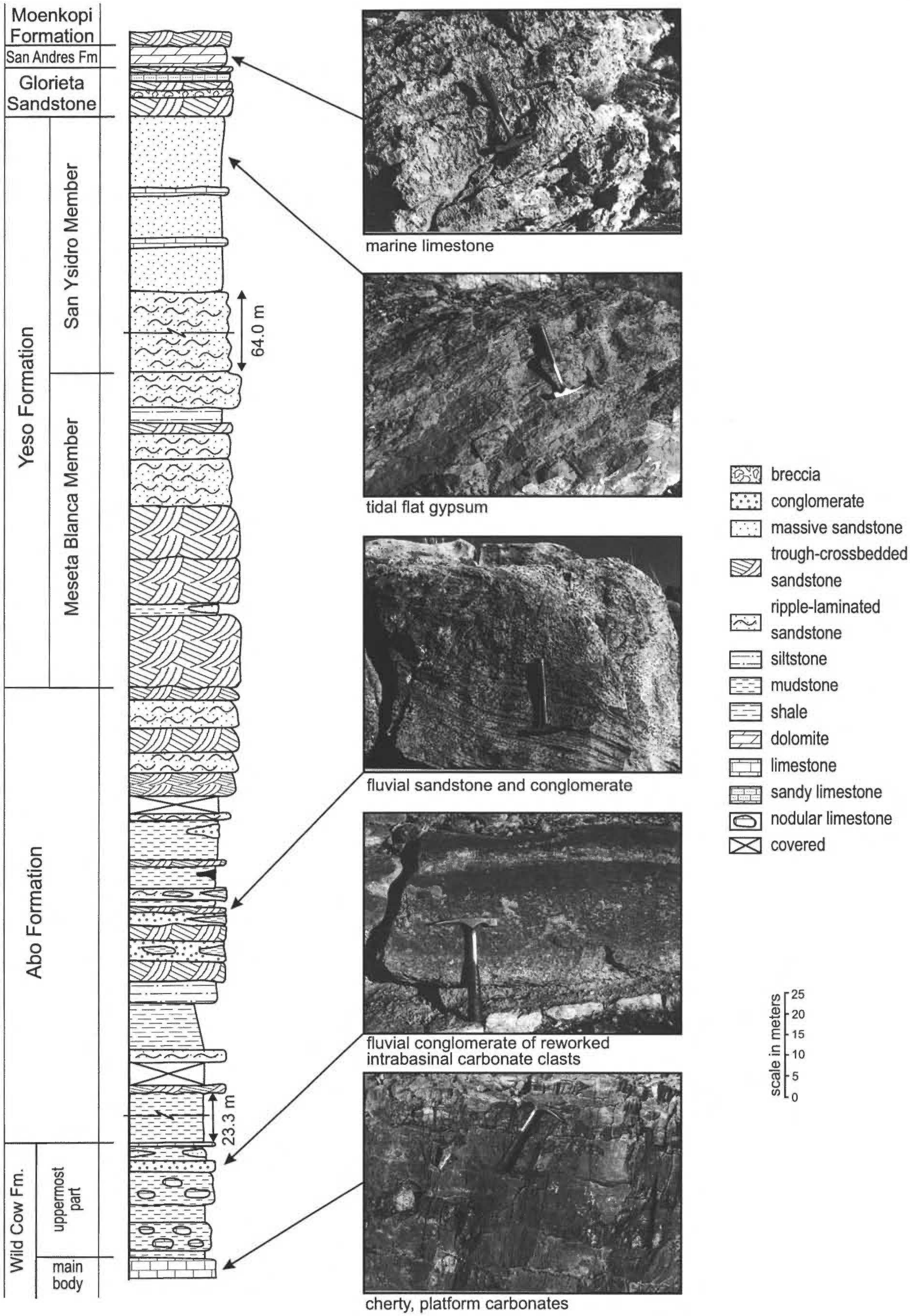

FIGURE 1.9. The Permian section at Stop 3. See Lucas et al. (this volume) for a detailed description of the section.

stones. **0.2**

29.8 Note "Pay Troll" sign to cross bridge ahead. **0.2**

30.0 **Stop at power line, STOP 3**—Cuchilla de San Francisco. The purposes of this stop are to: (1) observe spring discharge issuing from the upper Madera Group at the San Francisco fault, and (2) walk from the upper Madera Group through the Permian and into the Middle Triassic section. ***NOTE:*** *Access to these sites must be obtained from Mr. Johnsonbough (spring) and the Diamond Tail Ranch (Permian section).* The rocks exposed at this stop record the waning stages of the ancestral Rocky Mountain uplift and subsequent destruction of those uplands by fluvial erosion. The Permian section (Fig. 1.9) begins as a transition from marine (Wild Cow Formation) to fluvial red-bed depositional environment (Abo Formation), has arid eolian (Yeso Formation) and nearshore beach facies (Glorieta Formation) in the middle, and ends with a return to marine carbonate deposition (San Andres Formation).

The uppermost Pennsylvanian–Permian section exposed here is the single best section of these rocks preserved around the Sandia uplift. A brief description (see Lucas et al., this volume, for more details) of this section follows: (1) uppermost Wild Cow (Madera) strata are bioclastic and micritic limestone with a prolific fossil assemblage dominated by brachiopods, bryozoans, crinoids and fusulinids; these are rocks of well-established middle Virgilian age, based on the fusulinid species (genus *Triticites*) they contain (Kues et al., 1997); (2) a 65–80-ft-thick mixed nonmarine-marine interval follows and consists of ledgy and nodular limestone, red mudstone and siltstone and intraformational limestone-cobble conglomerate; these are strata of the uppermost Wild Cow Formation of probable late Virgilian age; (3) as much as 395 ft of red mudstone, siltstone, trough-crossbedded sandstone, and limestone-pebble conglomerate are fluvial strata of the Wolfcampian Abo Formation; (4) the overlying Meseta Blanca Member of the Yeso Formation is as much as 200-ft thick and is dominantly trough-crossbedded, yellow-to-tan, eolianite sandstone; (5) the overlying San Ysidro Member of the Yeso is as much as 375 ft thick and mostly massive and ripple-laminated, thin-bedded, fine-grained sandstone, siltstone and beds of gypsum; (6) the Glorieta Sandstone sharply overlies the Yeso and is as thick as 36 ft and mostly brown, trough-crossbedded quartzarenite; (7) patchy and thin (up to 16 ft thick) gray limestone of the San Andres Formation, the youngest Permian strata preserved here; and (8) fluvial red beds of the Middle Triassic Moenkopi Formation. The ridge is capped and supported by coarse-grained fluvial sandstones of the Upper Triassic Agua Zarca Formation, the basal formation in the Chinle Group.

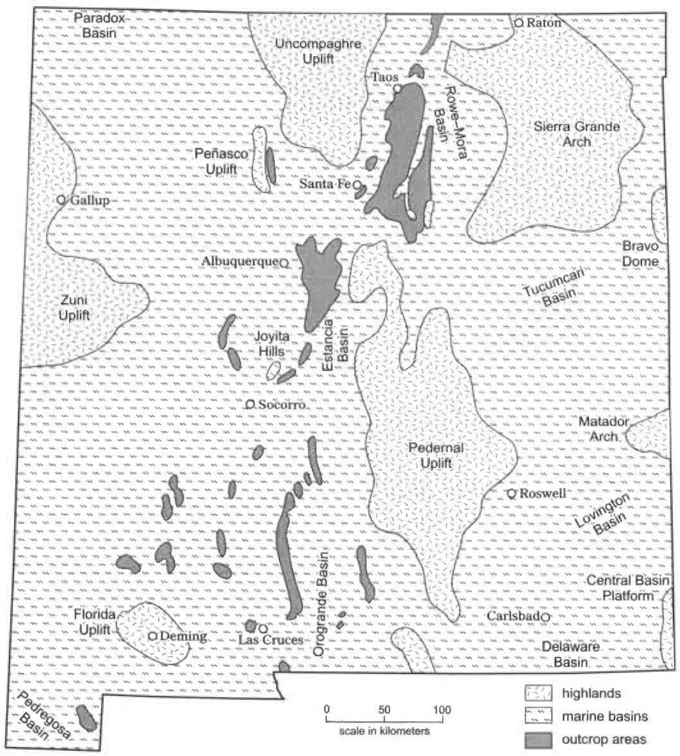

FIGURE 1.10. Paleogeography of New Mexico during the Pennsylvanian (modified from Armstrong et al., 1979).

During the Pennsylvanian, New Mexico was equatorial, near the western edge of the accreting Pangea supercontinent (Plate G). Lauraussia and Gondwana had just begun to join along the Hercynian megasuture, which produced a huge zone of dominantly convergent tectonism that extended from West Texas (Ouachita uplift) to what is now the Mediterranean Sea. This zone encompassed what is called the Alleghanian (= Hercynian = Variscan) orogenic belt. Pennsylvanian climates in the low latitudes were those of tropical coal swamps, but glacial ages in southern Gondwana brought ice sheets as far north as 30° S latitude. Relatively high Pennsylvanian sea levels flooded low-lying continental areas like New Mexico, so that by Virgilian time the state was a thinly distributed archipelago of basement-cored uplifts surrounded by shallow, carbonate platforms (Fig. 1.10).

Continued accretion of Pangea and the northward drift of the vast supercontinent played a large role in the changes that took place in the state across the Pennsylvanian-Permian boundary (Plate H). These changes initially reflect what has been termed the ancestral Rocky Mountain orogeny. Generally, this orogeny has been seen as the result of the collision of South and North America during the accretion of Pangea, which caused northwest–southeast crustal shortening in the western North American foreland. A series of northwest–southeast-oriented basement-cored uplifts and adjoining basins thus formed. By Early Permian (Wolfcampian) time, one huge uplift—the Uncompaghre highland of north-central New Mexico and south-central Colorado—became the dominant source of sediment in the northern part of the state (Fig. 1.11). Red-bed siliciclastics shed off the uplift by rivers generally flowing southward are termed Abo, Sangre de Cristo or Cutler, depending where you are in northern New Mexico, but they are a single lithosome. This time-transgressive lithosome (its base youngs southward) reflects deposition on vast alluvial plains and floodplains under hot, seasonally arid (truly monsoonal) climates.

Waning tectonism and increased aridification during late Early Permian (Leonardian) time (Plate K) resulted in major eolian deposition that varied from a thick continuous erg on the Colorado Plateau to an eolian-domi-

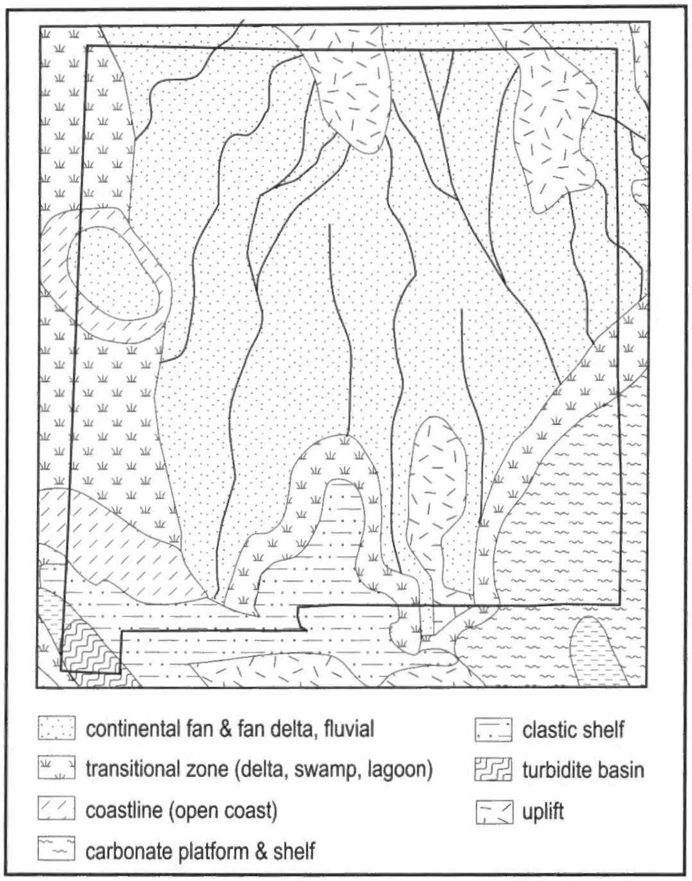

FIGURE 1.11. Early Permian (Wolfcampian) paleogeography of New Mexico during Abo Formation deposition (modified from Ye et al., 1996).

nated marginal marine, sabka, and/or lacustrine setting in central New Mexico. The Yeso Formation (Yeso means "gypsum" in Spanish) reflects these trends and becomes progressively more gypsiferous to the southeast, or towards the Early Permian shoreline.

Transgression of the Permian epicontinental seaway ensued in late Early Permian (late Leonardian) time and its effects are seen here at Placitas with the deposition of the Glorieta and San Andres formations. To the west on the Colorado Plateau, shallow near-shore marine limestone and shale was deposited, but in central New Mexico, the transgression is marked by a quartzose barrier-island beach sand sheet (Glorieta Sandstone). Culmination of the transgression in San Andres Formation time saw the return of marine conditions to a tectonically stable continental margin and associated carbonate deposition. The upper portion of the San Andres Limestone locally preserves paleokarst features presumably formed during a protracted period of eustatic fall and/or epeirogenic uplift during the Late Permian–Early Triassic. If rocks of Early Triassic age were deposited in central New Mexico, they were stripped prior to resumption of deposition of the Moenkopi Formation in the Middle Triassic. Deposition of the Moenkopi Formation heralded the initiation of large, through-going fluvial systems that originated in former highlands to the south, and southeast. These fluvial systems persisted as very large, coarse sand and-gravel-bed rivers through Agua Zarca Formation deposition during the Late Triassic. The fluvial deposits represent a protracted period of time from the Middle Triassic through the Late Jurassic when central New Mexico, and much of the western United States experienced variable, but slow rates of subsidence and the persistence of subaerial continental depositional environments.

A dozen major springs discharge adjacent to the San Francisco fault, and north of the Cuchilla de San Francisco, in the vicinity of the old San Francisco Springs Ranch. The springs discharge from either the Madera Group aquifer, as it is tectonically thinned and ultimately truncated by the San Francisco fault, or from Santa Fe Group sediments along deeply incised reaches of San Francisco Creek further north. Depth to water ranges from 0 to 40 ft in the Madera Group east of the San Francisco fault to 200 ft and more in the Santa Fe Group immediately west of the fault. A decrease in hydraulic head of about 200 ft east to west across the fault implies a reduction in permeability associated with the fault plane or the adjoining Santa Fe Group (Johnson, this volume). A conceptual model of ground water flow for the Madera Group aquifer along Cuchilla de San Francisco (Johnson, this volume) includes a hydrologic no-flow boundary along the stratigraphic contact with the Abo Formation, a low-flow boundary along much of the San Francisco fault north of Tecolote, and a large discharge area and low-flow boundary along the San Francisco fault between the toe of Cuchilla de San Francisco and the truncation of the Madera Formation at the San Francisco fault 0.6 mi to the north. Significant vertically upward hydraulic gradients, manifest in the numerous springs and artesian wells in the area, are characteristic of the damage zone in the Madera Formation parallel to the fault, and the discharge area that covers the northern third of the Cuchilla de San Francisco aquifer.

An interesting feature of the some of the springs, particularly those approximately 1 km north of this stop, are travertine deposits. These deposits locally make large constructional mounds, interbedded with Santa Fe Group basin-fill sediments, and now exhumed by recent exhumation of the rift flank. The mounds attest to the longevity of the local ground water flow system and if they can be dated, would provide some constraints on rift basin rates of sedimentation.

After stop, return to buses and retrace route back to NM-165. **1.1**

31.1 Santa Fe Group is exposed in gullies and washes to the west. **0.7**

31.8 Fantastic view ahead of northern end of Sandia Mountains. **0.2**

32.0 Las Huertas valley visible at 2:00. **0.4**

32.4 Cross Las Huertas Creek. **1.2**

33.6 **Turn right** on NM-165 and retrace route to I-25. **0.8**

34.4 Qp2 visible at 1:00 to 2:00. **1.5**

35.9 Panoramic view ahead across the rift and to the eastern edge of the Colorado Plateau. White Mesa exposing gypsum of the Jurassic Todilto Formation at 12:30, Cabezon basaltic plug at 1:00, Jemez Mountains at 1:30, and Santa Ana Mesa at 2:00. **3.4**

39.3 Quaternary pediments cut atop the upper Santa Fe Group visible at 3:00 in the arroyo wall about 0.5 km in the distance. **1.5**

40.8 **Turn right** on ramp to I-25 north. **0.9**

41.7 Exposures to your right are red-colored facies of the Loma Barbon Member of the Arroyo Ojito Formation. **0.5**

42.2 Western Mobile gravel pit within Sierra Ladrones Formation to the right. The gravel pit on the right is developed in axial stream facies of the Upper Santa Fe Group strata equivalent to part of the Sierra Ladrones Formation to the south. Armor plates (scutes) of a glyptodont (*Glyptotherium*) from this pit indicate the Irvingtonian land-mammal "age" (early–middle Pleistocene: Lucas et al., 1993). **0.7**

42.9 Octopus plug of Canijlon Hill volcano, a 2.61 ± 0.09 Ma Pliocene maar is visible at 9:00. Associated phreatomagmatic deposits (Kelley and Kudo, 1978) are not visible across the river to the west. The maar was formed by magma that rose through (formerly) buried and saturated Santa Fe Group basin fill. The San Felipe volcano field is visible in the background at 9:00. Axial Rio Grande gravel are exposed at 3:00. **1.6**

44.5 Gravel pit to right and Santa Ana Mesa to your left. Notice the prominent down-to-the-west Algodones fault that offsets the basalts of San Felipe Mesa. The basalts of San Felipe volcanic field have been dated as 2.5 ± 0.3 Ma (K-Ar date; Bachman and Mehnert, 1978) and more recently as 2.411 ± 0.03 Ma and 2.60 ± 0.15 Ma (Ar-Ar date; McIntosh, unpublished data). The basalts overlie basal surge deposits, axial stream gravel of the ancestral Rio Grande, and reddish sand and gravel derived from the ancestral Rio Jemez drainage. In the northern part of Santa Ana Mesa, the basalts are interbedded with volcaniclastic deposits of the Cochiti Formation (Cather and Connell, 1998). Younger piedmont alluvial gravel of the Lookout Park Formation (out of view to the west; Smith and Kuhle, 1998) as well as axial-stream deposits of the Sierra Ladrones Formation, overlie the basalts. Recent recognition of various piedmont-derived gravel challenges the traditional, simpler view that basalts in the middle Rio Grande valley flowed across a regional Pliocene erosion surface defined as the Ortiz pediment (Johnson, 1903; Ogilvie, 1905; Kelley, 1977). Local detailed mapping convincingly shows that numerous regional unconformities and subsequent burial by axial stream and/or piedmont-derived gravel is common in the rift during see-saw-like subsidence of the rift basins (Smith and Kuhle, 1998). **0.7**

45.2 Cross the valley of Las Huertas Creek. Here, its flow is ephemeral. **1.1**

46.3 Continue on I-25 passing the Algodones exit (Exit 248). First settled in 1839, the village of Algodones (Spanish for "cotton") probably derived its name from the cottonwood trees in this area. The hummocky topography flanking the basalt flows of Santa Ana Mesa consists of Pleistocene slumps and landslides. **1.2**

CERROS DEL RIO VOLCANIC FIELD

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The Cerros del Rio volcanic field (CRVF; Fig. 1.12) is located west of Santa Fe, New Mexico and covers over 800 km^2. The field is located on the margin of the Española basin where a right-lateral offset separates the Española and Santo Domingo basins of the Rio Grande rift. The CRVF is adjacent to the Jemez Volcanic Field, but considered to be a distinctly separate field. The upper Tshirege Member of the Bandelier Tuff (1.4 Ma., Bailey et al., 1969) overlies the distal northern edge of the CRVF flows in the White Rock Canyon area. The field is truncated by an abrupt 160-m escarpment on the southwest, along La Bajada fault. To the east, the base of the CRVF flows is visible where it overlies the Pojoaque Member of the Tesuque Formation. The volcanic section thins to 30 m to the east and to 3 m to the southeast, while to the north and northwest, along White Rock Canyon, the exposed section is consistently 300 m thick. The northwestern margin of the flow field appears to be about 2 km west of the present Rio Grande beneath the Bandelier Tuff. This distribution pattern implies that the flows filled in a topographic depression in the vicinity of the modern White Rock Canyon. The CRVF was first studied in the 1970s (Aubele, 1978a, b; 1979), including detailed mapping and petrology and first recognition of the maars of White Rock Canyon (Aubele, et al, 1976). Subsequent geochemical studies (Baldridge, 1979; Duncker, 1988; Duncker et al., 1991), geologic mapping west of White Rock Canyon (Dethier, 1997) and a field guide to the maars of White Rock Canyon (Heiken, et al, 1996) have added to the understanding of this field.

Unless otherwise attributed, the following is summarized from detailed mapping by Aubele (1978a). Approximately 60 volcanic vents have been identified within the CRVF; and most are marked by cinder-spatter cones. Intrusions include several volcanic necks, several dikes consistently trending to the northeast, and at least one shallow sill exposed on the east side of White Rock Canyon. Phreatomagmatic eruptions occurred throughout the activity of the field and several well-exposed maars, tuff rings and tuff cones have been identified within the field. White Rock Canyon, 300-m deep, has exposed a thick sequence of intercalated maar deposits, lake beds, river gravels, basaltic intrusions, and early hawaiite lava flows, with some repetition of lava flow units due to toreva block faulting. Because of extensive landslides, the

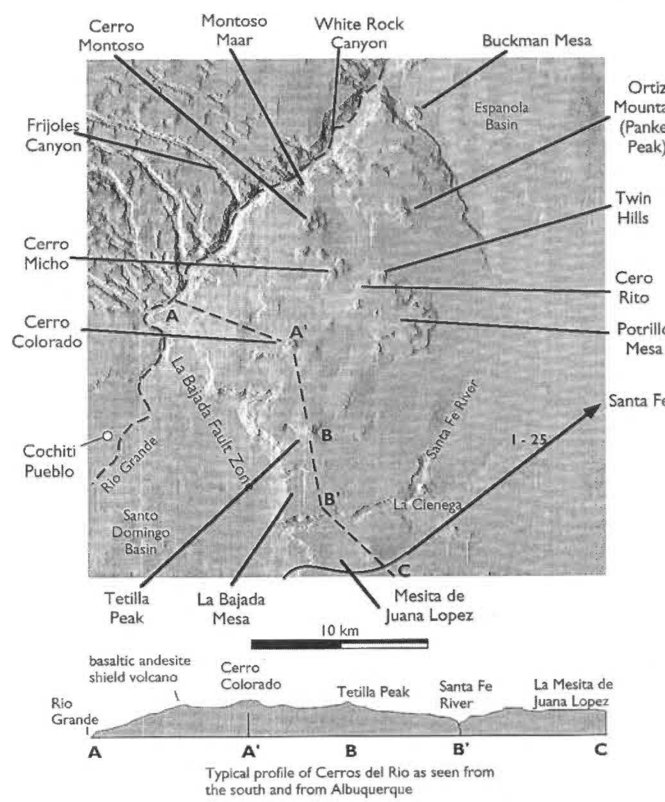

FIGURE 1.12. Digital topography shaded relief map and cross section of the Cerros del Rio volcanic field.

maar deposits of White Rock Canyon are best seen in side canyons. The source of the deposits is a line of vents that appear to have followed a NE trend parallel to the present river. At least 5 well-exposed vents have been identified in side canyons, in Caja del Rio Canyon near Buckman Mesa (Aubele, 1978a) and at La Mesita (Heiken et al., 1996). One of the more unusual vents in this field is Montoso Maar (Aubele, et al., 1976; Aubele,1978a, b; 1979), which has been dissected to a depth of 200 m on the east side of White Rock Canyon, and reveals a complete section of its internal stratigraphy and ring fracture zone. The abundant phreatomagmatic deposits in and near White Rock Canyon have been interpreted as evidence of a through-going drainage in the area at the time of the eruptive activity of the CRVF.

The extrusive rocks of the CRVF predominantly consist of alkali basalt (hawaiite), basaltic andesite and andesite (based on whole-rock major-element oxides and using standard classification systems for volcanic rocks). Dominant extrusive activity in the field apparently began with extensive hawaiite flows that now form the north and south margins of the field (Aubele, 1978a, b; 1979; Duncker, 1988; Dethier, 1997). Eroded remnants of early cinder cones and phreatomagmatic eruptions are exposed in and near White Rock Canyon. This activity was followed by eruptions of calc-alkalic andesite forming highly visible "flow-domes" resembling flat-topped mesas with abrupt convex slopes of an average height of 67 m and stubby flow-lobes. Ortiz Mountain and Potrillo Mesa are examples. During and following the andesitic eruptions, extrusions of hawaiite (example, Cerro Rito) and basaltic andesite (example, Cerro Micho) occurred along a zone of vents trending NW–SE in the center of the field. Late-stage cinder cones were erupted during the final activity of many vents, including the andesite flow-domes (example, Colorado Peak). The oldest exposed flow unit (hawaiite) in the north has been dated at 2.6 ± 0.4 Ma. and one of the two stratigraphically youngest flows in the field, the hawaiite of the Twin Hills, has been dated at 2.5 ± 0.2 Ma (Bachman and Mehnert, 1978).

Exposures of tholeiite, identified only on the west side of White Rock Canyon, have led Dethier (1997) to postulate a tholeiitic shield volcano west of the Rio Grande beneath the Bandelier Tuff. It is unclear where this volcano occurs stratigraphically in the history of the field because it does not directly contact any unit mapped to a source vent east of the canyon. Rounded andesine and quartz phenocrysts (the quartz is always surrounded by small acicular clinopyroxene) occur in all of the rocks of the field with the exception of the three youngest hawaiite flows, and are interpreted to be the result of crustal contamination. Some contamination of the evolved lavas of the CRVF is probable, but there is no strong evidence that this contamination was responsible for their origin (Duncker et al., 1991).

The upper member of the Bandelier Tuff overlies the hawaiite west of White Rock Canyon and is exposed in one location on the east side. Here, an eroded valley in the hawaiite served as a channel for the tuff, which contacts the underlying basalt and ash unconformably and appears to lap up on the east wall of the canyon. Extensive airfall deposition of ash and pumice from the Valles eruption must have covered the entire Cerros del Rio field; and probably helped to preserve some of the original volcanic landforms while contributing to the development of Quaternary soils in the area. In most cases, this blanket of pumice and ash has been eroded and redeposited in low-lying areas.

The landforms visible in the CRVF represent primary volcanic flow and edifice topography, with a total depth of erosion estimated to be 30–80 cm. However, in a larger sense, the CRVF offers a way to reconstruct the structural, temporal, and topographic implications of basin subsidence and erosion in the Santo Domingo and Española basins. The fan and stream deposits of the Santo Domingo basin adjacent to La Bajada overlie basalt flows that dip toward the east at about 10°. Projected extension of these flows positions them about 660 m below the basalt capping Mesa Negra de la Bajada, the southernmost flows of the CRVF. Since the mesa is bounded on the west by La Bajada fault, it seems reasonable to suggest that the basalt was displaced downward to the west by movement along the fault. To the east, continued subsidence of the Española basin may be inferred by steeper dips measured in the Pojoaque Formation than those seen in the CRVF flows that overlay the Pojoaque. Through-going streams in the vicinity of the modern Rio Grande and Santa Fe River were truncated by the subsidence of the basins and eastward tilting of the uplifted block of volcanic rock to the east of La Bajada. Ponding of the drainage, which once flowed southwest, occurred in the Cienega and White Rock Canyon areas. The Rio Grande and Santa Fe River reacted to the change in base level by cutting narrow gorges. The Rio Grande, trapped between the lava flows of the CRVF and the Bandelier Tuff began to downcut to form White Rock Canyon within the last 1 Ma. Where the uplift was steepest, close to the fault zone, the canyon became narrow and deep. To the north, the river was able to meander and the canyon widened. The Santa Fe River moved to the south around the volcanic field to meet the reestablished Rio Grande.

The Cerros del Rio volcanic field is notable because of its location within the Rio Grande rift at a point where the rift is offset. The unusual combination of alkali basalt and andesite may be due to the location of the field at the rift offset. The northwest-trending line of vents that dominantly erupted hawaiite may reflect a flexure line between the rift's subsiding basins. Extensional fractures would be logical conduits for the rapid rise of alkalic magma from deep sources. The CRVF is also notable because it records the complex interaction between the Rio Grande and recent volcanism. The Rio Grande cut the present White Rock Canyon within the past 1 Ma., but the long history of aggradation of fluvial sediments, down-cutting by the river, and deposition of volcanic material, as well as tectonic activity associated with the rift basins, has resulted in a complex, vertically stacked volcanic field.

47.5 The highway straddles a boundary between predominantly piedmont-derived facies to the east and predominantly axial stream facies of the Santa Fe Group to the west. **1.2**

48.7 Cross several down-to-the-west faults that are part of the Santa Ana accommodation zone. Kelley (1977) does not name these specific faults, but they strike slightly east of north as splays off of his Valley View fault that we passed at Mile 19.5. **0.3**

49.0 Ascend a hill underlain by gently north-dipping axial sand and gravel of the Sierra Ladrones Formation. **1.5**

50.5 Crest of hill. Note good exposures of the gray-colored axial stream facies of the Sierra Ladrones Formation overlain by brownish-colored, eastern piedmont-derived facies. Locally, these piedmont facies carry a dark, manganese-rich cement and surficial stain. **0.5**

51.0 **Leave I-25 at San Felipe Pueblo exit** (Exit 252), **exit to right**. **0.3**

51.3 **Turn right** at stop sign onto Hagan Road. Proceed straight (east) at the casino (east). **0.2**

51.5 Pavement ends, proceed straight (east) on dirt road (**stay right** around chain-link fenced area) up Tonque Arroyo drainage in relatively flat-lying strata of the Santa Fe Group. **0.3**

51.8 Note prominent white ash (Guaje; 1.57 ± 0.06 Ma; Bill McIntosh, personal commun., April 1999) in Santa Fe Group to right. **0.6**

52.4 Ortiz Mountains at 12:00. Dirt road curves left. This curve marks the easternmost limit of axial stream facies of the Santa Fe Group (Cather and Connell, 1998). The western limit of axial facies at this latitude lie beneath the basalts of Santa Ana Mesa. **0.2**

52.6 Terrace of Tonque Arroyo is well exposed to the left across the arroyo. **0.4**

53.0 Tonque Arroyo and gypsum mine are visible ahead in footwall of San Francisco fault. Gypsum mine is in

Middle Jurassic Todilto Formation, the source of most of the gypsum being commercially mined in New Mexico (Weber and Kottlowski, 1959; Austin and Barker, 1998). Lower, dark gray limestone (Luciano Mesa Member) of the Todilto Formation is also present here. **0.5**

53.5 Cross Tonque Arroyo. **0.2**

53.7 Exposures of arroyo alluvium to the left. **0.5**

54.2 Badlands and hoodoos developed in Santa Fe Group at 3:00. **0.1**

54.3 **Turn right** as the road forks. **0.1**

54.4 Terrace gravel to the left capped by piedmont alluvium derived from reworked Todilto Formation. **0.2**

54.6 Cross the San Francisco fault at a highly oblique angle. The fault strikes between the slightly indurated Santa Fe Group and Todilto Formation in slope at 9:00. The throw on the fault at this point is thought to be in excess of 14,700 ft. Triassic Chinle Group, Jurassic Entrada Formation, and Jurassic Todilto Formation exposed in escarpment to left. To right is reddish brown Triassic Chinle Group (Petrified Forest Formation) in wall of Tonque Arroyo and overlying orange sandstone/siltstone of the Dewey Bridge Member of the Entrada Sandstone. **0.2**

54.8 Dark red beds of Chinle Petrified Forest Formation to right in Tonque Arroyo. **0.1**

54.9 Jurassic Todilto Formation in roadcuts. The sharp contact between the Jurassic Entrada Sandstone and limestone of basal Todilto Formation can be seen on the north side of the road. **0.5**

55.4 Traverse a Holocene terrace of Tonque Arroyo. **0.3**

55.7 Road meets Salt Wash Member of Morrison Formation on left. Native American petroglyphs are preserved above on the cliff faces. **0.3**

56.0 Cross Tonque Arroyo. **0.3**

56.3 **STOP 4**—The Triassic and Jurassic section (Fig. 1.13). The purpose of this stop is to observe a well-exposed portion of the Mesozoic section represented by the Triassic Chinle Group through the Middle Jurassic Todilto Formation. This stop requires a moderately strenuous walk. ***NOTE:*** *Permission to observe the rocks at this stop must be obtained from Diamond Tail Ranch. The Diamond Tail property here borders San Felipe Pueblo and it is important not to enter Pueblo land without expressed written permission from the Governor and tribal council.* We will walk about 0.6 mi south to the hogback held up by the Jurassic Todilto Formation. Along the way, our path takes us down section into Tonque Arroyo and across the base of the Cretaceous represented here by the Mancos Formation, which unfortunately is not well exposed. The Mancos Formation represents maximum marine flooding associated with the Cretaceous interior seaway.

The yellowish-colored sandstones (~110–205 ft thick) that rise on the far side of the arroyo wall are the Jurassic Salt Wash Member of the Morrison Formation. Continuing to the south takes you down section through the yellowish sandstones into buff-colored sandstones overlying maroon-colored shale of the Summerville Formation. Picking a Salt Wash-Summerville contact here (Fig. 1.14) is a useful field exercise. Upper Summerville sandstones are much finer grained and lack the pebbles characteristic of basal Morrison (Salt Wash Member). This Summerville-Morrison contact is thought to be a regional unconformity of relatively short (within a single stage) duration.

Vertebrae and teeth of the Jurassic sauropod dinosaur *Camarasaurus grandis* have been recovered from the Summerville in the Hagan basin (Pigman and Lucas, 1989; Lucas et al., 1995). We continue to weave through little slot canyons incised in the lower Salt Wash Member and upper Summerville sandstones where cultural horizons (hearths) are locally preserved in the arroyo fills plastered against the arroyo walls. The trail takes us out of the little canyons and onto the dipslope of the ridge here underlain by red beds of the Jurassic Summerville Formation (138–154 ft). We continue down section through the Summerville Formation to the ridge crest where the gypsum and limestone members of the Todilto Formation are well exposed. Beneath the Todilto Formation is the yellow and orange-colored Entrada

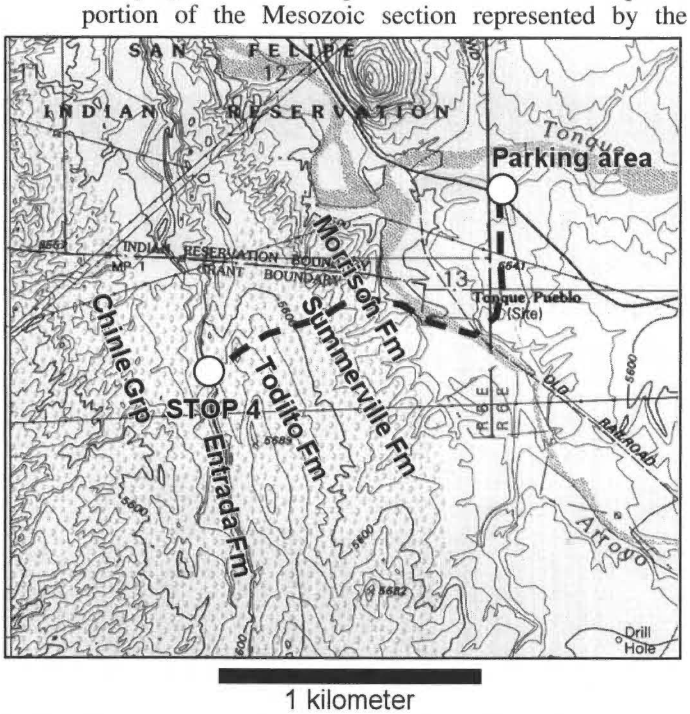

FIGURE 1.13. Annotated topographic map showing walking path of Stop 4.

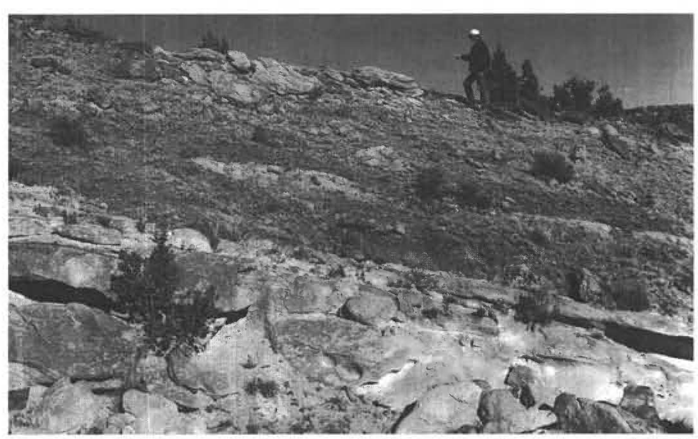

FIGURE 1.14. Photograph of a part of the Mesozoic section exposed at Stop 4. Man is standing on basal coarse-to-pebbly fluvial sandstone of Salt Wash Member of Morrison Formation. Light-colored sandstones in foreground are in upper part of Summerville Formation.

FIGURE 1.15. Panoramic view of Upper Triassic, Middle Jurassic and Upper Jurassic strata to northwest of Stop 4. From left, units are Chinle Group (in strike valley), Entrada Sandstone and Todilto Formation (strike ridge beneath power poles), Summerville Formation (middle ground), and Morrison Formation (buttes on right side of the photo).

Sandstone (~130 ft). The broad strike valley in front of you to the south is underlain by the maroon-colored Chinle Group. As you look southward from the stop, you see the crest of Cuchilla de San Francisco, which is the north-dipping cuesta held up by the Agua Zarca Formation of the Chinle Group. Beyond that cuesta, to the south, is our previous stop close to the Pennsylvanian-Permian boundary. Thus, between the two stops is a single, essentially homoclinally dipping section of Pennsylvanian through Middle Jurassic strata (Fig. 1.15).

By Late Triassic time, New Mexico was about 10°N of the paleoequator as a result of the continued northward drift of the Pangean supercontinent (Plate I). The state, as mentioned earlier, was wholly continental, and covered by floodplains. These rivers flowed north northwesterly from the rift shoulder of the opening Gulf of Mexico basin to a western Pangean shoreline that closely approximated the present Nevada-Utah state line. The thick (up to 1970 ft thick) succession of siliciclastic red beds deposited by these rivers is the Chinle Group.

Late Triassic climates across Pangea have been termed "megamonsoonal" (Dubiel et al., 1991). With the Pangean landmass centered near the equator during the Triassic, and with a prominent Tethyan bight, climate models suggest a truly monsoonal climate of only two seasons, wet and dry (Plate L). The abundant rainfall was concentrated in the summer months, and there was little annual temperature fluctuation. During the Northern Hemisphere summer, the northern landmass would have become relatively hot, whereas the southern landmass would have been relatively cool. Moisture from Tethys would have been pulled into the Northern Hemisphere low-pressure cell, producing extensive rains, whereas the Southern Hemisphere high-pressure cell would have remained relatively dry. During the Southern-Hemisphere summer this process would have occurred in reverse. Thus, seasonality across Triassic Pangea would have been alternating, hemisphere-wide wet and dry seasons.

During the Jurassic, as Pangea rapidly fragmented, North America rapidly drifted northward (Plate J). By Middle Jurassic time, New Mexico was well north in the belt of northeast trade winds (about 20° N) (Plate L). Here in the Hagan basin, as well as across New Mexico, there is a substantial hiatus (about 40 Ma) between the youngest Triassic rocks of the Chinle Group and overlying Middle Jurassic eolianites of the Entrada Sandstone.

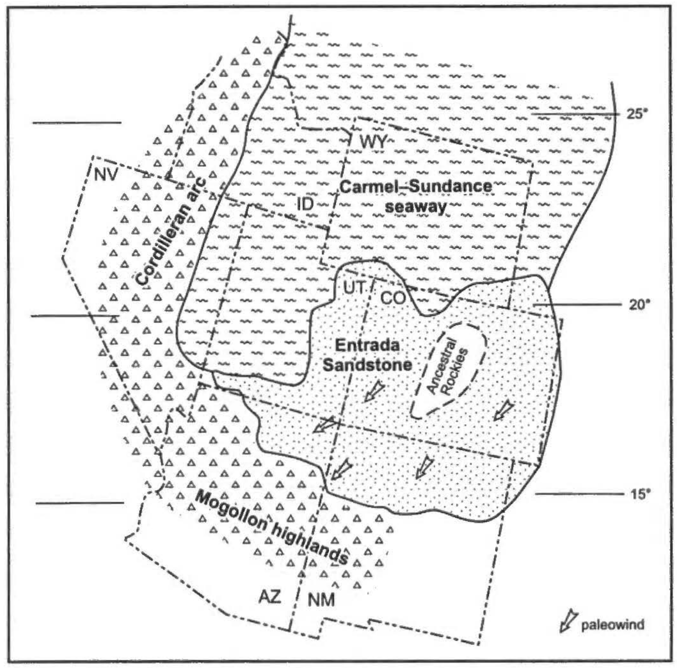

FIGURE 1.16. Paleogeography of the Western Interior during deposition of the Middle Jurassic (Callovian) Entrada Sandstone (modified from Lucas and Anderson, 1996).

Entrada deposition took place in a vast sand sea that extended from southeastern Utah across Colorado, northeastern Arizona, and northern New Mexico into western Oklahoma (Fig. 1.16). Wind directions were dominantly to the southwest.

The Entrada section here belongs to the Dewey Bridge (lower) and Slick Rock (upper) members. Dewey Bridge deposits are mostly ripple-laminated and bioturbated red-bed siltstone and very fine-grained sandstone. They may have initially been eolian deposits, but have obviously been worked or reworked by water. This aqueous deposition of the Dewey Bridge Member is thought to reflect the maximum transgression of the Carmel seaway. This raised regional base level high enough that the early phase of the Entrada erg (Dewey Bridge Member) was not wholly eolian in origin.

However, later Entrada deposition of the Slick Rock Member was wholly eolian. The well-sorted yellow sandstones of the Slick Rock Member usually display large-scale trough crossbeds and are a classic dune field eolianite.

Near the end of Entrada deposition, a second transgression of the Cordilleran seaway took place. This was the Curtis transgression of middle Callovian time, and it resulted in the formation of a vast salina basin that extended across northern New Mexico from the Four Corners region to near Santa Rosa in Guadalupe County (Fig. 1.17). The shallow saline lake thus formed had a maximum surface area of about 34,000 mi^2 and led to deposition of the Todilto Formation (Kirkland et al., 1995). Early deposition produced up to 43 ft of thinly laminated kerogenic limestone, the Luciano Mesa Member of the Todilto. Drying out of the salina basin produced a thick pile (up to 200 ft thick) of evaporite gypsum, the Tonque Arroyo Member.

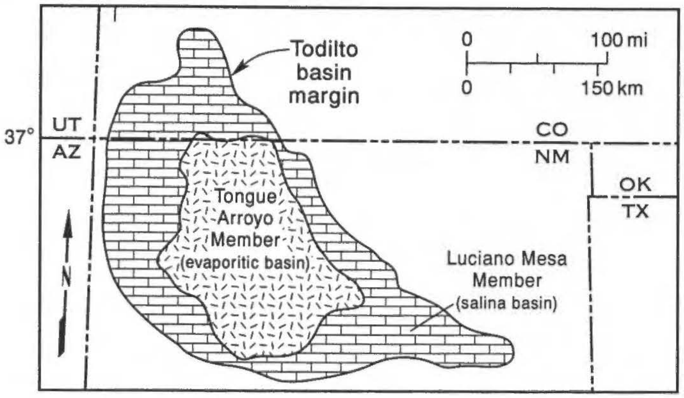

FIGURE 1.17. Extent of the Middle Jurassic Todilto salina basin (after Lucas and Anderson, 1996).

FIGURE 1.18. Photograph of oil saturated and stained Entrada Sandstone cropping out in Arroyo Cuchillo at the south end of the Hagan embayment. Hammer handle points to area of greatest saturation.

HYDROCARBON INDICATIONS IN THE ENTRADA SANDSTONE AND THE TODILTO FORMATION ON THE OUTCROP IN THE HAGAN EMBAYMENT

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While drilling the first oil and gas test in the southern part of the Hagan embayment in July 1976, the writer visited several outcrops in Arroyo Cuchillo 2.0 mi south of the drilling well. In the southern part of sec. 2, T12N, R6E a large north-trending, west-dipping, normal fault, which we called the Bicentennial fault, is exposed at this location. At the arroyo bottom this fault juxtaposes the Cretaceous Mancos Shale down against the Jurassic Entrada Sandstone and the Todilto Formation. Although generally covered, this fault can also be found near the center of sec. 11 in several arroyo exposures. On the up-thrown footwall block of the fault, both south and north of Arroyo Cuchillo, oil-stained Entrada Sandstone and Todilto limestones and anhydrites are dragged down into the fault zone and locally exposed in several areas for over 0.5 mi along the fault's trend (Fig. 1.18).

At these locations the Entrada Sandstone is often stained dark brown to dark gray with dead oil saturation. Most of this staining and dead residual oil saturation is found near the contact with the overlying

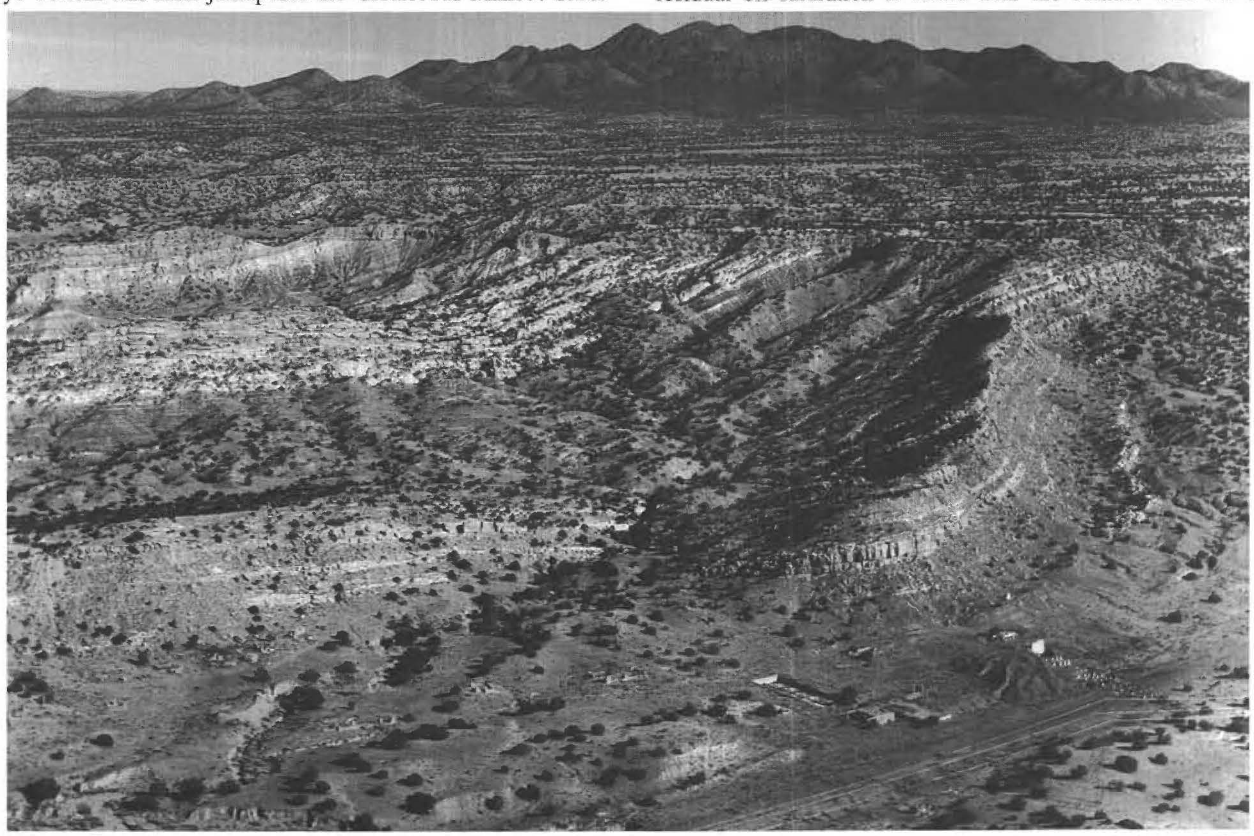

FIGURE 1.19. Aerial photograph looking toward the Ortiz Mountains (NE) and encompassing the area of Stop 6. The buildings in lower right foreground are the ruins of the town of Hagan. Hagan was settled in the strike valley underlain by Mancos shale. Coal was mined from the Menefee Formation, fluvial sandstones which hold up the first large, light-colored ridge behind the town. To reach Stop 6 the field trip will follow the arroyo (lower left part of the photo) through the Menefee Formation and remainder of the Mesa Verde Group (Cretaceous) up to the upper contact between the second light-colored ridge, and dark-colored shales. This is the Mesa Verde Group-Diamond Tail Fm (Cretaceous–Eocene) contact. The Galisteo Fm rises as the third light-colored ridge in the middle background. Note the distinct unconformity formed by the Ortiz pediment, truncating the dipping Mesozoic and early Cenozoic rocks, and buried by the Tuerto Formation. (photo taken by J. W. Estep).

Todilto Limestone, but has been found as far as 13 ft below the contact, and commonly along fractures and small faults in the Entrada Formation (Fig. 1.19). In some areas the residual dead oil saturation is relatively uniform and in other locations it is confined to zones of better porosity in the sandstone. Much of the outcropping Entrada Formation is bleached white on the surface in this area and may indicate oxidation and bleaching of residual oil from continued exposure on the outcrop.

When first observed the staining was believed to be from manganese or other minerals. However, the interstices between the sand grains, when viewed with the hand lens and under the microscope, reveal that the pore spaces are clogged with dead oil, and the stained sands are cut with chlorathane. The cut yields a weak to strong, slow milky white to pale yellow cut fluorescence, and leaves a pale milky white to yellow fluorescence ring on the cut plate.

The writer believes this occurrence of oil in the Entrada Formation is due to movable oil that migrated up the adjacent fault zone in the past from deeper in the section. The oil has selectively moved out into the porous zones in the Entrada Formation adjacent to the fault. On the outcrop it appears to be more indicative of an exhumed migration path of hydrocarbons, than a previously extensive oil accumulation. In either event, it is significant in that it proves movable hydrocarbons have been generated and were migrating in this part of the Hagan embayment at some time in the past, and it is an encouraging sign for oil and gas explorationists.

In addition to the interesting oil shows in the area is an unusual facies of limestone found in the Todilto Limestone above the Entrada Formation. Just above the usual thin, organic-rich, laminated, black and organic-rich limestone beds that usually overlie the Entrada Formation, there are also what appears to be small buildups and beds of dark brown limestone grainstone debris (or possible algal plate(?) reefal buildups) with high porosity. This unusual facies is always found about 3.5 ft above the Entrada and is also sometimes oil stained and cut.

This facies has not been studied in detail, but is probably a secondary limestone micro-breccia derived from differential solution of the thick overlying anhydrite beds that are interbedded with laminated limestone. These beds and pods shrink and swell along the outcrop and get as thick as 8 ft locally. If this type of bedding were present over an extensive area in the subsurface it would probably provide an excellent oil or gas reservoir. The individual limestone particles are self-supporting and are only loosely cemented where observed on the outcrop.

A second interesting hydrocarbon occurrence is found at the north end of the Hagan embayment at the gypsum quarry and along the county road just west of the quarry in the southeast quarter of sec. 36, T14 N, R5E (Mile 54.6 on the road log). Here, chunks of Todilto anhydrite and limestone can locally be found with heavy sticky black oil and tar, and tar stains in fractures and on bedding planes on both the outcrop and in loose blocks lying along the road. The mining operations in the quarry have conveniently blown chunks of the rock out and beyond the quarry proper where it now liters both sides of the road. Most of the oil-stained samples have been found here in the easy to reach road right of way.

The low-viscosity oil and tar is abundant enough in some samples to readily stain your hands while handling the samples. It is probable that this heavy black oil and tar were generated in-situ from the organic-rich, black-laminated limestones of the basal Todilto Limestone during the time of greatest depth of burial and prior to the uplift and tilting of the western flank of the embayment. No typing of the oil has been attempted on these small samples. It is highly likely however, that it would have a similar PNA profile as the low-viscosity oils being produced from the Entrada Formation oil fields in the San Juan Basin, and which have been shown to have been sourced from the Todilto Limestone.

These surface shows and the numerous shows of oil and gas from the Cretaceous and Jurassic rocks in the few wells that have been drilled in the basin are not surprising. The presence of source rocks in both the Jurassic Todilto Limestone and the Cretaceous Mancos Shale, combined with the history of deep burial and favorable maturation, suggest the Hagan embayment will continue to be an attractive frontier exploration target for oil and gas in the future.

After the stop, retrace your hike, reload buses, and continue northeast on the county dirt road toward Hagan. **0.1**

56.3 Ruins of Tonque Pueblo and a former brick-making operation to your right. The road here traverses poorly exposed Mancos Formation. The Mancos Formation in the Hagan basin is characterized by approximately 660 ft of a black fissile shale, overlain by the 20-ft-thick Semilla Sandstone followed by another 65 ft of dark shale leading up to the fossiliferous, calcareous Juana Lopez Member. Approximately 200 ft of dark shale overlying the Juana Lopez Member contains a paraconformity, placing about 20 ft of El Vado (Fort Hays Member[?]) sandstone and 590 ft of dark gray, calcareous Niobrara Formation over the lower portion of the Mancos Formation. A complete, well-exposed section of the Mancos Formation is difficult to find in the Hagan basin as the section is both tectonically thinned and commonly lies beneath arroyos in strike valleys. Deposition of the Mancos Formation represents maximum transgression of the Late Cretaceous seas into New Mexico during global greenhouse conditions. **0.2**

56.5 A thick, Quaternary eolian mantle, exposed here, locally blankets the bedrock. Note Espinaso Ridge, the destination for Optional Stop 7. **0.2**

56.7 Cross the down-to-the-west Diamond Tail fault, placing younger Niobrara Formation in the hanging wall against lower Mancos Formation in the footwall ahead of you. The fault is covered by alluvium at this point, but is well exposed along its strike in arroyo cuts to both the north and south. **0.4**

57.1 Diamond Tail Ranch, on the left. Approximately 2 mi to the north, Union Carbide explored for uranium in the Eocene Galisteo Formation in the 1970s, abandoning the project in the 1980s due to high production costs. The deposits are low grade and consist of uraninite and coffinite sand coatings in roll-front deposits in the fluvial sandstones of the Galisteo Formation. No uranium has actually been produced from this region; however, oil shows found in some of the core holes sparked the first oil and gas tests drilled in this basin (Black, this volume). **0.5**

URANIUM-SELENIUM DEPOSITS IN THE GALISTEO FORMATION, HAGAN BASIN, SANDOVAL COUNTY, NEW MEXICO

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Uranium was first discovered in the Hagan basin in November 1954 by an U.S. Atomic Energy Commission (AEC) aerial radiometric survey (U.S. AEC, 1966, p. 50; Chenoweth, 1979). Although there has been no uranium or selenium production from these deposits, there has been considerable exploration. George Giranudo and W. S. Jackson staked the We Hope and Rabac claims (sec. 19, 30, 31, 32, T14N, R16E, sec. 4, 5, 6, 8, 9, T13N, R6E) soon after the aerial radiometric survey results were released and began surface sampling. During 1958, the McGraw-Hughs Petroleum Company drilled in the area and blocked out 330,000 mt of ore containing 0.26% U_3O_8. The Dial

Exploration Company also began drilling in the Hagan basin for uranium in 1958 and continued until the early 1960s. In 1958, the company reported an ore body of 12,000 mt of 0.31% U_3O_8. The uranium market became depressed in the late 1950s, and the company began examining the potential for selenium. In 1960, the company reported reserves of 1.1 million mt of ore containing 0.03–0.05% Se and 275,000 mt of ore containing 0.05–0.1% Se (U.S. AEC, unpublished memorandum, 24 November 1960).

Union Carbide Corp. Metals Division acquired the property in the mid-1970s. Later exploration drilling by Union Carbide Corp. estimated reserves at the Diamond Tail deposit (sec. 16, T13N, R6E) as 410,000 kg of uranium at a grade of 0.09% U_3O_8 at depths of approximately 3–120 m (Moore, 1979). Additional mineralized zones exist in secs. 9 and 16, T13N, R6E (Moore, 1979, fig. 1). The Diamond Tail decline was driven in 1977 to test underground mining conditions and to provide ore for metallurgical testing. The decline is 90 m long at an angle of approximately 19°. Union Carbide also planned to extract uranium by in-situ leaching technology using sulfuric acid. Changing economic conditions forced Union Carbide Corp. to suspend mining plans of this deposit in 1980. Many of the drill logs are on file at the NMBMMR Petroleum Library.

Uranium occurs as several roll-front-sandstone bodies within high-energy, braided-stream deposits of a complex alluvial fan sequence in the Galisteo Formation (Eocene). The Galisteo Formation consists of 261–1295 m of red to white mudstone, sandstone, and conglomerate and ranges in thickness from 275 to 1200 m (Gorham and Ingersoll, 1979). It rests unconformably on the Cretaceous Mancos Shale and is conformably overlain by the Espinaso Formation. Uranium-bearing latite dikes and sills, probably related to the overlying Espinaso Formation intrude the Galisteo Formation in the area (Chenoweth, 1979; McLemore, 1983). The Galisteo Formation was derived mostly from Laramide uplifts consisting of Proterozoic through Cretaceous rocks (Gorham and Ingersoll, 1979).

Uranium is associated with selenium, pyrite, and carbonaceous material in bleached, fine- to coarse-grained quartz sandstones. Molybdenum is locally common along the margins of the uranium deposits. The uranium deposits are typically within bleached gray–green–white sandstones and conglomerates with interbedded green mudstones and are surrounded by the red sandstones and conglomerates. The impermeable green mudstones may have helped confine the mineralizing fluids. Uraninite, coffinite, and uranophane occur as sand coatings in roll-type bodies (Moore, 1979). A sample of the ore pile at the Diamond Tail decline contained 0.064% U_3O_8 and a trace of Se (McLemore, 1983).

It is unlikely that the uranium-selenium deposits in the Hagan basin will be mined by conventional underground methods in the near future. However, the deposits may be amenable to uranium in-situ leaching, and as the market for uranium improves, exploration and testing in this area for uranium could resume.

57.6 Ruins on left are the old ghost town of Coyote, a former coal-mining town between 1904 and 1919. The mines were in the Menefee Formation that crops out east of the ruins. The road (in Mancos Shale) descends to Arroyo Coyote, a tributary to the larger Arroyo Uña de Gato. Note a low gravelly terrace to your right. **0.2**

57.8 Cross Arroyo Coyote and a down-to-the-southeast, northeast-striking normal fault that repeats the section recognized by offset strike valleys and ridges to the west. Ridges here are the Cretaceous marine Point Lookout Sandstone and the large nonmarine, fluvial "Harmon" sandstone in the Menefee Formation. This largely fluvial sandstone body near the base of the Menefee is easily mistaken for the Point Lookout, but its lack of marine fossils, its coarser and poorly sorted sands, abundant feldspar and fluvial cross beds, and its petrified-wood fragments, as well as its stratigraphic position above the main coal measures, identify it as a fluvial sand complex.

In contrast, the Point Lookout Sandstone is fossiliferous and here contains well-preserved shark teeth. The Point Lookout Sandstone represents a progradational marine package, sourced from poorly defined uplifted areas to the southwest, into the shoaled Cretaceous seas following Mancos Formation time. The marine facies are followed up section by coal-bearing, fluvial–deltaic and fluvial facies of the Menefee Formation. Small-scale transgressive and regressive cycles, particularly well preserved in the Point Lookout Sandstone, may indicate Milankovitch-scale (10^4–10^5 yrs), climatically driven variations in sediment supply (Wright, 1986). Larger-scale eustasy and poorly understood tectonic subsidence that cannot be directly attributed to Sevier orogeny foreland basin development accommodate the smaller-scale fluctuations in shoreline position caused by the variations in sediment supply. **0.2**

58.0 Cross Arroyo Coyote again. **0.1**

58.1 Drive up through the "Harmon" sandstone, which is above the main coal measures near the base of the Menefee. The Menefee contact with the underlying Point Lookout Sandstone is well exposed 1600 ft to the north where these rocks are truncated by the Diamond Tail fault. **0.2**

58.3 Cross Arroyo Coyote a third time. At this point you cross a covered east–northeast, down-to-the-north normal fault that offsets the strike valleys and ridges of the Menefee Formation to the east on the south side of the fault. **0.1**

58.4 Note in the roadcut to the left a down-to-the-east fault that places a Menefee Formation shale against a Menefee Formation sandstone. **0.3**

58.7 Road on strike valley in lower Menefee Formation; Point Lookout Sandstone underlies the ridge to your right. **0.5**

59.2 Menefee Formation on left. Gravelly terraces preserved along the stream valley walls. **0.2**

59.4 Note dark, thin, nearly vertical Tertiary dike exposed to left. Iron gate posts are on both sides of road and a windmill is to your right. The ridge to your left is capped by Galisteo Formation fluvial sandstone and conglomerate containing numerous petrified logs. **0.2**

59.7 Cross gully. **0.3**

59.9 Descend through the "Harmon" sandstone. **0.2**

60.1 Petroglyphs high on the cliff to left. **0.2**

60.3 Cross under power line. Another Tertiary dike is exposed on right and left. Dike is mapped as following an east–northeast-striking fault (Kelley and Northrop, 1975). Note flat-topped ridges in the immediate foreground. Some of ridge tops are concordant with the base of the Tuerto Formation that we will observe at Stop 6 (Fig. 1.19). **0.1**

60.4 **OPTIONAL STOP 5**—The Cretaceous section, The Dalton-Hosta turnaround, and the Diamond Tail fault (Fig. 1. 20). The purposes of this stop are: (1) to walk down section through a unique portion of the Cretaceous section and examine the cumulative structural effects of Laramide faulting and uplift of the Sandia block on the west-dipping Diamond Tail fault; and (2) discuss the constraints that the Dalton-Hosta pinchout places on Laramide dextral offset for this portion of the Rio Grande rift. This 1.25-mi-round-trip walking tour begins at the

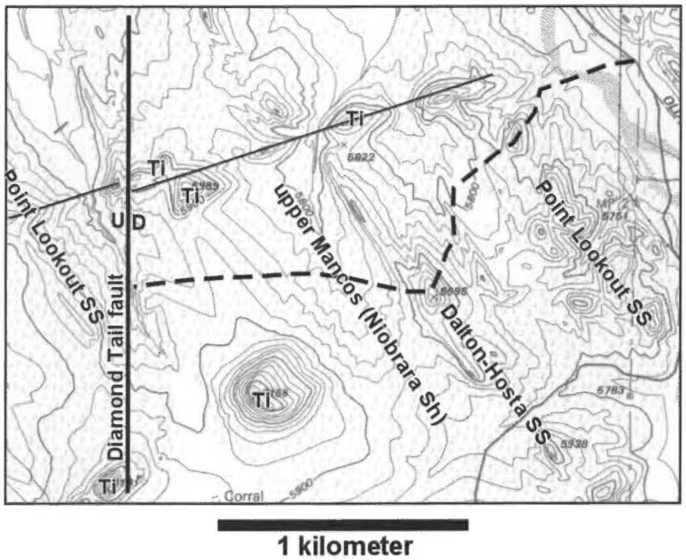

FIGURE 1.20. Annotated topographic map showing walking path for Optional Stop 5

windmill 660 ft west of Mile 60.4 and proceeds west across the alluviated valley of Arroyo Uña de Gato inset across the Menefee-Point Lookout Formation contact and up onto the hogback formed by the Point Lookout Sandstone. A description of the Point Lookout Sandstone can be found at Mile 57.8 of the road log.

By Late Cretaceous time, New Mexico was near its present latitude (Plate N). Worldwide sea level was at an all-time high, and an epeiric sea cut North America into western and eastern landmasses. New Mexico was on the eastern shoreline of the western landmass (a Cordilleran highland: Plate N), so that, in general, the eastern part of the state was sea, and the western part was land. The climate was warm, wet, and tropical (Plate Q).

From the top of the Point Lookout Formation ridge, descend through distal fringe sandstone and siltstone into the strike valley formed by the upper Mancos Shale. The next hogback to the west, formed by the merger of the transgressive Dalton and regressive Hosta sandstones, is reached by a 10-min walk. On the Dalton-Hosta hogback, we are far enough seaward that these two sandstones have merged into one marine-beach sandstone complex and cannot be identified as separate units. The hogback lacks the usual intervening nonmarine section between the sandstone bodies, so the transgressive and regressive packages are not easily recognized except near the transition into the marine shales that envelope them. In this area, there are an abundance of oyster reefs and abundant pelecypod fossil beds that yield numerous molds and casts. Very thin 2–4-in.-thick carbonaceous beds in the center of this sandstone complex reportedly have been seen approximately 2 mi to the southeast, and if present, may represent the last vestiges of the intervening Crevasse Canyon Formation nonmarine section in this part of New Mexico. The Hagan basin is a classic location in which to view the Dalton-Hosta turnaround and its associated paleontology and stratigraphy. These abundant beach sandstones thin to the north and within 4.5-mi pinchout completely. This pinchout is especially important structurally because as a piercing line, it helps place a maximum constraint on the amount of dextral movement that can have taken place across this portion of the Rio Grande in Laramide time (Woodward et al., 1997).

Continue your walk through the Dalton–Hosta sandstones for another 5 min and then descend into the strike valley of the lower Mancos Shale. As you cross the Mancos Shale (another 5 min) notice the ridge ahead of you with the light-colored sandstones. This ridge is underlain by the Point Lookout Sandstones and overlying Menefee Formation, again on the hanging wall of the westward-dipping Diamond Tail fault. As you walk west, you will cross the trace of the north-striking fault, and will walk from the Niobrara Formation into the Menefee Formation. The fault is well exposed in numerous small arroyo cuts at this location and dips 30–34° to the west. Selenite from the fault zone often marks the strike of the fault where it is covered between arroyos. The beds on both sides of the fault (outside of the drag zone) dip easterly at 30–35°. If these beds are rotated flat, it would produce an original dip of 60–70° on the Diamond Tail fault. (A discussion on the implications of this early to mid-Tertiary faulting on oil and gas exploration in the rift will be held here on the outcrop).

After the stop, return to the windmill and continue to Stop 6. **0.1**

60.5 Greater Hagan. Hagan is a former coal-mining town that prospered from 1902 to 1931. At the height of mining, some 500 people resided here. The last residents left the town in the 1950s. **0.1**

60.6 **STOP 6**—The Cretaceous, Eocene, and Pliocene(?) section (Fig. 1.21). The purposes of this stop are to: (1) walk through a portion of the Cretaceous section and across the unconformity at the base of the early Eocene Diamond Tail and Galisteo formations; and (2) observe the Ortiz pediment and associated Tuerto Formation. ***NOTE:*** *Permission to observe the rocks exposed at this stop must be obtained by Diamond Tail ranch.* This stop requires a 15-min moderately strenuous walk to the Diamond Tail and Galisteo formations, and another 10-min walk to the Tuerto Formation exposure.

By Eocene time, North America had become a single, integrated landmass after the Late Cretaceous–Paleocene final regression of the Western Interior epeiric seaway (Plate O). The Laramide orogeny was undergoing its final pulse, so that the Rocky Mountain foreland of the western United States was a complexly deformed region

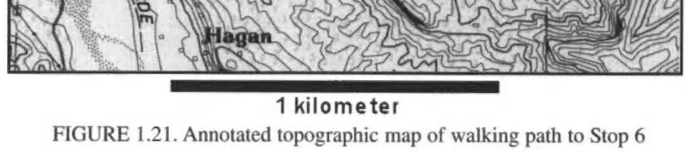

FIGURE 1.21. Annotated topographic map of walking path to Stop 6

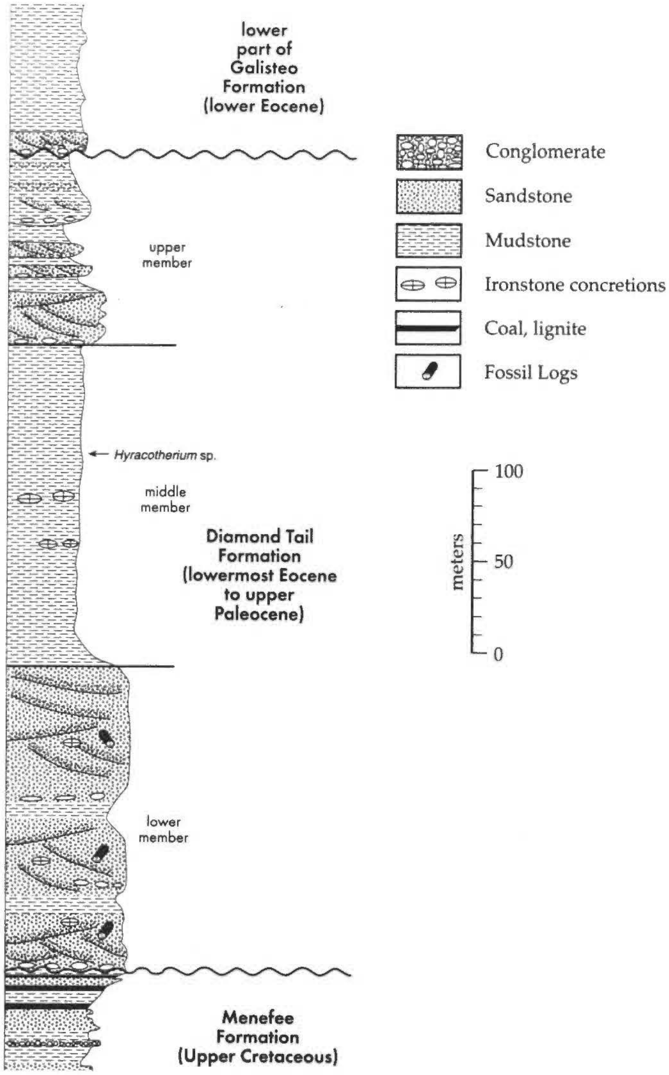

FIGURE 1.22. Measured section of the Diamond Tail and Galisteo formations at Stop 6 (from Lucas et al., 1997).

of basement-cored uplifts and adjoining fluvial–lacustrine basins. Warm, subtropical climates prevailed (Plate R), and siliciclastic red beds accumulated, such as those of the Diamond Tail and Galisteo formations seen at this stop.

At its type section, the Diamond Tail Formation is 1450 ft thick (Lucas et al., 1997; Fig. 1.22). It disconformably overlies coal-bearing strata of the Menefee Formation (Picha, 1982) and is disconformably overlain by the Galisteo Formation. Here, three informal members of the Diamond Tail Formation can be recognized.

The lower member is 540 ft thick and is mostly grayish-orange and yellowish-gray, medium- to coarse-grained, trough-crossbedded sandstone and conglomeratic sandstone. The sandstone is subarkosic to arkosic, and conglomerate clasts are dominantly quartzite and chert with a diameter of up to 0.2 in., although a few larger (up to 1.5-in. diameter) clasts are present. Thin beds and lenses of olive-gray mudstone are a minor constituent. Ironstone cannonball concretions are common; logs and fragments of silicified wood are locally present. This lower member of the Diamond Tail Formation at its type

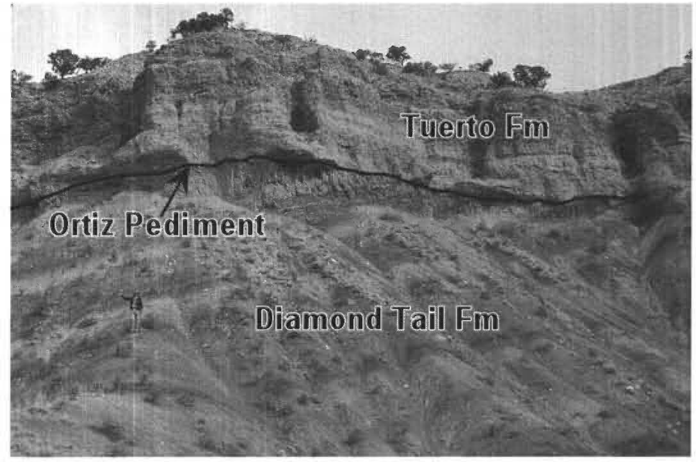

FIGURE 1.23. Annotated photograph of the Tuerto Formation, Ortiz pediment, and Diamond Tail Formation.

section forms a prominent hogback between strike valleys formed by Menefee coals, lignites, carbonaceous shales, and lenticular sandstones below and variegated mudstones of the middle member of the Diamond Tail Formation above. The basal contact is marked by a pronounced disconformity, with conglomeratic sandstone of the basal Diamond Tail Formation overlying fine-grained sandstone and carbonaceous shale of the Mesaverde Group. The middle member is 575 ft thick and forms a northwest-striking valley at the type section. It consists of variegated light olive to maroon mudstone and minor sandstone. Mudstones contain abundant sideritic concretions, many of which are cannonball shaped. The upper member of the Diamond Tail Formation at the type section is 330 ft of sandstone and mudstone similar in many features to the lower member. Sandstones are mostly subarkoses that are yellowish gray to grayish orange and trough crossbedded. Some sandstone beds are pebbly, with numerous clasts of gray-to-white quartzite with diameters of up to 0.2 in. Mudstone is a subordinate part of the unit and is greenish gray. The upper member forms a hogback together with overlying basal conglomerate and sandstone of the Galisteo Formation. The base of the Galisteo Formation is readily selected above the upper member at the base of a laterally continuous conglomerate that has a coarse-grained, subarkosic, very pale orange to pale yellowish-brown matrix. Clasts with diameters up to 1.5 in. consist mostly of chert, quartzite, and Paleozoic limestone and sandstone. Paleozoic clasts become much more abundant higher in the section.

Disconformably overlying the Galisteo Formation at this locality are approximately 32 ft of indurated Tuerto Formation gravel (Stearns, 1953a; Fig. 1.23). The Tuerto Formation represent an east-thickening interval of coarse sand and gravel sourced in the Ortiz Mountains. The gravels bury a regional, low-relief erosion surface or pediment ("conoplain" of Ogilvie, 1905) that extends in a rough conical pattern from the Ortiz Mountains, beveling the axis and faulted east limb of the synclinal Hagan basin (Fig. 1.24). The cutting of the pediment and deposition of the gravel may not be genetically related, but the advanced calcic soil development in the gravel at this location attest to great antiquity. A Pliocene or possibly late Miocene age is inferred by the burial of these gravel

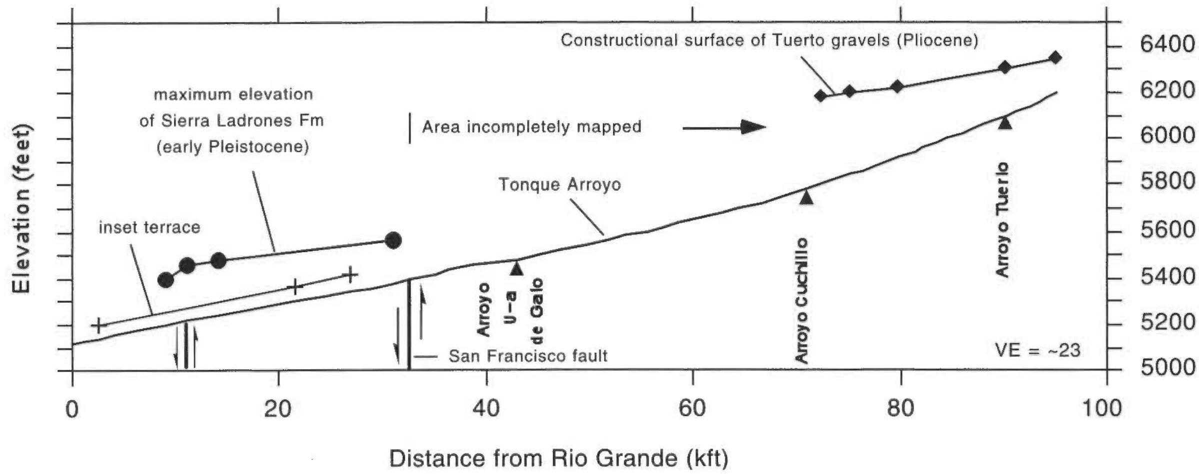

FIGURE 1.24. Preliminary long profile projection of the Tuerto Formation westward to the Santa Ana basalts (modified from Connell, in progress).

by basalt flows of the Cerros del Rio volcanic field northwest of Cerritos, NM, dated between 2.5 ± 0.2 and 2.8 ± 0.1 Ma (K-Ar dates; Bachman and Mehnert, 1978). Cutting of the Ortiz pediment was likely accomplished by unincised fluvial systems during a protracted period of base-level stability. In contrast, deposition of the Tuerto Formation represents a change in sediment supply, discharge, or both to necessarily steepen fluvial gradients through aggradation that buried the pediment. Such adjustments of fluvial systems are widely recognized across the southwest in the late Pliocene and have been hypothesized to be related to the climate changes accompanying the initiation of northern-hemisphere glaciation. However, if we accept the Bachman and Mehnert K-Ar dates for the Cerros del Rio basalts and the gravel buried by the basalt is truly the Tuerto gravel, deposition of the Tuerto gravel would have to significantly predate the first northern-hemisphere glaciation at 2.4 Ma. The Tuerto Formation gravels are auriferous, reflecting their Ortiz Mountain source. They have long been exploited by small-scale mining operations willing to import water for panning. In the absence of abundant local water, commercial hydraulic mining is not economically feasible. Ironically, Thomas Edison found that the gravels were too damp for electrostatic separation of the gold.

Well-exposed Quaternary deposits ranging from fine-grained, laminated silts to coarse-grained gravel are present along the hike to the Diamond Tail Formation. The laminated deposits are a facies not well represented in arroyos of the rift or Colorado Plateau. They may indicate recent large-magnitude floods and local slackwater deposition in this narrow bedrock canyon.

MULTISTAGE, MULTIDIRECTIONAL HORIZONTAL COMPRESSION DURING LARAMIDE AND MID-TERTIARY DEFORMATION EAST OF THE RIO GRANDE RIFT, NORTH-CENTRAL NEW MEXICO

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In recent years, no area of the Laramide foreland has been a greater focus for tectonic dispute than north-central New Mexico. Chapin and Cather (1981) proposed two stages of Laramide shortening, with the ENE-trending shortening followed by a second stage of NE-trending transpression which they linked to right-lateral slip and axial basin sedimentation paralleling the Neogene Rio Grande rift. Chapin (1983) tried to quantify the amount of right-lateral strike slip using separations of Precambrian lithologies and their aeromagnetic signatures. Karlstrom and Daniel (1993) and Daniel et al. (1995) summed these right-lateral separations and estimated 50–170 km of right-lateral slip in a zone of strike-slip faults paralleling the Rio Grande rift. Following the hypothesis of Chapin and Cather (1981), they concluded that the slip was probably Laramide in age.

In contrast, Dickinson et al. (1988) and Yin and Ingersoll (1997) contested the existence of a dual-phase record of sedimentation in Laramide basins. Yin and Ingersoll (1997) extrapolated evidence for unidirectional shortening in Wyoming (Paylor and Yin, 1993; Molzer and Erslev, 1995; Stone, 1995) and east-central Colorado (Erslev et al., 1996) to the rest of the foreland and proposed that axial basins represented synclinal troughs caught between converging thrusts. Woodward et al. (1997) questioned the use of right-lateral separations of Precambrian lithologies and magnetic anomalies to prove Laramide strike slip by showing that isopach maps of Mesozoic strata from McKee et al. (1956) show no right-lateral separations. In response, Cather (in press) compiled new isopach maps and interpreted the isopach patterns and pinch-out data for nine Mesozoic units as either permissive or supportive of significant right-lateral slip of Laramide age.

This paper will address the history of post-Cretaceous horizontal shortening and the possibility of distinct stages of Laramide deformation by summarizing minor fault patterns in north-central New Mexico. A more comprehensive paper covering faulting from both sides of the Rio Grande Rift is currently being prepared and will be available by the September field trip of the New Mexico Geologic Society.

Minor fault data were collected at 41 localities east of the Rio Grande Rift in northern New Mexico. Because this research focused on Laramide faulting, localities with rocks older than the Pennsylvanian-Permian Sangre de Cristo Formation were not considered due to the possibility of fractures related to pre-Laramide tectonism. Localities exposing Neogene rocks were not considered since they were presumed to show only Rio Grande rift faulting, which was not the focus of this study.

Localities crossed the southern plunge of the Sangre de Cristo arch and bracketed the Tijeras-Canoncito (Lisenbee, 1979) and Picuris-Pecos (Bauer and Ralser, 1995) fault systems. These fault systems define the southern and eastern boundaries of the Galisteo basin, which contains the late Paleocene to early Eocene Diamond Tail Formation and the Eocene Galisteo Formation. Stratal thickening of these clastic sedimentary rocks to the southeast combined with paleocurrents paralleling the Tijeras-Canoncito fault system indicate synorogenic sedimentation, perhaps at the releasing bend of a right-lateral fault system (Cather, 1992; Abbott, 1995).

The best developed slickensides on minor faults were found in silica-cemented quartzarenites. Because more highly folded strata have complex slickenline orientations due to the added complexities of fold-related slip and rotations of early-formed slickenlines, this study concentrated on localities with strata dipping less than 35°. At each outcrop, slickenside strike and dip as well as slickenline trend, plunge, and shear sense (Petit, 1987) were measured. The fault data were plotted in stereonets (Fig. 1.25), which were also used to plot ideal s_1 trends (Compton, 1966) paralleling the acute bisectors of conjugate faults. Ideal s_1 axes were calculated by moving half the conjugate bisector angle (2a) in the direction of maximum compression from the slickenline within the plane containing the slickenline and the pole to the fault. The a angles used to calculate the ideal s_1 trends are assumed to be 25°, consistent with Byerlee (1978).

Stereonets of slickenline and ideal s_1 orientations from localities east of the Rio Grande rift (Fig. 1.25) show a multi-modal distribution of the minor faults. The occurrence of ideal s_1 trend modes 60° apart and consistent cross-cutting relationships indicate that one orientation of s_1 is unlikely to have generated these faults. Northeast-striking, high-angle faults commonly show right-lateral slickenlines reactivated by left-lateral shear during later faulting. North-striking, high-angle fault planes commonly have right-lateral slickenlines that are cut by dip-slip slickenlines presumably related to Rio Grande rifting. Where cross-cutting relationships are not evident, the chronology of fault slip can be estimated by the more complete preservation of the latest fault striations. These relationships consistently show that the more north-trending slickenlines associated with NNE-trending ideal s_1 directions post-date more east-trending slickenlines associated with E-trending ideal s_1 directions.

The regional extent of these deformations is indicated by the wide distribution of multi-modal ideal s_1 directions. Of 41 localities, 7 contained faults indicating only E-trending ideal s_1 directions, 16 contained faults indicating only NNE-trending ideal s_1 directions, and 18 contained faults indicating both E-trending and NNE-trending ideal s_1 directions.

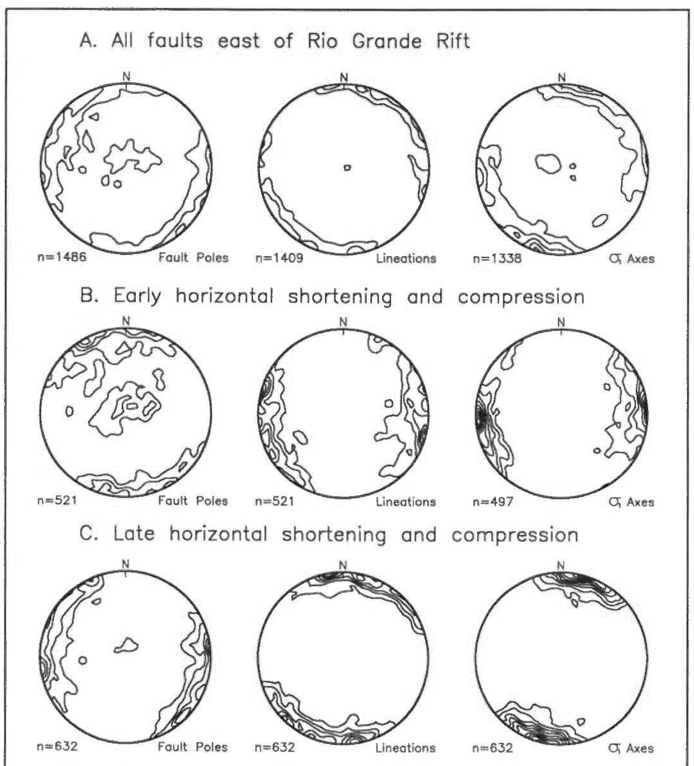

FIGURE 1.25. Contoured stereonet plots of (**a**) all faults east of the Rio Grande rift and (**b**, **c**) two subsets of the faults indicating horizontal compression. Data is contoured using the Schmidt method with 2% contours.

The faults indicating horizontal shortening were separated into two subsets (Fig. 1.25). The nearly E-trending subset has an average slip direction of 084-02 (trend-plunge) and an average ideal s_1 direction of 081-01. The NNE-trending subset has an average slip direction and ideal s_1 orientation of 197-02. A major difference in these subsets is that the more E-trending subset contains more thrust faults (145 out of 521 faults) than the NNE-trending subset (26 out of 632 faults). This suggests that thrust faulting was not important during the later stages of Laramide deformation. Trends of both left-lateral and right-lateral slickenlines are distinctly trimodal and define a trimodal array of s_1 trends. This suggests three distinct directions of horizontal compression and shortening. Unfortunately, cross-cutting relationships between NE- and NNE-directed faulting were not observed in the field.

Limits on the absolute age of these stages of faulting can be derived by the ages of the cross-cut strata. Although late Pennsylvanian–Permian strata might contain pre-Cretaceous deformation, all the fault sets cutting these strata also cut the Cretaceous Dakota Formation. Faults cutting Tertiary rocks give some surprising time constraints on the stages of horizontal shortening and compression. At the intersection of the Picuris-Pecos and Tijeras-Canoncito fault systems, the late Paleocene–early Eocene Diamond Tail Formation contains N-striking right-lateral faults cutting conjugate thrusts with E–W-trending slickenlines. These thrusts may reflect the last stage of E-trending shortening. Three adjacent localities in the overlying Galisteo Formation of Eocene age expose N-striking right-lateral and NE-striking left-lateral faults with no evidence of faults indicating E-trending shortening. This suggests that the transition between these two stages occurred sometime in the Eocene.

While the Galisteo Formation and its faults are cut by the undeformed Galisteo dike (27 Ma by K-Ar), north-striking strike-slip faults cut two units of similar age, the 28 Ma ($^{40}Ar^{39}Ar$, P. Bauer, personal commun.) Llana Quemado breccia and associated Picuris Formation rocks (with 25-Ma Amelia tuff, P. Bauer, personal commun., 1999) south of Taos and the 24.1-Ma (K-Ar) Eagle Rock dike south of Raton. Associated dip-slip normal faults strike E–W, suggesting transtensional deformation. These faults indicate that the latest phase of north–south strike-slip faulting is post 25 Ma in age, at least 15 Ma past the usually cited close of the Laramide!

In north-central New Mexico, minor faults indicate multi-stage, multi-directional horizontal shortening and compression during Tertiary deformation. Consistent cross-cutting relationships show that early Laramide east–west shortening on thrust and strike-slip faults was followed by late Laramide and mid-Tertiary strike-slip faulting. These faults indicate counterclockwise rotation of shortening and compression directions from N80ºE (early Laramide) through N45ºE (late Laramide) to N10ºE (mid-Tertiary).

These observations suggest a continuum between early Laramide thrusting and Rio Grande normal faulting. As the axis of Laramide shortening rotated to the northeast, horizontal extension increased, causing a transition from mixed thrust and strike-slip faulting to mostly strike-slip faulting. During the mid-Tertiary, continued rotation and increasing horizontal extension may have caused transtensional mid-Tertiary deformation, which was then followed by Neogene east–west extension. This hypothesis suggests that mid-Tertiary transtension initiated the "early rift" basins along the trend of the current Rio Grande Rift and provided conduits for mid-Tertiary igneous activity. Mid-Tertiary transtensional deformation may be the missing link between Paleogene Laramide shortening and Neogene Rio Grande rifting.

After the stop, retrace the walk to the buses and return to I-25 by the same route. **2.4**

63.0 With the exception of Quaternary eolian and alluvial deposits, there is virtually no soil development and/or thick regolith mantling bedrock in the Hagan basin. This observation is typical of New Mexico, and generally of the entire western United States. It speaks to the relatively rapid regional Quaternary rates of erosion and exhumation of the Rocky Mountains by climate change, epeirogenic rock uplift or both. **2.0**

65.0 Ahead, note Salt Wash and Brushy Basin members of Morrison Formation. The road here intersects the Dakota Formation, with the Jackpile Member of the Morrison Formation faulted out. A coarse-grained fluvial terrace of Tonque Arroyo is exposed at 11:00 across the arroyo. **0.9**

65.9 Summerville Formation underlies the strike valley here. **0.3**

66.2 Note dark red Summerville Formation ahead between the Todilto Formation and Salt Wash Member of the Morrison Formation. **1.7**

67.9 The San Francisco fault lies ahead at 1:00, buried here by a Quaternary terrace. **1.3**

69.2 Cross wide alluvial valley bottom of Tonque Arroyo. **0.8**

70.0 **LOG TO OPTIONAL STOP 7**—Arroyo del Tuerto, time permitting. **In the event of time constraints, we may turn left and head back to Albuquerque on I-25 south**.

70.0 **Turn right** to go north on I-25. **0.7**

70.7 Pumiceous beds, perhaps reworked Guaje ash (1.6 Ma) are exposed in roadcuts to your left. This is the same ash visible at Mile 51.8. **1.0**

71.7 Highway descends through distal eastern piedmont deposits of Santa Fe Group overlain by Quaternary eolian deposits. Axial Santa Fe Group deposits are exposed at lower elevations in valley at 10:00. **0.2**

71.9 Cross Arroyo de la Vega de los Tanos. Exposures of axial Santa Fe Group facies here contain clasts of the lower Bandelier Tuff. **0.5**

72.4 Note Espinaso Ridge underlain by uppermost Eocene and Oligocene Espinaso Formation over upper Galisteo Formation at 2:00–2:30. The abrupt end of Espinaso Ridge occurs at the San Francisco fault. **2.4**

74.8 **Leave I-25 at Budaghers (Exit 257), exit to right**. The exit ramp brings you up to the San Francisco fault. **0.4**

75.2 Stop sign. **Turn right**. Note the extensively cemented sandstones of the Santa Fe Group and minor travertine located on the San Francisco fault to your right. **0.1**

75.3 **Turn right** on frontage road and head south. **0.4**

75.7 Pavement ends at Arroyo Vega Tanos Road. **Proceed on dirt road to the left. 0.9**

76.6 Ranch on left; **drive to right of stock pens.** This is the Ball Ranch private land owned and operated by Mr. Orville Moore. ***NOTE:*** *You must obtain permission to pass prior to continuing through the gate.* **0.1**

76.7 Travertine ridge in the Santa Fe Group to your left. **Proceed to the right through the gate** to cross a big arroyo. After crossing arroyo, the yellow sandstone to left of road is in the Eocene Galisteo Formation. **0.2**

76.9 Cross the gully. To your left is the Eocene Galisteo Formation. **0.5**

77.4 Nice view of the dip-slope of the Sandia Mountains to the south. **0.5**

77.9 **To the left, an unimproved road proceeds to a windmill.** Here, an excellent section of the upper Galisteo Formation, disconformably overlying the Menefee Formation, dips northeast below Espinaso Ridge. The Diamond Tail Formation is missing here. **0.2**

78.1 **Road forks, bear left**. You now cross into the footwall of the San Francisco fault. Numerous east–northeast-striking, predominantly down-to-the-north faults cut the Cretaceous through Oligocene section in the San Francisco fault footwall. **0.3**

78.4 Road is in the Menefee Formation. **0.1**

78.5 Pass into red beds of the Galisteo Formation. **0.3**

78.8 Pass a windmill. Nice view of Espinaso Ridge ahead of you and to the left. Locally there are thick eolian mantles with well-developed, reddened calcic soils. **0.2**

79.0 Low outcrops of Menefee Formation sandstone. **0.3**

79.3 To your left just before we cross the wash are exposed dark brown conglomerate beds of basal Galisteo Formation. These beds are mostly sandstone and conglomerate consisting of detritus recycled from Paleozoic and Mesozoic strata, with subordinate Precambrian quartzite and granite. Maximum clast size approaches 20 in. Paleoflows indicated by pebble imbrication are southward. Both paleoflow and compositional data suggest a Santa Fe Range source (Gorham, 1979; Gorham and Ingersoll, 1979). **0.2**

79.5 Pass a windmill. **0.1**

79.6 Proceed through gate and cross the wash. **1.1**

80.7 Top of a low hill provides a nice view of the Hagan basin at 2:00–3:00. Notice the Triassic and Jurassic section with the light-colored Jackpile Sandstone on the ridgetops. **0.2**

80.9 **Road forks, stay to the left 0.7**

81.6 Proceed through the gate. **The road forks, proceed to the right** and drop into Galisteo Formation badlands. **0.4**

82.0 **Road forks, proceed to the left. 0.2**

82.2 Cross the arroyo and then **turn left**. **0.5**

82.7 **STOP 7**—Type Espinaso Formation. **Stop near old well**. The purpose of this stop is to observe the Late Eocene–Oligocene record of deposition in the Hagan basin, here represented by a thick pile of volcaniclastic sediments, and walk the arroyo upstream to the contact with the overlying Santa Fe Group. Approximately 2300 ft of steeply dipping sandstone, mudstone, and siltstone of the Galisteo Formation are exposed in the headlands of Arroyo del Tuerto ("Arroyo Pinovetito" of some authors), part of a northwest–southeast-trending belt of Galisteo outcrops in the Hagan Basin (Stearns, 1943; Harrison, 1949; Gorham, 1979; Gorham and Ingersoll, 1979). Here, the Galisteo Formation disconformably overlies the Mesaverde Group to the west and is overlain by the Espinaso Formation to the east (Fig. 1.26). Lee and Knowlton (1917), Stearns (1943), Harrison (1949), Gorham (1979), and Lucas (1982) have already described the geology of the Galisteo Formation in this area. Here, we focus on the upper 160 ft of the Galisteo, the strata in the headlands of Arroyo del Tuerto that have produced fossil mammals. The stratigraphically lowest fossil occurrences in the headlands of Arroyo del Tuerto are near the top of a thick sequence of sandstones (Fig. 1.26). The fossiliferous sandstone is yellow, arkosic, coarse-grained-to-conglomeratic, and contains numerous petrified logs, some more than 3 ft in diameter. Gorham (1979) and Gorham and Ingersoll (1979) assigned this sandstone to their upper yellow pebbly sandstone member of the Galisteo Formation. Variegated red and green mudstones overlie the upper yellow pebbly sandstone. The most prolific vertebrate-fossil locality in the Galisteo

FIGURE 1.26. Photograph of contact of Galisteo and Espinaso formations at Stop 7.

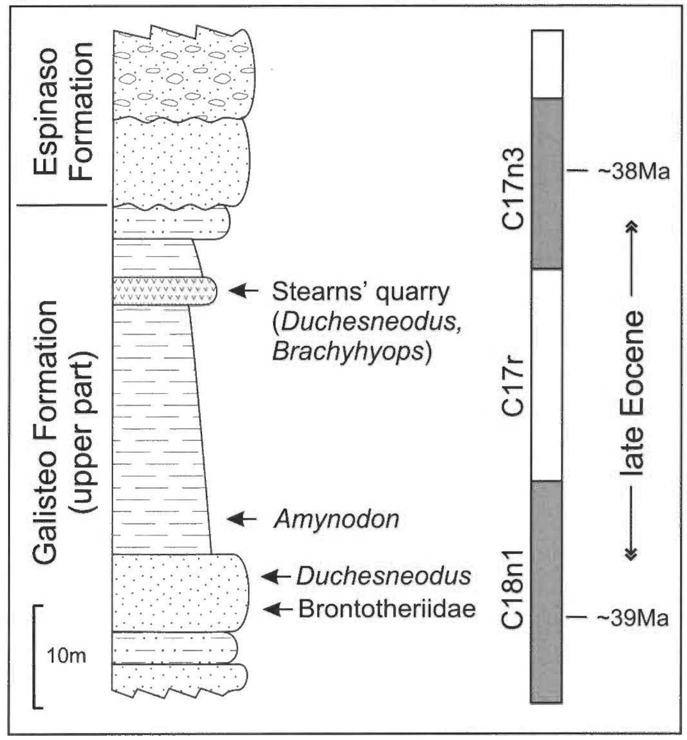

FIGURE 1.27. Lithostratigraphy and magnetic stratigraphy of the Arroyo del Tuerto section, after Lucas (1982, fig. 7) and Prothero and Lucas (1996), showing location of NMMNH vertebrate-fossil localities. NMMNH locality 874 produced NMMNH P-27591, M_1 of *Brachyhyops viensis*.

Formation is located high in the sequence of mudstones, in a distinctive bed of green, bentonitic claystone that is about 6.5 ft thick (Fig. 1.27). Stearns (1943, p. 310–311, fig. 7) first described this locality, and it often is referred to as "Stearns' quarry." The quarry contains hundreds of disarticulated bones almost exclusively of titanotheres, though some other kinds of mammals are present (see Lucas and Estep accompanying minipaper). The bones are extremely fragile, and although field parties from various institutions have collected here, much material still remains in the quarry. Disbrow and Stoll (1957) and Smith et al. (1991) included the bentonitic stratum of Stearns' quarry in the Espinaso Formation because of the presumed volcanic origin of the bentonitic layer. However, Stearns (1943), Harrison (1949), Gorham (1979), Gorham and Ingersoll (1979), and Lucas (1982) placed the Galisteo-Espinaso contact above the quarry level, at a brown, medium-grained sandstone that is overlain by tuff and breccia typical of the Espinaso Formation.

Smith et al. (1991) described the stratigraphy of the Espinaso Formation (Stearns, 1953b) along Arroyo Tuerto, and Erskine and Smith (1993) considered the petrology of conglomerate clasts and sandstones in the same section. The approximately 1300 ft of volcaniclastic strata consist of a lower interval (~1000 ft thick) of calc-alkaline detritus, with hornblende or hornblende and clinopyroxene as ferromagnesian silicate phases, abruptly followed by alkaline detritus lacking hornblende and containing, instead, Fe-rich clinopyroxene with or without biotite. The Espinaso Formation is composed mostly of conglomerate and pebbly sandstone interpreted to represent deposition on a broad braid plain with headwaters in the coeval Ortiz Mountains magmatic center, approximately 10 mi to the east (Smith et al., 1991). Interbedded with these sedimentary deposits are rare ignimbrite, fallout tephra layers, and block-and-ash flow deposits, all of primary volcanic origin. The Espinaso Formation grade downward into the Galisteo Formation, which accounts for the varied interpretations for the position of the contact between the two units. The Espinaso Formation is overlain unconformably by sandstone and pebbly sandstone of the Santa Fe Group just north of where Arroyo del Tuerto is incised through Espinaso Ridge. Stearns (1953a) tentatively assigned these younger strata to the Abiquiu Formation, although they might be more reasonably correlated, from a lithofacies standpoint, with the Zia Formation. Large and Ingersoll (1997) note that the composition of these sandy beds is distinct from either the Abiquiu or Zia formations.

BRACHYHYOPS (MAMMALIA, ARTIODACTYLA) FROM THE GALISTEO FORMATION AND ITS BIOCHRONOLOGICAL SIGNIFICANCE

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Fossil mammals from the upper part of the Galisteo Formation in north-central New Mexico belong to the Tonque local fauna of Lucas and Kues (1979) and are of Duchesnean (late Eocene) age (Lucas, 1982, 1992). The primary basis for the Duchesnean age assignment is the presence of the Duchesnean index taxon, the brontothere *Duchesneodus* at NMMNH (New Mexico Museum of Natural History) locality 874 ("Stearns' quarry"), in the uppermost Galisteo Formation outcrops in Arroyo del Tuerto (Lucas, 1982; Lucas and Schoch, 1989). Here, we document the presence of another important Duchesnean index taxon at locality 874 (Fig. 1.27), the entelodont artiodactyl *Brachyhyops*.

NMMNH P-27591 is a right M_1 of *Brachyhyops viensis* Russell. (Fig. 1.28). This well-worn tooth is 19.2 mm long, has a trigonid width of 13.7 mm and a talonid width of 13.2 mm. The bunodont, brachydont crown is supported by two roots, one under the trigonid, the other under the talonid. The trigonid is wider than the talonid, and heavy wear has obliterated most of the crown morphology. Nevertheless, the tooth is clearly entelodont and in size and morphology closely fits the M_1 of

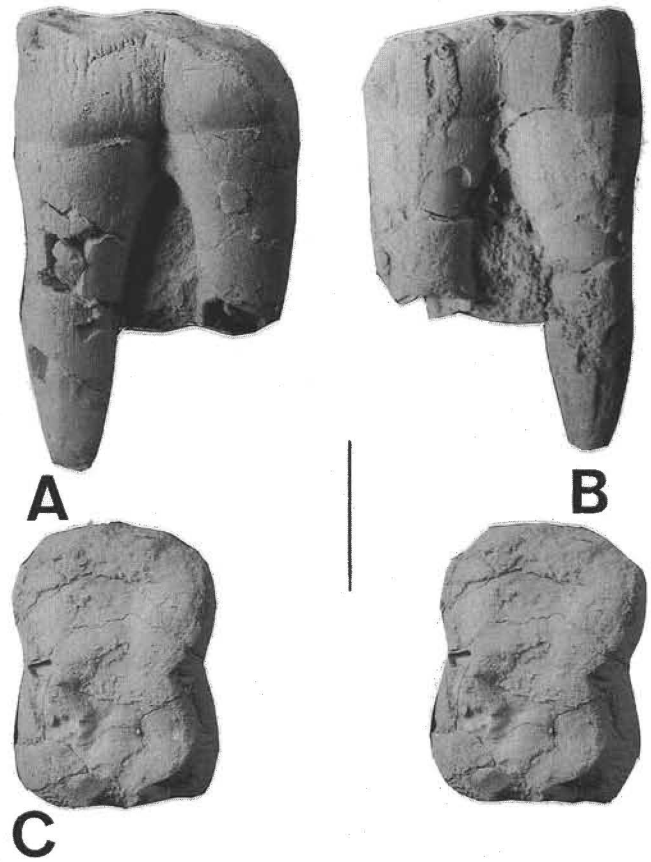

FIGURE 1.28. NMMNH P-27591, M_1 of *Brachyhyops viensis* in: **A**, lingual; **B**, labial; **C**, stereo occlusal views. Bar scale = 1 cm.

already described specimens of *Brachyhyops* (Wilson, 1971, fig. 3; Russell, 1980, fig. 1). The Galisteo Formation tooth is closest in size to *B. viensis* Russell and thus somewhat larger than the M_1 of *B. wyomingensis* Colbert, so we identify it as *B. viensis*.

The presence of *Brachyhyops* in the upper Galisteo Formation is significant because:

1. This is the second record of *Brachyhyops* from New Mexico. The other is from the upper part of the Baca Formation in west-central New Mexico, a unit correlated to the upper part of the Galisteo Formation (Lucas, 1983). This correlation is strengthened by the presence of *Brachyhyops* in the upper Galisteo Formation.
2. The first appearance of *Brachyhyops* is indicative of the Duchesnean land-mammal "age," so its presence reinforces a Duchesnean age assignment to the upper Galisteo Formation.
3. Prothero and Emry (1996) suggested that *Brachyhyops* is indicative of late Duchesnean time. Based on both mammalian biochronology and magnetochronology (Lucas, 1992; Prothero and Lucas, 1996), the Tonque local fauna was previously considered late Duchesnean. The presence of *Brachyhyops* supports that age assignment.

After stop retrace route out to I-25 and proceed south to Albuquerque on I-25.

End of First-day Road Log.