First-day road log: From Santa Fe to Nambe, Cundiyo, Espanola, Abiquiu and Ghost Ranch

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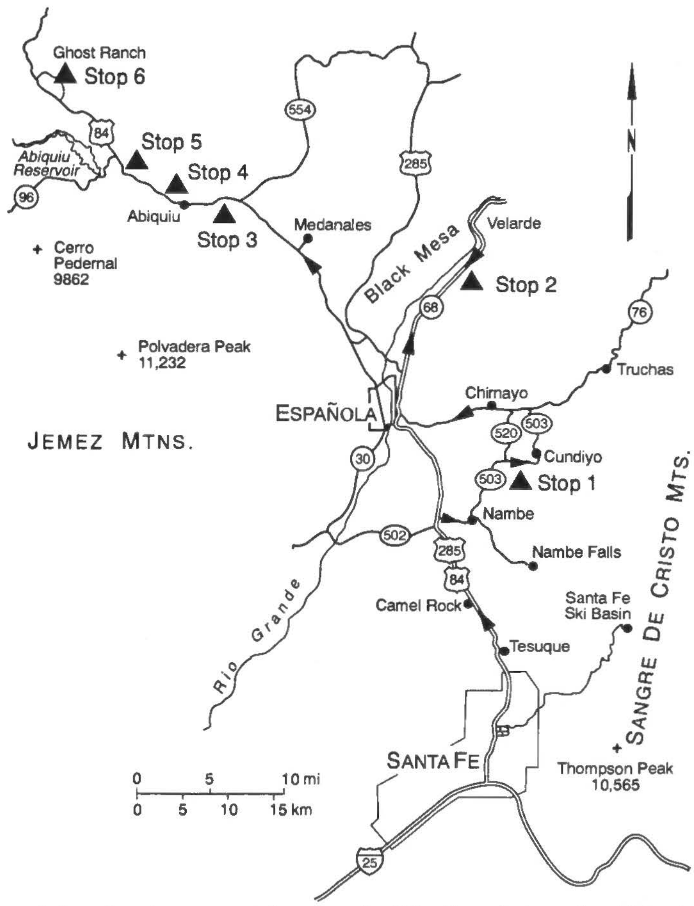
FIRST-DAY ROAD LOG, FROM SANTA FE TO NAMBÉ, CUNDIYO, ESPAÑOLA, ABIQUIU AND GHOST RANCH

GARY A. SMITH, PAUL W. BAUER, SPENCER G. LUCAS, MARK A. GONZALEZ, JAMES M. BARKER, FRANK E. KOTTLOWSKI, GEORGE S. AUSTIN and DAVID W. LOVE

THURSDAY, SEPTEMBER 28, 1995

Assembly point: **High Mesa Inn parking lot, Cerrillos Rd., Santa Fe.**
Departure time: **7:30 a.m.**
Distance: **91.6 miles**
Stops: **6**



Summary

The first day of the field conference examines the stratigraphy and structure of the Española Basin and Abiquiu embayment parts of Rio Grande rift and border rocks of the Sangre de Cristo Mountains and Colorado Plateau. The trip begins by heading north from Santa Fe within the eastern Española Basin. Supplemental Log 2 leads to Nambé Falls and Nambé Lake where Proterozoic and Pennsylvanian rocks of the Sangre de Cristo Mountains are exposed adjacent to and beneath Miocene rift-basin fill.

Stop 1, south of the historic village of Chimayo, provides an overview of the boundaries of the Rio Grande rift and the rift-filling Tesuque Formation. The route then skirts along the depositional contact between the Tesuque Formation and the Proterozoic rocks of the Sangre de Cristo Mountains near the village of Cundiyo. The trip then turns westward down the valley of the Rio Quemado and Santa Cruz River to Española. North of Española, in the village of Alcalde, participants will visit the Adobe Factory (Stop 2) and learn about the process of making New Mexico's most well known building material. The route returns to Española and then heads westward across the Rio Grande into the Abiquiu embayment along the Rio Chama. Stop 3 provides an overview of the Tertiary stratigraphy of the Abiquiu embayment, Quaternary evolution of the Rio Chama valley, and an opportunity to visit a pre-Columbian ruin. Farther west, at Stop 4, participants will examine the Abiquiu Formation, backdrop to many movie scenes and Georgia O'Keefe paintings, and also representing the distal sedimentary record of middle Tertiary volcanism in the San Juan Mountains and Latir volcanic fields.

Stop 5 is located at the well-exposed western margin of the Rio Grande rift, where the basin fill is faulted against flat-lying Permian and Mesozoic rocks of the Colorado Plateau. Unconformities between Jurassic and Eocene strata and between the Eocene strata and the Abiquiu Formation provide evidence for an earlier Laramide ancestry for the rift-bounding Cañones fault zone and arguable evidence for Oligocene subsidence of the Abiquiu embayment. The field-trip route then continues westward onto the Colorado Plateau to Ghost Ranch, nestled amongst picturesque mesas of Triassic, Jurassic, and Cretaceous strata and home to New Mexico's state dinosaur, the small

theropod *Rioarribasaurus* (nee *Coelophysis*). After a barbecue and tour of Ghost Ranch museum and dinosaur quarry, we return to Santa Fe.

Mileage

0.0 Intersection of St. Francis Drive (US–84/285) and Cerrillos Road (NM–14) in Santa Fe. **Drive north on US–84/285.** Cerrillos Road subparallels the buried Santa Fe River fault zone that trends E–NE beneath the Pliocene–Pleistocene Ancha Formation, which is the "bedrock" under the High Mesa Inn. Thin sands and gravels of the erosional-constructional Airport surface cap the Middle terraces, and then as St. Francis Drive crosses the Santa Fe River just south of Alameda Street, we drop onto Recent alluvium, a half-mile-wide strip mainly north of the river.

The fault zone has a stratigraphic displacement about 1800 ft in the foothills. To the northwest, north of the river valley, badlands carved in the Miocene Tesuque Formation extend westward from the foothills. To the southeast, only a few patches of Tesuque outcrops border the foothills. Most of the southern plains are underlain by Ancha Formation, capped by thin scattered alluvial gravel. In the foothills along the Santa Fe River (Canyon Road in easternmost Santa Fe city), Proterozoic rocks on the south face downdropped Pennsylvanian strata on the north. This fault zone may be the eastern extension of Cather's (1992) Santa Ana accommodation zone. **1.6**

GEOLOGIC SYNOPSIS OF LA VILLA REAL DE LA SANTA FE DE SAN FRANCISCO DE ASSISI

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Agua es vida, water is life in semi-arid New Mexico. Thus the first Spanish settlement of Santa Fe in 1609, was just west (at the present Plaza) of a cienega (marshy area) on the north side of the Santa Fe River flood plain. The cienega was fed by springs at the foot of nearby bluffs (Ft. Marcy area) of west-dipping Tesuque Formation. Most of the pre-1950 city west of the foothills is built on the (1) WSW-trending flood plain and lowest terrace of the Santa Fe River; (2) the medium-level terrace, which borders the river to the south; and (3) the Airport and Plains surfaces farther south, which are cut on the Ancha Formation. Canyon Road goes eastward into the foothills, paralleling the Santa Fe River fault zone (SFRf), which near Twomile Reservoir shows Mississippian–Pennsylvanian strata on the north downthrown against Proterozoic granite gneiss on the south.

North of the river valley the piñon-covered dissected piedmont is cut in the westward-dipping Tesuque Formation beds and is the site for rapidly expanding mansion developments, such as the Governor's Mansion. Along a north-trending line from the west side of Cerro Gordo north to Bishop's Lodge, the west edge of the foothills, along the Cerro Gordo fault, the Tesuque is downdropped to the west against Mississippian–Pennsylvanian strata or Proterozoic rocks to the east. East of the fault zone a 2-mi-wide, east–west, 4-mi-long, north-south block, of mainly Pennsylvanian and Proterozoic rocks, is in turn down-dropped along the Aztec fault against upfaulted Proterozoic to the east, higher in the foothills.

South of the SFRf, in the foothills, Proterozoic rocks crop out, with only a few small horsts of Pennsylvanian strata along Camino Santander, Apodaca Hill, and Camino Militar. Many of the ancient adobe casas along the river's canyon are built on the Middle terrace (20–30 ft above the river, possibly correlative with Pinedale Glaciation on Lake Peak and Santa Fe Baldy) or on the few remnants of the High terrace (45–60 ft above the river, possibly Bull Lake Glaciation outwash).

In general, this southwest corner of the Sangre de Cristo Mountains is a westward-dipping ramp with Cenozoic sediments lapping eastward onto remnants of late Paleozoic strata and the main mass of Proterozoic rocks. There are many minor (200–1000 ft) down-to-the-west faults near the mountain front. North of the SFRf the faults trend north; to the south the trends are NW to NNW, and with larger displacements. Stratigraphic displacement along the SFRf is perhaps 2000 ft near Twomile Reservoir, but gravity surveys near High Mesa Inn suggest only 200± ft of throw. Similar relationships could be caused by 2 mi of right-lateral movement.

1.6 Veterans cemetery on right is in Tesuque Formation of the Santa Fe Group. Three physiographic surfaces form the piedmont west of the Sangre de Cristo Mountains. Developed on the Ancha Formation south of the Santa Fe River and on the Tesuque and Ancha (farther west) Formations north of the river, they are partly erosional and partly constructional. The Divide surface is the highest (at the top of the divide 2 mi ahead), the Airport surface is the lowest, and to the south, a slightly higher Plains surface forms the interstream divides.

Glacial moraines at the base of the glacial cirques on Lake Peak and Santa Fe Baldy (high peaks to the east) were identified by Richmond (1963) as pre-Wisconsinan, Bull Lake Glaciation, Pinedale Glaciation, and a Neoglacial moraine. The Santa Fe River and Rio Tesuque head in these cirques. In the foothills, four alluvial terraces and outwash deposits younger than the Airport surface were mapped by Kottlowski and Baldwin (Spiegel and Baldwin, 1963). Two low alluvial terraces are upper Holocene, with the lower possibly related to Neoglacial events. The Middle terrace, 20–30 ft above Santa Fe River channels, may be associated with the Pinedale Glaciation, and the High terrace, 45–60 ft above channels, may correlate with Bull Lake deposits. Erosion and modern construction have obscured the two lower terraces. **0.8**

2.4 From 12:00 to 5:00, on skyline, are Proterozoic rocks of the southern Sangre de Cristo Mountains. The Governor's Mansion is 0.75 mi to the southeast amid the other costly haciendas. In the foothills, 1.5 to 3 mi to the east, a 4-mi-long, N–S outcrop of Mississippian and Pennsylvanian strata forms a faulted, downdropped, W-tilted block, mostly poorly exposed amid piñon forest and home construction.

Mississippian strata are thin and discontinuous beneath the erosional surface at the base of Pennsylvanian beds. In Little Tesuque Creek Canyon, 0.3 mi upstream from Bishops Lodge, 26 ft of Espiritu Santo Formation sandstone and shaly limestone overlie Proterozoic granite gneiss and are disconformable beneath 26 ft of Tererro massive limestone. Basal Pennsylvanian sandstone fills depressions on truncated Tererro limestones. Upstream 0.8 mi, where Hyde Park Road enters the canyon, Pennsylvanian sandstones overlie decomposed granite gneiss.

The lower 50 to 75 ft of Pennsylvanian are "Sandia"-type sandstones, pebbly conglomerate lenses, shales, thin calcarenites and coal lenses. Above are intertongued limestones and light gray to pale red shales with some lenses of medium-grained sandstones, as much as 350 ft thick beneath the truncating Miocene Tesuque Formation. Sutherland and Harlow (1973) collected Morrowan and Atokan fossils from this outcrop, and assigned them to their La Pasada Formation. **0.8**

3.2 Roadcuts in Tesuque Formation along west side of road. **0.3**

3.5 Crest of hill leading down to Rio Tesuque drainage. View to the north across badlands eroded in Miocene Tesuque Formation in Española Basin, basalt-capped Black Mesa, and Tusas Mountains on skyline. On a clear day, in the very far distance at 12:00, San Antonio Mountain, a Taos plateau volcano on the Colorado–New Mexico border, is visible from here. Sangre de Cristo Mountains to the east. Strata in the Tesuque Formation badlands type area (Spiegel and Baldwin, 1963) dip 5–30° to the west with dips generally increasing to the east. Gently west-sloping surfaces on top of Tesuque outcrops, the Divide surface, is a Quaternary pediment surface with thin gravel veneers. Farther west, the Ancha Formation is unconformable on the Tesuque.

The Española Basin is an asymmetric west-tilted graben. The Sangre de Cristo Mountains rise above the east side of the basin, and Neogene volcanic rocks of the Jemez Mountains overlap the faulted western margin (Fig. 1.1). The north end of the Mississippian–Pennsylvanian block is about 1.5 mi to the northeast near Bishops Lodge. In the foothills, the basal Tesuque Formation overlies the Pennsylvanian, and then a short distance to the east and north, the Proterozoic rocks. Pennsylvanian shales once were quarried by State Penitentiary inmates to make bricks. Some of the lenticular coals in the northeastern part of Santa Fe, along with Pennsylvanian limestones, were utilized to make lime in a small kiln (destroyed by modern construction).

The type section of the Tesuque Fm (Spiegel and Baldwin, 1963) is along Tesuque Creek northeast of Bishops Lodge, where only the lower part of the unit is present; it thickens westward to more than 4000 ft at the east edge of Cerros del Rio. In this area it consists mainly of debris from Proterozoic rocks with some limestone fragments in lower beds. Near Bishops Lodge the lower 0–110 ft are of light gray to reddish brown conglomerate to siltstone with basal boulder conglomerate. It is overlain by the Bishops Lodge (mappable) Member, 50–530 ft of light gray volcanic sandstone and siltstone with weathered pebbles of porphyritic andesite and blocky massive tuff. Above are typical grayish orange, moderate reddish orange, and light brown, calcite-cemented sandstones and siltstones with conglomerate lenses near the foothills. Southeast of Bishops Lodge local, thin, olivine basalt flows and tuffaceous sandstones occur 140 ft above the Bishops Lodge Member. As Ingersoll et al. (1990) and Cather (1992) noted, the Bishops Lodge is a southeastern equivalent of the Abiquiu Formation. **1.8**

5.3 Several Quaternary pediment and strath surfaces cut on Tesuque Formation are visible between the highway and the Sangre de Cristo Mountains to the right and left. **0.5**

5.8 Entrance to Santa Fe Opera on left. **0.9**

6.7 Entering Tesuque Indian Reservation. Excellent view ahead of gently west-dipping pediment surface. The foreground is drained by the Rio Tesuque. Santa Fe ski area is located in the high-country bowl at 3:00. The High "Bull Lake" terrace is on the left, west side, of the highway, and the Middle "Pinedale" terrace is off on the right 0.2 mi. **0.9**

7.6 Crossing Rio Tesuque. High and Middle terraces ahead, west of the highway. Two lower terraces occur along the "Rio", and have been dated between A.D. 1880 and 2230 B.P. (Miller and Wendorf, 1958). **0.2**

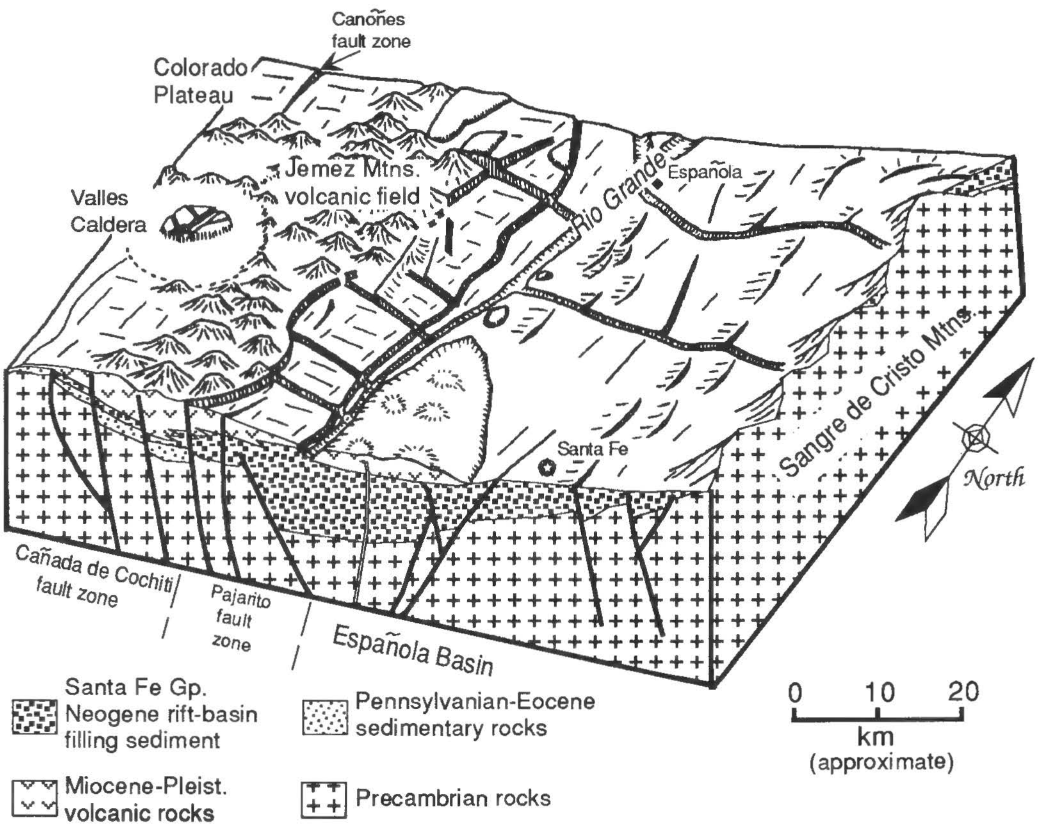

FIGURE 1.1. Block diagram illustrating the general structure and stratigraphy of the Española Basin (modified from Golombek et al., 1983).

7.8 Junction with county road 73 to Tesuque; continue north on US–84/285. View to the west of the Jemez Mountains and the prominent Pajarito Plateau, underlain by Pleistocene Bandelier Tuff and Pliocene Puye Formation extending eastward to the Rio Grande. **3.3**

11.1 Camel Rock on left. This erosional feature resembling a dromedary is sculpted in alluvial sediment of the Tesuque Formation (Fig. 1.2). Erosion has considerably modified the "camel" during the past 45 years; it may not be recognizable in 2040. Since 1924, several paleontologists from the American Museum of Natural History Frick Laboratory have collected and described the vertebrate fossils (including camels!) found in the Tesuque Formation. Two of these workers, Ted Galusha and John Blick (1971), also completed a thorough stratigraphic study of the Tesuque strata. They divided the Tesuque in this area into (in ascending order) the Nambé, Skull Ridge and Pojoaque Members. Based on fossil mammals, the Nambé Member is of late-early Miocene (late Hemingfordian) age; the Skull Ridge Member is of early-middle Miocene (early Barstovian) age; and the Pojoaque Member is of late-middle Miocene (late Barstovian) age. The mammals from these units are mostly camels, deer, antelope, rhinoceroses, horses, gomphotheres (primitive elephants) and carnivores. Together with magnetostratigraphy and radiometric ages, the fossil mammals provide a remarkably precise Neogene chronology in the Española Basin.

East of the road are excellent outcrops of the Skull Ridge Member of Galusha and Blick (1971). The prominent white tephra layer is white ash #2 of Galusha and Blick, repeated across north-south striking normal faults. The older white ash #1 is visible along the road a short distance to the north. These tephras, and others, are nearly continuously exposed for 12 mi to the north of here and serve as important stratigraphic markers in the Tesuque Formation. Izett and Naeser (1981) reported a zircon-fission-track age of 14.6±1.2 Ma for white ash #2, but vertebrate biostratigraphy and magnetostratigraphy suggest an age of about 16 Ma (Barghoorn, 1981; Tedford and Barghoorn, 1993). A more recent $^{40}Ar/^{39}Ar$ date of 15.42±0.06 Ma for sanidine in the younger white ash #4 (W. McIntosh and J. Quade, personal commun., 1995) support the magnetostratigraphic and vertebrate paleontology assessments of the age of these strata. The ashes are of biotite rhyolite composition and were possibly erupted in the Jemez Mountains, although sources in southern Arizona, Nevada and southern Idaho cannot be excluded. The oldest such rhyolites exposed at the surface in the Jemez Mountains (Canovas Canyon Rhyolite) are about 13.5 Ma (Gardner et al., 1986). The Tesuque ashes may be a record of Jemez volcanism that is older than what is presently exposed in the volcanic field. **0.5**

FIGURE 1.2. Camel Rock.

11.6 View at 12:00 in middle distance of the Pojoaque Bluffs, type area of the Pojoaque Member of the Tesuque Formation of Galusha and Blick (1971). The earliest Santa Fe Group fossil mammals were collected in this area in 1873 and 1874 by members of the Wheeler Survey (Lucas and Schoch, 1983). The famed paleontologist Edward Drinker Cope described these fossils (some of which he collected in 1874), first bringing to scientific attention the record of Neogene mammals preserved in this area. West of the Pojoaque Bluffs and across the Rio Grande are outcrops of mesa-capping gray strata of the Puye Formation (including the Totavi Formation of Waresback and Turbeville, 1990) overlying pink sediment of the upper Miocene Chamita Formation. **1.8**

13.4 Cross Arroyo Cuyamungue. Several miles west, along the Rio Grande, is the ghost town of Buckman, formerly a village and station on the D&RGW Railroad. It was founded about 1900 by H.F. Buckman, an Oregon lumberman who had sawmills and timber holdings on the Pajarito Plateau. Buckman was the location of the original bridge across the Rio Grande that led to the Los Alamos Ranch School (now the City of Los Alamos). **1.9**

BUCKMAN WELL FIELD

Amy C. Lewis

Daniel B. Stephens and Associates, 6020 Academy Rd. NE, Albuquerque, NM 87109

The Buckman well field was developed by Public Service Company of New Mexico and put into operation in July 1972 to supply the city of Santa Fe. The field consists of seven wells drilled to depths of 1000–1400 ft below land surface. The well field is about 15 mi northwest of the city of Santa Fe, near the abandoned town of Buckman on the east side of the Rio Grande. Santa Fe currently has the capacity and water rights to divert 13,000 acre-ft per year (afy) from three sources: the Santa Fe River (up to 3300 afy), the Tesuque Formation aquifer in the vicinity of the city (up to 4340 afy), and from the Buckman well field (up to 5600 afy). In 1993, the total diversion by the city was near 12,000 afy, indicating the growing city will need to tap another source of water in the very near future. A likely source of water is the San Juan–Chama water that can be diverted directly from the Rio Grande. In the Buckman production wells, water levels have dropped up to 56 ft/yr over the past 10 years (R. Jorgenson, personal commun., 1994). The Buckman wells draw water from a confined production zone that is not replenished at a rate equal to the amount pumped. In Santa Fe city, production well levels have been declining at approximately 2.5 ft/yr during the past 40 years.

15.3 Enter Pojoaque Pueblo, located just southeast of the confluence of the Rio Tesuque and Rio Pojoaque. **1.0**

16.3 Intersection with NM–502 to Los Alamos. **Stay in right lane** and continue north on US–84/285. Pojoaque Bluffs visible to west. **0.5**

16.8 **Turn right (east) at traffic light onto NM–503**. Drive east along the Rio Pojoaque. **0.4**

17.2 Arroyo scarps on right expose west-dipping Tesuque Formation. **0.5**

17.7 Periodic bank erosion along the river has resulted in installation of a wire and riprap stabilization system. **1.0**

18.7 Village of Nambé. According to Pearce (1965), Nambé is Tewa, *nambay-ongwee*, for "people of the roundish earth." Sacred Heart Church on right. **0.9**

19.6 Prominent outcrops of white ash #1 in the Tesuque Formation to the right of the road (Fig. 1.3). **0.4**

20.0 Junction on right with road to Nambé Falls and Nambé Lake, which are described in Supplemental Road Log 2. Main roadlog continues north on NM–503. **0.8**

20.8 Southeastward view of angular unconformity between west-dipping Tesuque Formation and Quaternary pediment gravel on north side of east-trending ridge. **0.1**

20.9 Milepost 4. **0.2**

21.1 View at 10:00 of east-facing bluff with prominent exposure of white ash #2 within the Skull Ridge Member of the Tesuque Formation as defined by Galusha and Blick (1971). The ash rests just below a distinctive transition from pink siltstones below, to tan sandstones above. This vertical facies change is present at this stratigraphic position, as marked by the ash, over an area of at least 29 mi^2 within the basin. At 2:30, the high, angular peaks on the skyline are the Truchas Peaks. **1.3**

CONTRASTING MODES OF TEPHRA PRESERVATION IN THE SKULL RIDGE MEMBER OF THE TESUQUE FORMATION

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The ash beds of the Tesuque Formation, particularly the Skull Ridge Member, were first described by Galusha and Blick (1971) in their study of regional stratigraphy and vertebrate paleontology. Approximately 40 ash layers are recognized in the Skull Ridge Member. Of these, Galusha and Blick (1971) labeled the most conspicuous white ashes 1 through 4, and the gray ashes between white ashes #2 and #3, as 2a–2d. Utilizing magnetostratigraphy and vertebrate biostratigraphy, Barghoorn (1981) and Tedford and Barghoorn (1993) assigned an age of about 15.5 to 16.5 Ma to this stratigraphic interval, which is consistent with a new $^{40}Ar/^{39}Ar$ date of 15.42 ± 0.06 Ma for white ash #4 (W. McIntosh and J. Quade, personal commun., 1995). Sources for these tephras have not been identified. Although in close proximity to the Jemez Mountains, the Skull Ridge ashes are older than the 13 Ma rhyolites cited by Gardner et al. (1986) as marking initial Jemez volcanism. If the Skull Ridge ashes were derived from Jemez vents, those vents are buried beneath younger volcanic rocks. White ash #2 is located near an abrupt transition between red mudstone-dominated strata, below, to buff sandstone-dominated strata above. This stratigraphic transition has been traced over a 29 mi^2 area where the ash is almost continuously exposed. This change in depositional environment is illustrated in the Arroyo Seco area by the preservational style of white ash #1 and the gray ashes above white ash #2.

FIGURE 1.3. Outcrops of white ash #1 capping west-dipping cuestas within Tesuque Formation at mile 19.6. This ash marks the contact between the Nambé and Skull Ridge Members of the Tesuque Formation (Galusha and Blick, 1971). Sangre de Cristo Mountains form the eastern skyline.

White ash #1 has a continuous distribution over a strike distance of 3 km and exhibits a rather even thickness, ranging from 1.5 to 1.9 m. The slight variation in thickness is generally due to the original topography the ash was laid upon. The basal 1–2 cm is a bentonite that rests on micaceous siltstone (Fig. 1.4). Above the bentonitic layer is generally a 35–50-cm-thick layer of mixed ash and red mud. The remainder of the bed is composed of graded horizontal laminated and ripple-cross-laminated vitric ash mixed with variable amounts of fine- to medium-grained arkosic sand. Root traces and burrows are in the ash bed and it typically grades abruptly into arkosic sandy siltstone.

The gray ashes, 2a–2d, are also reworked and mixed with varying sized arkosic sand. These ashes vary in thickness from 2–50 cm. The gray ashes are not laterally continuous but are both truncated by, and overthickened within, channel-fill units 2–7.5 m wide. An example of one of the many channels associated with the gray ashes is shown in Figure 1.4B.

The depositional environment for gray ashes 2a–2d contrasts with that for white ash #1. We interpret white ash #1 to have been deposited on a broad, low-relief floodplain. This setting explains the tabular geometry, lack of channels, association with arkosic muds and fine sands, and presence of lower-flow-regime sedimentary structures, burrows and root traces. Because of the general similarities between white ash #1 and white ash #2, both were probably deposited in a similar environment. The gray ashes were deposited on a piedmont characterized by closely spaced, shallow channels. In this setting, the ashes were more poorly preserved because of erosion and redeposition in the channels. A simple Walther's law approach would suppose that the abrupt facies change above white ash #2 to be the consequence of lateral migration of consanguineous floodplain and channel facies. Presence of ash beds as time lines conclusively shows, however, that these two facies associations are nowhere time equivalent, but represent intervals of distinctly different depositional processes on the piedmont. Cavazza (1989) hypothesized that grain-size variations in Tesuque strata are somehow related to varying rates of subsidence in the Española Basin. Our observation of pond deposits below white ash #2 and abundant eolian sand above that ash suggest the possibility of a climatic influence.

All ash beds in the Skull Ridge Member have been reworked and mixed in varying degrees with arkosic sediment eroded from the Sangre de Cristo Mountains. Ashes redistributed on broad floodplains remain as laterally continuous stratigraphic markers. Those eroded and redeposited by channelized flows are less continuous and have more limited stratigraphy utility. The *original* fallout thickness for any of the tephras is unknown and cannot, therefore, be used to constrain the locations for the eruptive vents.

22.4 View straight ahead of west-dipping beds of the Tesuque Formation. The Tusas Mountains form the skyline at 10:00–11:00. Tesuque Formation also underlies the gently west-dipping Truchas surface (Manley, 1976) on the skyline. This high-level surface is cut on basin-fill within the topographically expressed Picuris embayment, which interrupts the continuity of Sangre de Cristo Proterozoic rocks to the north of the Rio Quemado. Hollywood westerns are occasionally filmed in these picturesque Santa Fe Group badlands. **1.5**

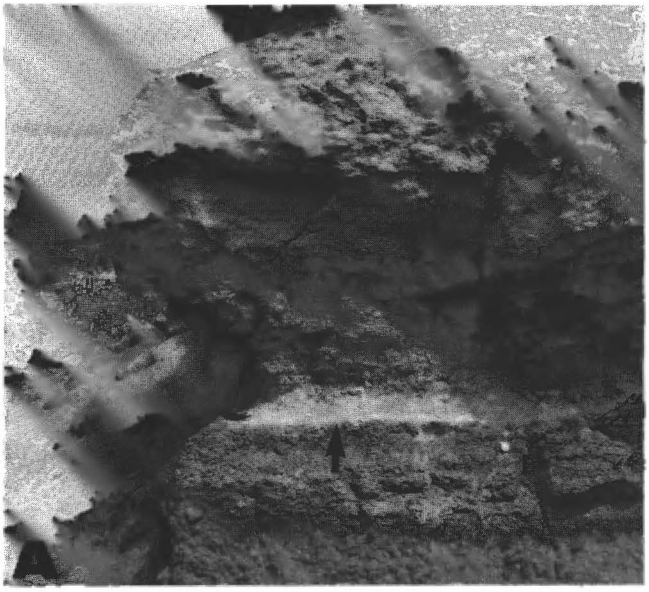

FIGURE 1.4. A, Typical outcrop of white ash #1 with the entire thickness exposed. Arrow marks the contact between ash and the underlying blocky siltstone. Note hammer for scale. B, Channel filled with dark gray ash 2b; base of the channel is indicated by arrows. Note the broad channel-form stratification and the underlying sandstone. Staff is 2.5 m long.

23.9 Milepost 7. Highway curves to right. View straight ahead of gently west-dipping pediment surface (Fig. 1.5) in Proterozoic granite leading up to the base of Sierra Mosca (11,765 ft) and The Dome (11,275 ft). **0.6**

THE PLIOCENE(?) BORREGO PEDIMENT SURFACE AND DEVELOPMENT OF THE WESTERN SANGRE DE CRISTO MOUNTAINS FRONT

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A forested upland surface covering about 105 mi^2 and sloping westward at 2-3° forms the flank of the Sangre de Cristo Mountains, west of the high peaks of the Santa Fe Range, from near Santa Fe to Truchas (Fig. 1.5). Cabot (1938) briefly described this feature as the oldest of many pediments in and adjacent to the Española Basin but, despite the large scale of this striking geomorphic feature, no significant further attention has been paid to it. We propose the name Borrego surface for this now-dissected pediment, which includes Mesa Borrego south of Truchas (Fig. 1.6A).

The Borrego surface truncates Proterozoic bedrock and projects under Cenozoic deposits of the Picuris embayment north of Truchas. Rounded pediment lag gravels are sparsely preserved on the Borrego surface, but no stratified deposits or soils whose characteristics might be used to directly estimate the age of the pediment remain. In the vicinity of Truchas, Manley (1976) identified three major "pediment" surfaces cut across Miocene Tesuque Formation basin fill. From oldest to youngest, these surfaces were named the Osa, Entranas and Truchas. Recent reconnaissance suggests that these "pediments" are probably alluvial fills now occupying the high interfluves of a landscape that has undergone significant topographic inversion. Late Cenozoic gravel underlying the Truchas surface of Manley (1976) unconformably overlies the Tesuque Formation in the Picuris embayment and projects south where it locally unconformably overlies Proterozoic rocks of the Borrego surface south

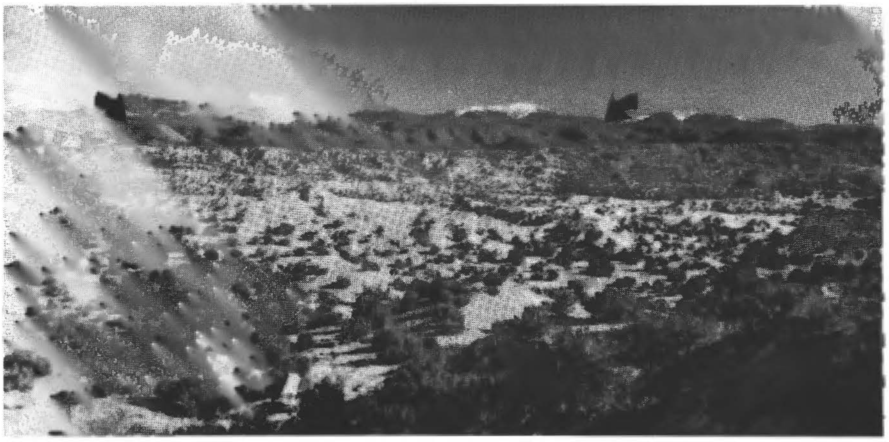


FIGURE 1.5. Eastward view of the Sangre de Cristo Mountains from a point about 3 mi west of mile 23.9. Light-colored outcrops of the Miocene Tesuque Formation in the foreground. Arrows point to a nearly flat, ponderosa-covered, pediment surface cut on Proterozoic rocks in front of the prominent peaks of the Sangre de Cristo Mountains on the skyline (from left, The Dome, 11,275'; Sierra Mosca, 11,765'; Santa Fe Baldy, 12,622'; Lake Peak, 12,409'). The left arrow points to Mesa Borrega, which forms part of this pediment. Deep canyons have been incised into this surface, the most obvious of which are those occupied by the Rio Frijoles (visible in front of Sierra Mosca) and Rio Nambé (between Santa Fe Baldy and Lake Peak). The middle-ground escarpment between the dark Proterozoic rocks and lighter Tesuque Formation has been interpreted as an exhumed depositional contact or as a fault escarpment by various workers.

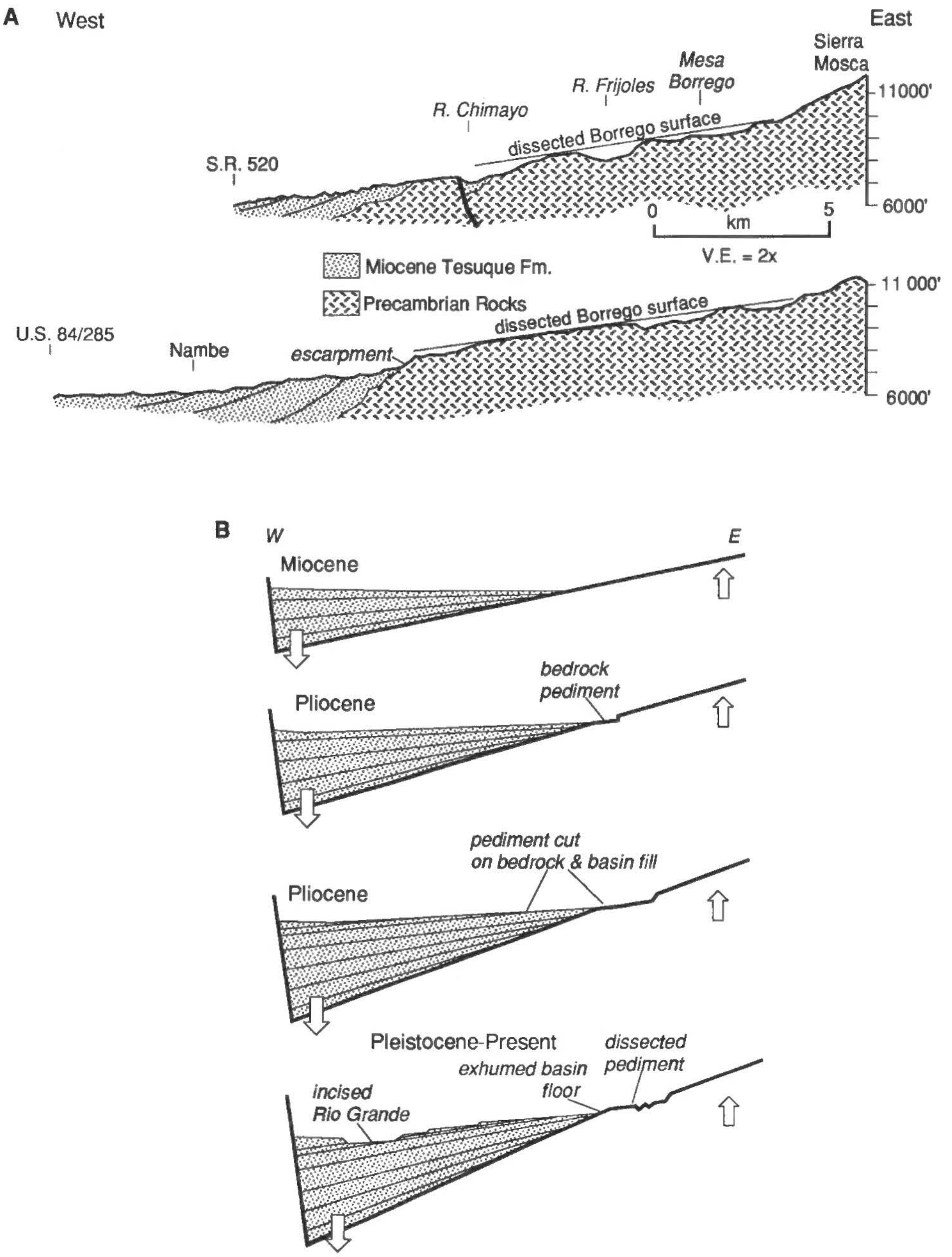


FIGURE 1.6. A, East-west geologic profiles near the latitudes of Santa Cruz Lake (top) and Nambé (bottom) showing the dissected Borrego pediment surface. Form lines in the Tesuque Formation indicate stratal dips (from Kelley, 1978, and Smith, unpubl.) adjusted for the illustrated vertical exaggeration. B, Schematic diagrams showing possible development of pediments on the eastern side of the Española Basin concurrent with deposition in the western part of the basin (e.g., Pliocene Puye Formation). Following incision of the Rio Grande, these eastern pediments were dissected and softer basin fill was preferentially excavated to exhume the original basin floor. The escarpment between the basin-fill badlands and the dissected bedrock pediment, also labeled in the lower profile of Figure 1.6a, may not, therefore, be of tectonic origin.

of Truchas (Kelley, 1978). A younger alluvial fill inset below the Truchas surface contains tephra correlated to the Guaje Pumice of the Bandelier Tuff (Manley, 1976), which has been mostly recently dated at 1.51 +0.03 Ma (Spell et al., 1990). Because the Truchas surface is, therefore, older than about 1.5 Ma and the Borrego surface is contemporaneous with or older than the gravels underlying the Truchas surface it is likely that the Borrego surface is Pliocene age or older (i.e., >1.64 Ma). It is conceivable that the Borrego surface is a complex, polygenetic surface, not strictly correlative to the sub-Truchas surface in the Picuris embayment, but rather the equivalent of all three of the high surfaces identified by Manley (1976) in the northern Española Basin.

Pediments are thought to represent a long period of base-level stability when hillslopes and river profiles have sufficient time to reduce relief to their base level of erosion (e.g., Ritter et al., 1994, p. 258-263). We propose that the Borrego pediment, and older erosion surfaces in the Picuris embayment, formed at the same time as deposition was occurring in the western Española Basin and partly or wholly before incision of the Rio Grande in the latest Pliocene or early Pleistocene. The timing of regional incision is constrained by a 1.7±0.1 Ma age on tephra (Turbeville, 1991) in the upper Puye Formation, which underlies the Pajarito Plateau on the western side of the basin. Initial incision of the Rio Grande had ensued by the early Pleistocene because the Puye Formation underwent dissection before eruption of the Bandelier Tuff at 1.51 Ma.

Formation of the Borrego pediment during basin subsidence is illustrated in Figure 1.6B. Neogene, down-to-the-west tilting of the Sangre de Cristo block exposed Proterozoic bedrock on the east side of the Española Basin. Concurrent deposition of basin-fill sediment occurred at a rate equal to basin subsidence, such that streams draining the hanging-wall block were able to attain and maintain a graded profile over a

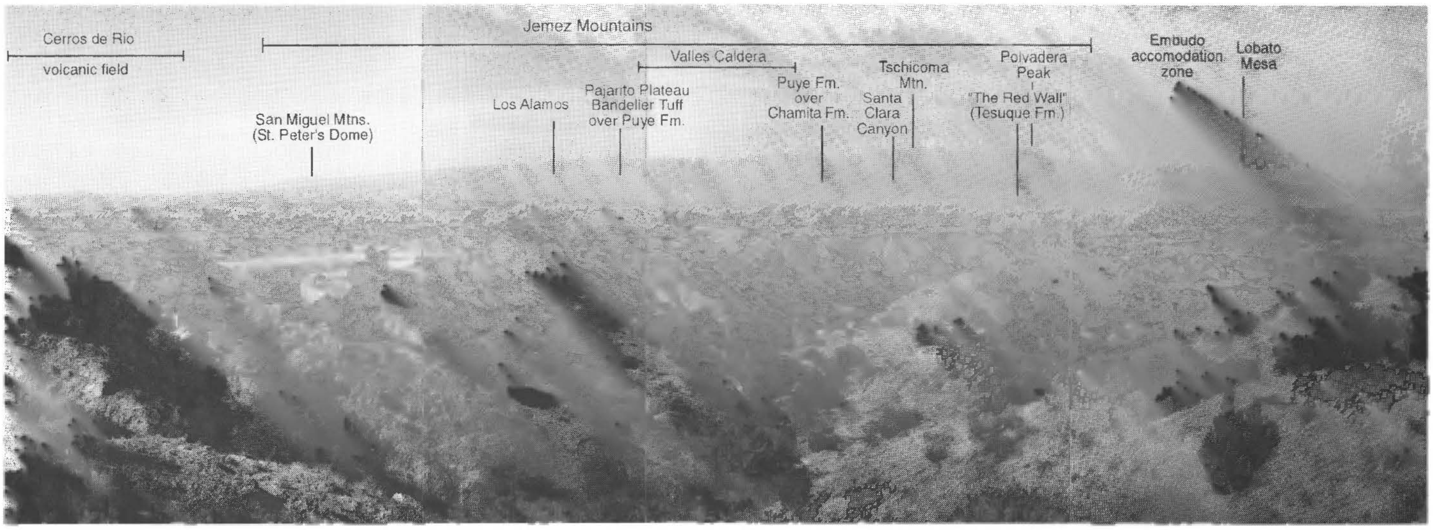


FIGURE 1.7. View westward at Stop 1. Foreground and middle ground outcrops are west-dipping beds of the Nambé and Skull Ridge Members of the Tesuque Formation. Arroyo Seco trends obliquely from the right edge of the photo to the center. The Red Wall is at the extreme right edge, capped by a white ash layer. The Jemez Mountains form the skyline. The highest peaks, Tschicoma Mountain (center, 11,561') and Polvadera Peak (right, 11,232') are upper Miocene or lower Pliocene composite volcanoes

protracted period of time. Minor base-level changes were rather rapidly expressed in the soft strata of the Tesuque Formation, but the hard Proterozoic rocks provided a more resistant buffer to fluvial erosion. In this manner, the Española Basin sediments could experience several cut-fill cycles, now expressed by the Osa, Entranas, and Truchas fills with a common bedrock counterpart in the Borrego surface. Widespread incision in the Española Basin and abandonment of the Borrego surface is coincident with major latest Pliocene or earliest Pleistocene base-level drop of the Rio Grande and a climatic transformation to more seasonal, Quaternary-type high-magnitude, low-frequency storm events. During the Quaternary, the basin-fill sediments have been dissected into intricate badlands while the Borrego surface was stripped of most of its thin alluvial cover and incised by canyons up to 820 ft deep.

Quaternary erosion in the Española Basin has preferentially removed the poorly consolidated basin-fill sediment so that depositional contacts between the Tesuque Formation and underlying Proterozoic basement are widely exposed near the Sangre de Cristo Mountains front (Galusha and Blick, 1971). The exhumed basin floor is shown schematically in the lowest diagram in Figure 1.6B. As shown in the lower profile of Figure 1.6A, the resulting steep topographic step at the contact between the Tesuque Formation and the basement rocks is a significant escarpment.

The structural significance of this escarpment has been very controversial. Cabot (1938) showed clear evidence for faulting along segments of the escarpment, but the magnitude of displacement along these faults is unclear and is possibly less than 100 m (Vernon and Riecker, 1989). These faults displacing the Tesuque Formation against Proterozoic rocks along the eastern side of the basin are not demonstrably more significant than the myriad of other modest-displacement faults with surface expression entirely within the Tesuque Formation that are present across the entire width of the basin (Galusha and Blick, 1971; Kelley, 1978). Spiegel and Baldwin (1963), Kelley (1978), Cordell (1979) and Vernon and Riecker (1989) interpreted the topographic escarpment at the mountain front to represent a zone of faults (Santa Fe fault zone of Kelley, 1978) that mark the eastern boundary of the Española Basin. Manley (1976, 1979a) interpreted field relationships and gravity data to be most consistent with the lack of a significant border fault. Her interpretation is most consistent with the mapping of Galusha and Blick (1971) near Santa Cruz Lake, which shows depositional contacts between the basement rocks and the basin-fill sediment. A similar contact is shown in the lower profile in Figure 1.6A, although Kelley (1978) inferred the presence of a fault here; note that the slope of the basement surface on the escarpment is nearly coincident with the dip of the overlying Tesuque strata that are interpreted to have been deposited upon it during early stages of basin tilting. Although structural processes cannot be wholly discounted, the presence of the escarpment may be largely or entirely the result of erosional planation of basement and basin-fill rocks prior to and after initiation of Rio Grande incision, followed by preferential erosion of softer basin fill to expose the original basin floor, inclined moderately steeply from the upland Borrego pediment surface.

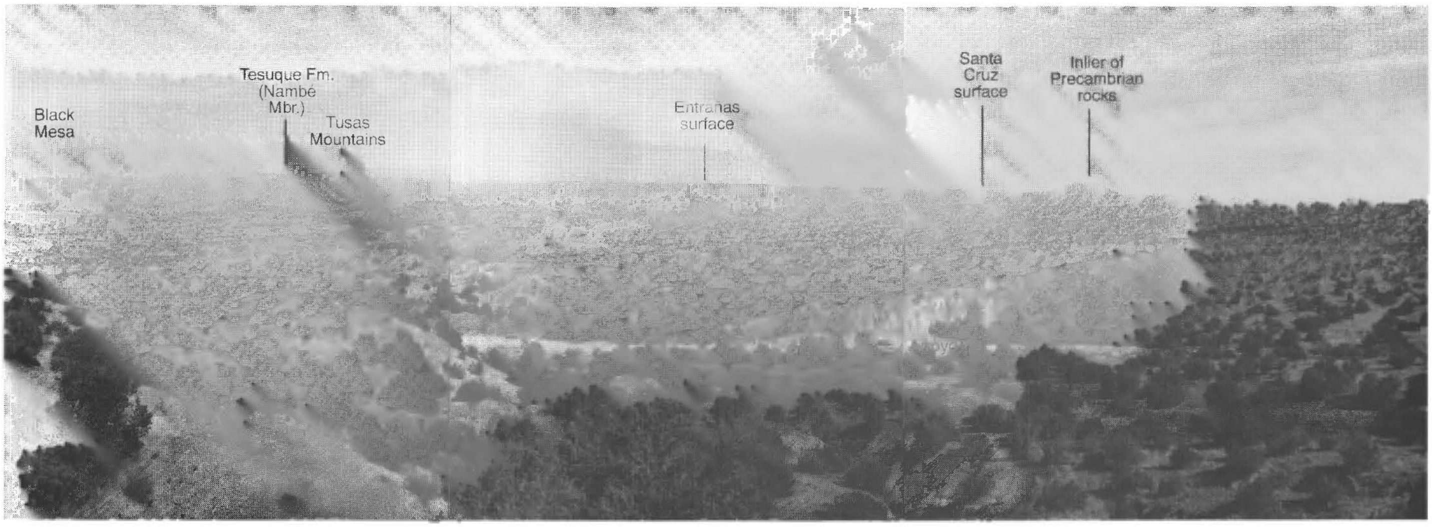
24.5 Junction with NM–520 to Chimayo; continue east on NM–503. **0.3**

24.8 **STOP 1. Pull out on left** (north) side of road at milepost 8 in Highway Dept. storage area.

Overview of Española Basin. This roadside pullout provides an excellent opportunity to view the large-scale geologic features of the Española Basin and adjacent regions. The Sangre de Cristo Mountains rise abruptly to the east. A variety of Proterozoic metavolcanic and granitic rocks underlie this part of the range (Miller et al., 1963). Sierra Mosca and The Dome rise above Mesa Borrego and equivalent high plateaus that define a dissected high-level erosion surface (Fig. 1.5). Southeast of Truchas, gravel rests on this surface; elsewhere it is generally devoid of sediment cover. This is the highest of several geomorphic surfaces in this part of the Española Basin and is probably Pliocene in age (see above).

To the north are views of the Tesuque Formation truncated by the Santa Cruz surface (foreground, to east of NM–520) and the higher Truchas surface (in background). The prominent knob projecting above the Santa Cruz surface directly to the north is an exhumed paleo-hill of Proterozoic rock surrounded by the Tesuque Formation. The contact between Proterozoic rocks and the Tesuque Formation is largely depositional in this area. The mountain front is largely unfaulted (Galusha and Blick, 1971; Kelley, 1978) and its steep relief is a consequence of erosion of the Tesuque Formation away from the original nonconformable surface, which now dips 35–45° to the west.

The view to the northwest is over west-dipping beds of Tesuque Formation. Black Mesa, capped by Sevilleta basalt that flowed south from the Taos Plateau volcanic field, looms above the confluence of the Rio Ojo Caliente (beyond) and the Rio Chama (left) west of the Rio Grande. The Tusas Mountains, a Laramide uplift of Proterozoic rocks frosted with distal volcanic and volcaniclastic rocks



that are the namesakes of the Tschicoma Formation and the Polvadera Group volcanic rocks. The dissected mesas at the base of the Jemez Mountains form the Pajarito Plateau. Volcaniclastic sedimentary strata of the Puye Formation, eroded from the large composite cones, underlie the plateau on the right. To the rear and left, the Puye Formation is overlain by lighter colored Pleistocene Bandelier Tuff.

derived from the San Juan Mountains volcanic field in southern Colorado and Latir volcanic field near Taos, forms the skyline beyond Black Mesa. The Rio Chama flows through the Abiquiu embayment, a structural platform in the western Rio Grande rift between the Colorado Plateau, visible on the skyline to the left of Black Mesa, and the deeper Española Basin in the foreground (Baldridge et al., 1994).

Looking directly westward, Miocene rift-filling sediment of the Tesuque Formation dominates the foreground (Figs. 1.7–1.9). The prominent wash leading westward through the basin fill is Arroyo Seco. A distinctive red hued cliff with white-ash stripes to the north of Arroyo Seco is the Red Wall locality of Galusha and Blick (1971). The area around the Red Wall provides superb exposures of the stratigraphic relationships between the Skull Ridge and Nambé Members of the Tesuque Formation, as defined by Galusha and Blick. The prominent ash that is visible about two-thirds of the way up the Red Wall is white ash #2, seen previously to the south.

The Jemez Mountains dominate the western skyline. Most high peaks visible from this point are upper Miocene and Pliocene volcanic centers of the Tschicoma Formation. Alluvial fans derived from erosion of the centers deposited the Puye Formation, which is the gray rock underlying the Pajarito Plateau extending eastward from the Jemez Mountains to the Rio Grande. To the south, orange cliff-forming Pleistocene Bandelier Tuff overlies the gray Puye Formation. The Bandelier Tuff was erupted in two caldera-forming episodes in the central Jemez Mountains at about 1.4 and 1.1 Ma. The abrupt topographic step from the Tschicoma highlands to the Pajarito Plateau marks the position of the Pajarito fault, which forms the western boundary of the Española Basin.

The view to the south is largely obscured by adjacent high ridges. To the southwest, however, can be seen the approximately 60 cinder cones of the Pliocene Cerros del Rio volcanic field (Aubele, 1978), which flanks the southeastern Jemez Mountains. The Sandia Mountains form the skyline.

ESTIMATED RATES OF QUATERNARY CRUSTAL EXTENSION IN THE RIO GRANDE RIFT, NORTHERN NEW MEXICO

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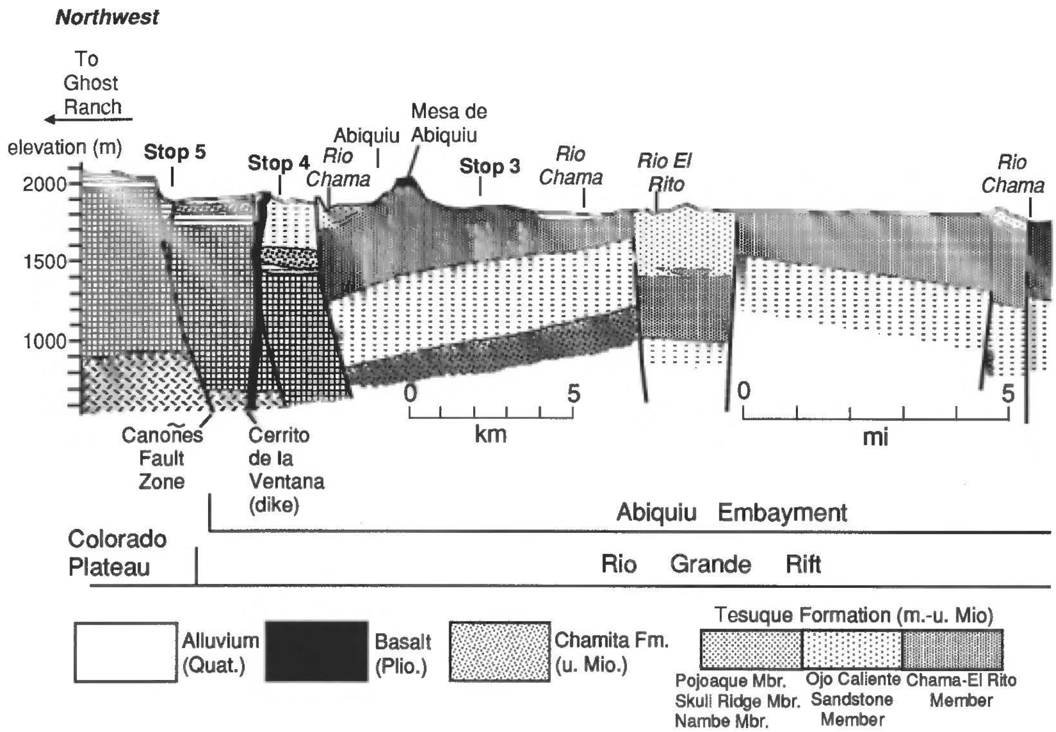
This study assesses Quaternary rates of horizontal E–W extension in the northern Rio Grande rift, based on slip rates of primary faults bordering and within the major rift basins. The Rio Grande rift in northern New Mexico consists of several north-trending asymmetric basins, including the San Luis, Española and Santo Domingo Basins (Fig. 1.10). The polarities of these half grabens change across accommodation zones that traverse the rift at high angles. The amount of Neogene extension within each rift basin decreases northward, with at least 28% extension in the southern Albuquerque Basin, at least 17% in the northern Albuquerque Basin, and about 8 to 12% in the San Luis Basin (Keller and Cather, 1994; Kluth and Schaftenaar, 1994; Russell and Snelson, 1994). On a regional scale, the present least principal stress direction is horizontal and trends roughly WNW (Sanford et al., 1991; Zoback and Zoback, 1989). In this analysis, we use estimated Quaternary slip rates on individual faults to assess cumulative rates of E–W extension along three regional transects across the northern Rio Grande rift.

The San Luis Basin is an east-tilted half graben with several kilometers of west-down displacement on the Sangre de Cristo fault along its eastern margin, and a gentle homocline along its western margin (Chapin and Cather, 1994). Compared with other major basins of the Rio Grande rift, the San Luis Basin is structurally uncomplicated, with few major intrabasin faults (Kluth and Schaftenaar, 1994).

The Española Basin, in contrast, is a west-tilted half graben that contains several intrabasin faults. The east-down Pajarito fault forms the western margin of the basin, and has had about 1.5 km of late Cenozoic displacement (Gardner and Goff, 1984). The eastern margin of the Española Basin lacks a well-defined, continuous fault, and has had little or no discrete west-down displacement (Baltz, 1978). Discontinuous intrabasin faults exhibit east-down and west-down displacements and likely accommodate distributed strain related to westward tilting of the basin (Biehler et al., 1991).

The Santo Domingo Basin is located between the Española and northern Albuquerque Basins (Fig. 1.10). The basin is an east-tilted half graben bordered on the east by the La Bajada fault (Stearns, 1953b; Kelley, 1978) and on the west by a distributed zone of faulting and flexuring grouped herein as the San Felipe fault zone (Smith et al., 1970; Baltz, 1978). Intersections between the La Bajada and Pajarito faults at the



northern end of the basin and between the San Felipe fault zone and Sandia-Rio Grande fault (Wong et al., 1995) suggest that the Santo Domingo Basin itself may transfer extensional strain between the Española and northern Albuquerque Basins.

Considerable data exist on the rate of vertical movement along major rift-border and intrabasin faults in the northern Rio Grande rift (Table 1). Extension in the southern San Luis Basin is accommodated primarily by the rift-margin Sangre de Cristo fault and the intrabasin Los Cordovas fault zone (Personius and Machette, 1984). For the Sangre de Cristo fault, Menges (1988, 1990) reported a post-Pliocene vertical slip rate of 0.15 to 0.25 mm/yr, and we assume a median value of 0.20 mm/yr (Table 1). The Los Cordovas fault zone has displaced a middle Pleistocene geomorphic surface about 15 m (Kelson, 1986), thus yielding an estimated average long-term vertical slip rate of 0.02 mm/yr (Table 1).

Seven primary faults are identified in the Española Basin (Fig. 1.10). The Pajarito fault exhibits 81 m of displacement of the 1.2 Ma upper Bandelier Tuff, averaged along the fault trace (Wong et al., 1995). These data yield an average vertical slip rate of 0.07 mm/yr. At the latitude of the Española transect (Fig. 1.10) the Rendija Canyon Guaje Mountain faults displace the upper Bandelier Tuff about 25 and 20 m, respectively (Wong et al., 1995), both of which yield a vertical slip rate of 0.02 mm/yr. The east-down Sawyer Canyon fault exhibits about 25 m of displacement of the upper Bandelier Tuff (K.E. Carter, personal commun., 1994), suggesting an average vertical slip rate of about 0.02 mm/yr. The Puye fault zone consists of several east-down faults that exhibit evidence of multiple Pleistocene ruptures (LaForge and Anderson, 1988). There is 9 m of displacement of a Pleistocene surface that may be as young as 350 ka (Dethier et al., 1988) across a primary strand of the fault zone, suggesting an estimated vertical slip rate of 0.03 mm/yr (Wong et al., 1995).

There are little or no data on the rates or amounts of displacement across the Pojoaque and Nambé fault zones. The Pojoaque fault likely is part of distributed brittle deformation within the western part of the Española Basin, which has subsided about 60 m in the past 3 Ma (the Velarde graben of Manley, 1979a). We estimate an upper bound for the long-term average vertical slip rate on the fault of 0.02 mm/yr (Table 1), based on the assumption that a 1-2-m-high fault scarp could survive at most only 100,000 to 150,000 years in the climatic and geologic environment of the northern Rio Grande rift (M.N. Machette, written commun., 1994). The presence and continuity of the Nambé fault zone are debatable: field mapping shows a series of discontinuous faults (Cabot, 1938; Spiegel and Baldwin, 1963; Galusha and Blick, 1971; Baltz, 1978), whereas air-photo interpretations suggest a more continuous structure (Vernon and Riecker, 1989). As with the Pojoaque fault zone, we estimate an upper bound for the long-term average vertical slip rate on the fault of 0.02 mm/yr (Table 1).

Along the Santo Domingo transect to the south of the Española Basin, we consider the Jemez-San Ysidro fault zone, which likely borders the northwestern margin of the Albuquerque Basin, and three faults bordering the Santo Domingo Basin (Fig. 1.10). The Jemez-San Ysidro fault zone used herein includes the Jemez fault of Goff and Shevenell (1987) and the San Ysidro fault of Hawley and Galusha (1978). Goff and Shevenell (1987) noted 50 m of displacement of the 1.2 Ma upper Bandelier Tuff across the Jemez fault, which yields an estimated long-term vertical slip rate of 0.05 mm/yr (Table 1). The San Felipe fault zone as used herein includes the Santa Ana, Luce, Algodones and associated faults, which overall border the north-trending San Felipe graben (Smith

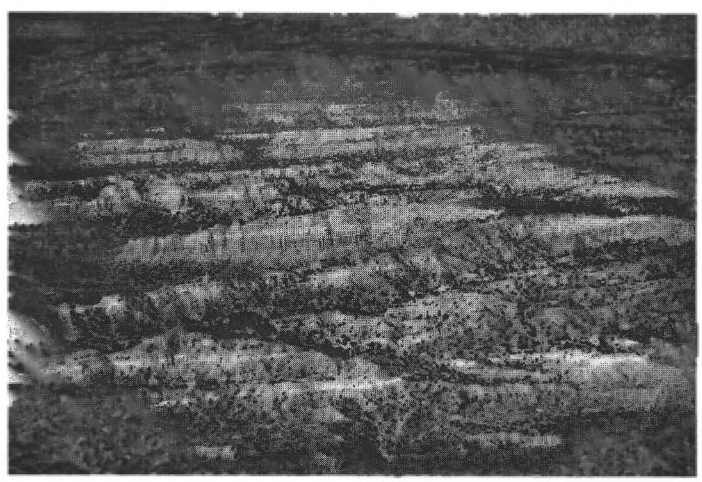


FIGURE 1.9. Oblique aerial view looking WNW across the Tesuque Formation badlands west of Stop 1. Prominent white bands are white ash #2 of Galusha and Blick (1971) structurally repeated across numerous north-striking, down-to-the-east normal faults. Valley of the Santa Cruz River downstream from Chimayo is visible in the upper right.

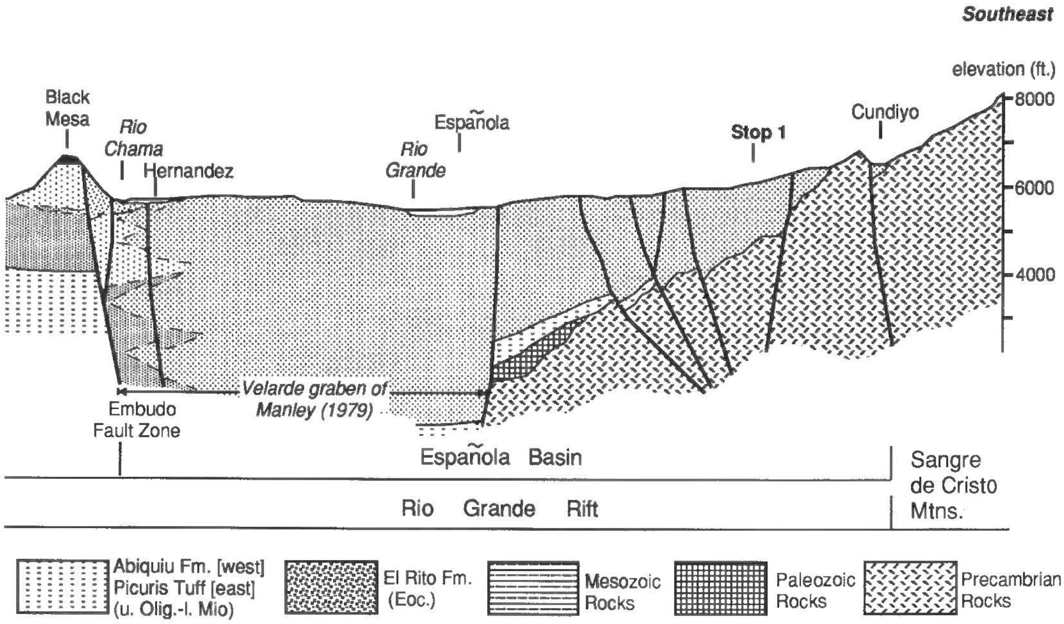


FIGURE 1.8. Generalized geologic cross section across the northern Española Basin and Abiquiu embayment showing locations of Stops 1,3,4 and 5 in relation to rift structure and stratigraphy. Cross section is based mostly on the map of Kelley (1978) and the geophysical interpretations of Golombek et al. (1983) and Baldridge et al. (1994).

et al., 1970; Kelley, 1977; Hawley and Galusha, 1978). The faults displace 2.5 Ma basalt of Santa Ana Mesa (Bachman and Mehnert, 1978), and are associated with topographic scarps developed in basalt as much as 50 m high. We assume the presence of two primary fault strands bordering the San Felipe graben, and, based on these data, conservatively estimate a long-term vertical slip rate of 0.04 mm/yr for the entire zone (Table 1). There are no available data on the Quaternary slip rate of the San Francisco fault; we assume a value equal to that on the La Bajada fault based on comparable geomorphic expression and probably similar tectonic role in the rift (Wong et al., 1995). The La Bajada fault is located at the base of a 160-m-high escarpment developed in 2.5 Ma basalt (Aubele, 1978; Bachman and Mehnert, 1978), which yields an estimated vertical slip rate of 0.06 mm/yr (Table 1).

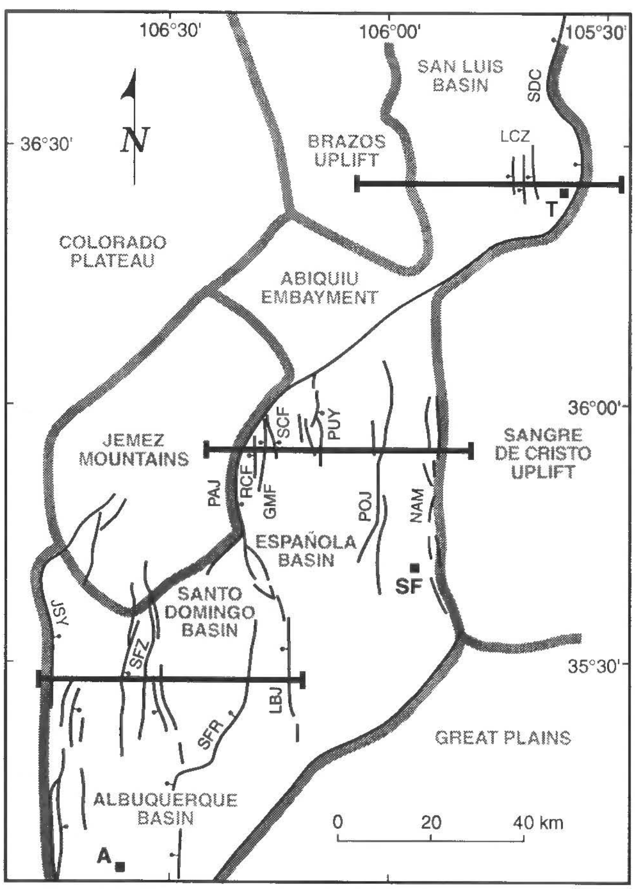


FIGURE 1.10. Primary fault strands of the northern Rio Grande rift. See Table 1 for fault names. T = Taos; SF = Santa Fe; A = Albuquerque.

Rates of regional crustal extension can be estimated assuming that all of the extension is accommodated by brittle deformation on identified faults; the faults dip 60° through the seismogenic crust; and the direction

TABLE 1. Estimated Quaternary vertical slip rates and calculated extension rates, northern Rio Grande rift.

Fault	Best Estimate Quaternary Vertical Slip Rate (mm/yr)	East-West Quaternary Extension Rate (mm/yr)
San Luis Transect		
Sangre de Cristo fault (SDC)	0.20	0.12
Los Cordovas fault zone (LCZ)	0.02	0.01
		Total: **0.13**
Espanola Transect		
Pajarito fault (PAJ)	0.07	0.04
Rendija Canyon fault (RCF)	0.02	0.01
Guaje Mountain fault (GMF)	0.02	0.01
Sawyer Canyon fault (SCF)	0.02	0.01
Puye fault zone (PUY)	0.03	0.02
Pojoaque fault zone (POJ)	0.02	0.01
Nambe fault zone (NAM)	0.02	0.01
		Total: **0.11**
Santo Domingo Transect		
Jemez-San Ysidro fault (JSY)	0.05	0.03
San Felipe fault zone (SFZ)	0.04	0.02
San Francisco fault (SFR)	0.06	0.03
La Bajada fault (LBJ)	0.06	0.03
		Total: **0.11**

of extension is orthogonal to fault strike. We acknowledge that many, if not all, of the faults compiled herein may be listric in nature, and may have shallower dips at depth. Based on these assumptions and available vertical slip rates, we provide a first approximation of Quaternary extension rates across the rift. As shown on Table 1, the rate of extension along the San Luis, Española, and Santo Domingo transects ranges from 0.11 to 0.13 mm/yr. This range is surprisingly narrow considering that the number of faults crossed by each transect ranges from two to seven. This analysis does not account for ranges in slip rate values, and therefore provides no information on the uncertainty in the regional extension rates. Undoubtedly, some of the rates used are too low, and probably some are too high. Overall, however, this analysis supports an interpretation that the rate of regional Quaternary extension across the northern Rio Grande rift is about 0.1 mm/yr. The calculated extension rates given above do not show a northward decrease, as might be expected from the amounts of Neogene extension given by Chapin and Cather (1994). The discrepancy may be related, in part, to the poor constraints on estimated fault slip rates. Alternatively, if the rates of Quaternary extension are comparable among rift basins, the greater cumulative amounts of Neogene extension in the south suggest a northward progression of rifting.

Return to highway and continue eastward to Cundiyo. 0.5

25.3 Ledge-forming conglomeratic sandstones of the Nambé Member of the Tesuque Formation exposed to the left of the road. **0.3**

25.6 Junction with road to overlook of Santa Cruz Lake. Continue east on NM–503. **0.1**

25.7 Roadcut in Nambé Member of the Tesuque Formation. **0.3**

26.0 Milepost 9. View down valley to left (north) illustrates depositional contact between Tesuque Formation, on west, with dark Proterozoic amphibolite cut by granite sills, on east (Fig. 1.11). The map by Miller et al. (1963) is nearly devoid of faults in this area. In contrast, Kelley's (1978) map of the Española Basin shows numerous large-displacement, north-striking, normal faults through here. Galusha and Blick (1971; Fig. 1.12) sketched several examples of the depositional contact in this area to emphasize the lack of faulting along this part of the Sangre de Cristo mountain front. Even though large faults do not separate Proterozoic from Tertiary here, the Proterozoic rocks are extensively fractured and contain numerous minor faults. A moderately SE-dipping fault in the streamcut ahead contains oblique fault striae that plunge 30°S. **0.1**

26.1 Road nearly coincides with contact between Tesuque Formation, on right side of road, and Proterozoic granitic rocks, across wash on left side of road. Miller et al. (1963) mapped the enormous granitic terrane along the western Sangre de Cristo Mountains as Embudo Granite, a general term originally used in the Picuris Mountains. Subsequent more detailed mapping has shown that the Embudo Granite is a complicated plutonic complex that probably spans more than 200 Ma. **0.4**

26.5 Roadcut in granite on left. Most of the Proterozoic rocks here are metaintrusive rocks of some sort. The predominant lithology is reddish-orange, equigranular, ± tectonically foliated, fine-grained granite with abundant pods and stringers of pegmatite and quartz. Pegmatites range in thickness from a few centimeters to a few meters, and many show considerable range in grain size. Other common rock types are mafic schist, amphibolite and gneiss, all of which contain a moderately SE-dipping foliation. Tight folds in the gneisses and schists are common, as are gently to moderately SE-plunging extension lineations. **0.1**

FIGURE 1.11. Northward view from road at mile 26.0, illustrating depositional contact (at tip of arrow) between west-dipping Tesuque Formation (left) and Proterozoic metamorphic and plutonic rocks (right); also see Fig. 1.12A. Prominent pinyon and juniper studded hill in center is a knob of Proterozoic rocks that has been exhumed from beneath the Tesuque Formation along the south side of Santa Cruz Lake (also see Fig. 1.12B).

26.6 Roadcut to left shows a variety of Proterozoic rocks. Granite, with screens and xenoliths of amphibolite and mafic schist, is present along the western part of the exposure and grades through a zone of foliation-parallel granitic intrusions into amphibolite with steep, E-dipping foliation. In one spot is a spectacular example of cuspate-lobate folding between granite and schist. The schist has been preferentially eroded, leaving the fold mullion surface fully exposed. The outcrop also contains delta porphyroclasts whose asymmetrical tails suggest top-to-the-north (reverse) ductile shearing. Asymmetrical minor folds show both reverse and normal sense-of-shear. Toward the central and western part of the roadcut recumbently folded compositional layering and foliation are cross-cut by a sub-horizontal, lenticular, complexly zoned, 6-ft-thick, garnet-bearing, granitic pegmatite (Fig. 1.13). The pegmatite contains an axial, fine-grained phase, that is symmetrically flanked by coarse, outward-radiat-

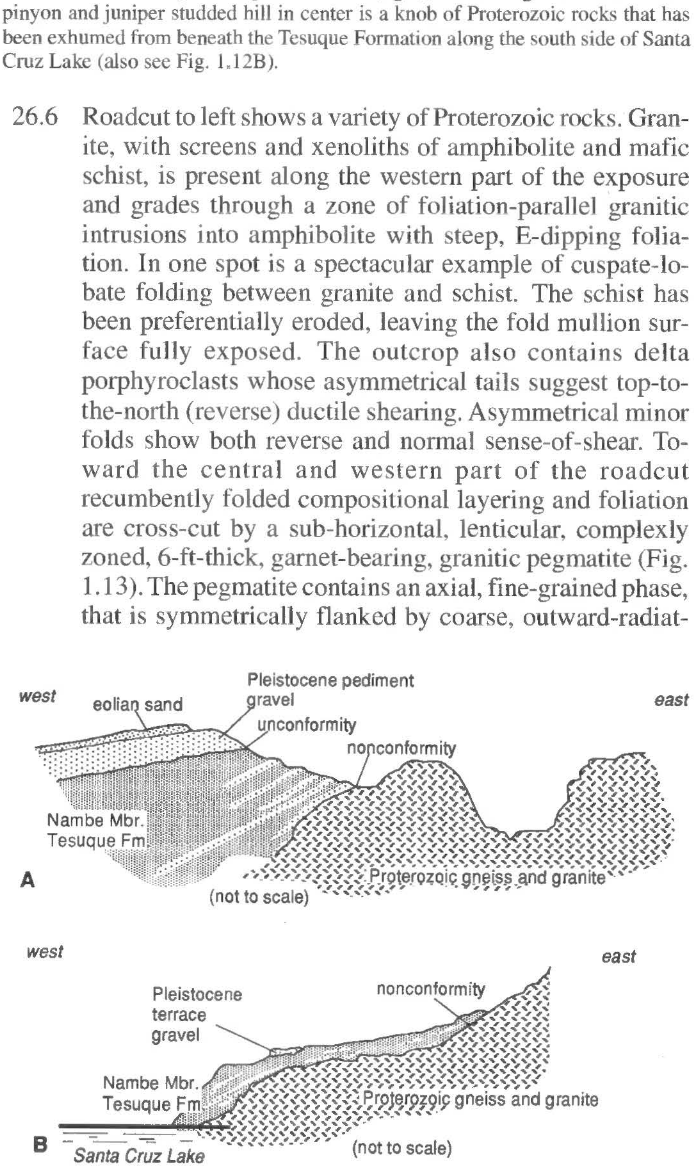


FIGURE 1.12. Cross sections (modified from Galusha and Blick, 1971, fig. 11) of depositional contacts between the Tesuque Formation and the Proterozoic basement rocks in the area west of Cundiyo. A, Cross section in vicinity of photograph shown in Figure 1.11. B, Cross section along western margin of Santa Cruz Lake.

ing feldspar crystals. In places, the granite is cut by three generations of cross-cutting felsic dikes. **0.4**

27.0 Proterozoic granitic gneiss in roadcut on right contains medium-grained porphyroclasts of K-feldspar, cut by coarse-grained, deformed and undeformed pegmatites. These rocks are highly fractured; Kelley (1978) placed a major, down-to-the-east normal fault a few meters east of here. View to the east of canyons incised through the erosion surface cut on Proterozoic rocks to form Mesa Borrega. **0.3**

27.3 Steep, curvy descent into Cundiyo. Cundiyo, derived from the Tewa Indian word for "the round hill of the little bells", is an isolated community of related families at the confluence of the Rio Frijoles and Rio Medio. Just above the town are the ruins of an ancient adobe pueblo, perhaps the original Nambé Pueblo. The tiny Cundiyo Grant was deeded in 1743 by Governor Mendoza. Nearly all of the families in Cundiyo have the surname Vigil, and all are related by blood or marriage. The common ancestor, Capt. Jose Antonio Vigil, had five sons who divided up the land. The land has been repeatedly subdivided subsequently, but always as the property of a Vigil. Traditionally, the men found wives in surrounding villages, while the women moved away to start families. Weaving and agriculture have historically been the primary trades. **0.2**

27.5 View to the east of Proterozoic rocks along Rio Frijoles. The well-developed joint sets are typical of Proterozoic rocks of much of the southern Sangre de Cristo Mountains. **0.2**

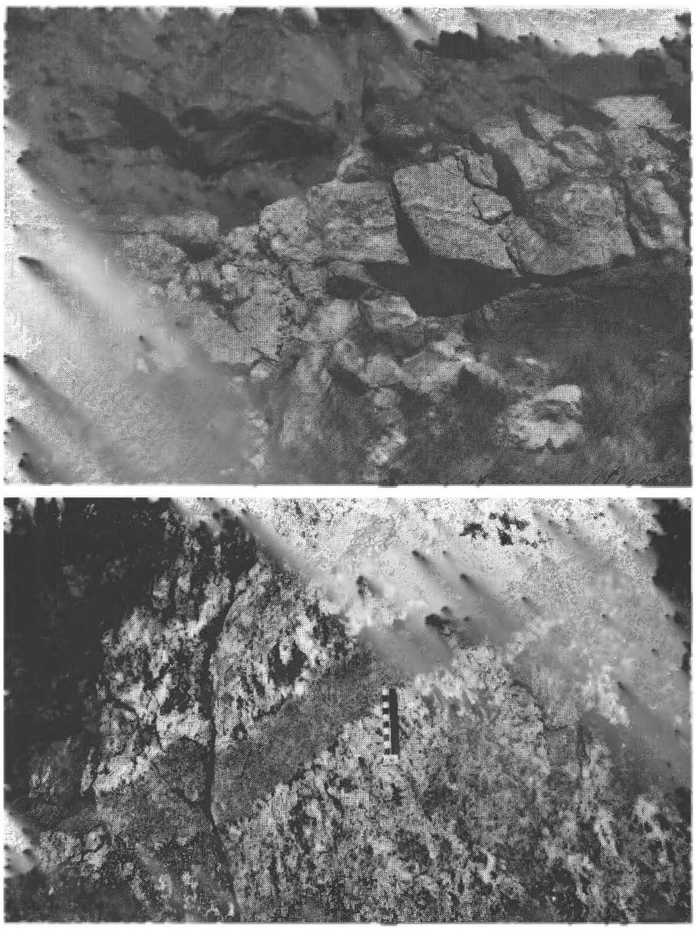


FIGURE 1.13. A, Light-colored, zoned pegmatite cutting steep foliations in Vadito Group amphibolite at mile 26.6. B, Close view of pegmatite with axial, fine-grained phase, flanked by coarse, outward-radiating feldspar crystals.

27.7 From small pulloff on the right, just after the very tight curve left, is good view in cliffs of complex intrusive/tectonic interlayering of Proterozoic rocks, with pink-orange granites in mafic schists and amphibolites. **0.2**

27.9 Near milepost 11 is a view to the east across the Rio Frijoles of light-colored, poorly consolidated sediment of the Tesuque Formation resting unconformably on Proterozoic rocks. Proterozoic metamorphic rocks are also exposed along the ridge immediately west of the road. The highway and stream are following the trace of a north-striking, down-to-the east normal fault. Similar east-down faults are the dominant structural feature in the Española Basin to the west. **0.2**

28.1 Roadcut in Proterozoic granitic and metamorphic rocks. **0.1**

28.2 Crossing Rio Medio at its confluence with Rio Frijoles to form the Santa Cruz River. The Proterozoic rocks in this canyon are predominantly strongly deformed, fine-grained, gneissic rocks that are laced with layer-parallel felsic veins. The gneiss protolith was most likely granitic rock. Coarse-grained pegmatites cross-cut the gneisses. Abundant remnants of mafic schist and amphibolite are strung out along the moderately south-dipping foliation. Compositional layering is folded by mesoscopic, asymmetric, north-verging folds with gently plunging hinges. Thin quartz and pegmatite veins are ptygmatically folded within the gneiss. In general, the impression is of a history of high-temperature shearing and folding of a mid-crustal plutonic complex. Overprinting the Proterozoic ductile deformation is ubiquitous Phanerozoic brittle deformation. All rocks are highly fractured and faulted. One moderately south-dipping fault plane by the bridge contains down-dip fault striae. **1.2**

29.4 Roadcuts through Quaternary alluvium with calcareous soils under the Santa Cruz surface of Manley (1979b). **0.5**

29.9 Milepost 13. **0.2**

30.1 Slight angular unconformity between Tesuque Formation and younger Quaternary gravel of the Santa Cruz surface (Fig. 1.14). Just ahead is entrance to Santa Cruz Lake. **0.1**

FIGURE 1.14. Angular unconformity between Tesuque Formation (dipping moderately to the left) and gravels associated with the Quaternary Santa Cruz surface, mile 30.1.

30.2 Forest Road 306 on right leads back into the Proterozoic high country and Mesa Borrega. **0.3**

30.5 Spectacular vista of Jemez Mountains and Pajarito Plateau before beginning descent through roadcuts exposing about 65 ft of ancestral Rio Quemado gravel that fills a paleochannel below the Santa Cruz surface. Some cobble-rich layers show imbrication indicating westward paleoflow. **0.3**

30.8 Winding descent to Rio Quemado valley (Fig. 1.15). Sedimentary fill of Penasco embayment in the northeastern Española Basin visible on skyline. Several terrace levels discernible along the northern side of the valley. Correlative terrace gravels are exposed in roadcuts. **0.3**

31.1 Entering the village of Rio Chiquito. **0.2**

31.3 Crossing Rio Quemado. **0.2**

31.5 **Take left fork in road to join NM–76 west. 0.9**

32.4 Milepost 9. Large earthen dam on right across Arroyo de la Cañada Ancha (Wide Canyon). **0.7**

33.1 Junction with NM–520; continue west on NM–76. Ortega's Weaving on the left has a fine selection of books on northern New Mexico. Entering village of Chimayo (name from Tewa word *tsimayo* meaning "good flaking stone"). About 2 mi to the southwest, amid the rugged hills, the Castell and Wigzell No. 1 Kelly Federal oil test was drilled in 1961. The upper 2460 ft were in the Tesuque Formation overlying Pennsylvanian limestones (T.D. 2703 ft; sec. 11, T20N, R9E). **0.5**

33.6 Scenic outcrops of Tesuque Formation south of river are eroded into spires and pinnacles. **0.6**

34.2 Road crosses Arroyo de la Cañada Ancha. Flash floods were a problem here prior to construction of the earthen dam upstream. **0.5**

34.7 View to south of white ash #2 within the Skull Ridge Member of the Tesuque Formation. Note the transition from fine-grained pink facies below the ash to lighter colored sandy facies above the ash as noted at mileage 21.1, which is 6 mi to the south of here. **1.3**

36.0 Entering Santa Fe County. **3.7**

39.7 Junction with NM–106. Continue west on NM–76. **0.5**

40.2 Junction with NM–583. Continue west on NM–76. **1.0**

41.2 La Paragua restaurant on right displays much of the local stratigraphic section in its stone walls, including malachite-green Proterozoic quartzite from Copper Hill in the Picuris Mountains. **0.1**

41.3 Junction with NM–68 (Riverside Drive) in Española. **Turn right (north). 0.7**

42.0 Junction with NM–583/584 (Fairview Drive). Continue north on NM–68. **1.1**

43.1 Fairview post office on right. Bluffs at 1:00 consist of west-dipping Tesuque Formation with inset late Pleistocene terrace gravel and overlying remnants of a valley-border alluvial wedge similar to buried Rio Grande gravels and alluvial wedge beneath the current route (Fig. 1.16). The terrace gravel is approximately 100 ft above the present Rio Grande. *Succinea* snail shells found within the flood plain deposits overlying the ancestral Rio Grande gravels have amino acid ratios similar to dated shells found at similar levels along the Rio Chama (Dethier and McCoy, 1993). Dethier and McCoy (1993) interpreted the gravel terraces and accompanying alluvium to have been deposited prior to 26,000 years ago, before late Pleistocene (Wisconsinan) incision of the Rio Chama and Rio Grande to form the present flood plain and alluvial valley border depositional system. **1.6**

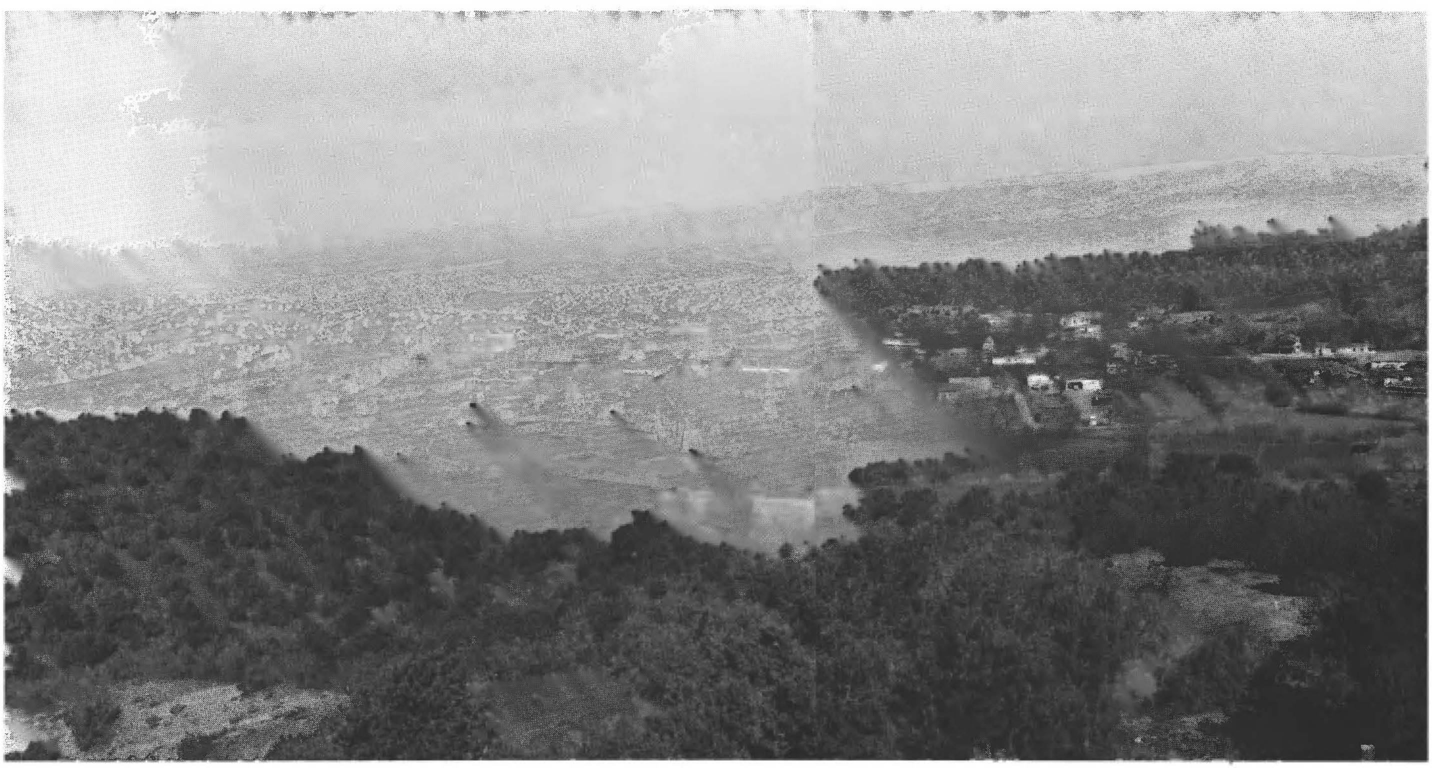


FIGURE 1.15. View to the northwest across the Rio Quemado valley from mile 30.8. Badlands eroded in the Tesuque Formation in the middleground are locally truncated by prominent strath terraces. Pliocene basalt of Black Mesa is visible in the background at the right and extreme left side of the photo.

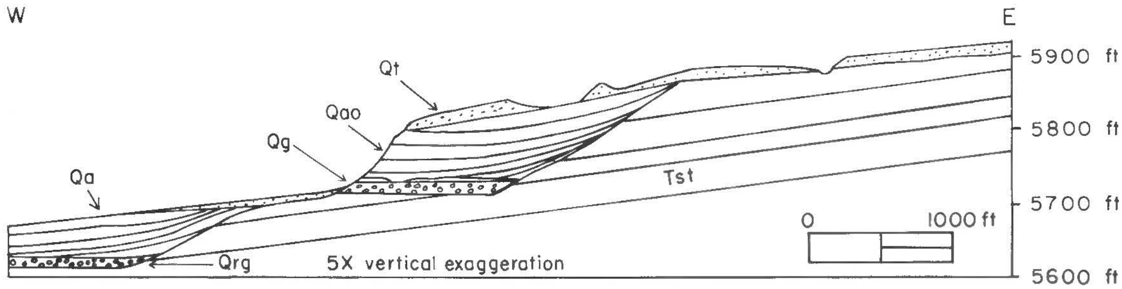


FIGURE 1.16. Cross section of bluffs east of San Juan Pueblo showing terrace gravel of ancestral Rio Grande (Qg) on dipping bedrock (Tst), buried by alluvial fan deposits (Qao) with coarser alluvial at the top (Qt). Alluvium of present valley border (Qa) grades west to present Rio Grande and buries former gravel and flood plain of Rio Grande (Qrg).

HYDROCOMPACTIVE SOIL FIELD EXPERIMENTS NEAR ESPAÑOLA

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After several reports of ground subsidence and homes with cracking foundations in the Española area in November, 1984, the New Mexico Civil Emergency Preparedness Division in Santa Fe asked the New Mexico Bureau of Mines and Mineral Resources (NMBMMR) to investigate. Because of the unknown nature, but rapid rate of local subsidence, and at the urging of local politicians, the Governor declared an emergency in December and required the NMBMMR to investigate the geologic causes of the damage. Other state agencies and the Red Cross were called upon to help the affected residents.

Hydrocompactive soils were suspected from the beginning, but all other hypotheses had to be considered because local residents had not heard of compactive soils and were looking for possible responsible parties to sue. Other explanations included (1) ground vibrations from heavy traffic along the main roads, (2) ground vibrations from explosives detonated for a nearby seismic survey by a petroleum exploration company in November, 1984, (3) ground-water fluctuations or subsurface "diversions" due to new water wells, (4) gravel mining in quarries 1 mi west of the affected area, (5) earth deformation such as subsidence along active faults and related seismic shocks, (6) increased precipitation, (7) karst, (8) underground mine collapse, (9) compaction of organic matter at depth, (10) compaction along a buried bluff line of the ancestral Rio Grande, or (11) expansive soils. The geologic investigation gathered data to test each of the possibilities. Beyond determining the geologic explanation for the damage, the NMBMMR wanted to investigate possible methods of salvaging damaged structures or designing foundations that would resist damage in the eventuality of similar subsidence in the future. The NMBMMR also wanted to make a series of recommendations concerning zoning and building practices in areas of hydrocompactive soils. The initial geological report was due in four months and the final report in six months. The reports from the investigation include Johnpeer et al. (1985a, b), Shaw and Johnpeer (1985a, b), Reimers (1986), and Love et al. (1987). This mini-paper summarizes the results of field experiments undertaken during the emergency investigation and is extracted from the above references. "Soil" in this summary refers to all piedmont alluvium above the local bedrock or above the buried floodplain of the ancestral Rio Grande beneath El Llano.

Field experiments were done on undeveloped land south of Española High School to demonstrate the relationship between ground wetting and subsidence, to test induced hydrocompaction as a stabilization technique, and to test the performance of different concrete-foundation designs. The main experimental area was on an almost undisturbed and unirrigated Holocene alluvial apron that had about 30–40 ft of aggradation above bedrock. The control area was farther down the alluvial apron in an area that had been farmed and irrigated for at least 300 years. The control area did not respond to addition of water in the initial experiments so later hydrocompaction experiments were only carried out in the unwatered area. The control area received deep injection, shallow injection, and shallow pond water of more than 24,500 gallons for more than 84 days with no signs of any subsidence. Moisture-density monitoring wells showed as much saturation as at the other experimental sites.

Three experiments demonstrated the behavior of local hydrocompactive soil and the behavior of slab foundations built upon it. The first experiment injected water into the soil along a 30-ft vertical column of 2-inch perforated pipe. Later, two shallow injection pipes and a small surface pond were added because most of the water initially dissipated at the bottom of the deep hole and the surrounding soil column was not wetted. Only minor subsidence occurred in this experiment.

In the second experiment, water was injected in a single 2-inch PVC perforated pipe 10 ft long. Several thousand gallons were run into the pipe and surrounding ground over seven days before collapse began. The experiment ceased after 16 days when collapse was no longer apparent and a total of 16,880 gallons of water had been injected. Ground subsidence reached a maximum of 2.2 ft and affected an area of 600 sq ft (Fig. 1.17). This amount of water injected at this depth is similar to the amount of water a typical Española family of four would contribute in a month and a half to a septic tank buried at about the same depth.

The third experiment tested the feasibility of uniformly settling slab foundations using water injection into hydrocompactive soils. A conventional (welded-wire-mesh reinforced, 4 in. of concrete) slab and a more heavily reinforced slab each measuring 10 by 15 ft were constructed above hydrocompactive soil. The reinforced slab was constructed following the Building Research Advisory Board (BRAB) recommendations for slabs on expansive soils (Clemence and Finbarr, 1981; Post-Tensioning Institute, 1980). Five shallow (10 ft) injection wells and ten monitoring wells (depth approximately 40 ft) were placed in and around

FIGURE 1.17. Collapse and fissures caused by shallow injection during experiment two.

the slabs. Subsidence of the slabs began 13 days after injection began, with addition of 19,880 gallons of water. Both slabs subsided 1.4 ft and remained level, but the ground subsiding around the slabs continued to expand laterally after subsidence in the center ceased.

On a micro (grain-to-grain) scale, hydrocompactive soils can have several different open packing arrangements (Barden, 1971). Scanning electron micrographs showed that the soils beneath El Llano had three hydrocompactive types, including silt grains between sand grains, aggregated clay between sand grains, and clay menisci between sand grains. In the ground, contacts between grains experience both normal and shear forces. Point contacts between almost cohesionless grains in Española's collapsible soils have clay menisci bridges which, when dry, increase resistance to shear. When wetted, the clays swell, become plastic, or even become resuspended, reducing resistance to shear. The sand grains are able to rotate or shear past each other to pack closer. Increased normal forces (load, including weight of added water) increase the close packing as well. In these soils with low clay content, the change from dried, flocculated, to plastic, or dispersed clay is not volumetrically significant, so reduction of pore volume is the primary reason for collapse (Reimers, 1986).

On a macro scale, repacking wet soil in part of a larger soil volume sets up compressional and tensional forces. These forces propagate radially as the wetting front moves and collapse takes place. Moreover, as soil first undergoes wetting, expansive clays may cause compressive forces as well. In the second experiment, the ground surface actually swelled up before it collapsed. The resultant subsidence-forming forces are shown in Figure 1.18. The cohesive soil properties that probably determine crack spacing remain to be determined.

Hydrocompactive soils may be dealt with in several ways, depending on local conditions. The problem is more difficult to solve in developed areas where infrastructure (roads, pipelines, powerlines, water, sewers) is in place and where houses have already been built. It is easier to prevent when development and construction are first proposed.

In undeveloped areas, hydrocompactive soils may be detected using a combination of field and laboratory techniques. Field mapping may show the presence of young, silty-sandy alluvial fans, drainageways with natural collapse depressions, or even open fissures. Seismic studies may show particularly low-velocity layers near the surface. Drilling to take undisturbed samples and split-spoon samples can show low-density, low-blow-count sediment beneath the surface. Laboratory testing of differences in consolidation of undisturbed dry and wetted samples is perhaps the least expensive indicator of hydrocompactive soils, but such testing is not unambiguous.

Depending on thickness of the problem soils, they may be excavated and compacted, foundation pilings may be sunk through the soils to rest on more stable bedrock or other deposits, or the soils may be compacted either by wetting or by dynamic consolidation (pounding with a large weight). Compaction is preferable to preventing moisture from entering the ground after construction has taken place. In developed areas, moisture must be controlled so that the soil does not become wetted to any great depth. Precautions should be taken to double-seal water and sewer lines. Moisture buffers (bentonite plugs) should be placed in utility trenches beneath foundations. Septic tanks should be avoided. Houses should have roof gutters and downspouts which discharge away from house foundations. Runoff from streets and other impervious areas should be shunted into uncollapsible areas or storm sewers. Desert landscaping, drainage away from buildings, and impermeable geomembranes around foundations should help prevent moisture from reaching hydrocompactive layers. Excessive watering or any standing water should be avoided.

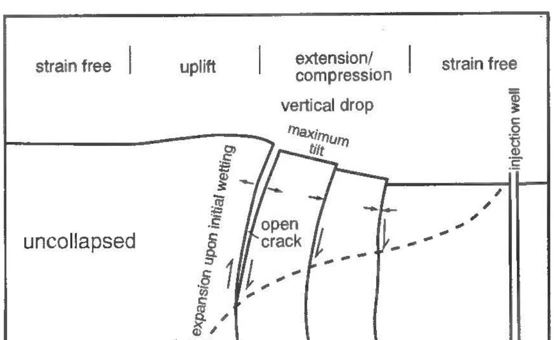

FIGURE 1.18. Schematic cross section of macro strain during hydrocompaction.

Soil grouting and other heat and chemical treatments of hydrocompactive soils have not proved successful, although they have worked in carefully controlled experiments. In general, any increase in moisture or weight exacerbates the problem. Building with BRAB-like reinforced foundations gives the possibility of mud-jacking and releveling any structure if necessary, whereas building with conventional slab foundations does not allow for later corrections, and such foundations are likely to crack and move differentially.

GEOLOGY AND GROUND WATER OF THE EL LLANO AREA

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El Llano is a neighborhood on the NE side of Española, between Santa Cruz and San Juan Pueblo. During the study of hydrocompactive soils in this area by the New Mexico Bureau of Mines and Mineral Resources (NMBMMR) in 1985 (see Love, et al., above), the subsurface geology and ground-water hydrology was investigated to determine its relation to the problem soils. The dominant bedrock unit in this part of the Española structural basin is the Tesuque Formation of the Santa Fe Group (Galusha and Blick, 1971; Tedford, 1981). The Pojoaque Member of the Tesuque Formation crops out in the high bluffs that flank the inner Rio Grande Valley east of El Llano and adjacent parts of San Juan Pueblo and Santa Cruz.

Quaternary units truncating the Santa Fe beds cap several levels of valley border erosion surfaces (Kelley, 1978; Johnpeer et al., 1985b; Gonzalez and Dethier, 1991; Dethier and McCoy, 1993). The hydrologically most important of these units lies beneath El Llano and consists of 30–120 ft of alluvium overlying up to 20 ft of latest Pleistocene ancestral Rio Grande sandy gravel. The gravel was probably deposited by the Rio Grande during the last glacial maximum between 15,000 and 25,000 yrs ago. The overlying alluvium has been deposited as alluvial fans prograding across the former Rio Grande floodplain during latest Pleistocene and Holocene time. The Rio Grande continues to flow at about the same level as the older deposits, but on the west side of the valley at the present time. The river controls the level of ground water in the valley.

During the NMBMMR study, ground water conditions in the El Llano area were of special concern because the shallow, water-bearing deposits are an important reservoir of high-quality water. This resource is widely utilized for both community and domestic water systems and must be protected. Depths to the top of the zone of saturation range from slightly less than 30 ft to more than 100 ft (Fig. 1.19). Studies by Borton (1974) in the southeastern part of Rio Arriba County show that ground water moves westward toward the river from the principal area of recharge near the Sangre de Cristo Mountains. Near El Llano, shallow ground water flows southwestward (Borton, 1974), which is towards the local ground water discharge area in the lower part of the Española Valley near San Ildefonso.

Two major aquifers exist in the El Llano area. East of the Rio Grande and north of the Santa Cruz river valleys the principal aquifer is the Tesuque Formation. The other is "the alluvium of major stream channels" (Borton, 1974, p. 353) and includes the buried river gravel in the El Llano area. During the course of the NMBMMR study, direct obser-

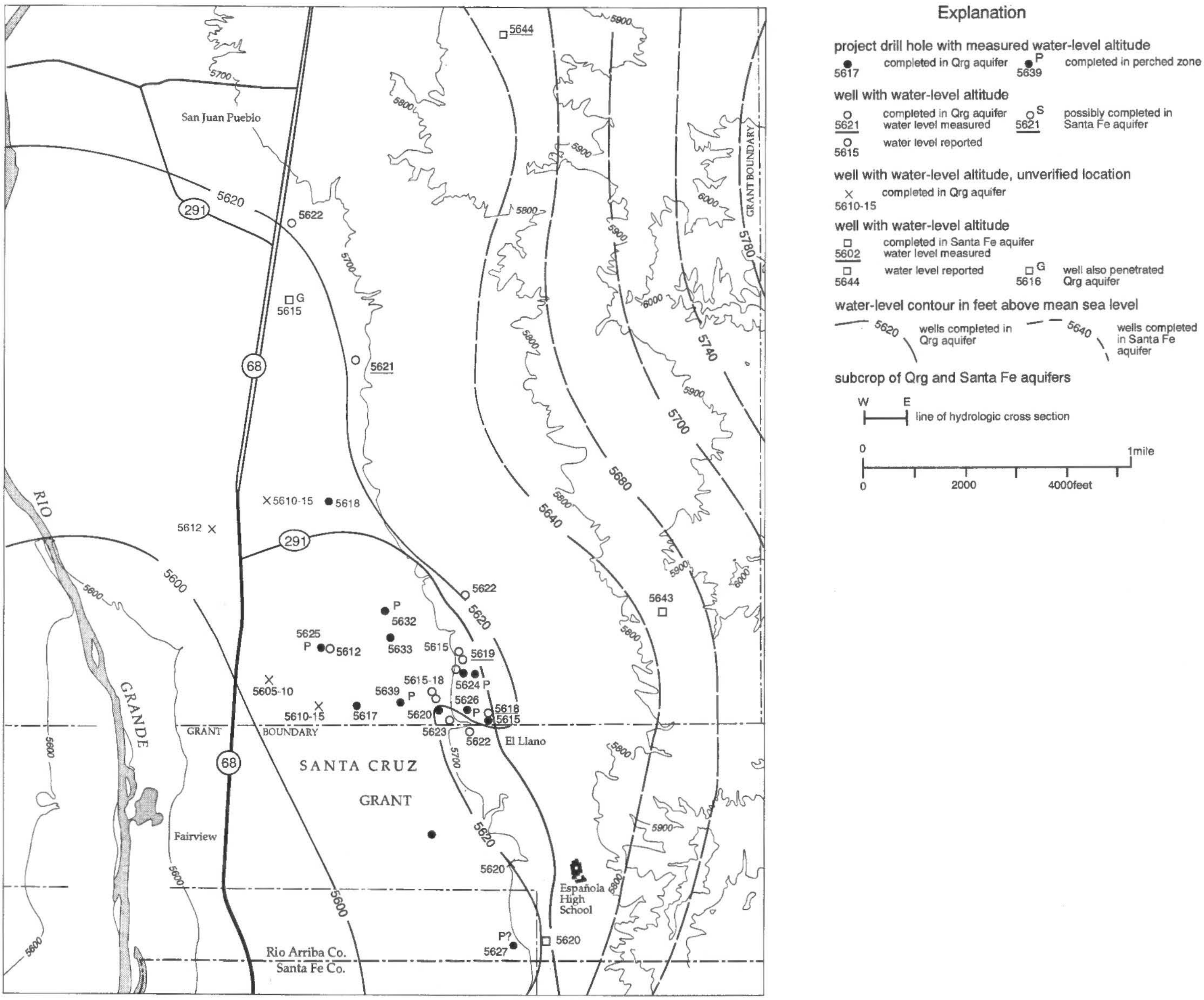

FIGURE 1.19. Water-table configuration in the El Llano area.

vations of ground water conditions were only made on the river gravel unit and overlying alluvial deposits. No monitoring wells penetrated the Santa Fe Group.

The direction of shallow ground-water flow (Fig. 1.19) agrees with the general mountain-to-valley and down-valley water-table gradients previously determined by Borton (1974) and Coons and Kelly (1984). However, ground water elevations near El Llano are higher than the water table in the area adjacent to the Rio Grande floodplain south of Ranchitos; and they are lower than the levels measured by Borton (1974) in wells on San Juan Pueblo lands to the north and east. Examination of water-table contours and individual water-level measurements indicates that the top of the saturated zone is not a smooth surface with uniform west to southwest gradient. Instead, the surface is almost level in most of the area, with slight local depressions and mounds.

North and east of Española Municipal Airport and near the High School (about 1 mi SE of El Llano) there is a marked increase in the water-table slope relative to areas to the west (100 ft/mi vs. less than 10 ft/mi; Fig. 1.20). Wells to the east appear to be developed in the Santa Fe Group–Tesuque Formation, and steeper water-table gradients reflect relatively low hydraulic conductivities of partly consolidated, fine, sandy to silty aquifer sediments. Work by Hearne (1980) on the Tesuque aquifer system in the nearby Pojoaque River basin indicated that conductivities are in the 0.5–2 ft/day range.

All domestic wells in the El Llano community area and much of the valley to the west appear to be completed in the buried river-gravel unit. Hydraulic conductivities of this clean gravel and sand unit should be significantly higher than conductivities in the Tesuque Formation, even though specific field measurements have not been made in the Española Valley. The very low water-table gradients (commonly less than 5 ft/mi) in the valley area therefore reflect a shallow aquifer system that can transmit water at linear velocities many times faster than water-bearing units in the Tesuque Formation. At the above noted hydraulic gradients and conductivities, linear velocities for ground water flow in the Tesuque Formation should range from 0.1–0.2 ft/day. Velocities in the river-gravel unit could be at least 10 times greater.

Local recharge to the river-gravel aquifer includes seepage from natural drainageways crossing the area, infiltration of water from irrigation canals and field spreading sites, and seepage from other sources related to intensive urban and suburban land use. Another probable source of recharge to the river-gravel unit is upward leakage from the underlying Santa Fe (Tesuque) aquifer, but verification of this recharge component was beyond the scope of the El Llano investigation.

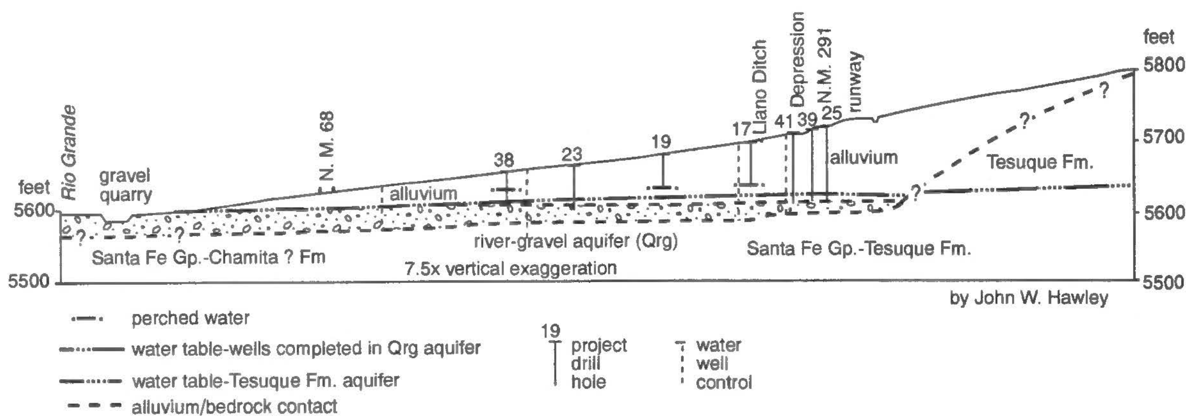

FIGURE 1.20. West-east hydrologic cross section through the El Llano area.

The NMBMMR study complemented an ongoing NMED study of nitrate contamination of the shallow aquifer. The NMBMMR's involvement began after noting the high moisture contents at depth in alluvial deposits cored near the El Llano community well and in an area where waste-water effluent may be contributing to ground-water recharge. The 1982 nitrate level in the community well was 8.39 ppm and approaches the upper recommended limit (10 ppm) for a community water-supply system. As of June 28, 1985, nitrate concentrations exceeding 10 ppm had been noted in two domestic wells in the El Llano community. Elevated concentrations of Mn (0.2 ppm or higher), another pollution indicator, were also noted in one domestic well and four monitoring wells in the area (Earp, 1985).

44.7 Junction with NM–74. Continue north on NM–68. **0.3**

45.0 Official Scenic Historical Marker on right. **0.4**

45.4 View to the west (left) of Black Mesa and underlying Chamita Formation. Black Mesa is capped by a 2.78±0.44 Ma basalt flow (Manley, 1976), the plan form of which suggests flow down an ancestral Rio Grande channel. The lava buried alluvium and the T4 surface of Gonzalez (1993). The poorly consolidated sandstone and mudstone below the basalt are strata of the upper Miocene–lower Pliocene Chamita Formation, which contains a diverse mammalian fauna (Galusha and Blick, 1971) of late Miocene (Clarendonian–Hemphillian) age, most of it collected along the east flank of Black Mesa (MacFadden, 1977). Chamita Formation fluvial deposits indicate a mixed provenance of Proterozoic metamorphic and granitic rocks and Tertiary volcanic detritus derived from the northern Sangre de Cristo Mountains. Numerous tuffaceous intervals mark Jemez Mountains fallout tephra (W. McIntosh and J. Quade, personal commun., 1995). **0.5**

45.9 At 1:30 the rounded range in the far distance is the Picuris Mountains. Just to the south is the Picuris embayment, backed by the angular, Paleozoic-capped Jicarita Peak at 2:00. At 3:00, the Truchas Peaks are on the skyline, with the Santa Fe Range to the south. **1.9**

47.8 Enter Alcalde (Spanish for "mayor or judge or advocate"). **0.1**

47.9 **STOP 2. Turn right into the Adobe Factory. Park to left in the yard.**

THE ADOBE FACTORY

George S. Austin[1] and Edward W. Smith[2]

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New Mexico is the leading U.S. producer of commercial adobe bricks. North-central New Mexico, from Belen to Taos, is the center of the industry. In 1987–1988, 33 commercial adobe-brick producers, 28 companies with pressed-earth block machines, and 2 rammed-earth contractors were located in the state (Smith and Austin, 1989). Since then, the number of commercial adobe-brick producers has decreased to 12 to 15 (depending on the year). Although pressed-earth block machines no longer operate, they are manufactured at several locations for export to other countries. Both rammed-earth contractors continue to produce bricks for several homes a year.

Commercial adobe-brick production, averaging about three million in the late 1980s, has remained fairly constant. Large producers increasingly are able to turn out superior adobes and transport them on pallets to a distant job site at a price acceptable to the higher-income home builder. The Adobe Factory is the top producer in New Mexico at 700,000–1,000,000 adobes annually.

In 1976, an Adobe Factory crew of three produced 500 standard New Mexico adobes (4" x 10" x 14") per day using wooden forms and wheelbarrows. Owner, manager, and our host Mel Medina, has expanded the working and storage area from 10 acres to 25+ acres over the past 18 years. In 1978, a commercial Adobemaster was purchased and used for two years. However, production remained at 500 adobes per day, and so it was decided to construct and use a series of 10-adobes-per-ladder-type molds. This required a larger production crew, capable of producing 5000 adobes per day.

In 1989, the Adobe Factory purchased a self-propelled mechanical adobe layer from the Eight Northern Indian Pueblos Council operation at San Juan Pueblo. The mechanical adobe layer was developed by the Hans Sumpf Company in Madera, California. The machine now in use was built by the Structural Steel Company of Pinedale, California. It uses a standard 25-brick metal molding form, but can also fabricate custom-sized blocks (Fig. 1.21). The chief advantage of this system is the savings in labor, as the hand-lifting of molding forms is eliminated. Other advantages include the consistently uniform quality of adobes and the ease with which different sizes can be made by a simple change of the metal form.

The Adobe Factory can operate for a normal frost-free period of 150 days, from May 1st to October 15th. Most of the blocks have been semistabilized with enough asphalt emulsion for protection during summer rains. The stockpile is usually sold by December 1st.

Adobes can be made from a variety of materials, but the most suitable in the Rio Grande valley is a sandy loam. A typical New Mexico adobe soil averages 67% sand-and-larger-size, 27% silt-size, and 6% clay-size material (Austin, 1994). Clays in these soils consist of sub-equal parts of expandable (mixed-layer illite-smectite and smectite) and non-expandable (kaolinite, illite, chlorite) clay minerals. Soluble minerals in New Mexican adobe soils, principally carbonates and sulfates, which contribute to the hardness and durability of adobes, averages about 10% (Austin, 1990).

The Adobe Factory source is Quaternary alluvial deposits (stream channels, floodplains, terraces and alluvial fans), derived mainly from the Tesuque Formation. A sample of adobe soil analyzed in 1988 was composed of 76% sand-or-larger, 9% silt, and 15% clay (Smith and Austin,

FIGURE 1.21. Hans Sumpf self-propelled adobe layer in operation at the Adobe Factory. A frontend loader is behind the machine after having dumped a bucket of mud into the adobe layer's hopper.

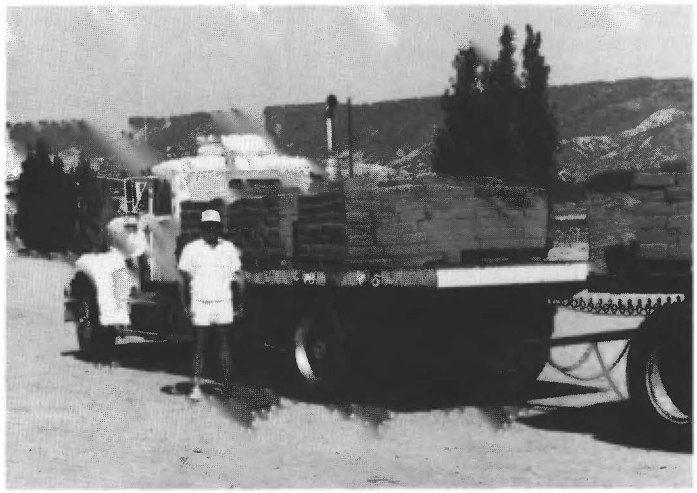

FIGURE 1.22. Adobe Factory owner Mel Medina by loaded delivery truck.

1989). The clay minerals were 50% mixed-layer illite-smectite, 20% illite, 20% kaolinite, and 10% smectite. The sample contained about 1% carbonate and sulfate soluble in the 1N solution of EDTA, a high-pH organic acid.

Alluvial sandy loam from the adobe drying yard and other private acreage is stockpiled before delivery to the screening and pug mill plant. The loam is conveyed to a screen over a two-shaft pug mill studded with short paddles that mixes the adobe soil. An operator controls the feed of soil, water and asphalt emulsion in the pug mill. The blend is mixed for several minutes before being dumped into a large mudpit. Mud is moved by front end loader to the self-propelled adobe layer. The blocks are molded in a large field adjacent to the mixing plant, using the mechanical adobe layer that molds 25 blocks at a time. The steel mold can be raised and lowered, while a movable hopper feeds the adobe mix into the mold compartments. As the machine is driven over a smoothly scraped surface of the adobe drying field the bottomless mold is lowered onto the scraped surface, and the adobe mix is fed into the mold from the hopper. The hopper scrapers level the top of the adobe mix and the steel mold is raised, leaving the blocks on the ground. As the machine moves forward the mold is spray washed before being lowered for the next filling. After 3–5 days, the blocks are turned up on edge, cleaned and scraped, allowed to dry for several weeks, and finally stacked on pallets. Each of four semi-trucks with trailers can deliver between 1200–1500 adobe blocks per load (Fig. 1.22). A spider fork-lift that fits on the back of the trailer is used for unloading at the construction site.

In 1994, Adobe Factory bricks were 55¢ each, most of which were sold in the Santa Fe area. Lesser numbers were shipped throughout New Mexico, as well as to Colorado and Texas.

Return to NM-68 and turn left (south) towards Española. **5.9**

53.8 **Turn right** at traffic light at intersection with NM–583/584 (Fairview Drive). **0.4**

54.2 Cross Rio Grande. Ahead are visible several geomorphic surfaces in front of the Jemez Mountains. **0.9**

55.1 **Turn right** at intersection with US–84/285. **0.7**

55.8 Official Scenic Historical Marker on right. **0.2**

56.0 Roadcut through alluvium underlying the Q4 geomorphic surface of Dethier et al. (1988). The age of this surface is estimated at 75-135 ka based on a variety of data, including degree of soil development, rock-varnish-cation ratios determined for gravel clasts, and amino-acid racemization of molluscs (Dethier et al., 1988). **0.3**

56.3 View of Española valley and Sangre de Cristo Mountains. **2.7**

59.0 San Jose Church on left. The view to the east from this site was made famous by Ansel Adams' 1943 photograph, "Moonrise over Hernandez". In this vicinity the highway crosses the northeast-striking Embudo fault zone (a.k.a. Santa Clara fault zone), which is the structural accommodation zone between the Española and San Luis Basins in the Rio Grande rift (Chapin and Cather, 1994). Aldrich and Dethier (1990) postulated, on the basis of map relationships and stratigraphic arguments, that movement on the Embudo Fault prior to about 10 Ma was predominantly dip slip but has been predominantly strike slip since that time. Dip slip movement produced the western boundary to the Velarde graben, the structurally deepest part of the Española Basin (Manley, 1979a, b). At this point the fieldtrip route crosses from the Española Basin into the Abiquiu embayment, a structurally shallow platform within the western Rio Grande rift between the Colorado Plateau and Española Basin (Baldridge et al., 1994). **0.3**

59.3 Black Mesa and pinkish Chamita Formation in slopes to right across Rio Chama. Southwest of the Rio Chama the base of the Chamita Formation is gradational with eolian sandstone of the Ojo Caliente Sandstone Member of the Tesuque Formation (Dethier and Manley, 1985; Aldrich and Dethier, 1990). The Ojo Caliente, in turn, grades downward into alluvial strata of the Chama-El Rito Member, primarily derived from the San Juan volcanic field and Tusas Mountains (Ekas et al., 1984; Aldrich and Dethier, 1990). Ingersoll et al. (1990) and Ingersoll and Cavazza (1991) also presented evidence for a local source of volcaniclastic debris in the Chama–El Rito, the Plaza volcanic center, that is now obscured beneath volcanic rocks of the Taos Plateau. The Ojo Caliente Sandstone and Chama–El Rito Members of the Tesuque Formation are roughly age-equivalent to the Nambé, Skull Ridge and Pojoaque Members in the Española Basin. **0.8**

60.1 Junction with NM–74 on right. Continue straight on US–84. **0.3**

60.4 View to north of the northern Jemez Mountains. High peaks are eroded composite volcanoes of the upper Miocene and Pliocene Tschicoma Formation. Chamita Formation and a basalt flow are visible to the south of the road. **1.2**

61.6 Route division for routes US–84 and 285. Continue straight (north) on US–84. **0.5**

62.1 Lobato Basalt flow in roadcut. This lava flow, erupted in the northeastern Jemez Mountains, is intercalated with the lower strata of the Chamita Formation (Dethier and Manley, 1985) and has been dated by K-Ar at 9.6±0.2 Ma (Baldridge et al., 1980). About 3.7 mi to the southwest of here, approximately 12 Ma basalts are intercalated with basal Chamita Formation, providing a local age for the Chamita Formation - Ojo Caliente Sandstone Member contact (Aldrich and Dethier, 1990). The oldest dated Lobato Basalt lavas are 14.1±0.3 Ma (Dethier et al., 1986) and are the oldest unambiguous volcanic rocks erupted in the Jemez Mountains. **1.1**

63.2 Crossing Rio del Oso; confluence of Rio Ojo Caliente and Rio Chama obscured by cottonwoods and salt cedar to the right. Prominent ridges in Ojo Caliente Sandstone Member of the Tesuque Formation on the right are a consequence of preferential cementation along fractures. **0.8**

64.0 View ahead of the Tusas Mountains and the sedimentary fill of the Abiquiu embayment. The Tusas Mountains are cored by Proterozoic metavolcanic rocks, quartzite and felsic intrusions (Wobus, 1984). These mountains were raised as part of the northwest-trending Brazos uplift during the Eocene Laramide orogeny. Oligocene and Miocene volcaniclastic sediment eroded from the San Juan Mountains and Latir volcanic fields rest on top of the Proterozoic rocks and local accumulations of Eocene El Rito Formation. The volcaniclastic strata (Abiquiu Formation, Los Pinos Formation and Chama-El Rito Member of the Tesuque Formation) also contain locally erupted volcanic rocks within the Abiquiu embayment (May, 1984). **1.5**

65.5 Milepost 201. **1.6**

67.1 Good view straight ahead of margin of Colorado Plateau marked by flat-lying red beds of Triassic and Jurassic age. Prominent mesa ahead on right features white, fluted outcrops of lower Miocene Abiquiu Formation. **0.3**

67.4 Junction with NM–233 to Medanales. Continue straight on US–84. Hill to left of road is capped by an erosional remnant of the alluvium underlying the Q2 surface of Gonzalez (1993) (Fig. 1.23). An erosional escarpment near the top of the hill exposes a deposit of Lava Creek B ash, which was erupted from the Yellowstone caldera at about 620 ka. Basin-fill strata northeast of the Rio Chama are primarily Chama-El Rito Member and those to the southwest are mostly eolian Ojo Caliente Sandstone Member. Medanales is located near the center of a NNE-trending graben within the Abiquiu embayment. **1.8**

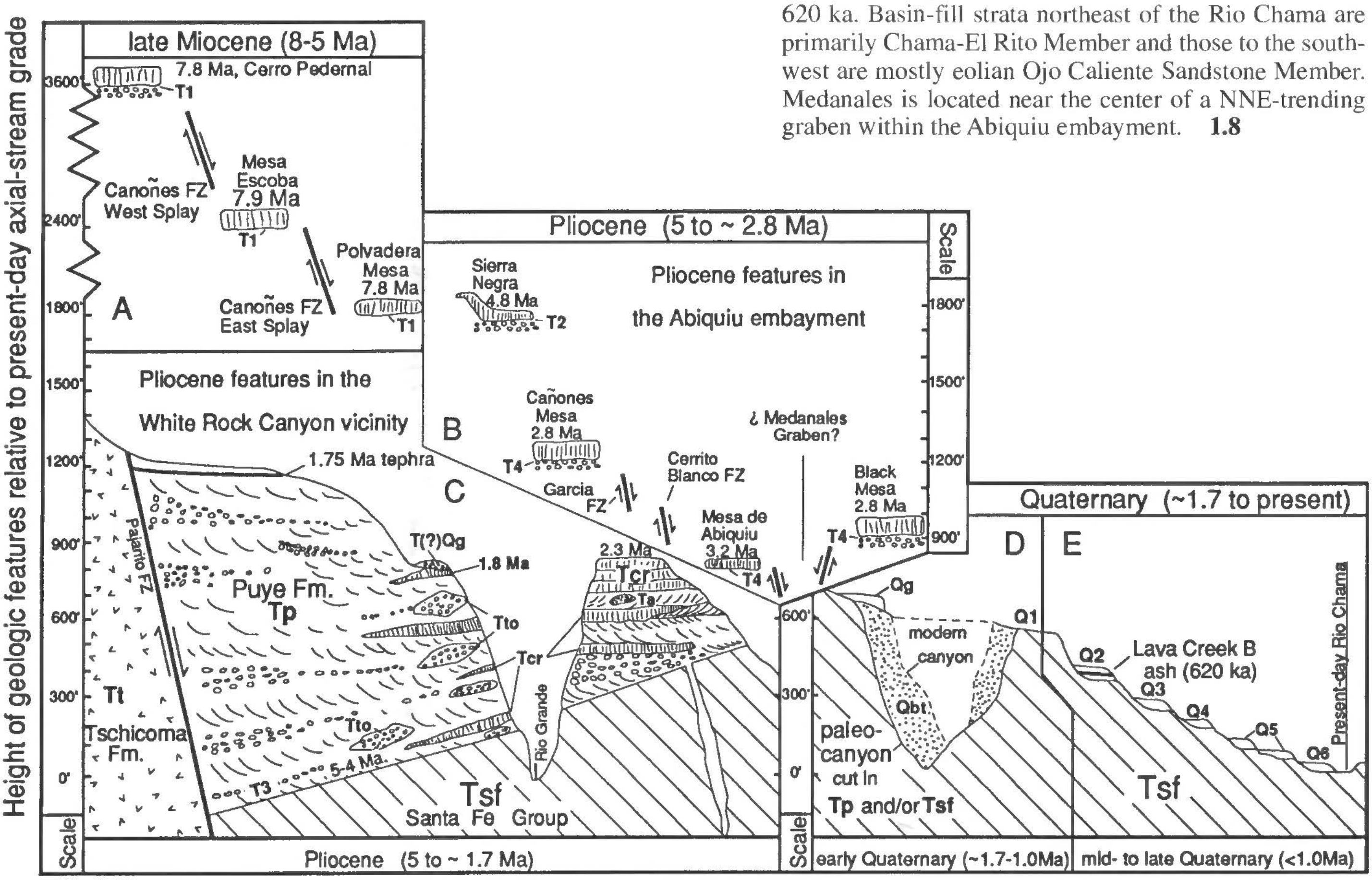

FIGURE 1.23. Schematic diagram illustrating the position (relative to present axial-stream base level) of late Cenozoic features found along the margin of the Rio Grande rift from Ghost Ranch to White Rock Canyon. **Panel A** depicts features formed during the late Miocene and subsequently offset by faulting. Note the break in scale for panel A. **Panels B and C** depict geologic features formed during the Pliocene and subsequently offset by faulting and tilting. **Panel B** highlights paleo-base-level features in the Abiquiu embayment, while **Panel C** illustrates those features in the western Española Basin, including burial during the Pliocene of unit T3 (basal Totavi Lentil) by progradation of the Puye fan, and west-tilting of rift-fill sediment in the Española Basin by Pliocene (and Quaternary) faulting along the Pajarito fault zone. The contrast between Pliocene base-level fall in Panel B and overall Pliocene base-level rise in Panel C illustrates the control of intra-rift tectonism (i.e., movement on the Embudo and Pajarito fault zones) on the geomorphic evolution of the Española Basin. **Panel D** shows early Quaternary geomorphic evolution in the study area, specifically a period of early Quaternary (pre-Bandelier) incision to form canyons, and the period of early Quaternary (Bandelier) aggradation to back-fill the recently carved canyons. **Panel E** illustrates a mid- to late Quaternary period of incision, which re-excavated canyons to form the present system of drainages along the flanks of the Jemez Mountains, and the flight of mid- to late Quaternary terraces, Qg, Q1–Q6, found along the axial and tributary drainages (revision of Gonzalez and Dethier, 1991). Key to symbols: Q1–Q6, inset alluvium; Qg, upland gravel; Qbt, Bandelier Tuff; T(?)Qg, upland gravel; T4, Neogene alluvium; Tp, Puye Formation; Tto, Totavi lentil; T3, Neogene alluvium; Ta, Ancha Formation; Tcr, Cerros del Rio basalt; T2, Neogene alluvium; T1, Neogene alluvium; Tsf, Santa Fe Group.

FIGURE 1.24. Sierra Negra as seen from near mile 72.6. Lower Pliocene basalt caps upper Oligocene-lower Miocene Abiquiu Formation (left background) and middle Miocene Chama-El Rito Member of the Tesuque Formation (right background and foreground).

FIGURE 1.25. View to the NNE from top of Q3 geomorphic surface at Stop 3. Outlines of room blocks and plazas marking the Poshuouinge ruin are visible on the Q5 surface in the foreground. Sierra Negra forms the skyline. The strath terrace defining the Q3 surface forms the prominent bench at the base of Sierra Negra. Photo by M.L. Rhoads.

69.2 Crossing La Madera Arroyo. **2.1**

71.3 Roadcuts expose ancestral Rio Chama terrace gravels resting on Ojo Caliente Sandstone Member. The terraces in this vicinity correspond to units Q4 and Q5 of Gonzalez (1993). The gravels contain abundant, rounded clasts of Proterozoic crossbedded quartzite that were probably derived from the Ortega Formation of the Tusas Mountains. **1.3**

72.6 Junction with NM–554 toward El Rito. Continue straight on US–84. Conspicuous mesa to north is Sierra Negra (Fig. 1.24, see description at Stop 3). View ahead (west) of white Abiquiu Formation, west of the Medanales graben, and Colorado Plateau redbeds on the horizon. **1.4**

74.0 **Turn left on poorly marked paved road into parking lot just before Los Trujillos Country Store.** Sign reads: Santa Fe National Forest, Poshuouinge.

STOP 3. Poshuouinge ruin geomorphology. A short hike from the parking area permits superb viewing of the Abiquiu embayment and upper Cenozoic gravels and geomorphic surfaces associated with the incision of the Rio Chama. The Poshuouinge ruin, typical of 15th and 16th century habitation in this region, is located on the Q5 surface of Gonzalez (1993); the trail continues to an overlook on the higher Q3 surface. Gravels associated with each surface rest on straths cut on the Chama-El Rito Member of the Tesuque Formation. The mixture of Proterozoic (quartzite and granite) and volcanic (mostly basalt, minor andesite) distinguishes these gravels as marking the former courses of the Rio Chama, rather than a tributary stream. The 620 ka Lava Creek B ash is present near the top of the alluvium underlying the Q3 surface in numerous exposures to the south.

The most prominent feature to the NNE is Sierra Negra (Fig. 1.25). Northeast-striking faults marking the west edge of the Medenales graben run through the mesa and juxtapose white Abiquiu Formation on the left with buff-colored Chama-El Rito Member on the right. The mesa is capped by a cinder cone and lava flow that are not disturbed by the faults. The basalt, dated by K-Ar at 4.8±0.1 Ma (Baldridge et al., 1980), descended to the southeast from the vent and buried a gravel-filled channel of a tributary to the Rio Chama. The fault zone crossing Sierra Negra continues southwestward toward the village of Abiquiu. Small basalt intrusions and tuff rings are found along these faults within the Chama-El Rito strata.

To the south, on Lobato Mesa, Lobato Basalt rests upon the Ojo Caliente Sandstone Member of the Tesuque Formation. The Lobato Basalt at this locality has been dated by K-Ar at 7.8±0.5 Ma (Manley and Mehnert, 1981) and is one of numerous middle Miocene to Pliocene basalt flows erupted from largely obscured vents in the northern Jemez Mountains. Gravel beneath the basalt on Lobato Mesa contains Proterozoic rock types (Bailey et al., 1969) and presumably marks the course of an ancestral Rio Chama.

The view WSW, parallel to the highway, includes Mesa de Abiquiu capped by the 3.2±0.1 Ma (Baldridge et al., 1980) El Alto Basalt (Fig. 1.26). This lava flowed down an old tributary to the Rio Chama from a cinder cone west of Lobato Mesa and 6 mi south of the Rio Chama. The El Alto Basalt is inset below the Lobato Basalt (Fig. 1.27)

FIGURE 1.26. View to the west from Stop 3. El Alto Basalt caps Mesa de Abiquiu at the extreme left. Older Lobato Basalt caps mesas above white Abiquiu Formation in the center. The prominent ridge right of center is Cerrito Blanco, eroded from cemented Ojo Caliente Sandstone Member of the Tesuque Formation along a N–S-trending fault. Mesozoic rocks of the Colorado Plateau form the skyline in the upper right. Photo by M.L. Rhoads.

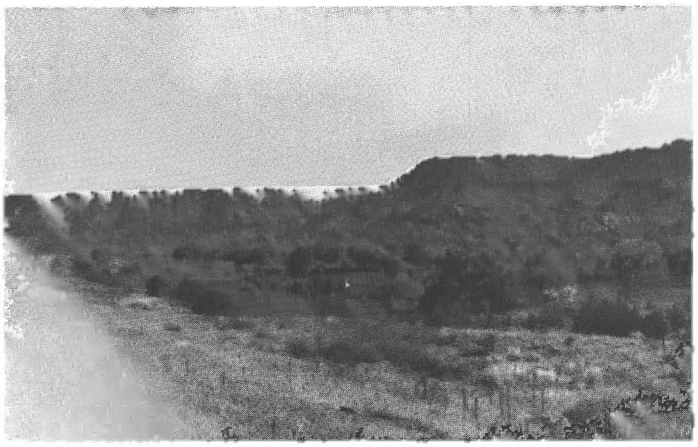

FIGURE 1.27. View to the east near mile 74, showing basalt-capped Mesa de Abiquiu (left and center) below basalt-capped Lobato Mesa (right). The approximately 900 ft elevation difference between these two mesa tops represents the base-level drop along the Rio Chama valley between approximately 8 Ma and 3 Ma, the ages of the two basalt flows.

and indicates about 900 ft of incision during the intervening time interval. A remnant of the Q2 surface of Gonzalez (1993) extends east-northeast from Mesa de Abiquiu.

Immediately to the north of the village of Abiquiu is Cerrito Blanco (Fig. 1.26), a ridge of indurated Ojo Caliente Sandstone along a fault that juxtaposes Abiquiu Formation, on the west, with Tesuque Formation on the east. A dike intruded into this fault zone has yielded a K-Ar date of 9.8±0.4 Ma (Bachman and Mehnert, 1978). On the western skyline are red to buff, flat-lying Triassic to Cretaceous strata of the Colorado Plateau. Outcrops of lower Miocene, white Abiquiu Formation dominate the middle ground. On the northwest skyline are red outcrops of Triassic rocks and Eocene El Rito Formation along the boundary between the Tusas Mountains and the Colorado Plateau.

Depart ruins and continue drive west on US-84. 0.2

74.2 View straight ahead of El Alto Basalt capping Mesa de Abiquiu. Top of Cerro Pedernal visible in background. **0.7**

74.9 Ruins of Santa Rosa de Loma de Abiquiu on right (Fig. 1.28). This Franciscan mission was established in 1773 along what was to become the Spanish Trail, which linked Santa Fe to California. Fathers Dominguez and Escalante visited the mission during their famous exploration of this region in 1776. **0.5**

75.4 At about 2:30, on the plateau in the middle distance across the river, is a magnificent Muslim mosque. **0.5**

75.9 Abiquiu Inn on right. **0.7**

76.6 Village of Abiquiu, colonized in 1754. The famed artist Georgia O'Keefe kept a home here for many years. **0.2**

76.8 Crossing Rio Chama. Directly to the north is the ridge of well-cemented Ojo Caliente Sandstone along the Cerrito Blanco fault zone described at Stop 3 (Fig. 1.29). West of the fault zone, white outcrops of Abiquiu Formation are conspicuous on both sides of the river. **0.4**

77.2 View straight ahead of Cañones Mesa capped by Lobato Basalt overlying Abiquiu Formation and, locally, Mesozoic rocks in the Cañones fault zone along the margin of the Abiquiu embayment. **0.8**

78.0 **STOP 4. Turn right** to Abiquiu Elementary School. **Follow dirt track along right side of parking lot** to Stop 4, located along Arroyo del Cobre and accessible from dirt track following power line (not advised for low-clearance vehicles or when road is wet).

Abiquiu Formation along Arroyo del Cobre. The upper Oligocene and lower Miocene Abiquiu Formation consists of three members (Vazzana, 1980) and was initially named the Abiquiu Tuff by Smith (1938). The lower member (Ritito Conglomerate of Barker, 1958 and Kelley, 1978) is 295 ft of conglomerate and arkosic sandstone derived from Proterozoic and Paleozoic rocks exposed to the north in the Tusas Mountains; this unit is exposed at Stop 5. The Pedernal member is a distinctive 1.6-11.5-ft thick interval of 1 to 4 discontinuous chert layers that may be a silicified pedogenic calcrete (Vazzana, 1980) marking an intraformational unconformity. The upper member, visible here (Fig. 1.30), is composed of approximately 600 ft of light-colored tuffaceous sandstone and siltstone. Vazzana (1980) measured paleocurrents in this area indicative of flow to the south-southeast.

Manley (1981) demonstrated that the Abiquiu Formation is laterally equivalent to the north to the Los Pinos

FIGURE 1.28. Ruins of the mission of Santa Rosa de Loma de Abiquiu, established in 1773. White castellated outcrops of Abiquiu Formation volcaniclastic strata are visible to the right of the ruin. Ridges visible behind the ruin are SE-dipping Mesozoic strata capped by Eocene El Rito Formation, just east of the rift margin.

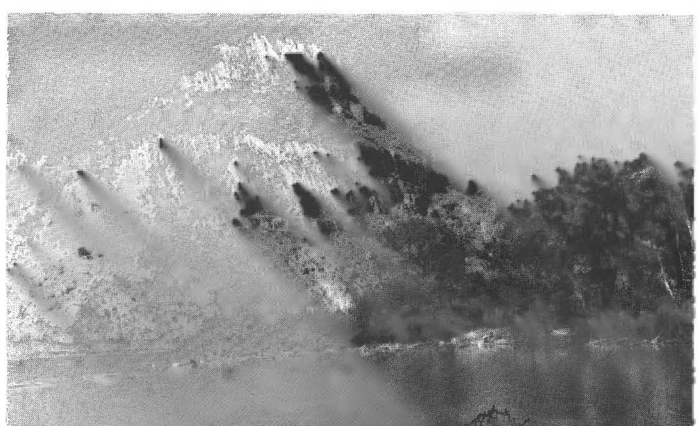

FIGURE 1.29. Cerrito Blanco looms above the Rio Chama at mile 76.8. This outcrop of Ojo Caliente Sandstone is strongly cemented as a consequence of fluids moving along the fault zone located along the west (left) side of the ridge (Baldridge et al., 1994). Note the prominent steep fractures, dipping at a high angle to the east parallel to the attitude of the primary fault.

Formation, an extensive volcaniclastic-sediment apron intercalated with and overlying outflow-sheet ignimbrites erupted in the southeastern San Juan Mountains. Ingersoll and Cavazza (1991) argued that all of the Abiquiu volcaniclastics were derived from the San Juan Mountains but, in the area of this stop, distinctive quartz and sanidine-bearing pumiceous sands and large clasts of Amalia Tuff attest to an additional source from volcanics erupted in the Latir volcanic field (Questa caldera) north of Taos (Smith, this volume). The Amalia Tuff outflow sheets extended westward from Questa across the south-flowing Los Pinos/Abiquiu drainages (Manley and Wobus, 1982). Rapid erosion of the pyroclastic deposits caused aggradation of Amalia-derived detritus in the Abiquiu embayment. This was followed by continued fluvial deposition of volcaniclastic debris from the Latir field. The sedimentology and stratigraphy of the Abiquiu Formation at this locality is described and interpreted by Smith (this volume).

About 3 mi to the north, up the Arroyo del Cobre, a long, narrow box canyon called Cañon del Cobre opens up. The canyon is floored by Pennsylvanian–Permian red beds of the Cutler Formation overlain around the canyon walls by Upper Triassic Chinle Group. Copper was mined until the early years of this century from Chinle (Agua Zarca Formation) strata here (see following minipaper). El Cobre Canyon also is famous as a locality for Late Pennsylvanian vertebrates, including the skeleton of the "stem" reptile *Limnoscelis* (e.g., Berman, 1993).

COLONIAL COPPER MINING IN NEW MEXICO

Marc Simmons

Cerrillos, New Mexico

Did the Spaniards of New Mexico ever develop their own copper industry? Scholars have always believed not. The copper pots and tubs of many sizes and the finely hammered chocolate cups that formed part of every colonial household were thought to have been made in central Mexico and brought northward by the early settlers. But now it appears likely that at least some of these copper wares were products of a local mining and metallurgical industry. If that's the case, the Southwestern frontier was not as backward and unfruitful as historians have let on.

FIGURE 1.30. Outcrops of Abiquiu Formation along Arroyo del Cobre at Stop 4. Lowermost strata are composed of a mixture of San Juan Mountains-derived volcanic debris and sand and gravel eroded from Proterozoic rocks. The upper half of the central pyramid-shaped outcrop is composed of pumiceous debris-flow deposits, some of which contain clasts of welded Amalia Tuff, erupted in the Latir volcanic field. The uppermost outcrops, at the extreme right, are composed of notably less pumiceous, fluvial volcaniclastic sediment also derived from the Latir field. Photo by M.L. Rhoads.

My interest in the subject was aroused several years ago while reading the personal journal of the young explorer, Lieutenant Zebulon Pike. In traveling down the Rio Grande from Santa Fe to El Paso in 1806, he observed that the trade caravans heading south for the Chihuahua market carried, among other sale goods, copper vessels.

This appeared strange since, if the history books were correct, copper articles should have been flowing in the opposite direction. So it made me wonder: could a Spanish copper works have once operated in New Mexico and its existence long since been forgotten? That intriguing question prompted me to begin some basic detective work.

It is well known that Spaniards discovered the famous Santa Rita copper deposits, near modern Silver City, in 1800 and began mining operations there in 1804. But the area was then outside New Mexico's political jurisdiction and all the metal obtained from ores went south by burro train to Janos and Casas Grandes. Besides, there is no record that any manufacturing of copper items was ever carried out on the site. Therefore, I decided to search elsewhere for clues to the mystery.

One day in looking over a copy of the detailed map of New Mexico made in 1779 by Don Bernardo Miera y Pacheco, I happened to notice that the mountains above the Chama River were identified as the Sierra del Cobre, or the Copper Range. Could this region have been the source of the Spaniards' copper, I wondered? Confirmation came later upon discovery of an economic report on New Mexico's resources made in 1831. At that date, the province formed part of the Republic of Mexico and the report was published in the **Registro Oficial**, the official daily of the Mexican government.

It stated that at the village of Abiquiu, some 20 leagues northwest of Santa Fe, the impoverished residents were mining copper and from it fashioning kitchen utensils by hammer. The location of Abiquiu is just south of the Sierra del Cobre. Further investigation revealed that in the mid–1850s several U.S. Army engineers were guided to the Abiquiu copper mines by a local resident. One of them wrote, "Here we found an entrance which led to a series of galleries. The roof is carefully braced and the work exhibits considerable skill in the use of tools. I attribute this to the earlier Spanish explorers."

Here then was evidence that colonial New Mexicans had indeed possessed a small copper industry of their own. More searching, this time in the Spanish Archives at Santa Fe, turned up documents that referred to copper mining in the San Pedro Mountains east of Albuquerque and at Copper Hill, a site below Taos. At the latter place, artisans were mentioned as turning out metalwares.

The next logical question seemed to be: Do any of these copper products survive today and, if so, can they be positively identified as having been made in New Mexico? Checking out the holdings of the Museum of New Mexico and several private collections, I located about two dozen pieces—pots, cups, plates, and church censers, all obviously old and crudely hammered—which seemed likely prospects.

Afterward, I visited archaeologists at Santa Fe's Laboratory of Anthropology and explained what I had discovered and what I still hoped to learn. They had a suggestion. The copper artifacts could be borrowed and sent to the Los Alamos Scientific Laboratory to be subjected to highly technical analysis. Geological studies had already demonstrated that Abiquiu copper showed rare traces of manganese, and ore from the old Copper Hill mine was mixed with tungsten. Thus these minerals could be expected to appear in the artifacts and point to the exact origin of the metal. The experiment promised to be an exciting adventure in using science to solve a historical problem. Unfortunately, my little project had to take a back seat at the Laboratory to many others more pressing, so that it may be months or even years before a body of data can be assembled.

Nevertheless, the information already collected has convinced me that Lt. Pike's chance remark about copper vessels being manufactured in New Mexico was an accurate one. No doubt, he would have been amazed if he could have foreseen that his simple statement, 150 years later, would open a new field of scholarly inquiry.

Retrace route past school to highway. **0.8**

78.8 **Turn right** and resume westward route on US–84. **0.1**

78.9 View to left across Rio Chama of Abiquiu Formation capped by Lobato Basalt. **0.4**

79.3 Ridge of Cerrito de la Ventana on right is held up by a dike (Fig. 1.31). Two faults intersect here; a N-striking fault and a NE-striking one parallel to the dike. Gonzalez and Dethier (1991) traced the N-striking fault, which they named the Garcia fault zone, across the Rio Chama to the south where it apparently offsets the Lobato Basalt by about 260 ft. **1.9**

81.2 Official Scenic Historical Marker on right. **0.1**

81.3 **STOP 5. Pull off carefully along shoulder on right side of road.**

Structural and stratigraphic relationships adjacent to the Cañones fault. Ahead, the highway climbs a moderate grade through flat-lying Permian and Triassic strata of the Colorado Plateau. The boundary of the Rio Grande rift is marked by the Cañones fault, which trends northeastward along the floor of the narrow valley at the bottom of the grade (Fig. 1.32). At this stop (Fig. 1.33), westward-dipping Jurassic strata are overlain, along a prominent angular unconformity, by red conglomeratic sandstone of the southeastward-dipping Eocene El Rito Formation (Fig. 1.34). The Jurassic beds and El Rito Formation are overlain by SE-dipping conglomerates of the lower member of the Abiquiu Formation. The Abiquiu Formation does not crop out well here, but a prominent zone of carbonate cementation produces a ledge along the basal unconformity. Attitudes of sandstone beds within the Abiquiu Formation suggest a low-angle (~10°) angular discordance with the El Rito Formation. A narrow basaltic dike intrudes these rocks but is not visible in the roadcut.

Different stratigraphic assignments have been offered for the Jurassic strata that are exposed here. Smith (1938) and Broomfield (1977) assigned these rocks to the Morrison Formation, whereas Manley (1982), Muehlberger and Muehlberger (1982), and Baldridge et al. (1994) represent the same outcrops as Entrada Sandstone. The assignment to the Morrison Formation is preferred for two reasons. First, the sandstones are interbedded with dark red mudstones and mudstone clasts are present as rip-ups within the sandstones. Mudstone is rare in the Entrada Sandstone and penecontemporaneous erosion of muddy substrate is more consistent with the fluvial processes that deposited the Morrison Formation than with the eolian processes responsible for deposition of nearly all of the Entrada Sandstone. Second, the sequence of west-dipping strata can be followed westward (up-section) through a series of poor exposures to well exposed greenish mudstone typical of the Morrison Formation. No faults are present between the buff to red sandstone and the green mudstone, nor is the Todilto Formation, a prominent gypsum in this region above the Entrada, present here. Further examination of the Jurassic strata in the Cañones fault zone may later favor assignment of the Jurassic sandstones in the road cut to the Bluff Sandstone and explicit assignment of the Morrison mudstones to the Brushy Basin Member (cf., Anderson, this volume). If this is the case, then the regional unconformity at the base of the Morrison Formation is present somewhere along the hillside to the north of the road, below the green mudstone outcrops.

The presence of El Rito Formation above tilted Jurassic strata indicates that the initial deformation of the Morrison Formation occurred during the Laramide orogeny. Because Mesozoic rocks are flat-lying west of the Cañones fault, this fault must also have been active during the Laramide deformation and has subsequently been reactivated as a rift-bounding structure. The angular discordance between the El Rito and Abiquiu Formations indicates that subsidence of the Abiquiu embayment was underway before initial Abiquiu Formation deposition in this area.

Continue westward on US–84. 0.2

81.5 Milepost 216. Crossing Cañones fault zone; leaving the Rio Grande rift and entering the Colorado Plateau. Red, horizontally ribbed rocks of the Permian Cutler Formation are overlain by lighter colored cliff-forming sandstones of the Upper Triassic Agua Zarca Formation of the Chinle Group (Lucas and Hunt, 1992).

Upper Triassic strata in the Chama Basin pertain to the

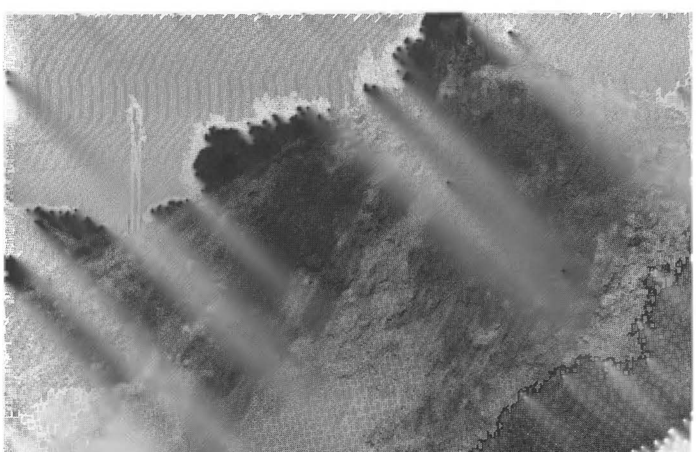

FIGURE 1.31. Dark, irregularly shaped intrusions of basalt comprising the Cerrito de la Ventana dike intruded into Abiquiu Formation at Mile 79.3.

FIGURE 1.32. Northeastward view of the Canones fault zone from a vantage point west of Stop 5, which is located at extreme right center. The main fault trace is to the right of the flat-lying Permo-Triassic strata visible along the left side of the photo. Rolling hills to the right (east) of the fault are underlain by gently east-dipping lower Abiquiu Formation gravel resting on west-dipping Jurassic Morrison Formation and locally on east-dipping Eocene El Rito Formation. Rio Chama in foreground.

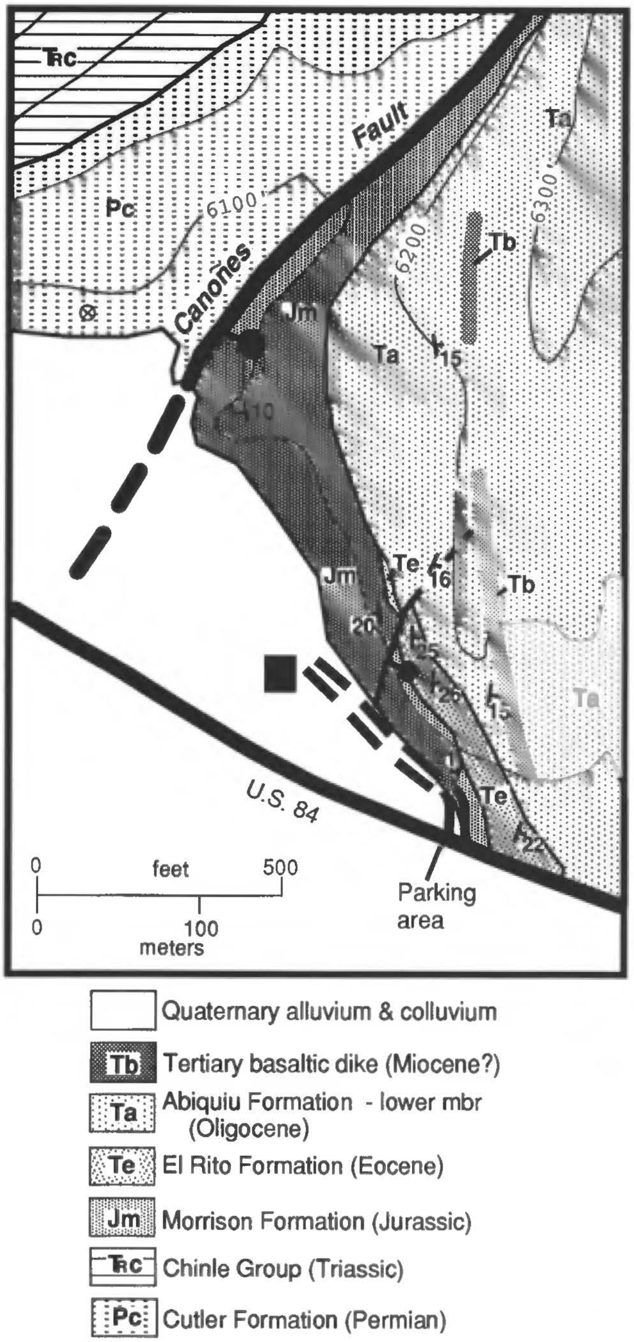

FIGURE 1.33. Geologic map of area at Stop 5, from unpublished mapping by G.A. Smith.

Chinle Group, which consist of five formations (in ascending order): Agua Zarca, Salitral, Poleo, Petrified Forest and Rock Point Formation (Fig. 1.35). These units represent a sequence of dominantly fluvial strata that spans the early Tuvalian (late Carnian) to the Rhaetian (Lucas and Hunt, 1992). Stratigraphic and paleontological data indicate that there are major unconformities at the base of the Poleo and Rock Point Formations. The Rock Point is only present in the vicinity of Ghost Ranch. Elsewhere, the Rock Point has been removed by erosion associated with the unconformity at the base of the Middle Jurassic Entrada Sandstone, which overlies the Chinle in this area. Vertebrate faunas are present in the Salitral, Petrified Forest and Rock Point Formations. **0.9**

FIGURE 1.34. Angular unconformity at Stop 5. West-dipping Jurassic Morrison Formation sandstone and mudstone are overlain by east-dipping, darker Eocene El Rito Formation. Grassy slopes beyond are underlain by lower Abiquiu Formation gravel that is inclined somewhat less steeply eastward than is the El Rito Formation.

82.4 Roadside rest area with picnic tables. View to south across Rio Chama is of Lobato Basalt resting on Middle Jurassic Entrada Sandstone. Note red slopes of Painted Desert Member of Petrified Forest Formation at 10:00 below Entrada Sandstone. **0.5**

82.9 Roadcut in Agua Zarca Formation. **0.6**

83.5 Milepost 218. **0.3**

83.8 View to south of Cerro Pedernal, type locality of the Pedernal chert member of the Abiquiu Formation (Vazzana, 1980). Slope-forming Abiquiu and Tesuque Formations are capped by Lobato Basalt. Cerro Pedernal is west of the Canones fault zone. The presence of the Abiquiu and Tesuque Formations here indicates that early to middle Miocene subsidence along this margin of the Rio Grande rift was insufficient to contain all sediment supplied from the north within the Abiquiu embayment.

AGE	LITHOSTRATIGRAPHIC NOMENCLATURE		LITHOLOGY
RHAETIAN		*J-2 unconformity*	
RHAETIAN	CHINLE GROUP	ROCK POINT FORMATION	
NORIAN	CHINLE GROUP	*Tr-5 unconformity*	
NORIAN	CHINLE GROUP	PETRIFIED FOREST FORMATION	
NORIAN	CHINLE GROUP	POLEO FORMATION	
CARNIAN	CHINLE GROUP	*Tr-4 unconformity*	
CARNIAN	CHINLE GROUP	SALITRAL FORMATION	
CARNIAN	CHINLE GROUP	AGUA ZARCA FORMATION	
CARNIAN		*Tr-3 unconformity*	

FIGURE 1.35. Lithostratigraphic nomenclature for formations of the Upper Triassic Chinle Group in the Chama Basin.

The 7.8 Ma Lobato Basalt is displaced about 1800 ft across the fault zone near Cerro Pedernal. **0.2**

84.0 Junction with NM–96 on left to Abiquiu Dam, Coyote, and Gallinas. Continue straight. View across Abiquiu Lake of Upper Triassic Chinle Group through Jurassic strata (of which the white, cliff-forming Entrada Sandstone is most prominent) to Upper Cretaceous Dakota Sandstone on the skyline. Abiquiu dam was completed by the U.S. Army Corps of Engineers in 1963 at a total cost of $20,430,000. The earth dam is 325 ft high and 1540 ft long. The reservoir has a maximum storage capacity of 1,374,000 acre-ft and is used for flood control. **1.2**

85.2 Vista from 9:00 to 3:00 of the classic, picturesque Triassic–Jurassic–Cretaceous sedimentary section of the Ghost Ranch area. **3.0**

88.2 North-striking fault crosses highway and places Poleo Formation on west against Petrified Forest Formation on east. Color change across fault is visible to the right. Note color-banded strata of the Petrified Forest Formation ahead at 12:00.

In 1874, E. D. Cope passed through the Chama Basin and collected vertebrate and invertebrate fossils near Gallina from the Petrified Forest Formation. These specimens included the type of the aetosaur *Typothorax*. Later, in 1881, David Baldwin collected additional Late Triassic fossils for Cope, including the syntypes of the dinosaur *Coelophysis bauri*. In 1911, S. W. Williston and Paul Miller (University of Chicago), E. C. Case (University of Michigan) and F. von Huene (University of Tubingen, Germany) also collected in this area. **0.5**

88.7 Variegated mudstone and sandstone of the upper Chinle Group overlain by massive, cliff-forming Entrada Sandstone (Fig. 1.36). In this area, the Petrified Forest Formation exhibits good examples of mudstone- and siltstone-filled channels. Brightly colored beds of the Petrified Forest Formation here are mostly waxy, swelling mudstones with a high content of volcanic ash. Areally extensive deep scours are full of pedogenically modified mudrocks and sandstone. These mudstone-filled scours represent gullying that has been documented in the Petrified Forest Formation elsewhere (Kraus and Middleton, 1987).

Petrified Forest Formation strata exposed here form a sharp contrast with overlying Rock Point Formation strata, which are rhythmically bedded fine sandstones, siltstones and mudstones that lack volcanic detritus. Here, they are freshly exposed and weather to form steep slopes and cliffs, but nearby, the Rock Point Formation is deeply weathered to form gentle slopes. Nevertheless, the clear contact of the Rock Point Formation with underlying volcanic-rich-mudstone-dominated strata of the Petrified Forest Formation is easily recognized in the field. **1.6**

90.3 **Turn right into entrance to Ghost Ranch.** Road is now at level of Poleo Formation. **0.4**

90.7 Movie-set log cabin on the right was used in the filming of Wyatt Earp (Fig. 1.37). **0.5**

91.2 Cross cattleguard and drainage. **0.2**

91.4 Bear left towards the museum. **0.2**

91.6 Ghost Ranch museum on the left. **Park in lot** for **STOP 6**, a walking tour of museum, Canjilon quarry, and Ghost Ranch *Coelophysis/Rioarribasaurus* quarry. To the north we are surrounded by the splendid Jurassic–Cretaceous section of this part of the Colorado Plateau (Fig. 1.38).

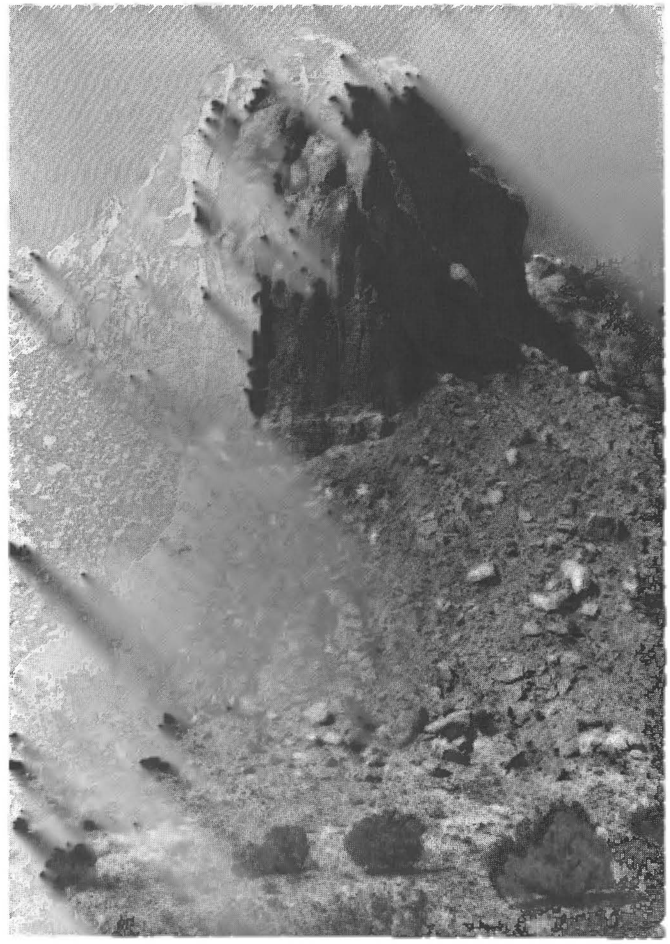

FIGURE 1.36. Massive Entrada Sandstone overlying mudstones of the upper Chinle Group. Mile 88.7.

The 21,000 acre Ghost Ranch was part of the lands granted to Pedro Martin Serrano in 1766. In the 1930s, Arthur and Phoebe Pack purchased a large portion of the land surrounding the present headquarters, and added to it over the years. They operated the property as a working and guest ranch until 1955, when they donated it to the Presbyterian Church. For the last 40 years, the Ghost Ranch Conference Center has functioned as a national adult study center and as a responsible steward of the northern New Mexico environment. Among other efforts at self-sufficiency, Ghost Ranch has pioneered the use of solar energy on the ranch and in nearby villages.

The Ruth Hall Museum of Paleontology contains numerous exhibits illustrating aspects of the small dinosaur *Coelophysis/Rioarribasaurus* and the giant thecodont reptiles called phytosaurs. The Florence Hawley Ellis Museum of Anthropology depicts 12,000 years of life in the Rio Grande–Chama–Gallinas valleys, with an emphasis on the concept of culture as an adaptive way of life. The ranch's High Desert Research Farm is designed to preserve and reestablish low-water/low-fertilizer cereal grains indigenous to Third World countries. Research findings and seeds are shared world-wide. Ghost Ranch Living Museum, several miles to the north on NM–84, is a conservation-oriented U.S. Forest Service facility that focuses on the history, geology, and animals and plants of this region.

FIGURE 1.37. Cliffs of Jurassic Entrada Sandstone rise above a movie-set log cabin and corral near the entrance to Ghost Ranch.

FIGURE 1.38. Jurassic and Cretaceous strata exposed to the north of Ghost Ranch. Lower cliffs are composed of Entrada Sandstone capped by Wanakah Formation. Interbedded slope-forming mudstone and ledge-forming sandstone comprise the Morrison Formation extending up to mesa-capping Dakota Sandstone.

The Canjilon quarry is the richest source of phytosaur specimens in the world. From 1928 to 1933, University of California expeditions led by Charles L. Camp collected a nearly complete skeleton and about 10 other skulls. These specimens represent two species of the genus *Pseudopalatus*. The aetosaur *Typothorax* is represented by incomplete, but articulated, skeletons. Later, Harvard University collected additional *Typothorax* specimens. The Canjilon quarry is located in the upper part of the Petrified Forest Formation in the NE¼ SW¼ SW¼ sec. 3, T24N, R4E, Rio Arriba County, New Mexico. Litwin (1986; also see Litwin et al., 1991) collected pollen from just above the Canjilon quarry, which he considered of early Norian age. The presence of the phytosaur *Pseudopalatus* and the aetosaur *Typothorax* also indicate a Norian age for the unit.

The Petrified Forest Formation in the Chama Basin represents the deposits of high-sinuosity river channels and associated floodplain areas that apparently developed thick paleosols, suggesting seasonal precipitation (Dubiel, 1989).

The Canjilon quarry was excavated during 1928, 1930 and 1933 by Charles L. Camp with the assistance of R. Arriss, H. Anderson, G. Barrington and S. P. Wells (Lawler, 1976). All of the fossils excavated are at UCMP (University of Chicago Museum of Paleontology, Berkeley). The collections were prepared, and partially curated, by WPA personnel during the 1930s, and Lawler further curated the material during the early 1970s. In the late 1930s, Harvard University collected two incomplete skeletons of *Typothorax* from the Canjilon quarry (Long and Ballew, 1985). This material has not been fully prepared.

The Canjilon quarry produced a nearly complete phytosaur skeleton, three incomplete skeletons and a total of 10 skulls and numerous postcrania (Lawler, 1976). *Typothorax* is represented by three articulated, incomplete skeletons (Long and Ballew, 1985). However, the articulated skeletons are scattered over a broad area and mixed with disarticulated specimens. Unpublished field notes of C. L. Camp and S. P. Welles indicate that the quarry matrix was reddish mudstone with calcareous nodules scattered through it, particularly at the base of the bone-producing interval (Lawler, 1976).

Although no explicit taphonomic analysis has been undertaken of the Canjilon quarry, it appears to represent a hydrodynamically sorted and/or scavenged assemblage (Hunt and Lucas, 1989). Lawler (1976) indicated that the field notes of the quarry workers suggest the depositional environment could have been a stream channel or pond. The former seems unlikely, given the fine-grained quarry matrix and the broad area encompassed by the quarry.

The Ghost Ranch dinosaur quarry is in the Rock Point Formation in the SE¼ SE¼ SW¼ sec. 1, T24N, R24E, Rio Arriba County. In 1874, E. D. Cope passed through the Ghost Ranch area on a journey from Santa Fe to Tierra Amarilla and collected fossil vertebrates near Gallina in Rio Arriba County. In 1881, David Baldwin, working for Cope, prospected Chinle outcrops around Capulin Mesa and near Ghost Ranch (Colbert, 1974). He discovered several bones that became the type specimen of *Coelophysis bauri* (see Padian, 1986). S. W. Williston and Paul Miller of the University of Chicago, E. C. Case of the University of Michigan and F. von Huene of Tubingen University explored the Ghost Ranch area in 1911, although their main collecting focus was on the older Permian strata in the region. Case found bones of *Coelophysis* just north of Cerro Blanco near Gallina. This locality was described as "less than one hundred feet above the basal Upper Trias sandstones" (Williston and Case, 1912, p. 11) and was thought to the type locality of *Coelophysis*.

In June 1947, E. H. Colbert and G. G. Simpson led an AMNH expedition to northern New Mexico. Colbert, assisted by George Whitaker and T. Ierardi, explored the Chinle Group strata in the Ghost Ranch area (Whitaker and Myers, 1965). Colbert went to Ghost Ranch for two reasons. First, he wanted to find more specimens of *Coelophysis*, which Cope (1887a, b) had described from fragmentary material. Indeed, he had examined the best locality data available, one of the labels with the *Coelophysis* specimens in Baldwin's handwriting. It read:

> Label Sack 2 Box 1 Prof. E. D. Cope. Contains Triassic or Jurassic bones all small and tender. Those marked in this sack found in same place about four hundred feet below gypsum strata 'Arroyo Seco' Rio Arriba Co., New Mexico. February 1881. No feet—

no head—only one tooth. D. Baldwin Abiquiu (Colbert, 1964, p. 3).

Second, Camp had decided to stop collecting Late Triassic vertebrates in New Mexico and had sent Colbert his locality data, including that concerning the Canjilon quarry at Ghost Ranch (Whitaker and Myers, 1965).

On 16 June 1947, George Whitaker found what was to become the Ghost Ranch dinosaur quarry. Colbert quickly recognized its significance, and contacted the AMNH (American Museum of Natural History). Carl Sorenson came from New York to assist with the excavation. During 1947 and 1948, AMNH excavated the quarry with much help from Arthur Pack, the owner of Ghost Ranch at the time. Specimens from this excavation were collected in large blocks. Most went to AMNH, but others were dispersed to several institutions.

The dinosaur quarry was closed by AMNH and reopened by David Berman in the mid 1980s. Blocks from the most recent excavation are at CM (Carnegie Museum of Natural History), NMMNH (New Mexico Museum of Natural History and Science) and MNA (Museum of Northern Arizona). The quarry is currently not being worked.

The following vertebrate taxa are known from the Ghost Ranch quarry: aff. *Synorichthys*, *Chinlea* sp., *Rioarribasaurus colberti*, *Redondasaurus bermani*, *Postosuchus kirkpatricki* and several new taxa of crocodylotarsans. The most spectacular elements of the quarry fauna are the articulated skeletons of *Rioarribasaurus colberti* (Colbert, 1947, 1964; Hunt and Lucas, 1991). Previous assignments of these specimens to *Coelophysis bauri* were in error, according to Hunt and Lucas (1991).

The Rock Point Formation was deposited in the Ghost Ranch area on lacustrine and playa mudflats (Dubiel, 1989). Abundant "lungfish" burrows and many smaller burrows and other bioturbation suggest periodic fluctuation in the level of standing water and corresponding transgressions and regressions of the lakeshore (Dubiel, 1989). The quarry itself is in a sequence of 11 siltstone beds, many of which are discontinuous (Schwartz and Gillette, 1986). These beds are intensively bioturbated, contain many silt rip-up clasts and have been interpreted by Schwartz and Gillette (1986) to represent a pond or shallow channel facies in a depositional low.

Rioarribasaurus colberti specimens abound in the lower part of the quarry and become increasingly uncommon upward through the sequence. They represent all ontogenetic stages from hatchlings to adults (Colbert, 1989). Some of the adults contain, within their rib cages, partial skeletons of juveniles, apparently indicative of cannibalism, not viviparity (bearing living young, rather than laying eggs) (Colbert, 1974). Skeletons are articulated or semi-articulated and show a range of completeness. Some skeletons display arched vertebral columns indicating desiccation and contraction of ligaments. Presumably a large group of *Rioarribasaurus* individuals was killed, carcasses desiccated and a flood washed them into a depositional low (Schwartz and Gillette, 1986).

The Rock Point and other uppermost Chinle Group formations (Redonda, Travesser) contain the most derived phytosaur, *Redondasaurus*. All these strata are Rhaetian in age.

SAN RAFAEL GROUP–MORRISON FORMATION CONTACT, GHOST RANCH, NEW MEXICO

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Previous workers in the Ghost Ranch area of north-central New Mexico have advocated the inclusion of more than 450 ft of post-Todilto Formation, Upper San Rafael Group strata in the Morrison Formation (Smith et al., 1961; Manley et al., 1987; Crouse et al., 1992). Whereas these strata are correctly assigned to the San Rafael Group in the southern San Juan Basin, 75 mi to the southwest, minor changes in color and weathering profile, and even more subtle changes in lithology between the two areas have prompted erroneous correlations. Detailed stratigraphic analysis of the post-Todilto section at Ghost Ranch, undertaken as part of a continuing regional investigation of the Morrison Formation, has demonstrated the lithologic and lithogenetic similarity of Ghost Ranch strata to San Juan Basin strata. Ghost Ranch strata are, moreover, assignable to the two formations recognized in the Upper San Rafael Group, Summerville Formation and overlying Bluff Sandstone. At Ghost Ranch the Summerville consists of nearly 263 ft of color-banded, parallel-bedded, silty mudstones and minor thinly bedded, very fine-grained sandstones. Overlying and intertonguing with the Summerville is a 190-ft-thick section of the Bluff Sandstone. The Bluff consists of crossbedded, very well-sorted, fine-grained sandstone, with a unimodal grain size distribution peaked in the 125–200 micron range. Although the grain size and sorting suggest an eolian origin, fluvial sedimentary features are present (crossbed type, clay clasts) and thus fluvially reworked dunal deposits are indicated. The top of the Bluff is a hiatus marked by a Mn oxide-stained interval, 4–6 in. thick, which is the local manifestation of the regionally traceable basal Morrison unconformity. Basal Morrison Formation strata at Ghost Ranch are pale olive or greenish-gray claystone and smectitic claystone similar to the type locality at Morrison, Colorado. These strata are herein assigned to the Brushy Basin Member.

Sedimentary features and fauna of the Morrison Formation are indicative of more mesic climatic conditions than those which prevailed during deposition of the sabkha-arid coastal plain-eolian dominated Upper San Rafael Group. This was in part due to the continued northward drift of Pangea which brought this area into the zone of prevailing westerlies at the onset of Late Jurassic time (Dickinson, 1989). Fluvial deposition systems, however, did exist locally in basin-marginal positions during upper San Rafael Group deposition, such as is seen in the Bluff Sandstone here and at Thoreau, New Mexico. Despite this local fluvial aspect of San Rafael Group strata, they are in general lithologically and texturally distinct from the higher energy Morrison sandstones.

A medium- to coarse-grained, granular and pebbly sandstone bed 75 ft above the base of the Morrison is lithologically similar to the type Salt Wash Member (pebbly litharenite to subarkose) and lithologically distinct from the San Rafael Group (Bluff) sandstones. Given the intertonguing relationship observed between the Salt Wash and overlying Brushy Basin Members throughout their area of mutual distribution, this locally prominent pebbly sandstone above the base of the Brushy Basin Member at Ghost Ranch is here correlated with the Salt Wash Member. As defined, the total Morrison thickness at Ghost Ranch is 210 ft.

End of First-Day Road Log.