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Second-day road log, from Santa Fe to Pecos, Rowe, Bernal, Romeroville, and Mineral Hill

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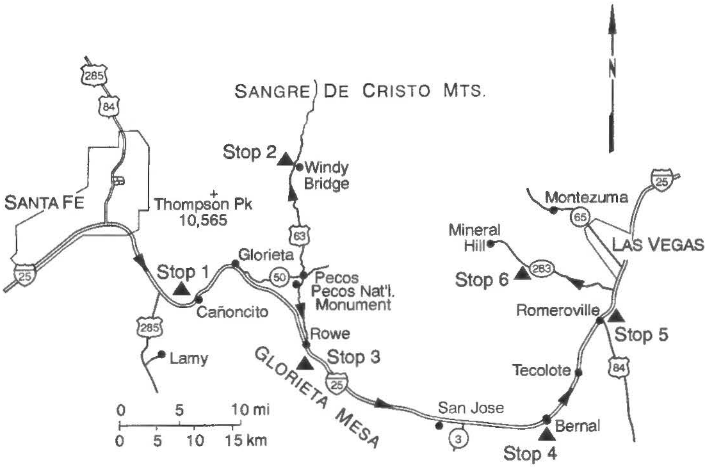
SECOND-DAY ROAD LOG, FROM SANTA FE TO PECOS, ROWE, BERNAL, ROMEROVILLE, AND MINERAL HILL

PAUL W. BAUER, CHRISTOPHER G. DANIEL, SPENCER G. LUCAS,
JAMES M. BARKER and FRANK E. KOTTLOWSKI

FRIDAY, SEPTEMBER 29, 1995

Assembly point:	High Mesa Inn parking lot, Cerrillos Rd., Santa Fe.
Departure time:	7:30 a.m.
Distance:	106 miles
Stops:	6



Summary

Today's tour from Santa Fe to Las Vegas traverses much of the stratigraphic section, from 1.7 billion year old gneisses to Cretaceous shales of the Raton Basin. Our stops will emphasize (1) the geometry and kinematics of the Picuris—Pecos, Garcia Ranch–Borrego, and Tijeras–Cañoncito fault systems, (2) Early Proterozoic metamorphic rocks of the southern Sangre de Cristo Mountains, (3) environmental concerns and remediative efforts along the Pecos River, (4) Paleozoic stratigraphy, (5) Laramide faults and folds, (6) the Mesozoic section on Glorieta Mesa, and (7) the Cretaceous rocks of the Raton Basin.

From Santa Fe, we proceed eastward on I-25 across Quaternary–Tertiary deposits and high geomorphic surfaces into the southernmost Proterozoic rocks of the Sangre de Cristo Mountains. At Stop 1, east of Cañoncito, granitic and tonalitic gneisses that appear to have intruded mafic country rock as the crust was being actively deformed, were later extensively faulted and fractured during Phanerozoic tectonism. Three major fault systems, the Tijeras–Cañoncito, Garcia Ranch–Borrego, and Picuris–Pecos, all intersect near Stop 1. The timing and nature of the displacement across these fault systems will be our primary focus. The faults have a complex movement history and ongoing studies are debating the timing and kinematics of faulting. As many as six or seven episodes of fault activation (and reactivation), ranging in age from Proterozoic to Neogene, have been suggested.

We continue eastward to Pecos, then turn northward where the Pecos River has exposed the great unconformity between Paleozoic sedimentary strata and Early Proterozoic rocks of the Pecos complex. At Stop 2, we examine the deformed 1.7 Ga Windy Bridge tonalite, discuss Paleozoic stratigraphy and tectonics of the southern Sangre de Cristo Mountains, and consider environmental problems along the Pecos River associated with long-abandoned mining operations at the Pecos Mine.

The road log next takes us southward down the Pecos River, past Pecos National Historical Park, towards Glorieta Mesa, where we ascend the mesa to examine the Artesia/Moenkopi Formation (formerly Bernal Formation) disconformity at Stop 3. We rejoin I-25 eastward to Stop 4, near Bernal, where we will discuss the Lower Permian Sangre de Cristo Formation, the Permian-Triassic disconformity, and the Laramide-age Bernal fault. As we continue northward on I-25, we travel up-section, crossing a variety of Laramide faults and hogbacks until encountering Cretaceous shales of the Raton Basin. The Laramide-age "Crestone hogback" at Stop 5 consists of steeply west-dipping Permian to Cretaceous strata that mark the boundary between the Sangre de Cristo Mountains and the flat-lying rocks of the Las Vegas sub-basin of the Raton Basin. Just north of Romeroville, we exit westward towards Mineral Hill for the final stop of the day, a spectacular vista of the southern Sangre de Cristo Mountains.

Mileage

0.0 Intersection of I-25 and Cerrillos Road exit. **Drive northeast on I-25.** Capping the Sangre de Cristos at 12:00 are twin peaks, Lake Peak (12,402 ft) on left and Penitente Peak (12,249 ft) on right; Santa Fe Baldy (12,622 ft) is at 12:15. Sinuous trend of Arroyo de los Chamios to the left, and Arroyo Hondo to the right, subparallel to the highway, are cut into the Ancha Formation. Highway is on the Airport surface. Note dinosaurs to right of on-ramp (Fig. 2.1). These lifesize creatures, which are being rounded up by a cowboy and his courageous Quarter Horse, were sculpted from urethane foam by an insulation company. **1.4**

1.4 Milepost 279. The highway runs along the top of the Santa Fe Group, mapped here as Plio-Pleistocene Ancha Formation by Kottlowski and Baldwin (in Spiegel and Baldwin, 1963). **1.6**

FIGURE 2.1. This "T. rex" is one of several urethane foam dinosaurs that are being rounded up just east of the Cerrillos Rd. and I-25 interchange.

3.0 Vista ahead of the southern Sangre de Cristo Mountains. On the skyline at 12:00 is Thompson Peak (10,554 ft). Lake Peak (12,409 ft), with radio towers, is at 11:00. All of the high country ahead consists of Early Proterozoic metamorphic and plutonic rocks. **0.4**

3.4 Milepost 281. From here, the Ancha Formation extends northward to the Santa Fe River, where it is overlain by several terrace deposits that are inset along the river drainage. North of the drainage, and north of the buried Santa Fe River fault zone, the Ancha gravels have been stripped away, exposing the unconformably underlying Tesuque Formation of the Santa Fe Group. Isolated remnants of the Ancha Formation remain along the foothills north of Santa Fe. **1.1**

4.5 St. Francis Drive exit to Santa Fe. The low hills in the foreground, (Talaya Hill at 11:00, 7088 ft; Atalaya Mountain at 12:00, 9121 ft; and Sun Mountain at 12:15, 7955 ft) are composed of Proterozoic granite with screens of felsic gneiss, amphibolite and schist. North of Talaya Hill, and north of Santa Fe River Canyon (11:00), low foothills consist of downdropped Pennsylvanian and Mississippian strata that rest unconformably on the Proterozoic. Highway is now on the Plains surface. **1.6**

6.1 Old Pecos Trail exit to Santa Fe. To the north and south are numerous small outcrops of Tertiary units exposed in drainages beneath a veneer of Plains surface gravels and a thin eastern wedge of the Ancha Formation. Truncated by the Ancha, in descending order are: main body of the Tesuque Formation; volcaniclastic beds of the Bishops Lodge Member of the Tesuque, correlative with the Abiquiu Formation; latitic to andesitic flows, breccias and volcanic sediments of the Espinaso Formation; and about 50 ft of reddish-brown non-volcanic sandstone and conglomerate, unconformable on Proterozoic rocks and composed of Proterozoic clasts. The basal red beds were mapped as Galisteo Formation by Kottlowski and Baldwin, but are correlated with the upper part of the Espinaso Formation by Smith et al. (1991) and Cather (1992). About 1000 ft to the north, the Bishops Lodge–Abiquiu unit overlies Proterozoic rocks, the Espinaso having been removed by pre-Abiquiu erosion. **0.6**

6.7 Roadcuts expose sand and gravel. **0.7**

7.4 Milepost 285, just south of bridge over Arroyo Hondo. Excellent section of pre-Ancha Formation Tertiary strata crop out along Arroyo Hondo Canyon, 0.5 mile west of I-25. Roadcuts are through fractured Proterozoic rocks, mainly gneisses and amphibolites. These rocks continue ahead. Note felsic dikes crosscutting gneiss. This unit, mapped as gneiss by Kottlowski and Baldwin (in Spiegel and Baldwin, 1963), predominantly consists of pinkish granitic gneiss and dark-greenish amphibolites, both of which contain a near-vertical tectonic foliation. The Proterozoic rocks are extensively intruded by felsic dikes and veins, and the entire complex is extensively sheared, faulted, and brecciated by a variety of typically high-angle, N-striking faults and fractures. Many of the high-angle faults contain dip-slip fault striae. All of the high knobs visible from here to the north and east are composed of similar Proterozoic rock. On the northeast edge of Santa Fe, along the canyon of Little Tesuque Creek, Mississippian–Pennsylvanian beds are not broken by brecciated, N-striking fault zones in the underlying granitic gneiss. **0.6**

8.0 About a mile to the right is Seton Village, originally established as a colony for naturalists by Ernest Thompson Seton. Seton was a well-known writer of books and articles on nature and animal life. He lived here from 1930 until his death in 1946. Ancha Formation, locally capped by thin gravels, overlies Proterozoic rocks at the east edge of the foothills near Seton Village, with the sinuous contact trending SSE. Some scattered outcrops of Espinaso Formation overlain by Ancha beds are cut by arroyos 0.2 mi west of the Proterozoic outcrops. At one locality Pennsylvanian strata overlying granite gneiss dip steeply eastward toward the foothills, suggesting minor faults. **4.4**

12.4 Milepost 290. At 8:30-9:00 are three high peaks on the skyline, the easternmost is Glorieta Baldy (10,199 ft), the central peak is Thompson Peak (10,554 ft), and the third set of twin peaks are Penitente Peak (12,249 ft) and Santa Fe Baldy (12,622 ft) near the Santa Fe Ski Area. Glorieta Baldy is accessible via a rough dirt Forest Service road that leads to a fire lookout. The low mountain in front of Glorieta Baldy is Shaggy Peak (8847 ft), composed of Proterozoic granitoids. Moench et al. (1988) named this granitic complex the Shaggy Peak batholith. Ahead on the skyline is Glorieta Mesa. The valley ahead was cut by Galisteo Creek. **0.3**

12.7 **Turn right** on Exit 290, onto NM-285. **Turn left** (north) on NM-285, pass under I-25. **0.6**

13.3 **Turn right** (east) on frontage road. Francisco Coronado, leading the first European incursion of New Mexico, marched through here in May, 1541. The Santa Fe Trail also parallels the road. **1.2**

14.5 Several roadcut exposures of deformed, intermediate composition biotite-rich granitoid with large (1-2 cm) feldspar megacrysts. The dominant foliation in these rocks dips steeply south, and contains a down-dip mineral lineation. Preliminary shear-sense from asymmetrical K-feldspar porphyroclasts indicates top-to-the-north (reverse) ductile shearing. **0.4**

14.9 Brittle faults are ubiquitous in all of these roadcuts. Most (or all?) of these faults are probably related to an extensive and complex, high-angle fault system that extends from Albuquerque to Taos. To the south, the NE-striking Tijeras, Gutierrez and Cañoncito faults link the Albuquerque Basin with the Sangre de Cristo uplift. From near Lamy northward, the N- to NE-striking Picuris-Pecos, Garcia Ranch and Borrego faults cut the length of the Sangre de Cristo uplift to where the fault system disappears into the southern San Luis Basin. Much of this 50-mi-long system is characterized by high-angle faults which split and join in complex sigmoidal patterns. Begin descent to Galisteo Creek. **0.1**

15.0 Milepost 8. **0.3**

15.3 **STOP 1. Pull off onto right shoulder. Beware of high-speed traffic.**

The Picuris-Pecos fault system. The first stop of the day is located in a structurally complex area near the intersection of the Tijeras–Cañoncito fault zone, the Garcia Ranch–Borrego fault and the Picuris–Pecos fault (Bauer and Ralser, see figs. 1, 2, this volume). Proterozoic rocks in the roadcuts are extensively faulted and fractured, and the primary objectives at this stop are to examine the pervasive brittle structures and discuss their geometries and kinematics. Examination of the Proterozoic-age ductile deformational features in the granite, and a discussion of their place in the Proterozoic tectonic history of New Mexico, are secondary objectives.

At this stop, the roadcut rocks display pervasive brittle deformation that is probably related to the Garcia Ranch and Picuris–Pecos faults. Although much of the deformation is within Proterozoic crystalline rocks, at the east end of the roadcut we find that brecciated granite is in high–angle fault contact with poorly exposed sandstone and mudrock of the Sangre de Cristo Formation (Fig. 2.2). Normal drag in the sedimentary rocks indicates a component of west–up movement, but fault striations on W-dipping faults a few feet to the west of the fault, in the Proterozoic rocks, are near horizontal. This suggests a net transcurrent slip across the fault zone.

The Picuris-Pecos fault (originally named the Alamo Canyon tear fault) was first recognized by Montgomery (1953) in the Picuris Mountains. He later mapped its southward continuation, and parallel faults, in the southernmost Sangre de Cristo Mountains (Miller et al., 1963). Budding (1972) mapped its southernmost exposure here in the Glorieta 7.5-min quadrangle. The fault system is composed of generally N-striking, high-angle faults that have been traced for more than 37 mi, from the northern Picuris Mountains south of Taos, to this spot. From here, the fault can be traced southward for an additional 15 mi, yielding a documented trace of 52 mi. Less well documented is a 20-mi-long fault that cuts Mesozoic rocks from the Lamy area southward (Read and Andrews, 1944).

FIGURE 2.2. View northeast across frontage road at Stop 1 of the Garcia Ranch fault, a steep, north-striking fault zone that here contains a component of west-up movement. Sandstone and mudrock of the Sangre de Cristo Formation, to right of hydrogeologist, show normal drag against Proterozoic granitoids to the left. All rocks in this roadcut are highly fractured and faulted. At left edge of photo, slickenlines on west-dipping faults are nearly horizontal, perhaps indicating a net oblique slip across the fault zone.

In summary, Bauer and Ralser (this volume) proposed the following history for the Picuris-Pecos fault system based on new mapping, new fission-track work of Kelley (this volume), and a review of previous work. (1) Pre-Pennsylvanian, post-1.4 Ga displacement on the Picuris-Pecos fault resulted in some unknown amount of right(?) slip and deflection and attenuation of Proterozoic supracrustal rocks and structures. (2) As per Sutherland (in Miller et al., 1963), a triad of Mississippian and Pennsylvanian west-up motions on the Picuris-Pecos fault resulted in deposition of sediments along the northern part of the fault. Paleozoic strike-slip motion is not documented, but is possible. (3) During the Laramide orogeny, at least 16 mi of right-slip occurred on the Picuris-Pecos fault. Contemporaneous displacement occurred on N-striking, high-angle faults to the east and west of the main fault. The overall geometry of the fault system was a positive flower structure, with dip-slip displacement dominating some subsidiary faults, such as the Jicarilla fault. Strike-slip, oblique-slip and dip-slip fault striae all developed contemporaneously on different fault strands. Perhaps faulting corresponded with the Eocene opening of the transtensional Galisteo Basin along the Tijeras-Cañoncito fault (Cather, 1992; Abbott et al., this volume). (4) During Neogene time, rift-related faulting was concentrated near here, rather than the Picuris Mountains, perhaps due to greater extension in the southern Española Basin versus the northern Española Basin (Chapin and Cather, 1994). Normal faulting may have been distributed over many reactivated(?), high-angle faults in the southernmost Sangre de Cristo Mountains (Kelley, below).

The Tijeras-Cañoncito fault system to the south consists of several NE-striking, high-angle faults that involve units as young as Quaternary in predominantly strike-slip movements. Although previous workers have concluded that the fault system has a Proterozoic ancestry (Kelley and Northrop, 1975; Lisenbee et al., 1979), new work indicates that the oldest documented activity on the system is Laramide in age. Right-lateral structural features and extensional collapse of the Eocene Galisteo Basin are evidence for right-lateral transtension during the Laramide orogeny. In the Golden area, an exposure of the Tijeras fault containing brecciated Oligocene(?) porphyry and offset Quaternary(?) deposits indicate Neogene fault reactivation.

Preliminary work on the Picuris–Pecos and Garcia Ranch–Borrego faults from this area and farther north shows two distinct fault plane orientations that may form a conjugate set. The average orientation of one fault set is N20°E, vertical; most of the sliplines show a shallow to moderate plunge to the SSW, but several plunge shallowly to the NNE (Fig. 2.3). The second fault set is oriented N75°E, vertical with a nearly horizontal distribution of

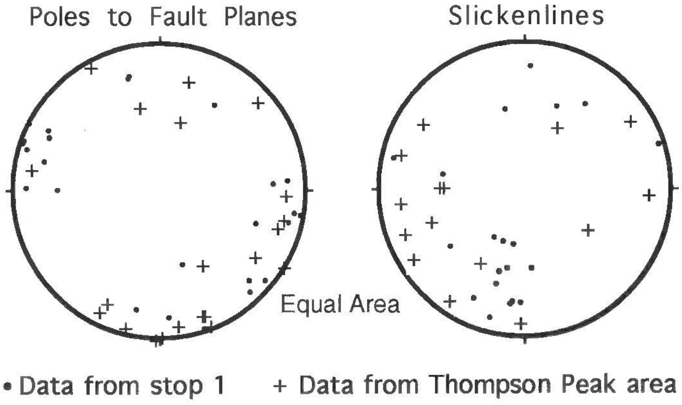


FIGURE 2.3. Equal area projections of poles to fault planes and slickenlines from outcrops at Stop 1 and the Thompson Peak area to the north.

slip lines that plunge shallowly both to the east and the west (Fig. 2.3). Drag folding and deflection of Proterozoic layering along the N20°E fault set consistently indicates right–lateral strike–slip and west-up movement. Drag folding and deflection of layering in the N75°E fault set was only observed twice and indicates left–lateral strike–slip with a south-down component. One subhorizontal fault with a gently S-plunging slip line was also observed in this area. Fault plane data collected over a larger area to the north shows the same fault orientations and displacements. The two fault sets appear to be almost equally well developed throughout the area. The slightly greater number of N-striking faults measured at Stop 1 may be a reflection of the E–W orientation of the roadcut.

The relative timing of movement between the two fault sets is not well documented. The ~55° angular relationship and opposing shear sense between the two fault sets suggests that they are conjugates. Their development is consistent with NE-directed shortening within a N–striking zone of right–slip (Fig. 2.4).

EVIDENCE FOR POST-LARAMIDE DISPLACEMENT ON THE PICURIS-PECOS FAULT

Shari A. Kelley

1431 11th Street, Los Alamos, NM 87544

The middle to late Cenozoic uplift history of the Santa Fe Range portion of the southern Sangre de Cristo Mountains is anomalous with respect to other mountain ranges bordering the northern Rio Grande rift. Recent models that describe rift flank development call upon significant isostatic uplift of mountain blocks adjacent to the side of asymmetric half-grabens bounded by master faults with large displacement. Mountain ranges on the hinged side of half-grabens tend to have lower relief. The development of the Sandia Mountains on the east side of the east-tilted northern Albuquerque Basin is a good example of the relationship between half-graben structure and the evolution of topographic relief. However, as noted by Biehler et al. (1991), the Santa Fe Range does not follow the expected trend. Although high topographic relief characterizes the Santa Fe Range, it is located on the hinged side of the west-tilted Española Basin. Geophysical studies by Biehler et al. (1991) revealed no major fault along the western side of the Santa Fe Range, and corroborated Baltz's (1978) view that the western margin of the Santa Fe Range and the eastern Española Basin form a nearly continuous west-tilted structural block.

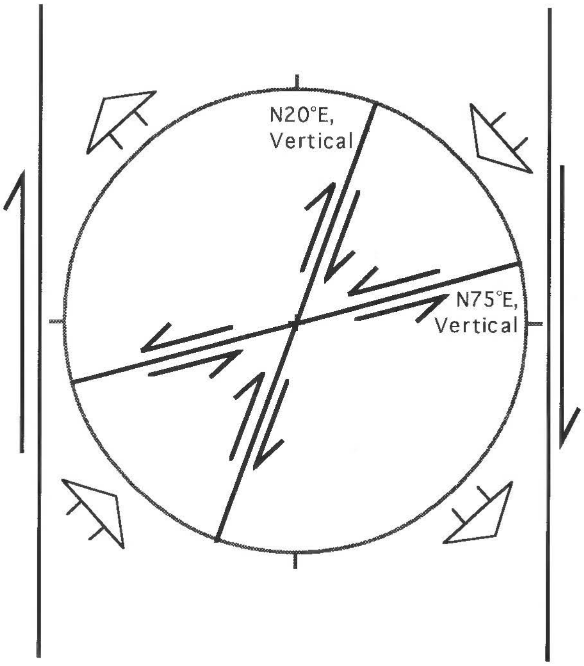


FIGURE 2.4. Speculative diagram showing that development of two NE-striking fault sets is consistent with NE-directed shortening within a N–striking zone of right slip. These faults are probably Laramide in age.

Kelley et al. (1992) also pointed out the anomalous nature of the Santa Fe Range. Apatite fission-track (AFT) ages of 50 to 70 Ma determined from an age-elevation traverse on Santa Fe Baldy (Kelley and Duncan, 1986) are among the oldest AFT ages found in mountain ranges bordering the northern Rio Grande rift. Recent determinations of AFT ages of 64.5 ± 6.0 Ma for Proterozoic granite exposed at the intersection of I-25 and US-285 and 60.6 ± 4.0 Ma for Proterozoic granite near the intersection of I-25 and Old Pecos Trail in Santa Fe confirm the results of the previous study. The preservation of old ages at high modern elevations led Kelley et al. (1992) to speculate that the Santa Fe Range may have once formed the eastern floor of a broad, shallow, early Miocene Española Basin. This interpretation is supported by the observations of Denny (1940), who noted that the Santa Fe Group near Santa Fe lacks abundant coarse-grained material. Denny (1940) proposed a source area for the sediments located well to the east of the modern range boundary. This interpretation implies that the modern topographic relief developed in the late Cenozoic.

If no major fault forms the western boundary of the Santa Fe Range, how was significant relief developed in the late Cenozoic? Vernon and Riecker (1989) and Biehler et al. (1991) suggested that much of the uplift was accomplished along faults within the range. The purpose of this study is to test whether the Picuris-Pecos fault along the east side of the Santa Fe Range may have accommodated some of this uplift. Although considerable geologic evidence indicates that the Picuris-Pecos fault has a long history of activity (Miller et al., 1963; Williams, 1990), little is known about the nature of motion along this fault in the middle to late Cenozoic.

In this investigation, AFT thermochronology is used to determine relative offset across the fault near the south end of the Santa Fe Range. AFT thermochronology has proven to be very useful in deciphering the cooling histories of mountain ranges in the Southern Rocky Mountains (Kelley et al., 1992; Kelley and Chapin, 1995). Along an age-elevation traverse through a mountain range, the AFT ages at high elevations are generally older than those at lower elevations. Fission tracks in apatite are produced at a constant rate controlled by the spontaneous fission decay of ^{238}U and are destroyed at a rate controlled by temperature and apatite chemistry. As rocks at depths of 1.8 to 3 mi in a mountain block begin to cool during uplift and erosion, the fission-track annealing rate is greater than the production rate, and no tracks accumulate (i.e., the AFT age is zero). As cooling continues, the apatite passes through a temperature range between 60 and 140°C, known as the partial annealing zone (PAZ), where partially annealed tracks are retained. If a sample cools rapidly through the PAZ (>5°C/Ma), the mean fission-track length is about 13.5 to 15.0 µm, the track length distribution is unimodal and skewed toward long tracks, and the AFT age can provide a close approximation for the timing of rapid cooling. If a sample cools slowly (<5°C/Ma), the mean fission-track length is <13.5 µm, the track-length distribution is broad and multimodal, and the AFT age cannot be used to directly determine the time of cooling. In the latter case, the thermal history can be extracted from the age and length data using fission-track annealing models that have been empirically calibrated in laboratory and geological settings (Corrigan, 1991; Crowley et al., 1991).

Samples for AFT analysis were collected along Forest Road 272 that leads to the campground on Glorieta Baldy. Two samples were taken from Proterozoic metasedimentary rocks located west of the Picuris-Pecos fault, and three samples, one Proterozoic tonalite and two sandstones from the Sangre de Cristo Formation, were collected from the east side of the fault. The results are summarized in Figure 2.5. The highest elevation sample on Glorieta Baldy, 93SDC15, has an age and track length distribution comparable to those observed elsewhere in the Santa Fe Range (Kelley et al., 1992). The AFT data for 93SDC15 record slow cooling during Laramide deformation. In contrast, the age of 33.8 ± 4.8 Ma for 93SDC16, located just west of the fault, is the youngest AFT age found so far in the Santa Fe Range. The Proterozoic tonalite (93SDC17) immediately to the east of the fault yielded an AFT age of 63.0 ± 11.4 Ma (no track length measurements due to low uranium concentration), which is again similar to AFT ages found in our previous study. The AFT ages for the Permian sandstones are related to AFT ages from the Pecos River valley, discussed by Kelley and Chapin (1995).

The break in the AFT age trend as a function of elevation across the fault clearly indicates significant up-to-the west, post-Laramide displacement across the Picuris-Pecos fault. If we assume that 93SDC15 and 93SDC17 were once in similar positions on the age-elevation trend prior to displacement, then we can estimate approximately 400 m of relative offset across this portion of the fault. The exact timing of this displacement cannot be determined directly from the 33.8 ± 4.8 Ma age for 93SDC16 because the bimodal track length distribution and short mean track length for this sample (Fig. 2.5) suggest a complicated cooling history. The thermal history derived using the forward models of Corrigan (1991) and Crowley et al. (1991) that best fits the age and length data requires the sample to cool slowly during Laramide deformation and to be at temperatures above 176°F until about 15 Ma, when the rock cooled rapidly to temperatures less than 104°F. The error in temperature is ±26°F and in age is ±5 Ma.

In summary, based on this preliminary study, the Picuris-Pecos fault has accommodated some of the middle to late Cenozoic uplift and westward tilting of the Santa Fe Range. The throw across the fault is only about 1300 ft in the vicinity of Glorieta Baldy, but the amount of offset may vary along the strike of the fault. Other major faults within the Santa Fe Range, such as the Garcia Ranch-Borrego fault, may also be important in the evolution of late Cenozoic relief in the range.

The Proterozoic Rocks at Stop 1. The dominant Proterozoic rock type in this area is a medium– to coarse–grained, strongly deformed granite containing a steeply south-dipping foliation and down-dip mineral extension lineation. Asymmetric K–feldspar megacrysts appear to be plastically deformed and show top-to-the-north (reverse) movement. The foliation in the granite is cut by melt–filled shear bands that dip moderately to the south and indicate top-to-the-north (thrust) movement (Fig. 2.6). Subordinate amphibolite is medium to fine grained and contains the same foliation and lineation as the granite. The amphibolite protolith is unknown, but was most likely mafic igneous rock. Granite dikes that crosscut amphibolite can be traced into the main granite bodies, indicating that the granite pluton is intrusive into the mafic country rock. Granitic dikes are both discordant and concordant to the dominant foliation in the amphibolite, and many are ptygmatically folded. The S-dipping foliation in the amphibolite appears to be axial planar to folded granitic dikes. The presence of ductilely deformed K–feldspar, melt-filled

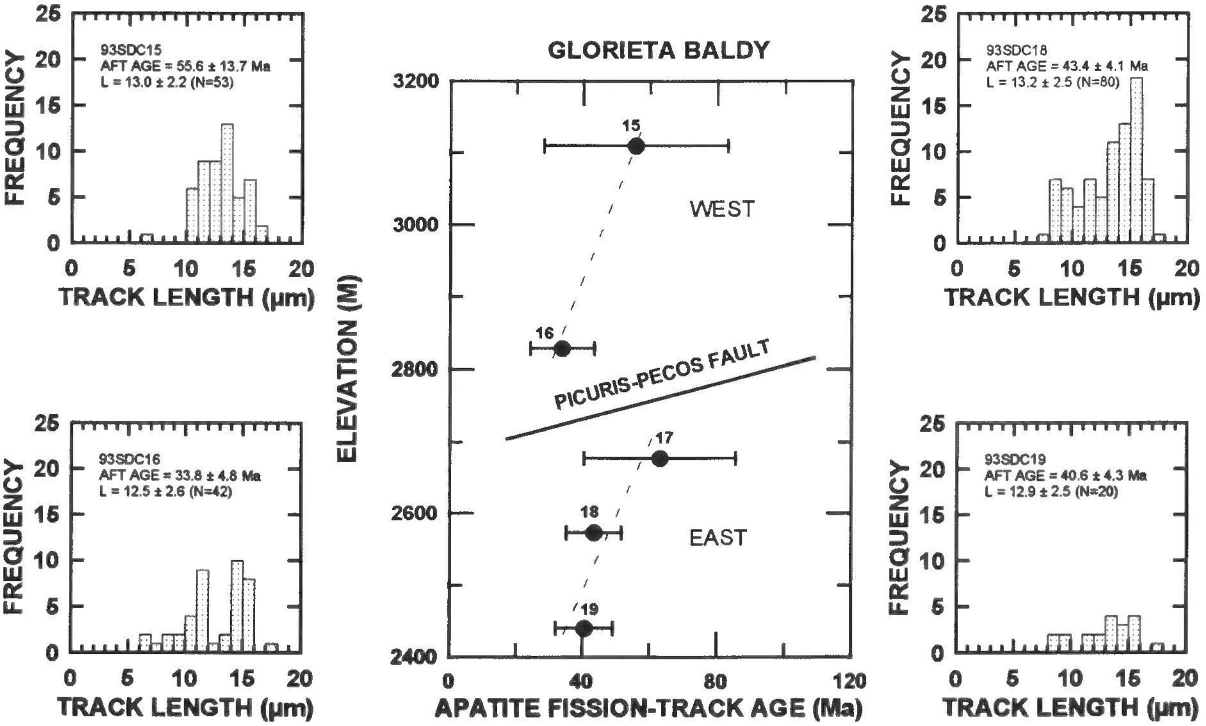


FIGURE 2.5. Apatite fission-track age as a function of elevation on the east side of Glorieta Baldy. Two sigma error bars are illustrated. The sample numbers are shown next to each sample, and are keyed to the text and to the track length histograms on either side of the plot. The sample number, AFT age, mean track length and standard deviation in ìm, and the number of track length measurements (N) are displayed on each histogram. No track length data are available for 93SDC17 due to the low uranium concentration in this apatite.

FIGURE 2.6. Enhanced photo of melt-filled shear band in the Proterozoic granitic rock just west of Stop 1. Shear bands suggest top-to-the-north ductile shearing in the presence of melt. View to the west on a nearly vertical plane.

shear bands, and both deformed and undeformed granitic dikes suggests that the granite was crystallizing during deformation. The age of the granite is unknown. However, the north–vergent thrusting shown by the melt-filled shear bands is the same movement sense documented in the Tusas, Picuris, Truchas and Rio Mora areas that is related to the ca. 1.66 Ga Mazatzal Orogeny (Grambling et al., 1989; Williams, 1991; Bauer, 1993).

As we drive eastward across the fault zone, we will be on Pennsylvanian-Permian Sangre de Cristo Formation and younger sedimentary strata until Pecos. **1.1**

16.4 KOA Campground on left. **0.5**

16.9 **Turn right** ahead and pass under I-25, then **turn left** and proceed on I-25 towards Las Vegas. Official Scenic Historical Marker reads:

> *Cañoncito at Apache Canyon: Strategically located where the Santa Fe trail emerges from Glorieta Pass, this is where Mexican governor Manuel Armijo prepared to defend New Mexico against the American Army in 1846. Here too Union forces destroyed a Confederate supply train on March 28, 1862 while the battle of Glorieta was in progress six miles to the east.*

0.2

17.1 North of highway is the Cañoncito church, and just beyond is the site of the Johnson Ranch house and Santa Fe Trail stage station, the last stop before Santa Fe. **0.1**

17.2 Crossing Apache Canyon at confluence with Galisteo Creek to right. Several splays of the Picuris-Pecos fault system have enhanced the geology of this area. Near the highway the faults are covered by alluvium in canyons. The W-dipping hogback ridge of yellow sandstone ahead is the Triassic Santa Rosa Formation. **0.1**

17.3 Roadcut through WNW-dipping Permian and Triassic strata (Yeso, Glorieta, San Andres, Artesia, Moenkopi and Santa Rosa Formations), some of which will be seen at Stop 3. This roadcut contains a variety of fault sets and a brittle strain gradient delineated by the distribution of small-magnitude faults. Four fault styles have been recognized here: (1) N30°E strike, vertical, striae plunge 25°SW; (2) dip 40° towards the SE, striae are horizontal to moderately SW-plunging; (3) dip 65° towards 200° (SSW), striae are horizontal to 20° W-plunging; and (4) dip 40° towards 060°, striae plunge downdip, drag features indicate reverse movement (top to E). From west to east, faults range from rare to pervasive, especially for the vertical N30°E set and the SW-dipping set. The rubble-covered drainage on left, just past vertical roadcuts at mi 17.3 or so, probably contains a buried, larger magnitude, NNE-striking, high-angle fault. Interestingly, the fault would be about on strike with the Picuris-Pecos fault to the north. **0.3**

17.6 On left is contact between Yeso and underlying Sangre de Cristo Formations. **0.4**

18.0 Milepost 295. The AT&SF railroad track parallels the highway on the right. In 1846, General Kearny's army marched by here on the way to Santa Fe to claim New Mexico for the U.S. **0.3**

18.3 Sangre de Cristo Formation channel sandstone at 3:00. The Sangre de Cristo consists of alternating arkosic sandstone and mudrock along here. The channel sandstones are wedge shaped and discontinuous. **0.2**

18.5 Good exposures of red mudrock and sandstone of Yeso Formation in railroad cut south of interstate. **1.4**

19.9 Exit 297 to Valencia. Continue on I-25. **1.5**

21.4 Glorieta Pass. This pass marks the drainage divide between Galisteo Creek, which travels westward to join the Rio Grande at Santo Domingo Pueblo, and Glorieta Creek, which flows eastward to the Pecos River a few miles south of Pecos. **0.3**

21.7 Baptist convention center on left. **0.3**

22.0 **Bear right** at Exit 299 to Glorieta and Pecos. **Turn left** at stop sign towards Pecos National Historic Park. **Cross over I-25. 0.3**

22.3 **Turn right** towards Pecos on NM-50. Official scenic historic marker on the right, reads:

> *Glorieta Pass. This pass served as a gateway through the mountains for Francisco Vasquez de Coronado in 1541 in route to explore the plains, for Spanish Friars attempting to convert Plains Indian Tribes in the 1660s, for Apaches and Comanches entering the Pueblo area from the East, and for the Santa Fe Trail from the 1820s to the 1880s.*

The pass is actually one mile to the northwest. **0.2**

22.5 Crossing cattleguard. The type locality for the Glorieta Sandstone is southeast of here near the top of the mesa. Between here and Pecos we descend through mudrocks and sandstones of Sangre de Cristo Formation into the underlying Madera Formation. The Sangre de Cristo here is about 1500 ft thick. **0.5**

23.0 Official scenic historic marker on the right reads:

> *Glorieta Battlefield. The decisive battle of the Civil War in New Mexico was fought at the summit of Glorieta Pass on March 28, 1862. Union troops won the battle when a party of Colorado volunteers burned the Confederate supply wagons, thus destroying southern hopes for taking over New Mexico.*

0.2

23.2 Milepost 1. On March 28, 1862, this valley was the site of the second day's battle of Glorieta Pass. **0.2**

23.4 Bridge over Glorieta Creek, and adobe ruins of a major Santa Fe Trail way-station known as Pigeon's Ranch. These buildings are all that remain of the original 23-room complex (Fig. 2.7). The NM Highway Dept. plans on moving

FIGURE 2.7. View north, across NM-223, of the well and adobe remains of Pigeon's Ranch, a major Santa Fe Trail way-station. The original 23-room complex was built by Alexander Valle in the 1850s. The ranch was prominent in the Battle of Glorieta, serving as a field hospital and morgue.

the road 50 yds to the south to protect this historic building. Alexander Valle built the combination ranch and Santa Fe Trail stop-over in the 1850s. The ranch changed hands repeatedly during the Battle of Glorieta, serving as a field hospital and morgue. The main battle was fought across the bridge to the west, on both sides of the highway. **0.7**

24.1 Just before Milepost 2, the dirt road on left is the Forest Service road that winds up to the fire lookout on the summit of Glorieta Baldy. The view from the top is spectacular, and although the road is very rough is places, one of the road loggers was astonished to see a Camaro at the summit. There is no report on how the vehicle got back down. **0.1**

24.2 Milepost 2. **0.6**

24.8 View ahead on skyline of Pennsylvanian sedimentary strata. **0.8**

25.6 San Miguel County line. **0.8**

26.4 Crossing an abandoned railway spur that linked the Santa Fe track to the American Metals Co. mill in Alamitos Canyon to the north. The mill processed massive-sulfide ore from the Pecos Mine (Fig. 2.8). **0.7**

27.1 Milepost 5. Forest Road B52 on left. **0.4**

27.5 Pecos Village limit, elev. 6900 ft. Begin descent into Pecos River Valley. **0.4**

27.9 Subtle scar on hill at 10:00 marks the route of the aerial tramway that moved ore from the Pecos Mine to the El Molino mill in Alamitos Canyon. **0.2**

28.1 Official scenic historic marker on left reads:

> *Pecos. The upper Pecos River Valley was on the frontier of Pueblo Indian civilization from at least the 13th to the 19th centuries, when the nearby Pueblo of Pecos was abandoned. Despite raids by various Plains Indian groups, Spanish-speaking settlers around 1825 founded what is today the Village of Pecos.*

0.1

28.2 **Turn north (left) on NM-63.** Recycled spirits of iron, such

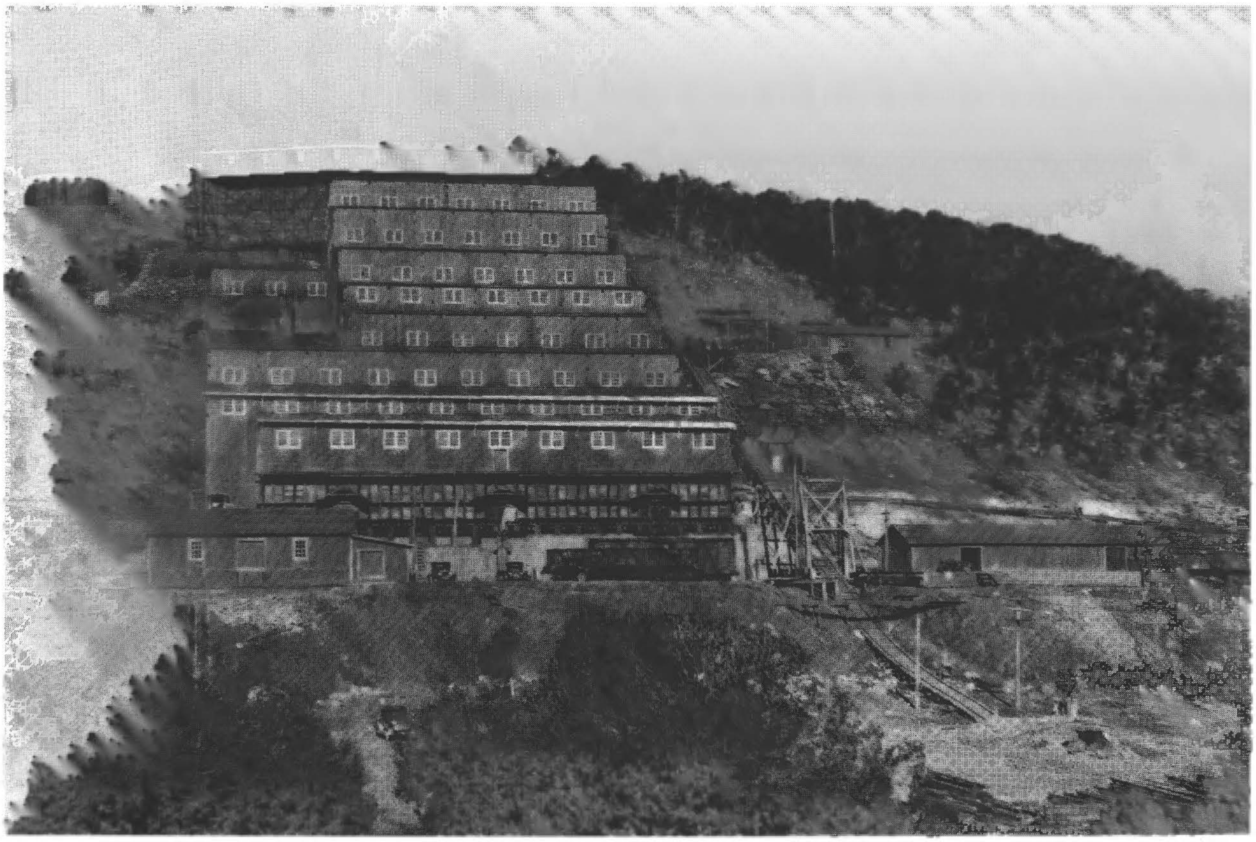


FIGURE 2.8. The Pecos mine is a perfect example of a mineral deposit that had to await the development of new technology before its products could be efficiently recovered. Located in 1881, some 40 years would pass before flotation metallurgy would unlock the values in the complex Katydid and Evangeline ore bodies. Here the Pecos mill at Alamitos Canyon, west of Pecos, is shown soon after commencement of operations in ca. 1927-1928. The lower terminus of the famed 12-mi aerial tramway, that connected the mine at Tererro to the mill, is seen in the upper portion of the photo. Photo courtesy of the Museum of New Mexico, negative #57192.

as this 12 ft tall *T. rex* on display here in Pecos are painstakingly fabricated from iron scraps by a local artist (Fig. 2.9). **0.3**

28.5 Crossing stream that drains Alamitos Canyon, the location of the El Molino mill for ore from the Pecos Mine. Acidic mill tailings in the canyon bottom have created an environmental problem that is currently being studied (Johnson and Deeds, this volume). **0.4**

28.9 Stone church with cemetery on right. **0.2**

29.1 Crossing the Pecos River. We are now crossing the crest of the Cañon de la Madera monocline (Johnson, 1973), one of a series of NE-trending folds and faults in this region. Along this fold, strata have downdropped on the south. This is also the approximate contact between the Sangre de Cristo Formation and the arkosic limestone member of the Madera Formation. **0.3**

29.4 Upper Madera Formation carbonates on right. **0.2**

29.6 Milepost 7. On left, just ahead, is the Benedictine Monastery, one of several monasteries and convents in northern New Mexico. This 1000 acre spiritual retreat, formerly the largest dude ranch in New Mexico, is known as Our Lady of Guadalupe Abbey. The coed monastery is home to about 30 monks, brothers and nuns, with a long list of applicants and retreatists waiting to get in. The solar-heated buildings include guest rooms, a chapel, a meeting hall, and an office-warehouse that contains Dove Publications, the monastery's publishing company. **0.1**

29.7 In 1956, when the 7th NMGS Fall Field Conference reached here, the paved road ended. **0.2**

29.9 We are now crossing a second NE-trending structure, the Monastery anticline of Johnson (1973). **0.3**

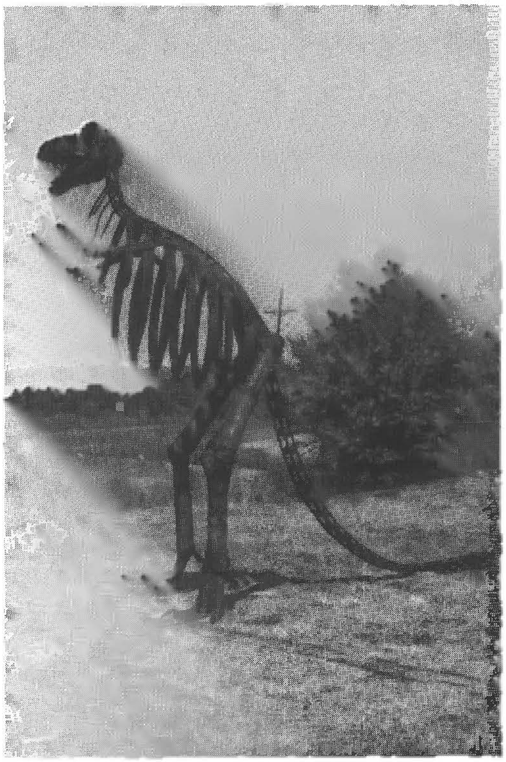


FIGURE 2.9. Charlie the "T. rex," 12 ft tall and 15 ft long, was created by artist Dan Klennert from welded scrap iron. This and other "recycled spirits of iron" were until recently on display at the Pecos River Trading Company. Note that this theropod is dining on femur of cow.

30.2 Good view of Paleozoic strata left, right, and ahead in cliffs. Regionally, Paleozoic rocks dip gently south to southwest, so that even though we climb in elevation northward along the highway, we go down-section. **0.4**

30.6 Milepost 8. Entrance to Monastery Lake on left. **0.3**

30.9 State fish hatchery on left. Crossing the Lisboa Springs fault, a minor displacement, down-to-the-SE splay of the Alamitos Canyon fault. Contact between upper arkosic member and lower gray limestone member of Madera Formation at river level. **0.7**

31.6 Milepost 9. Crossing the Alamitos Canyon fault, an arcuate, NE-striking, high-angle, NW-down structure. This fault, as well as the other faults and folds in this region, are Laramide in age. **0.2**

31.8 On right, "Watch for Rocks" sign states the obvious for us. **0.8**

32.6 Entering Santa Fe National Forest. Cliffs across river consist of 980-ft-thick lower gray limestone member of Madera Formation. **1.0**

33.6 Contact between ledge-forming Madera and underlying slope-forming, 345-ft-thick, clastic member of Sandia Formation across river. Black waste piles are from two small coal mines developed in the upper part of the Sandia Formation. The coal is at about the same stratigraphic horizon as the lenticular coal in the city of Santa Fe. **0.6**

34.2 Welcome to the Pecos complex (formerly known as the Pecos greenstone belt). Just ahead on left are our first glimpses of Proterozoic rock. The metaigneous rocks here have been interpreted as part of a 1.7 Ga subvolcanic complex that both underlies and intrudes a sequence of mafic and felsic volcanic rocks, cherty iron formation, and immature volcaniclastic sedimentary rocks (Robertson and Moench, 1979). **0.2**

34.4 Forest Service Dalton fishing site. Rest area with bathroom is ahead on right. We are crossing the great unconformity, which here separates Early Proterozoic metamorphic rocks from Mississippian sedimentary strata. The unconformity is nearly horizontal. Proterozoic rocks now begin to appear in roadcuts; as we ascend the canyon, we continue to descend stratigraphically. Proterozoic rocks here consist mainly of amphibolite intruded by pink granite. Many stratigraphic and paleontological studies have been made in the superb Mississippian and Pennsylvanian exposures along the west bank (Brill, 1952; Sidwell and Warn, 1953; Baltz, 1959; Miller et al., 1963; Kottlowski, 1961; Baltz and Read, 1960; Armstrong and Mamet, 1974; Sutherland and Harlow, 1973). These rocks are described at Stop 2 ahead. **0.7**

35.1 Dalton Canyon on left. **0.2**

35.3 Log cabin on right, poised above the Pecos River, has been donated to the Forest Service by owners on the condition that they can use it for as long as they live. Dark, fine-grained amphibolite on the left. **0.4**

35.7 Proterozoic mafic metavolcanic rocks at corner roadcut on left. **0.3**

36.0 Valley broadens ahead. **0.6**

36.6 Milepost 14. Macho Canyon on left and small church ahead. The low wall surrounding the church yard is composed almost entirely of Paleozoic sandstone and mudrock, presumably because of the strong bedding fissility and therefore suitability for building mortarless walls. The Proterozoic rocks around here lack the tendency to break along

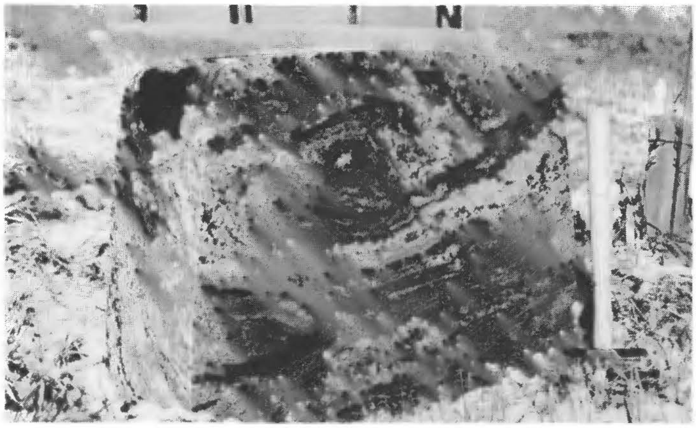


FIGURE 2.10. This spectacular metaigneous tombstone stands in front of the church near Macho Canyon on the Pecos River. It is a polished specimen of pink and black gneiss with highly contorted banding, and marks the grave of Agapito Cortez 1854-1949. The hammer was not used to sample this stone.

planes. However, a most spectacular metaigneous tombstone stands in front of the church (Fig. 2.10). **0.4**

37.0 Lazy Cougar Ranch on right. The small lake and large pit are the result of excavations for an ongoing sand and gravel operation. For the next 0.25 mi, the Proterozoic tonalite along the western slopes is intensely deformed by Phanerozoic brittle faults and fractures. Although a variety of fault systems are represented here, by far the most common is a set of steeply SW-dipping faults and fractures (Fig. 2.11). Over much of this area, the brittle deformation is so intense and closely spaced that textures in the tonalite are totally obscured. Slickenlines generally plunge moderately to the southeast. Many of the large tributary drainages of the Pecos River trend northwest along the faults. **0.3**

37.3 Field Tract Campground on the right. **0.1**

37.4 On left is a small pullout used by the Highway Department for storing road gravel. Notice alluvial/colluvial layering in hillslope deposits. Exposures of tonalite just upslope from here contain spectacularly folded mylonites that are cut by shear bands. **0.2**

37.6 Milepost 15. High on the slopes to our left are remnants of the 12-mi-long aerial tramway that transported Pecos mine ore to the mill in Alamitos Canyon. The tram was completed in 1927. In addition to the concrete tower foundations found on each ridge, artifacts such as heavy braided steel cables and bashed tram ore bins can be seen below the tram route. **0.4**

38.0 Sharp bend to left around an informative roadcut of multiply intruded tonalite. In this roadcut, tonalite has intruded mafic country rock, both are tectonically foliated, and both are cut by thin, low-angle, undeformed quartz-rich pegmatite veins. All of that is, in turn, crosscut by thicker, nearly vertical, undeformed felsic/intermediate dikes (Fig. 2.12). **0.1**

38.1 **STOP 2. Turn left into picnic area** parking lot at Windy Bridge.

Windy Bridge tonalite. Discussions at this stop will include the Early Proterozoic Windy Bridge tonalite and regional Proterozoic tectonics, Paleozoic rocks of the southern Sangre de Cristo Mountains, and modern environmental problems and remediation efforts along the Pecos River.

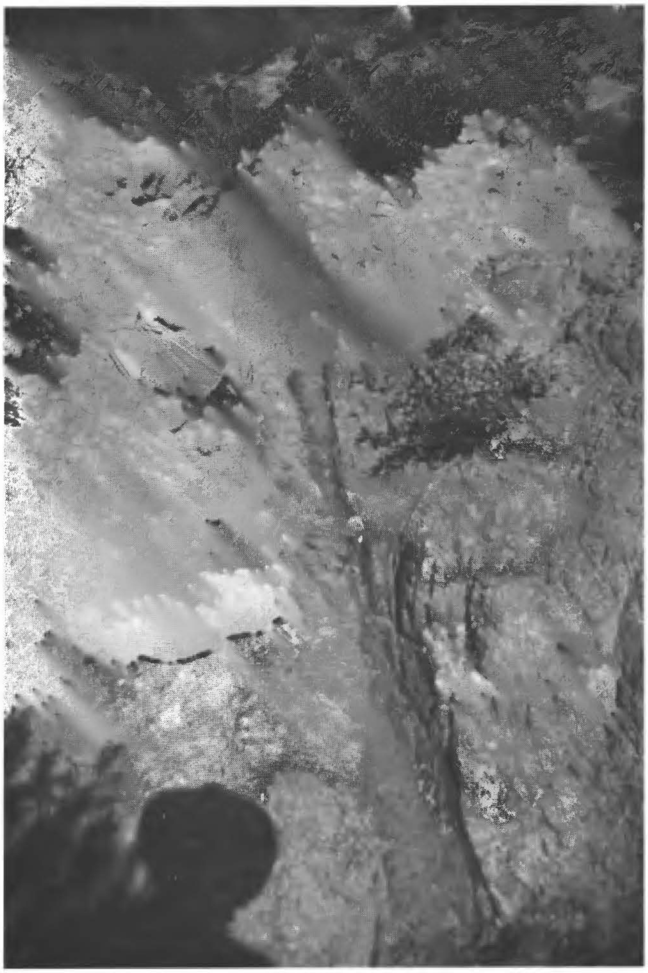


FIGURE 2.11. Proterozoic Windy Bridge tonalite is strongly fractured and faulted along the Pecos River. The NW-striking fault zone in this photo is defined by dark-colored, brecciated tonalite. Slickenlined faults separate the breccia zone from highly fractured tonalite. Slickenlines plunge gently to the southwest.

The 1.7 Ga Pecos complex is a heterogeneous, metamorphosed assemblage of subaqueous basalts, felsic volcanic rocks, iron-formation, sedimentary rocks, and a subvolcanic suite of tonalite-trondhjemite, diabase-gabbro, and other mafic and ultramafic rocks (Robertson and Moench, 1979; Robertson and Condie, 1989). The com-

FIGURE 2.12. Roadcut in Windy Bridge tonalite at sharp bend in highway just south of Stop 2. The tonalite has intruded mafic country rock, both of which are tectonically foliated, and both are cut by thin, low-angle, undeformed quartz-rich pegmatite veins. All of that is, in turn, crosscut by thicker, near-vertical, undeformed felsic/intermediate dikes.

plex was intruded by 1.6 Ga granites and quartz porphyries, and 1.4 Ga granites. Based on geochemistry, Robertson and Condie (1989) concluded that the greenstone belt may represent a back-arc basin remnant that extended far enough to form ocean crust and tap a depleted mantle source.

We are in the northern end of the Windy Bridge tonalite (Bauer and Pollock, 1992), a hypabyssal pluton that is coeval with and chemically related to the nearby greenstone belt (Fig. 2.13). Bowring and Condie (1982) reported a U-Pb zircon age of 1718±5 Ma for the tonalite. Just to the north, the tonalite is in contact with the Indian Creek granite (Bauer and Pollock, 1992), dated at ca. 1650 Ma (Robertson and Condie, 1989). Several miles to the west is the Jones rhyolite complex (1720±15 Ma) intruded by the Macho Creek granite (1480 Ma) (Robertson and Condie, 1989).

The Windy Bridge tonalite and Indian Creek granite are of special interest because they are in contact and they span the time of two major Proterozoic orogenies, the 1.72 Ga Yavapai orogeny and the 1.65 Mazatzal orogeny (Karlstrom and Bowring, 1991). In New Mexico, although direct evidence exists for the Mazatzal orogeny (Bauer and Williams, 1994), none has been reported for the Yavapai orogeny. It was hoped that a comparison of deformational features in the 1650 Ma Indian Creek granite with those of the 1720 Ma Windy Bridge tonalite would delineate differences that were due to the additional effects of Yavapai deformation in the tonalite. Unfortunately, the granite is at most, weakly deformed locally, and the contact between the two plutons is intrusive in places and tectonic in others.

The least deformed Windy Bridge tonalite is coarse grained and composed predominantly of feldspar, biotite and quartz. The most deformed tonalite is fine grained with coarse feldspar porphyroclasts, abundant quartz, and biotite. The tonalite contains numerous layers and lenses of foliated mafic schist and fine-grained felsic dikes (Fig. 2.14). Cross-cutting field relationships between tonalite and mafic schist are ambiguous, but the felsic dikes clearly crosscut the other two. Some felsic layers appear undeformed, whereas others share the tonalite foliation. Locally, quartz-rich pegmatites cut tonalite and mafic schist, but are cut by the felsic dikes. In places, the mafic layers are parallel to the dominant foliation, but in many areas the foliation is at an angle to tonalite/mafic schist contacts.

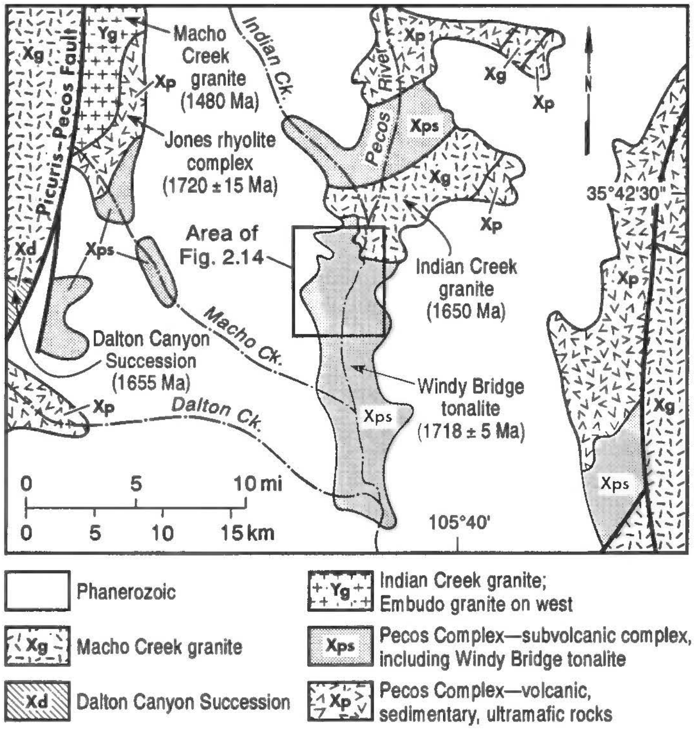


FIGURE 2.13. Map of Windy Bridge area on the Pecos River, showing generalized Proterozoic rock types with U-Pb zircon ages and location of detailed geologic map of Figure 2.14. Modified from Robertson and Condie (1989).

This northern half of the tonalite is only moderately deformed, whereas the southern half consists of intensely foliated to mylonitized rock. The dominant foliation is typically steeply S-dipping, with a moderately SW-plunging extension lineation. Small, flattened microgranitoid enclaves in the tonalite are generally aligned with the foliation and lineation. Locally, the foliation is cut by thin, steeply dipping shear bands that indicate oblique, top-to-the-northwest shearing.

The Indian Creek granite is an orange-weathering, fine- to medium-grained, pink to reddish-orange, equigranular granite. Except for locally adjacent to the tonalite contact, the granite is unfoliated to weakly foliated. Just to the north of here, on the east side of the highway, is the best exposure of the contact between the tonalite and the Indian Creek granite (Fig. 2.14). The contact is fairly planar, and appears to be, at least in part, tectonic. Both brittle and ductile deformation appear to be concentrated along the contact. Fault-striated slickensides exist along the contact, and local, thin quartz veins in the granite are parallel to the contact. A strong oblique foliation in the tonalite appears to deflect into subparallelism with the contact over a distance of about 3 ft.

Paleozoic stratigraphy. About 400 ft above us is the Proterozoic–Paleozoic unconformity. Here, the hiatus represents nearly 1.4 Ga of time. Early Proterozoic tonalite just beneath the unconformity is typically strongly spheroidally weathered. The following discussion on Paleozoic stratigraphy is modified from the 1979 NMGS Guidebook Day 3 roadlog.

The lower 100-130 ft of section above the Proterozoic is Mississippian, which is overlain in this area by a thick and relatively complete Pennsylvanian sequence, although only the lower half of the Pennsylvanian is exposed along the Pecos River. The Mississippian Arroyo Peñasco Group includes the basal Espiritu Santo Formation and overlying Tererro Formation. Near here, the Espiritu Santo includes a 5-ft-thick Del Padre Sandstone member at the base overlain by about 40 ft of the upper part of the Espiritu Santo. The sandstone member is a transgressive marine unit composed of quartz conglomerate, sandstone, siltstone and shale, which intertongue with upper Espiritu Santo carbonate rocks, and are most probably of Osagean age. Carbonate rocks of the upper part of the Espiritu Santo are dolomites, dedolomites and recrystallized limestones. Some of the layers are arenaceous and include thin sandstone lentils; the sandstones are identical to the Del Padre sandstones.

The character of the Espiritu Santo changes northward up the Pecos River valley, with the Del Padre becoming thicker and the carbonate-rock upper part of the Espiritu

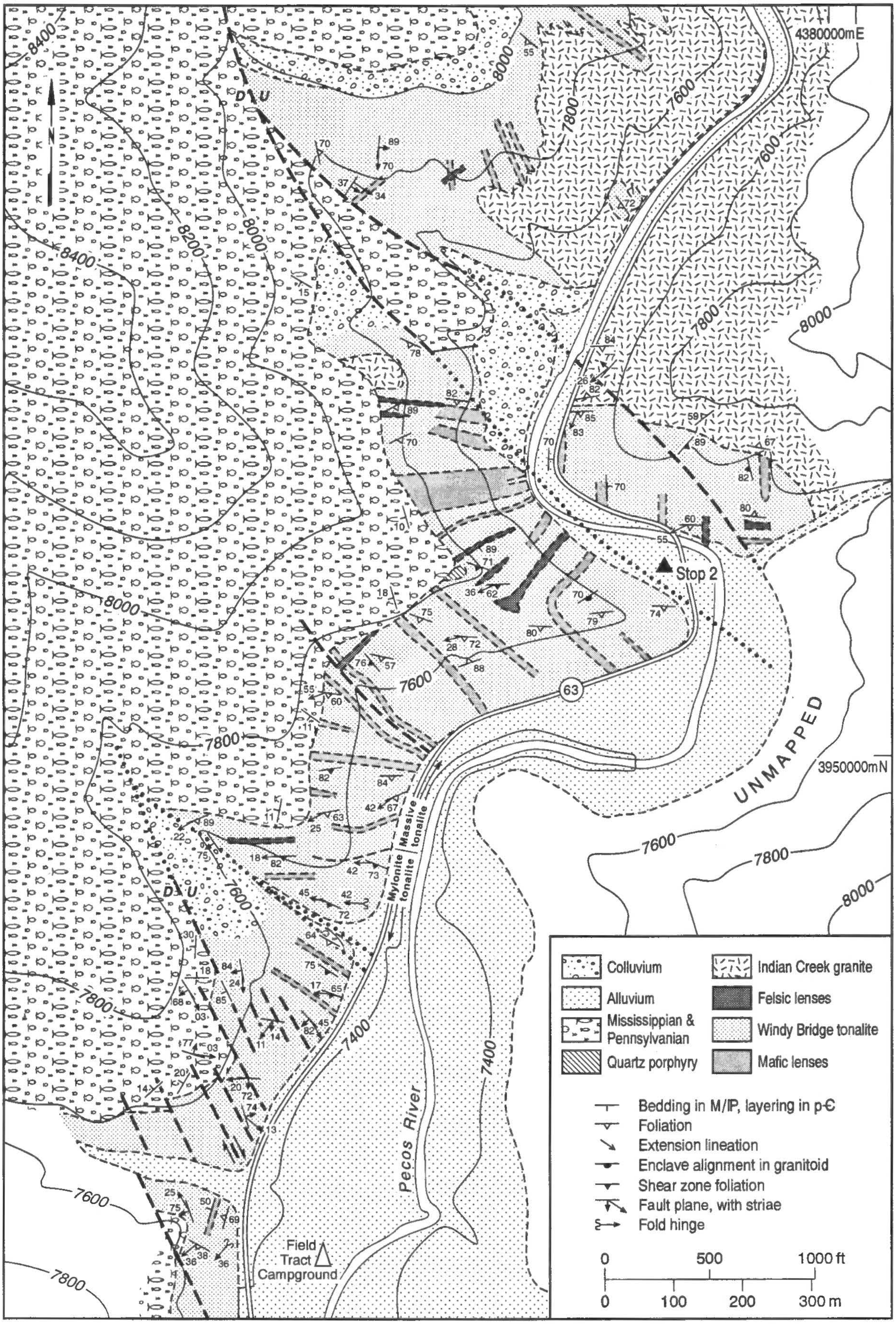


FIGURE 2.14. Detailed geologic map of Proterozoic geology near Stop 2, by P. Bauer.

Santo thinning. Thus, 13 mi north of the Dalton Bluff campground, the Del Padre Sandstone Member is 30 ft thick and the upper part of the Espiritu Santo is only 6.5 ft thick.

The Tererro Formation at Dalton Bluff consists of the basal Macho Member, middle Manuelitas Member and upper Cowles Member. The Macho Member, about 20 ft thick, is a collapse breccia unit resting unconformably on the Espiritu Santo, and consists of conglomerates with rounded to subrounded, poorly-sorted limestone clasts with an algal mudstone matrix. The unit is of early Meramecian age with the rest of the Tererro being middle and late Meramecian and Chesterian.

The Manuelitas Member, about 6.5 ft thick in this vicinity, is gray limestone, which in most places, consists of a lower thick-bedded oolitic limestone and upper silty fine-grained pelletoidal limestone. In places, large masses of limestone pseudobreccia and collapse features occur in the Manuelitas Member, due to karst development contemporaneous with deposition, or in Late Mississippian and Early Pennsylvanian time.

The Cowles Member, about 30 ft thick here, was removed by erosion locally prior to deposition of Lower Pennsylvanian rocks. It consists of siltstone, shale, pelletoidal fine-grained limestone and fine-grained ostracode limestone. The silty beds weather yellowish and contain scattered chert nodules.

Armstrong and Mamet (1974) suggested that the Del Padre Sandstone is a marine transgressive sandstone onlapping northward, and overlain by the upper part of the Espiritu Santo Formation, which is a succession of tidal-flat and sabkha deposits. The Macho Member records alternating conditions of marine deposition and evaporites, with periods of subaerial erosion and development of karst conditions. The Manuelitas represents a transgression and the Cowles Member is a regressive clastic phase of early Chesterian age.

Pennsylvanian units along the Pecos River have been treated in two ways. Mapping by the USGS, under the direction of Charles Read, grouped the lower, predominantly clastic part of the Pennsylvanian as the upper clastic member of the Sandia Formation; this is overlain by a middle, predominantly carbonate unit called the lower gray limestone member of the Madera Limestone, and the upper arkosic limestone member. Read and his coworkers noted that the Sandia Formation is about 345 ft thick at this locality and is overlain by about 900 ft of the lower gray limestone member.

The distinction between a lower clastic and a middle limestone unit is not as dramatic here as is in other localities, such as the Sandia Mountains. For these reasons, Sutherland (in Miller et al., 1963) did not use the term Sandia and Madera but introduced the La Pasada Formation, named for the village of Upper La Pasada, with its type locality at Dalton Bluff. Its base rests unconformably on Mississippian rocks. The top of the formation is about 125 ft below the crest of the bluff west of Dalton campground. It has a thickness of 980 ft, and is equivalent to the upper clastic member of the Sandia, plus the lower gray limestone member of the Madera, as used in this area by others (Brill, 1952; Baltz and Read, 1960).

The La Pasada here is primarily cyclic carbonate and clastic units in which the clastic proportion decreases upward and with the lowest 50 ft being characterized by dark-green mudstones resting on eroded Mississippian limestones. About 25% of the lower 195 ft of this section is sandstone and conglomerate of Morrowan age. In the overlying Atokan, about 175 ft thick, sandstone and conglomerate decrease to about 20% and the sandstone is better sorted and has carbonate cement. The upper part of the La Pasada is Desmoinesian (about 600 ft thick), and includes five cliff-forming units of gray fossiliferous limestone that has a distinctive wavy banded appearance.

Lateral facies changes occur in the lower part of the La Pasada. For example, west from the Dalton Bluff area, the limestones make up greater percentages of the lower part, so that on the west side of the Sangre de Cristo Mountains at Nambé Falls, it is almost 75% limestone. In contrast, to the east and northeast, the lower part of the La Pasada includes a larger percentage of clastic rocks. The Desmoinesian part of the La Pasada is relatively uniform.

The upper 125 ft of Pennsylvanian at this locality are in the Alamitos Formation of Sutherland (in Miller et al., 1963). The Alamitos contains more clastic beds than the upper part of the La Pasada, but the formational change is marked mainly by an upward increase in the percentage of feldspar throughout the southernmost part of the Sangre de Cristo Mountains. The Alamitos is about 1200 ft thick in the Pecos River Canyon area, although only the lower part of the formation occurs here. The basal beds are feldspathic sandstone interbedded with siltstone and shale, with some thin beds of gray limestone. The contrast between the quartz sandstone cemented by calcite in the upper part of the La Pasada and the feldspathic sandstone cemented by silica or clay in the lower part of the Alamitos is distinctive.

PECOS MINE AND ALAMITOS CANYON MILL

Virginia T. McLemore

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The Pecos mine, also known as the Cowles, Terrero, Hamilton, and Willow Creek mine, is located on the upper Pecos River, 12 mi north of Pecos (Fig. 2.15). The Alamitos Canyon mill (or El Molino mill) is located in Alamitos Canyon, 0.3 mi west of Pecos. The Pecos mine was one of the largest lead-zinc producers in New Mexico. The ore deposits consist of lens-shaped bodies of massive galena, sphalerite and chalcopyrite along shear and fracture zones within Proterozoic metamorphic rocks (Krieger, 1932a, b; Reismeyer and Robertson, 1979; McLemore, this volume).

The deposit was discovered in 1881 by a prospector named Case who found galena-sphalerite-chalcopyrite-rich outcrops near the confluence of Willow Creek and the Pecos River. In 1882, Case formed the Pecos Mining Co. and began locating and developing mining claims. In 1886, A.H. Cowles, a local hunter and trapper, acquired the claims and began patenting them as early as 1892. The last patents were issued in 1931.

Despite the local availability of timber, water and coal, development and production in the early years were difficult and slow because of poor accessibility and rugged terrain. In addition, metallurgical processes were used only on oxide ores, not the sulfide ores found at the Pecos mine. Minor production occurred in the early 1900s. In 1903, Cowles formed the Pecos Copper Co. in hopes of improving his investment, but closed the mine in 1907.

In 1916, the Goodrich Lockhart Co. began extensive drilling and development of the deposit (Hubbell, 1976). Several shafts were sunk and 12 levels were developed. The deepest level was 1700 ft, and the entire workings extended along two linear zones up to 2000 ft long (Matson and Hoag, 1930). Meanwhile, during 1921–1925, a new metallurgical process was developed for recovering lead and zinc from sulfide ores (Harley, 1940). The American Metal Co. (now AMAX Resource Conservation Co.) purchased the mine with the intent of utilizing this new process. Production began in 1927 with the completion of the Alamitos Canyon (El Molino) mill, 12 mi to the south (Fig. 2.15). The ore was hauled through the main three-compartment shaft, crushed at the surface, and then hauled by aerial tramway to the mill (Bemis, 1932; Anderson, 1938). Cut-and-fill and square-set-and fill mining techniques were employed (Matson and Hoag, 1930). Most of the stopes were backfilled after the ore was removed. The mill employed differential flotation processing techniques capable of processing 600 tons of ore per day (Bemis, 1932; Martin, 1931). The mill tailings were conveyed to the tailings ponds in Alamitos Canyon, downstream of the mill. Total production amounted to 2.3 million tons of ore worth over $40 million (Harley, 1940). Bad ground conditions and excessive mine water closed the mine in 1939. Minor reprocessing of mine dumps occurred in 1943–1944.

In 1939, the Pecos mine was transferred to the Pecos Estates, Inc. and in 1950, the surface was purchased by New Mexico to become part of the Bert Clancey Fish and Wildlife Area, administered by the New Mexico Game and Fish Department. The mineral rights were transferred to a trust and periodically leased to interested mining companies. State and federal agencies used materials from the mine waste pile at the Pecos mine for road construction and as fill in various campgrounds from the 1930s through 1970s. In 1979, Conoco leased the mineral rights at the Pecos mine and in 1982 Santa Fe Pacific Mining, Inc. subleased the mine. Santa Fe drilled 18 holes in 1983–1984. In 1988, Santa Fe determined that the mineralized zones at the Pecos mine were too deep and too small to be mined economically.

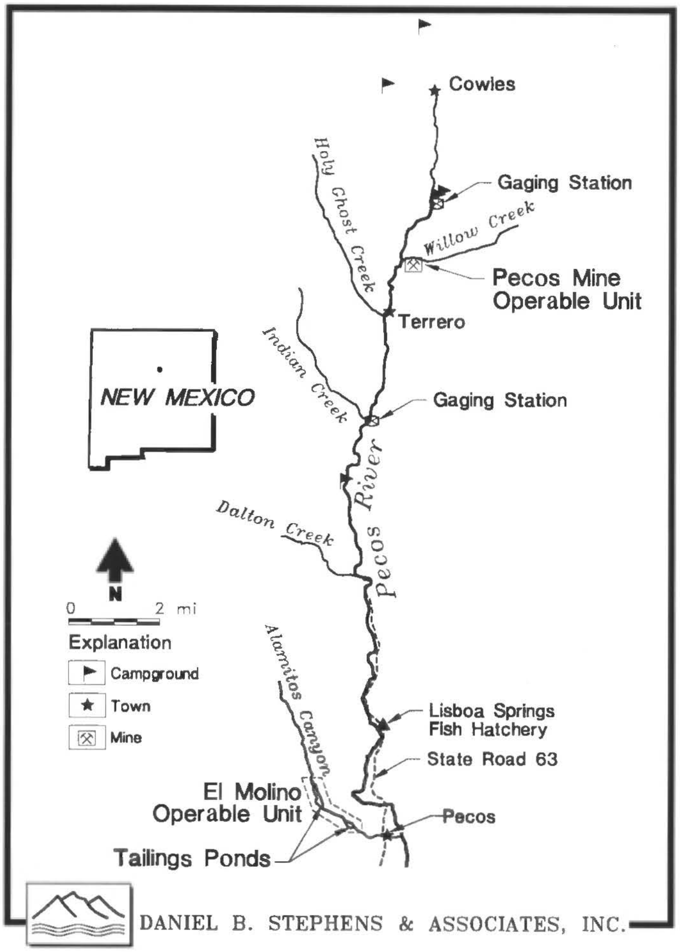

FIGURE 2.15. Location map of the Pecos mine and El Molino mill.

Pecos mine environmental issues. Three primary environmental problems are associated with the Pecos mine. The first is the mine and waste rock pile. The second is related to the El Molino mill in Alamitos Canyon. The third resulted from the use of mine waste rock for surfacing Forest Service roads and campgrounds in the area. The following two minipapers summarize the environmental programs at the mine and campgrounds, and Johnson and Deeds (this volume) addresses the millsite remediation.

A SITE CONCEPTUAL MODEL OF ENVIRONMENTAL ISSUES AT THE PECOS MINE

Peggy S. Johnson and Judith L. Deeds

Daniel B. Stephens & Associates, Inc., Albuquerque, NM 87109

The Pecos mine is located approximately 16 mi north of the Village of Pecos at the confluence of Willow Creek and the Pecos River (Fig. 2.15). The mine operated from 1926-1939 producing lead, zinc and small amounts of copper, gold, and silver from a massive sulfide deposit. Environmental concerns surrounding the mine are primarily associated with mine waste rock. The mine, 19 acres of associated waste rock dumps, 8-10 acres of wetlands located at the base of the waste rock dump, and affected portions of Willow Creek and the Pecos River are currently being investigated as a potential hazardous waste site under the Comprehensive Environmental Response, Compensation, and Liability Act (CERCLA). Public document repositories containing the administrative record for the site have been established for public viewing in Pecos and Santa Fe. Information presented for the Pecos mine has been compiled from company reports in the administrative record.

Under CERCLA, prior to closure, the mine site will proceed through a remedial investigation, a feasibility study, the design and construction of remediation and monitoring systems, and long-term operation and maintenance of the remedial and monitoring systems. As of March, 1995, the mine is entering the site characterization phase of the remedial investigation. Only limited, preliminary studies of the geology, hydrogeology, surface water hydrology, water quality, and site ecology have been conducted at the Pecos mine to evaluate contaminant releases associated with the waste rock materials, and to facilitate development of a site conceptual model. These investigations are summarized in the Pecos Mine Operable Unit Background Report (S.M. Stoller Corporation, unpubl. report, 1993), and form the basis for development of the Pecos mine site conceptual model (Fig. 2.16).

Waste rock piles generated during excavation and extraction of ore from the Pecos mine cover approximately 19 acres adjacent to the Pecos River. An estimated 95,000 yds^3 of waste rock are contained primarily in one large dump pile. The waste rock pile varies from less than 10 ft to more than 45 ft thick, and is underlain by either clay-dominated colluvial material or limestone bedrock. Texture and composition of the waste rock is heterogeneous. Finer sediments are concentrated in the upper portion of the pile, with lower portions dominated by high-porosity, coarse-grained materials. Waste rock mineralogy is dominated by silicate gangue minerals (quartz, chlorite, biotite, actinolite, sericite, tourmaline) and pyrite, with smaller amounts of galena and sphalerite.

Analytical results using both whole-rock analyses and EPA's Toxicity Characteristic Leaching Procedure (TCLP) indicate that lead and zinc, the two primary metals mined at the site, together with cadmium and copper, are present at elevated levels in both the whole rock and the TCLP extract. Concentrations of total lead in waste rock samples range from 41.8 to 26,320 ppm; TCLP lead levels in the extract solution range from 0.047 to 106 ppm. Corresponding values for zinc are 72.5 to 150,000 ppm and 0.09 to 770 ppm, respectively.

Due to the elevated metal sulfide content of some of the mine waste, the potential exists for acid rock drainage from the waste rock pile. Previous investigations of the acid-generating potential of waste rock materials have generally indicated that waste rock from the Pecos mine will produce acid. Significantly, samples of colluvium and bedrock collected

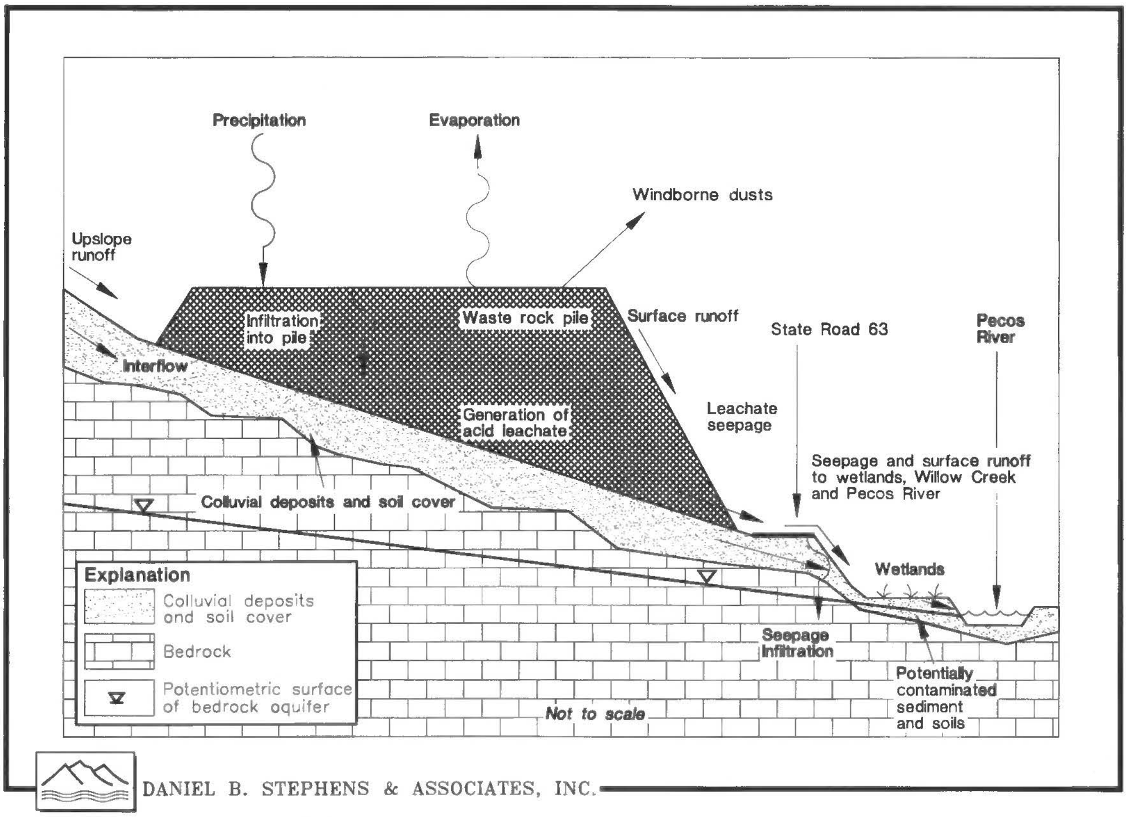

FIGURE 2.16. Pecos mine site conceptual model cross section.

below the base of the pile have strong acid-neutralizing potentials, which suggests that the underlying material should provide some buffer capacity for acid leachate and help attenuate transport of dissolved metals in infiltrating ground water. In general, natural leachate from waste rock samples is characterized by elevated total dissolved solids (TDS), sulfate, and metals including aluminum, copper, iron, lead, and zinc, and possesses similar qualitative chemical characteristics to seepage water discharging along the base of the waste rock pile.

The Pecos River flows southward approximately 500 ft west of the rock dump, and in this stretch has a recreational listing under the Wild and Scenic Rivers Act. Willow Creek flows west along the north edge of the waste rock pile, traversing waste rock material for approximately 250 ft prior to joining the Pecos River. Water in numerous discrete and diffuse seeps along the base and downslope of the waste rock pile originates from incident precipitation, surface runoff from the hillslope upgradient of the waste pile, shallow ground water (interflow) from the upgradient slope, and subsurface flow from Willow Creek. These seeps and the surrounding area of lower Willow Creek form a natural wetlands between the waste rock pile and the Pecos River. The number of seeps, area of diffuse seepage, and seep flow rates increase in response to storm events, indicating that seepage from the pile primarily originates as precipitation that infiltrates and flows rapidly through the pile. Long-term seasonal variations in seep flows appear to follow the same pattern as seasonal variations in rainfall and stream flow. During site visits in July and September, 1992, some seeps were completely dry.

Despite the attenuation potential of material beneath the waste rock, elevated levels of metals and low pH values have been detected in seeps downslope of the waste rock dump and adjacent to the Pecos River. Accordingly, the surface water pathway has been identified as a significant exposure pathway at the mine site. Because the area surrounding the mine does not have a high human population, the major concern at the mine is the potential ecological impact to the Pecos River system, and specifically surface water quality in the Pecos River, Willow Creek, and in the springs, seeps, and surface channels comprising the wetlands area below the waste rock pile. Elevated concentrations of dissolved zinc are of specific concern to the Lisboa Springs Fish Hatchery, located approximately 12 mi downstream of the mine on the Pecos River, because of the metal's potential toxicity on young fry.

Water quality in Willow Creek and the Pecos River has been affected by seepage from, or direct contact with, the waste rock material. Levels of dissolved cadmium, copper, and zinc exceed State of New Mexico acute and chronic water quality standards for aquatic life in some Willow Creek samples collected downstream of the waste rock pile and above the confluence with the Pecos River. These metals are not detectable in water samples collected upstream of the waste pile. Similarly, dissolved concentrations of heavy metals in Pecos River samples collected upstream of the waste rock pile are nondetectable, whereas low levels of aluminum, cadmium, copper, iron, lead, and zinc have been detected in some downstream samples.

The hydrogeology at the Pecos mine is currently being characterized. Fourteen monitoring wells and seven piezometers have been installed in and beneath the waste rock pile and in the surrounding area. The monitoring network provides water level and water quality data for ground water in surficial deposits, waste rock, mine workings, and Paleozoic and Proterozoic bedrock. These data indicate that saturated ground-water conditions exist in alluvium and colluvium adjacent to Willow Creek and the Pecos River, and at depth in the Proterozoic bedrock below the waste pile. The bedrock aquifer beneath the waste pile is confined by overlying, low-permeability Paleozoic sedimentary rocks. Water in the mine tunnels and shaft is in hydraulic connection with the bedrock aquifer.

The waste rock material contains water predominantly under unsaturated conditions. Saturated conditions may exist intermittently at the base of the waste rock pile along pre-existing topographic drainages. Clay and marlstone are present at certain locations below the base of the waste rock pile. These low permeability materials impede infiltration of water from the waste pile into the bedrock aquifer, and may cause temporary ponding in discrete areas along the waste-bedrock interface. Ground water is generally absent in the monitoring wells completed in the waste rock material, indicating that any interflow in the waste rock pile is episodic or of very low volume. There is no evidence for continuous flow within the waste rock or downward flow from the waste rock into the deeper bedrock aquifer.

Ground water in the underlying bedrock aquifer has not been affected by leachate from the waste rock materials and is generally of good quality. Ground water from shallow alluvial wells adjacent to Willow Creek is chemically similar to nearby surface and wetlands waters, and is distinct from ground water in the underlying bedrock aquifer. Dissolved concentrations of copper, iron, manganese, cadmium, lead and zinc are slightly elevated above federal MCLs in shallow wells adjacent to and downgradient of the waste rock area.

In summary, the primary environmental concern at the Pecos mine is associated with seep water quality and its potential for impacting the Pecos River surface water system. Seep waters are characterized by a range of Ph values (3.7 to 7.2) and elevated concentrations of heavy metals. Those waters with low Ph values of 3.7 to 4.8 contain elevated total and dissolved concentrations of cadmium, copper, lead and zinc. Although the potential exists for these waters to impact the surface water system, the wetlands area appears to have considerable acid-neutralizing capability and to be generally effective in attenuating transport of dissolved metals, possibly due to precipitation of metal sulfides and/or adsorption of metals on organic matter.

SUMMARY OF ENVIRONMENTAL SAMPLING AT FOREST SERVICE ROADS AND CAMPGROUNDS NEAR COWLES, NEW MEXICO

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In the mid 1970s, the U.S. Forest Service constructed campgrounds and access roads in the Cowles, New Mexico area with unprocessed waste rock obtained from the old Pecos Mine near Tererro, New Mexico. The Jack's Creek Campground and Trailhead, Panchuela Creek Campground, Winsor Trailhead parking area, and associated access roads (the site) were constructed or upgraded using the crushed mine waste material (Fig. 2.17). In the late 1980s, the Forest Service became aware that the materials used in the construction of the campgrounds and roads contained high levels of lead and zinc, potentially creating a health hazard for users of these forest facilities and for fish and wildlife. The contaminated road materials had eroded from the roads and campground pads, and had formed devegetated plumes of contaminated materials in areas down gradient from the roads.

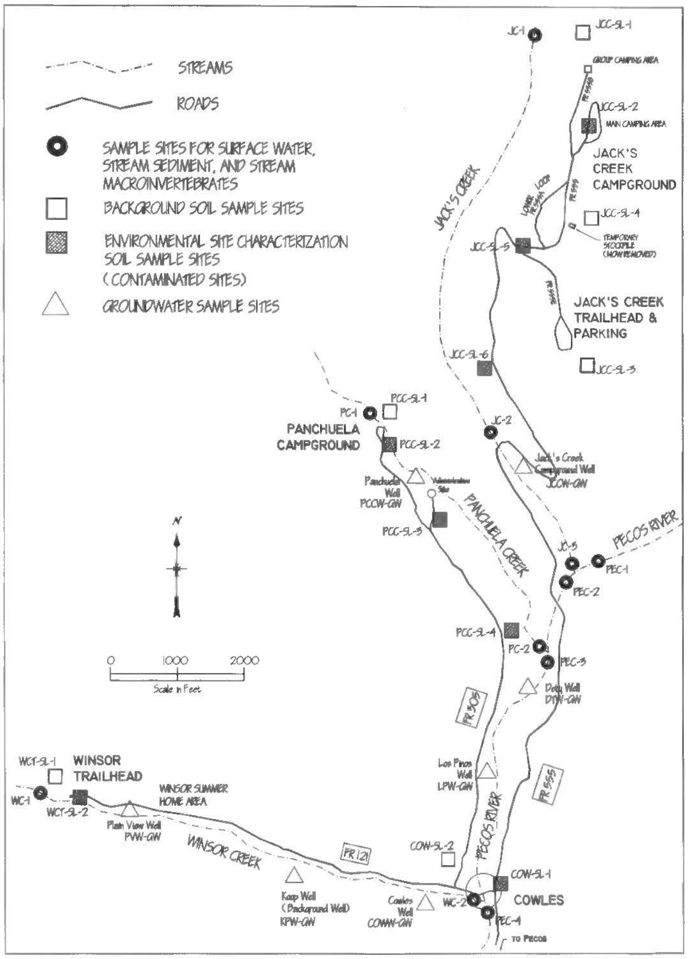

FIGURE 2.17. Map of upper Pecos River area showing sample sites for environmental investigation of Forest Service roads and campgrounds.

In 1994, the Forest Service initiated a Non–Time Critical Removal Action (NTCRA) for the removal and stabilization of the contaminated materials in the campgrounds. An Engineering Evaluation/Cost Analysis (EECA) (SFNF, 1994) evaluated alternative plans for the removal of the contaminated material, and established the criteria of 500 ppm lead in soil as the action level for the NTCRA. The alternative selected was removal of the contaminated plumes to the Site roadways where the contaminated materials were stabilized with lime and capped with asphalt to prevent future release of the material from the roads.

An environmental sampling and analysis plan was developed to support the NTCRA, which provided for sampling of soils, surface water, stream sediments, ground water, and stream macroinvertebrates. Soil samples were collected for several purposes. Background soil samples were collected from six locations near the Site campgrounds to establish the normal background soil conditions. Samples of the contaminated roads and campground pads were also collected from eight sites to characterize the contaminated material. Three soil samples were collected at each site to a depth of 18 in. Stream sediment samples were collected from 11 stream locations: upstream from each campground area (background sites), and from above and below confluence points on the Pecos River, Jack's Creek, Panchuela Creek and Winsor Creek. The background and contaminated soil samples, and the stream sediment samples were analyzed for 19 elements using atomic absorption spectrophotometry (AAS).

The background soil sample results established the normal background ranges of the 19 elements for the Site soils. All metals are within the normal range reported by Alloway (1990) for metals in sedimentary rocks and soils, except for silver. The minimum silver concentration obtained in the background soils (range 0.5 to 5.0 ppm, mean 1.3 ppm) is about twice the normal value reported for sedimentary rocks. The results of the analyses of the contaminated material established that, of the 19 metals investigated, copper (range 25 to 1311 ppm, mean 245 ppm), lead (range 37 to 10,600 ppm, mean 702 ppm), and zinc (range 485 to 33,550 ppm, mean 2,417 ppm) are significantly elevated in the waste rock. Other metals showing elevated concentrations are cadmium (range 0.7 to 124 ppm, mean 8.3 ppm), and to a lesser extent silver (range 1.0 to 38 ppm, mean 4.4 ppm). Concentration values obtained for As, Be, Cr, Hg, Mn, Se and V in the contaminated material are not significantly above background levels.

The results of analyses of the stream sediment samples established background conditions and explicitly show where contaminated materials had entered the stream. Background mean metals concentrations in the stream sediments are 7 ppm Cu, 8 ppm Pb, and 46 ppm Zn. An episode of increased soil erosion caused by construction activities on the Jack's Creek access road caused elevated metals in Jack's Creek below the road crossing. The stream sediment sample collected below the road crossing contained elevated zinc (1,160 ppm), lead (780 ppm), and, to a lesser extent, copper (144 ppm) concentrations. The effect of soil erosion apparently extended into the Pecos River as stream sediment samples collected below the confluence with Jack's Creek also showed slight elevations in Cu (59 ppm), Pb (323 ppm) and Zn (492 ppm) in 1994. Supplemental stream sediment sampling will be conducted after the Removal Action is complete to monitor the effects of the contaminated material in the streams.

Confirmation soil samples were collected to guide the removal action. After contaminated materials had been removed from an area, composite soil samples were collected and analyzed using XRF to determine if the soil was below 500 ppm lead. If the soil contained lead greater than

500 ppm, additional removal was performed until each site met the criteria. After the removal action was complete, grab soil samples were collected from a percentage of the formerly contaminated sites, and were sent to a laboratory for further confirmation that the removal action was successful. The results of the laboratory analyses confirmed the effectiveness of the removal action.

Surface water samples were collected at the 11 stream sediment sample sites, and ground water samples were collected from 7 drinking water wells at the site. The water samples were analyzed for major constituents and for a total of 19 elements (total and dissolved metals). The surface and ground water is a calcium bicarbonate-type water that contains a mean 116 ppm total dissolved solids (TDS) and 36 ppm hardness for the surface water, and a mean 169 ppm TDS and 50 ppm hardness for the ground water. The upstream surface water sites on the Pecos River and Jack's Creek contain TDS, calcium and bicarbonate values that are about twice that of Panchuela and Winsor Creeks. The downstream samples from the Pecos River show the dilution of these constituents below the confluence with each of these tributary streams.

The results of analyzing the surface water samples for total metals do not indicate that the surface waters have been significantly impacted by the contaminated soil at the site. The highest Zn value (0.28 ppm) was obtained from an unfiltered sample on the Pecos River which contained suspended sediment that contributed to the Zn content. The corresponding filtered water sample from this site did not contain Zn above the detection limit. The highest Pb concentration obtained in the surface water samples is 0.007 ppm from site PC–2, and only one Cu value above the detection limit (0.02 ppm) was obtained. All values for total metals in the surface water samples are substantially below their respective water standards set by the New Mexico Water Quality Control Commission (NMWQCC, 1995).

Preliminary results from sampling a portion of the ground water wells at the site do not show the influence of contaminated soil materials. The highest ground water values obtained for Pb (0.006 ppm) and Zn (0.22 ppm) are from a well that was sampled from a galvanized steel pipe. This well was inappropriately selected to represent background ground water conditions at the site. Water samples from the other wells contain lower Pb and significantly lower Zn values (< 0.05 ppm). All analytical results for metals in the ground water are also substantially below drinking water standards.

Stream macroinvertebrate samples were collected from the 11 stream sediment sample sites, and were analyzed for species content and species diversity. The samples contained macroinvertebrate communities that were moderately diverse and were moderate to high in terms of densities. Total densities ranged from 2,722 individuals/m^2 in Jack's Creek to 8,167 individuals/m^2 in Panchuela Creek. The total number of taxa varied from 22 in Jack's Creek to 33 in Winsor Creek. Species diversity indices ranged from 2.32 in Winsor Creek to 2.64 in the Pecos River. The results indicate no significant impact to the stream communities by the contaminated soil materials at the site. The U.S. Forest Service plans to monitor the site tri–annually for at least two years, after which a long term monitoring program will be developed and implemented.

Turn around and return southward to Pecos. **9.9**

48.0 Intersection of NM-223 with NM-63 in Pecos. Continue straight south on NM-63. **0.2**

48.2 U.S. Forest Service Pecos Ranger Station on the right sells detailed maps of National Forest land. **0.8**

49.0 View ahead and to right is of Glorieta Mesa, our destination for Stop 3. Across the Pecos River at 9:00 are several E- to NE-trending faults and folds mapped by Johnson (1973). The Los Cedros fault is a high-angle, down-to-the-south fault with perhaps 2000 ft of throw. The related Los Piñones monocline and Pecos Pueblo anticline are to the south of the fault. Structural relief on all three features dies out to the west, and none is mappable here along the highway. **0.5**

49.5 On the right, through the pinyon pines you can catch a glimpse of the sandstone ruins at Pecos National Historical Park. Both the 1956 and 1979 NMGS Fall Field Conferences visited the park. **0.5**

FEARED THROUGHOUT THE LAND

James L. Moore

Museum of New Mexico, P.O. Box 2087, Santa Fe, NM 87504-2087

"Cicuye is a village of nearly five hundred warriors who are feared throughout that country" (Winship, 1904, p. 147). Thus began Pedro de Casteñeda's description of Pecos Pueblo at the time of initial European contact with the pueblos of New Mexico during Coronado's expedition of 1540-1542. Pecos was renowned as a center of trade and the home of fierce warriors through most of its history. It was not until the savage Comanche onslaught of the mid-1700s that the power and prestige of Pecos began to wane. Kidder (1958) excavated in the Pecos area for 10 seasons between 1915 and 1929, thus beginning the transition to modern Southwestern archaeology. Other sources include a few university-sponsored excavations and surveys, projects associated with highway construction, and resource inventories at Pecos National Historical Park (PNHP).

Most studies of this area have focused on Pecos Pueblo and nearby large villages. Thus, little is known about pre-A.D. 1200 human occupation. Evidence for occupation during the Paleoindian period (ca. 10,000-5500 B.C.) is very limited. Only one Clovis-type projectile point is reported in the upper Pecos Valley (Nordby, 1981), and only one site that may date to that period has been recorded (Anschuetz, 1980). Although in the past, all Paleoindians were classified as big game hunters, we now suspect that Clovis people (10,000-9000 B.C.) were unspecialized hunter-gatherers, whereas Folsom and many later groups (9000-5500 B.C.) turned increasingly toward the specialized hunting of migratory game, particularly bison (Stuart and Gauthier, 1981).

The Archaic period (5500 B.C.-A.D. 400) is somewhat better understood, but data from the Pecos area is limited. Archaic peoples were mobile hunter-gatherers who moved camp several times a year, subsisting mainly on wild plants and animals. During the early Archaic (5500-3200 B.C.), people lived in family-based bands. Sites from this period tend to be small and uncommon. By the middle Archaic (3200-1800 B.C.) the population had grown, and sites are larger and more common. Corn was grown by the beginning of the late Archaic (1800 B.C.-A.D. 400), and by the end of this period the transition from a mobile hunting and gathering lifestyle to one based on sedentary farming had begun.

The paucity of Archaic sites is probably due to a lack of well reported large-scale survey projects, and does not necessarily imply a sparse population. While no definite early or middle Archaic sites have been recorded, projectile points from these periods were recovered during Kidder's excavations at Pecos, and are included in the collections stored at PNHP. These artifacts were probably collected from nearby Archaic sites by the occupants of Pecos Pueblo. A middle Archaic projectile point was found on a site near Pecos (Lent, 1992), and a possible early Archaic site was recorded near Rowe (Anschuetz, 1980). Other Archaic remains are mostly late, and are identified by the presence of Basketmaker II projectile points. These sites are mostly surface scatters of chipped stone artifacts containing occasional pieces of fire-cracked rock that represent the remains of hearths.

The Pueblo period began around A.D. 400 and lasted until A.D. 1838, when Pecos Pueblo was abandoned. Several changes in material culture and subsistence mark the beginning of this period. Two major innovations were introduced—pottery and the bow. The use of pottery for cooking and storage probably reflects reduced mobility, as these containers are more difficult to transport than baskets. The introduction of the bow may reflect a change in hunting techniques from a focus on ambush and knock-down power to one in which game was stalked and tracked after being wounded. While the hunting and gathering of wild foods remained important into the historic period, dependence on cultivated foods began increasing in the early part of the Pueblo period, leading to the development of small sedentary farming villages. This process intensified as the population grew, culminating in multistoried villages containing hundreds of people that were encountered by Spanish explorers.

The Pueblo occupation of the northern Rio Grande can be divided into four periods: Developmental (A.D. 600-1200), Coalition (A.D. 1200-1325), Classic (A.D. 1325-1600), and Historic (post-A.D. 1600). Early Developmental period sites are rare, and usually contain circular pithouses and surface storage structures. A shift from the occupation of pithouses to above-ground structures began in the late Developmental period, and communities containing definable clusters of villages appeared. Unfortunately, Developmental period sites are rare in the Pecos area. Three early Developmental period pithouses have been excavated at PNHP (Nordby and Creutz, 1993), but there is little other evidence of occupation in this area for the next 350 to 400 years.

The Coalition period is marked by a switch from carbon- to mineral-painted pottery, a population influx from the Four Corners region, and expansion of settlements into new environmental zones (Wendorf and Reed, 1955; Anschuetz, 1986). An apparent influx of population into the Pecos region around A.D. 1200 resulted in the construction of two large adobe-walled villages, Forked Lightning Ruin and Dick's Ruin (Kidder, 1958; Nordby, 1981). However, part of the population continued to live in smaller villages, few of which are documented. Both of these large villages were abandoned by A.D. 1300, and new villages such as Pecos Pueblo, the Hobson-Dressler Ruin, and an unnamed village were built with stone rather than adobe (Nordby, 1981). Numerous field houses served as temporary shelters for farmers tending their fields.

The Classic period is marked by the aggregation of smaller communities into large multistoried pueblos, often with several plazas. Several villages were occupied in the Pecos area during the early Classic period, including Pecos Pueblo, Arrowhead Ruin, Loma Lothrop, and Rowe Pueblo (Holden, 1955; Wait, 1980; Nordby, 1981). These villages were multistoried, and most contained up to several hundred rooms. Field houses continued to be used. Many examples of this type of site have been recorded (Anschuetz, 1980; Fliedner, 1981; Morrison, 1987). By A.D. 1450, Pecos Pueblo was the only occupied village in the region. Aggregation into a single large village may have been aimed at controlling the movement of people and goods through Glorieta Pass, though a defensive function has also been suggested. Trade relations between the pueblo and plains areas became formalized during this period (Spielman, 1982, 1983), and Pecos was a major trading center by the time the Spanish arrived in New Mexico.

The Historic period officially began with the founding of San Gabriel del Yunque by Oñate in 1598, though New Mexico was explored by several expeditions earlier in the sixteenth century. Casteñeda, who chronicled Coronado's expedition, described Pecos as a village whose houses stood four stories tall and contained nearly 500 warriors (Winship, 1904). There were no ground-floor entrances, and the village was enclosed by a low stone wall (Winship, 1904). The defensive nature of the village was remarked upon, as was the recent appearance of Plains Apaches on the scene, whose friendly trading relationship with Pecos lasted into the mid-1700s.

The first of several churches was dedicated at Pecos in 1617 or 1618, when the population was about 2000 (Kessell, 1979). Spanish priests campaigned to force the people of Pecos to accept Christianity and renounce their traditional religion, even going so far as to destroy ceremonial paraphernalia (Kessell, 1979). Friction over this and other Spanish policies nearly flared into open rebellion on several occasions.

An important source of income for Pecos during this period was the annual fall trade fair, which occurred near harvest time (Kessell, 1979). Most of this trade was with the Plains Apache, and provided goods for the Spanish population as well. Slaves were an important trade item, and the Spanish supplemented the supply available from the trade fairs by raiding Apache groups during the 1600s. This antagonized both the Apaches and their Pueblo trading partners, and caused the former to unleash a series of devastating raids against the Spanish and certain Pueblos in the 1660s and 1670s (Forbes, 1960). Several abortive rebellions by the Pueblos were put down before a general revolt in 1680 succeeded in expelling the Spanish from New Mexico. Most of the Pueblos and Apaches restored peaceful relations during their absence, and many Apaches aided the Pueblos during the Spanish reconquest in 1693 (Forbes, 1960).

Although the Spanish returned to New Mexico in 1693, sporadic rebellions continued until 1700. Pecos was split into two factions during this period, one pro- and the other anti-Spanish (Kessell, 1979). Even with this split, Pecos aided the Spanish army and settlers with food and warriors during the reconquest (Kessell, 1979). Factionalism continued until 1707 when the anti-Spanish group disappeared, perhaps having fled to the plains or to other Pueblo villages. From this time forth Pecos was a staunch ally to the Spanish, often furnishing troops for campaigns against hostile Plains Indians.

The decline of Pecos began with the arrival of the Comanches on the Plains. Their first recorded appearance in New Mexico was in 1705, when they appeared near Taos accompanied by their Ute allies (Thomas, 1932; Wallace, 1959; Noyes, 1993). The Comanches campaigned to drive the Apaches from the plains during the early 1700s, and part of their wrath was turned on the pueblos of Pecos and Galisteo, both trading partners to their enemies. However, it is likely that the loss of trade with the Apache, who were driven off the Plains by 1748, was more a factor in the decline of Pecos than were Comanche raids (Kessell, 1979). Losses to hostile Indian raids, disease, and perhaps the lure of a Spanish lifestyle caused a steady decline in population after the mid-eighteenth century. By 1800, nearby Spanish settlements were beginning to compete with Pecos for farming and pastoral land. Less than 20 Indians were left at Pecos in 1838 when they abandoned their village to live with their distant relatives at Jemez, the only other village that spoke their language. Neighboring Spanish families had begun to occupy the grant 10-20 yrs before this date, and remained in possession until the American period. The few early historic period sites that have been investigated include a seventeenth century Pecos farmstead, and the mid-nineteenth century Jose María Martínez Site, both along US-84 west of the village of Pecos.

50.0 Entrance to Pecos National Historical Park on the right. Official scenic historic marker reads:

> *Pecos National Monument. In 1541, Pecos Pueblo stood 4 to 5 stories high and accommodated a population of 2,000. The Spanish built two mission churches here in the 17th and 18th century. Disease, economic hardship, drought, and Comanche raids, all took their toll. In 1838, 17 inhabitants of Pecos moved to Jemez Pueblo where their descendants live today.*

0.5

50.5 Crossing Glorieta Creek. The Santa Fe Trail crossed here. Ahead on left is a historic building, now headquarters for the Forked Lightning Ranch (originally 13,600 acres, which included Pecos National Historical Park); previously the home of Greer Garson. The 20th century construction incorporates some original walls of Kozlowski's Ranch and Stage Station. Martin Kozlowski built the place from materials scavenged from the nearby Pecos mission and Indian ruins. He and his wife served meals to weary Santa Fe Trail stage passengers. The house was later used by Union forces as headquarters during the Civil War Battle of Glorieta. **0.7**

THE FORKED LIGHTNING RANCH

Paul W. Bauer

New Mexico Bureau of Mines and Mineral Resources, Socorro, NM 87801

Tex Austin, whose real name was Clarence Van Nostrand, was a showman extraordinaire. He produced the first Madison Square Garden rodeo in 1922, awarding $25,000 in prize money. He promoted "World Championship" rodeos and Wild West shows in Chicago, London, and elsewhere in Europe. In 1925, Tex began buying up pieces of the old Pecos Pueblo Grant. When he added 100,000 acres of grazing leases to the 5,500 acres of private land, the Forked Lightning Ranch was operational. His ranch house was designed by John Gaw Meem, the famed architect who is responsible for Santa Fe style architecture. The centerpiece was a huge, sculpted steers head that was mounted on the side of the house.

When the cattle business suffered, Austin turned the Forked Lightning into a dude ranch. Vacationers included the likes of Charles Lindberg, Will Rogers, the McCormicks of Chicago (makers of farm equipment and newspapers), and artist Randall Davey (who later moved to Santa Fe). After his enterprises failed and he lost his ranch during the Great Depression, Tex Austin committed suicide. In 1976, he was inducted into the National Cowboy Hall of Fame as the "Daddy of Rodeo".

The ranch was purchased in about 1936 by W.C. Currier, who sold it to Texan rancher and oilman E.E. "Buddy" Fogelson five years later. Fogelson, like Tex Austin, was a bigger-than-life Westerner who proceeded to increase the ranch holdings by more than 8000 acres. The ranch became a well known showcase of gracious Western hospitality when Fogelson married the actress Greer Garson in 1949. The couple raised Hereford beef, white Scottish longhorns, and prize-winning Santa Gertrudis bulls (Fig. 2.18).

In 1987, upon his death, Fogelson willed the northern 5500 acres, including the ranch house, to his wife, and the 8000 southern acres to his adopted son Gayle. Gayle Fogelson sold part of his property to a local ranching family and part to a developer (much to the consternation of his neighbors). In 1990, the Richard Mellon Foundation bought the Garson ranch and donated it to the National Park Service. Greer Garson used part of her earnings to build the well-known communication arts center at the College of Santa Fe.

51.2 On the skyline at 11:30 are communication towers on Glorieta Mesa. The towers are accessible from the road up Rowe Hill, and the view of the Pecos River Valley and the Sangre de Cristo Mountains is superb. **1.2**

52.4 At 9:00-10:30, in the distance is a large dome-like anticline that was believed to have developed during Late Pennsylvanian time, according to the 1956 NMGS Guidebook roadlog (p. 40, mile 5.1). The base of the Sangre de Cristo Formation rests disconformably on Pennsylvanian rocks on one limb of the dome, and the Sangre de Cristo thins from 1500 ft near Pecos to 600 ft just ahead near Rowe, suggesting that the Sangre de Cristo sediments were deposited over the domal relief. **0.3**

FIGURE 2.18. Bullet-riddled sign at the headquarters for the Forked Lightning Ranch near Pecos National Historical Park. The headquarters building served as a Santa Fe Trail stage station, Union headquarters during the Civil War Battle of Glorieta, and the home of actress Greer Garson. Garson and Texas oilman "Buddy" Fogelson raised prize-winning Santa Gertrudis bulls (a Texas shorthorn/Brahma cross) here in the 1950s.

52.7 Milepost 1. On left in near distance are working buildings of the Forked Lightning Ranch. **0.8**

53.5 NM State Highway Department maintenance yard on the left. At 9:00 is another low-relief fold, the Forked Lightning syncline. The highway is approximately on the Madera-Sangre de Cristo Formation contact. **0.2**

53.7 **Bear right** at sign for I-25 North. Proceed under interstate, and continue south on paved highway across cattle guard (do not enter onto I-25). **0.3**

54.0 Stop sign; **turn left** on NM-34. At the turn, the section exposed at 1:00-2:00 on Glorieta Mesa is Sangre de Cristo Formation (lowermost grayish red and gray sandstones), Yeso Formation (reddish brown sandstones and siltstones), Glorieta Sandstone (yellow sandstone bench capping the main escarpment), Artesia Formation (orange siltstones, much covered), Moenkopi Formation (grayish red sandstones, much covered) and Santa Rosa Sandstone (yellow sandstone forming the uppermost, deeply eroded benches) (Fig. 2.19). We will now drive through this section as we ascend Glorieta Mesa. **NOTE: The dirt road up Rowe Hill is steep, and unsuitable for buses. 1.2**

55.2 Junction with NM-34; **turn right** onto unpaved road. Cross railroad tracks. **0.8**

56.0 Cattleguard. Enter National Forest lands and begin ascent of Glorieta Mesa through Yeso Formation strata. **0.8**

56.8 Milepost 25 is at the contact of the Yeso with the overlying Glorieta Sandstone. Looking back at 8:00 reveals an outstanding view of the Glorieta Mesa escarpment and the Sangre de Cristo Mountains. **0.2**

57.0 Road crests Glorieta Mesa, revealing that it is not a mesa but rather a cuesta. Forest Road 326 is immediately to the right; **turn right** and cross cattleguard. **0.2**

57.2 Cross under power line. **0.4**

57.6 Cross cattleguard. **0.3**

57.9 Road forks; go left on lesser fork. **0.5**

58.4 **STOP 3. Glorieta Mesa.** Cattle tanks at 9:00 at curve in road; **stop here** to examine Permo-Triassic strata on hill to right and to discuss structure of Lamy-Galisteo Basin and Ortiz Mountains, which are visible to the south.

The youngest Permian strata exposed on this hill belong to the Artesia Formation (formerly Bernal Formation), here consisting of reddish brown (orange) ripple

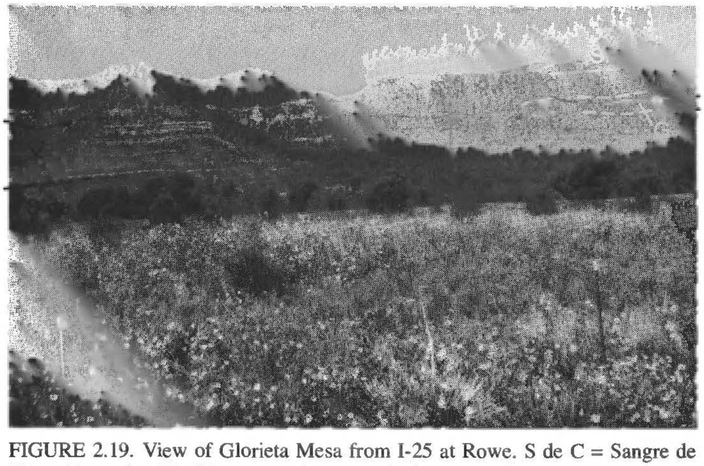

FIGURE 2.19. View of Glorieta Mesa from I-25 at Rowe. S de C = Sangre de Cristo Formation, Y = Yeso Formation, G = Glorieta Formation, M/A = Moenkopi/Artesia Formations, S = Santa Rosa Formation.

laminar siltstone (Fig. 2.20). The overlying Moenkopi strata are about 20 ft thick and consist of grayish red micaceous litharenites and intrabasinal conglomerates that are dominantly trough crossbedded or laminated. Lithology, bedforms, and color provide a striking contrast between the Moenkopi and underlying Artesia (Fig. 2.20), but this did not deter earlier mappers in this region from mapping them together as a single unit they identified as "Bernal Formation" (e.g., Read et al., 1944; Northrop et al., 1946; Wood and Northrop, 1946; Bachman, 1953; Johnson, 1970, 1973, 1974; Budding, 1972; Baltz and O'Neill, 1984, 1986). Lucas and Hunt (1987) and Lucas and Hayden (1991) first identified the lithologic distinctiveness of Moenkopi and Artesia strata in north-central New Mexico.

Artesia Formation strata represent a clastic shelf that developed landward of the giant Capitan reef system (Guadalupe Mountains near Carlsbad) during Middle Permian (Guadalupian) time. Moenkopi Formation strata were deposited in an inland basin by northerly and northwesterly flowing rivers during Middle Triassic (Anisian) time. The Artesia-Moenkopi disconformity thus represents about 20 million years (Fig. 2.21A). Nevertheless, local stratigraphic relief and rip-up associated with this disconformity is relatively limited.

At this stop, and across northern New Mexico, Upper Triassic strata of the Chinle Group disconformably overlie the Moenkopi Formation (Fig. 2.21B). Here, these strata are extraformational conglomerates and quartzose sandstones of the Tecolotito Member of the Santa Rosa Formation. These strata are trough crossbedded, brown, yellow, and gray and their base shows scour relief of up to 0.7 ft. The conglomerate clasts are Paleozoic limestone pebbles or rip-ups of Moenkopi lithics. The base of the Chinle Group is early Late Triassic (late Carnian), so the Moenkopi-Chinle disconformity encompasses about 15 million years. Santa Rosa strata were deposited by rivers with a paleoslope generally to the northwest during the initial phases of deposition in the vast Chinle basin, which extended from west Texas to Wyoming (Lucas, 1993).

View of Ortiz Mountains to the south. See Day 3 roadlog and associated papers for description of the Ortiz Mountains area. Also see Abbott et al. (this volume) for description of the Lamy-Galisteo Basin. After the stop, **retrace route to I-25. 4.7**

63.1 I-25 on-ramp, **turn right** and proceed east on I-25. **0.2**

63.3 Milepost 308. The Forest Service has a volunteer-staffed project called the Glorieta Mesa Rock Art Excavation and Recording Project, which involves excavation and recording petroglyphs at a 5000(?)-year-old Archaic rock art site on the mesa. Over 200 petroglyphs have been discovered at the site. Experts claim that this site is one of the most significant in North America because of the fine artistic quality of the glyphs, the unique elements of the artwork, the unique number and variety of design elements, and the potential for dating the site, using charcoal and rock varnish. **5.7**

69.0 We are entering a structurally complex area in which a number of high-angle, splayed faults have produced a series of grabens with associated folds. **1.3**

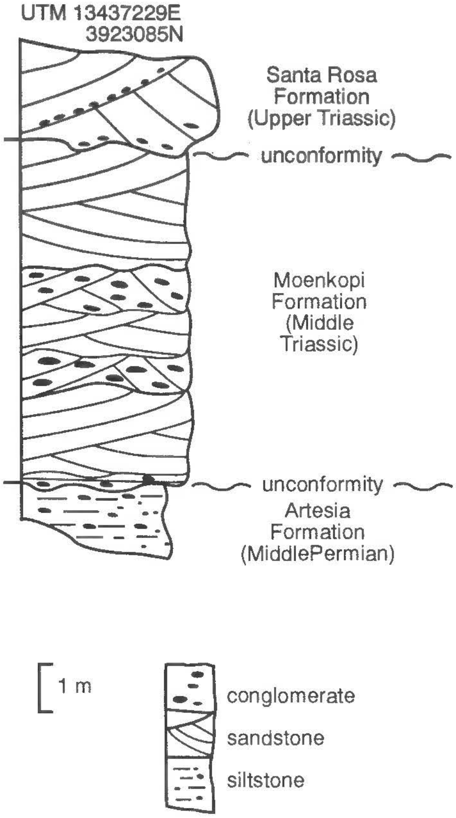

FIGURE 2.20. Measured section of Permian-Triassic strata at Stop 3.

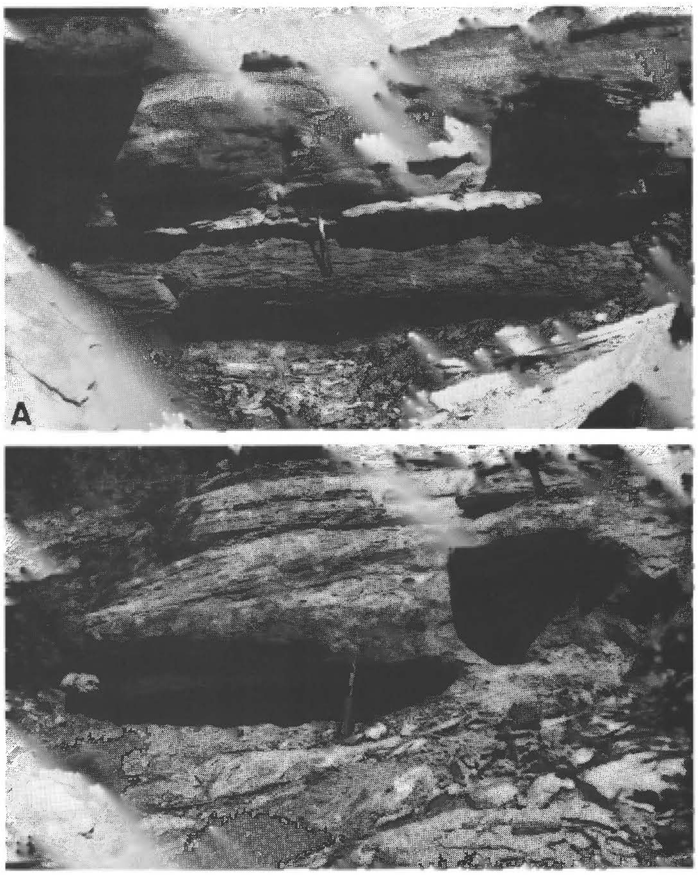

FIGURE 2.21. The two unconformities at Stop 3. A, Permian Artesia Formation beneath Middle Triassic Moenkopi Formation. B, Hammer marks contact between Moenkopi and Upper Triassic Santa Rosa Formation.

70.3 Milepost 315. The road here crosses erosional remnants of a high-level Quaternary alluvial deposit associated with the Pecos River. At least five vertically distinguishable strath terraces have been identified along the river here (Karas, 1987). These deposits were correlated on the basis of relative topographic position and degree of soil development. The oldest terrace, upon which we are driving, is 240 ft above modern river level and 820-2460 ft from the channel. The other, younger terraces are isolated, thin alluvial deposits that cover bedrock surfaces perched within the steeper inner valley. At least the oldest two terraces here are probably Pleistocene in age. Karas (1987) concluded that the Quaternary history of this part of the Pecos River Valley consisted of an overall trend of downcutting punctuated by periods of relative stability. No evidence was found for major Quaternary valley fill deposits in the valley, although he did find several fill units upstream along Glorieta Creek near the Pecos National Historical Park. **5.3**

75.6 Exit 319 to San Juan and San Jose. Continue straight. **1.2**

76.8 Crossing the Pecos River. Sangre de Cristo Formation exposed. **1.5**

78.3 Exit 323 to Villanueva State Park. The village of San Miguel lies about two miles south. Originally known as San Miguel del Bado (Saint Michael of the Ford), it is located where the Santa Fe Trail crossed the Pecos River, and was the southernmost point on the trail. The village contains a beautiful church built in 1806, complete with large cast iron bell forged in Cincinnati at the beginning of the Civil War. In 1846, General Kearny stopped in San Miguel to declare the New Mexican Territory part of the United States.

NM-3 to Villanueva traverses a broad valley developed in Lower Permian (Wolfcampian) strata of the Sangre de Cristo Formation. In this area, the Sangre de Cristo Formation is relatively fossiliferous and has produced supposed lungfish burrows (Vaughn, 1964) which are probably rhizoliths; reptile and amphibian footprints and invertebrate trails from local flagstone quarries (Hunt et al., 1990); and fossil bones of a xenacanth shark, a lungfish, labyrinthodont amphibians and primitive reptiles (Berman, 1993). This is the most fossiliferous outcrop belt of the Sangre de Cristo Formation known. **1.6**

79.9 Roadcuts are excellent exposures of cyclical, fluvially deposited red beds of Lower Permian (Wolfcampian) Sangre de Cristo Formation. **0.4**

80.3 Milepost 325. Rest area on right. **4.1**

84.4 Milepost 329. We are driving on the Madera Formation, but will shortly cross the Bernal fault into the Sangre de Cristo Formation. Starvation Peak to right consists of Yeso Formation capped by Glorieta Sandstone. Starvation Peak is said to have been named for 120 Spanish colonists who starved to death after taking refuge here during an Indian attack (Pearce, 1965). This tale is probably pure fantasy. The summit now displays a large Penitente cross and a beacon light. **0.6**

85.0 We are crossing the Bernal fault, a west-dipping reverse fault, presumably Laramide age. We will discuss this structure at Stop 4. **0.3**

85.3 **Bear right** at Exit 330 to Bernal. **0.2**

85.5 **Turn left** off of exit ramp and cross over I-25. The view ahead on the skyline is of the crystalline core of the southern Sangre de Cristo Mountains. Elk Mountain is the prominent peak. **0.2**

85.7 **Turn left** onto frontage road. Roadcuts display interlayered red mudrock and white sandstone of the Sangre de Cristo Formation. The eastward dips here are due to drag along the Bernal fault, which lies buried just to the west. **0.1**

85.8 **STOP 4. Pull off on left into graveled parking area.** The Santa Fe Trail ran just a short distance to the east of here.

Bernal. At this stop, our discussions will be limited to the Paleozoic-Mesozoic stratigraphy and Laramide structures. We have stopped in the Sangre de Cristo Formation, just east of the Bernal fault (Fig. 2.22). Bernal Butte to the east exposes Permian San Andres and Artesia Formations (base and lower slopes) overlain by Triassic Moenkopi and Santa Rosa Formations (middle-upper slopes and cap). This was the type locality of Bachman's (1953) Bernal Formation, a name widely applied to the youngest Permian strata in north-central New Mexico and misapplied to some Triassic strata as well. Bernal strata are simply a truncated western remnant of the much thicker Artesia Group of the east-central and southeastern New Mexico (Tait et al., 1962). Therefore, the name Bernal has been abandoned and replaced with Artesia Formation (Lucas and Hayden, 1991).

From this locale the large Laramide structure we are on is obvious judging from the great elevation difference between the Glorieta Sandstone-capped mesas to the east and Glorieta Mesa (the type locality, also capped by Glorieta Sandstone) to the south. Starvation Peak to the south sits approximately on the hinge of the Starvation Peak anticline, and just west of the Bernal fault. The NNW-striking fault was mapped by Johnson (1970) as a steeply west-dipping reverse fault that bifurcates to the north, and dies out to the south near Starvation Peak (Fig. 2.22). A mile to the north, a wedge of Proterozoic rocks on the hanging wall is juxtaposed against the Madera Formation. Johnson's cross section shows about 3000 ft of throw across the fault, as measured on the great unconformity (Fig. 2.22). The Proterozoic units here are typical of the southern Sangre de Cristo Mountains; mafic and felsic gneisses intruded by granites and pegmatites.

From here to the first exposure of Glorieta Sandstone along the highway westward (a map distance of about 0.5 mi), structure contours on the base of the Glorieta show 700 ft of drop on the Sarafina monocline (Fig. 2.22; Johnson, 1970). The folds (Starvation Peak anticline to the west, and Sarafina monocline to the west) have a drag-style geometry with the fault, and are presumably co-genetic with Laramide deformation (Fig. 2.22).

At this stop, the northern roadcut exposes the fluvial Lower Permian (Wolfcampian) Sangre de Cristo Formation of cyclical mudrock and sandstone (Fig. 2.23). On the west end of the roadcut is a covered contact between E-dipping Sangre de Cristo Formation and a conglomerate. Both units are cut by a flat, dissected, soil-covered pediment surface (Fig. 2.24). The Bernal fault lies buried just to the west. The conglomerate is composed of groundwater(?) cemented, subrounded pebbles and lithics, is poorly sorted and bedded, is matrix supported, and is of dubious origin. It may represent a debris flow that is in buried fault contact with the Sangre de Cristo Formation.

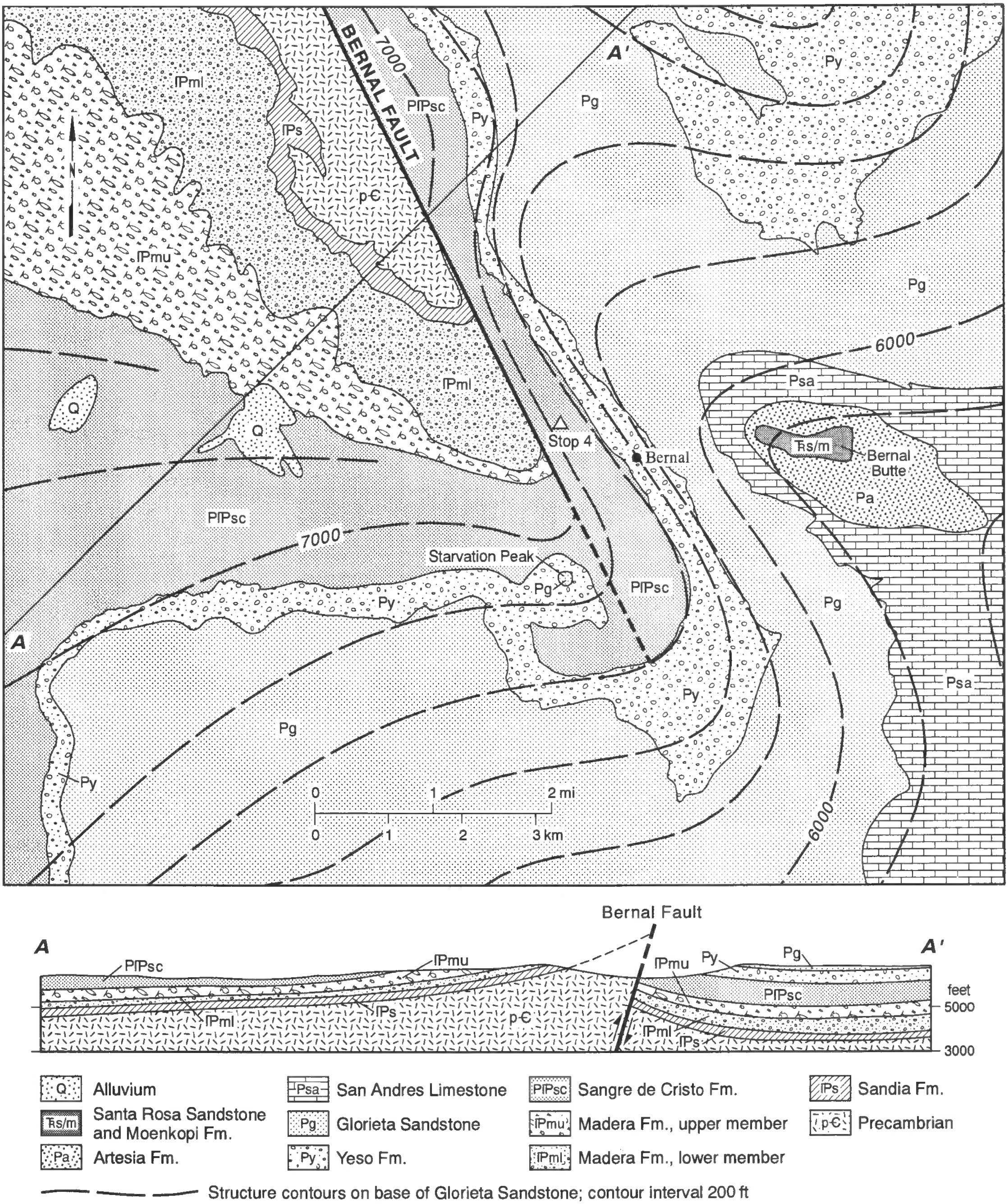

FIGURE 2.22. Geologic map and cross section of the Bernal area at Stop 4. Modified from Johnson (1970).

FIGURE 2.23. View north of east-dipping Sangre de Cristo Formation at Stop 4. Road sign approximately marks the hidden contact between the Sangre de Cristo Formation and an enigmatic sedimentary breccia. Both units are cut by a flat, dissected, soil-covered pediment surface. The Bernal fault, located some distance to the west, separates these rocks from the Madera Formation.

STRATIGRAPHY ACROSS THE PERMIAN-TRIASSIC DISCONFORMITY IN NORTH-CENTRAL NEW MEXICO

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Before 1987, geologists working in north-central New Mexico (western San Miguel, Santa Fe and Bernalillo counties) identified the youngest Permian strata as Bernal Formation disconformably overlain by the Upper Triassic Santa Rosa Formation. Lucas and Hunt (1987) recognized that the Bernal Formation of previous workers included in its upper part Middle Triassic rocks later assigned to the Moenkopi Formation. Lucas and Hayden (1991) advocated Tait et al.'s (1962) suggestion that in north-central New Mexico Permian strata previously termed Bernal Formation be referred to as Artesia Formation. The Permian-Triassic disconformity in north-central New Mexico thus is between the Artesia and Moenkopi formations (Fig. 2.25).

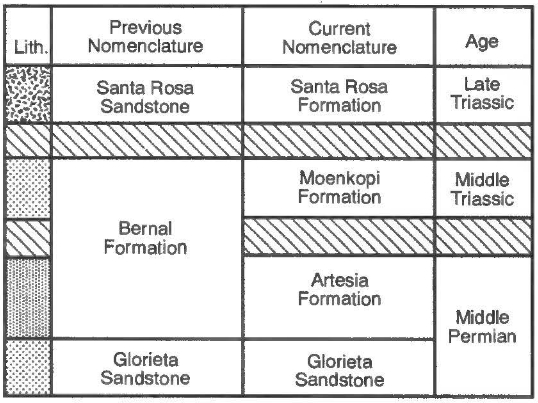
In north-central New Mexico, Permian strata previously termed Bernal Formation are the relatively thin (up to 100 ft) northwestern edge of the Artesia Group, a much thicker (up to 1700 ft) succession of five formations (ascending order: Grayburg, Queen, Seven Rivers, Yates and Tansill formations) well exposed in southeastern and east-central New Mexico. Artesia strata represent clastic and evaporite deposition on a broad shelf that formed northward and northwestward of the Permian reef complex of the Guadalupe Mountains of southeastern New Mexico-west Texas. The Artesia Group thus is of Middle Permian (Guadalupian) age. Strata previously termed Bernal are equivalent to some part of the lower two Artesia Group formations, the Grayburg and Queen. Available data do not allow a more precise correlation, so Bernal is best replaced by the term Artesia Formation until a more precise correlation with specific formations of the Artesia Group can be achieved.

In north-central New Mexico, Artesia Formation clastic red beds are overlain disconformably by Moenkopi Formation red beds. The capitosauroid amphibian *Eocyclotosaurus* from Moenkopi strata here indicates a Middle Triassic (Anisian) age (Lucas and Morales, 1985). Upper Triassic conglomerates and sandstones of the Santa Rosa Formation disconformably overlie the Moenkopi Formation in north-central New Mexico. No Upper Permian or Lower Triassic strata are present in north-central New Mexico, so the Permian-Triassic disconformity is a profound hiatus (Fig. 2.25) of at least 15 Ma on the Harland et al. (1990) timescale.

Artesia and Moenkopi red beds in north-central New Mexico can be easily distinguished from each other by lithology, texture, bedforms, color and fossil content:

FIGURE 2.24. Soil horizon over sedimentary breccia at Stop 4.

1. Artesia strata are sandstones, siltstones and gypsum. Sandstones and siltstones are quartzarenites and usually gypsiferous. Moenkopi strata are sandstones, conglomerates, mudstones and siltstones. No gypsum is present in the Moenkopi Formation, and sandstones are micaceous litharenites or lithic graywackes.
2. Artesia sandstones are well sorted, subrounded to subangular and very fine to fine grained. Moenkopi sandstones are moderately to poorly sorted, subangular to angular and fine to coarse grained.
3. Artesia sandstones are laminated, ripple laminated and massive (bioturbated); crossbedding is rare, and beds are laterally persistent. Moenkopi sandstones and conglomerates are mostly trough crossbedded and lenticular.
4. Artesia strata are moderate reddish brown ("orange" or "brick-red"), whereas Moenkopi strata are grayish red.



Lith.	Previous Nomenclature	Current Nomenclature	Age
▒	Santa Rosa Sandstone	Santa Rosa Formation	Late Triassic
▨	▨	▨	▨
░	Bernal Formation	Moenkopi Formation	Middle Triassic
▨		▨	▨
░		Artesia Formation	Middle Permian
░	Glorieta Sandstone	Glorieta Sandstone	

FIGURE 2.25. Nomenclature and age of strata that encompass the Permian-Triassic disconformity in north-central New Mexico.

5. Artesia strata are unfossiliferous except for bioturbation, whereas Moenkopi strata have vertebrate bones and coprolites, footprints, charophytes and ostracods.

Artesia and Moenkopi strata thus can be easily separated on the outcrop. Despite this, previous mapping in north-central New Mexico (e.g., Read et al., 1944; Wood and Northrop, 1946; Johnson, 1970, 1973, 1974; Budding, 1972) mapped both formations together as Bernal Formation. The Moenkopi Formation disconformably overlies the Artesia Formation throughout north-central New mexico, and mappers should distinguish the two units in the future.

Return to I-25 and continue northward. 0.3

86.1 At I-25 on-ramp. **1.4**

87.5 Flat-lying quartzarenites of Permian Glorieta Sandstone in roadcuts, cut by small, west-dipping normal faults. **0.9**

88.4 The Glorieta Sandstone caps mesas to the west of the highway at 10-11:00, having slopes of Yeso Formation. Ahead, the Pennsylvanian and Permian strata pass through several gentle folds before plunging into the Raton Basin. **0.3**

88.7 Roadcuts display deformed gypsiferous strata of the Yeso Formation. **1.4**

90.1 Gently west-dipping Yeso Formation red beds in roadcuts. **0.5**

90.6 View at 10:00 of the high country, including Hermit Peak, a massive bluff of Proterozoic granite. **0.5**

91.1 Exit 335 to Tecolote, continue on I-25. Crossing Tecolote Creek. Tecolote (Spanish for owl) was settled in 1824 by Salvador Montoya. Between 1850 and 1860 it served the U.S. Army as a forage and corn post during the Indian campaign. The AT&SF railroad stop was named in 1883 (Pearce, 1965). **2.7**

93.8 Milepost 338. Tecolote Peak at 9:00 is composed of Glorieta Sandstone over Yeso Formation. **1.0**

94.8 Roadcut on left reveals steeply dipping quartzarenites of Glorieta Sandstone. We now will drive through a Laramide structural feature that Kelley (1972) termed the Anton Chico monocline, which represents the southwestern structural edge of the Las Vegas sub-basin of the Raton Basin. In so doing, we will ascend through generally east-dipping Permian (Glorieta-Artesia), Triassic (Moenkopi-Chinle Group), Jurassic (Entrada-Todilto-Summerville-Morrison) and Lower Cretaceous (Dakota Group) strata to emerge in essentially flat-lying Upper Cretaceous (Graneros-Greenhorn) strata in the vicinity of Las Vegas. **0.2**

95.0 Sandstones cropping out to left belong to the Santa Rosa Formation of the Upper Triassic Chinle Group. The covered strike valley just behind us is underlain by Artesia and Moenkopi red beds. **0.6**

95.6 **Take Exit 339** to US-84, Romeroville and Santa Rosa. **0.2**

95.8 **Turn right** at end of off-ramp, and then **turn left** onto frontage road north along I-25. Official Scenic Historic Marker reads:

> *Interstate 25 cuts through dipping strata that form hogback ridges between the Great Plains and the southern end of the Rocky Mountains. The Santa Fe Trail from here to Santa Fe, followed a natural valley eroded in less resistant strata between the mountains to the north and Glorieta Mesa in the south. Elevation 6,200 feet.*

0.2

96.0 Sandstones in roadcuts are Trujillo Formation, a medial sandstone complex of the Upper Triassic Chinle Group. **0.6**

96.6 **STOP 5. Romeroville Gap. Pull off to the right** to examine Jurassic and Lower Cretaceous strata. The Jurassic rocks are discussed in the accompanying minipaper. The Lower Cretaceous strata belong to the Dakota Group as redefined in northeastern New Mexico by Kues and Lucas (1987), Lucas and Kisucky (1988) and Lucas (1990). These rocks encompass three formations (ascending order): Mesa Rica, Pajarito and Romeroville. The Mesa Rica and Pajarito are of late Albian age; the Romeroville may be earliest Cenomanian, but its exact age is uncertain.

In sequence stratigraphic terms, two sequences are present here: Mesa Rica-Pajarito and Romeroville-Graneros-Greenhorn. Mesa Rica and Romeroville quartzarenites represent transgressive systems tracts with disconformable bases. Late transgressive and highstand systems tracts of each sequence are recorded by the Pajarito and by the Graneros-Greenhorn, respectively.

On topographic maps, this hogback is called The Creston. On Johnson's (1974) geologic map of the Apache Springs 15-min quadrangle, this structure is named the Romeroville monocline. US-84 follows the monocline until the structure dies out 12 to 15 mi south of here. No fold-parallel faults have been mapped to the south. To the north however, the maps of Elmer Baltz (1972) show an important component of reverse faulting parallel to the hogback. The largest of these, the Montezuma fault, is a moderately dipping fault that has placed Pennsylvanian over Permian.

THE JURASSIC SECTION AT ROMEROVILLE, SAN MIGUEL COUNTY, NEW MEXICO

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Approximately 545 ft of Jurassic strata are well exposed at Romeroville Gap by the highway cut of I–25 (Figs. 2.26, 2.27). Mankin (1958, 1972), Lucas et al. (1985a, b) and Lucas and Kietzke (1986) are among those who have described this section in detail. The Romeroville Jurassic section is the best exposed Jurassic section along the New Mexico portion of the Sangre de Cristo front range and provides essential data for correlating Jurassic strata of the Colorado Plateau with Jurassic strata of the Southern High Plains.

The base of the section begins with 6.6 ft of exposure of the upper part of the Middle Jurassic (Callovian) Entrada Sandstone. These strata are yellowish gray, fine-grained, well sorted quartzarenites of eolian origin. They lithologically resemble and occupy the same stratigraphic position as the strata long and widely termed Entrada on the Colorado Plateau. The local name Ocate Sandstone (Bachman, 1953) and the High Plains name Exeter Sandstone (Lee, 1902) for these strata are superfluous, and the name Entrada Sandstone is best applied to them throughout their outcrop belt from the San Rafael Swell of east-central Utah to the High Plains of western Oklahoma (Lucas et al., 1985a).

The Middle Jurassic (Callovian) Todilto Formation, a limestone interval about 16 ft thick, overlies the Entrada Sandstone at Romeroville Gap. It consists of a lower, laminar limestone and an upper, "crinkly" limestone (Lucas and Kietzke, 1986). Both units are organic-rich and cyclically bedded. The Todilto Formation extends from the Colorado Plateau of northwestern New Mexico/southwestern Colorado to Romeroville and both up the front range as far north as Sapello and out onto the Southern

High Plains to Luciano Mesa east of Santa Rosa on the Guadalupe-Quay County border (Lucas et al., 1985a; Lucas and Kietzke, 1986). The Todilto Formation is a thin, very distinctive lithosome readily correlated over its vast outcrop belt.

Above the Todilto at Romeroville Gap are about 50 ft of green and red laminar shale and siltstone with some nodular chalcedony and two devitrified, kaolinitic ash beds. Dinosaur footprints are present in these strata (Lucas et al., 1990). Mankin (1958, 1972) assigned these strata to the Morrison Formation, but others (e.g., Lucas et al., 1985a, b) assigned them to the Bell Ranch Formation, a local northeastern New Mexico name (Griggs and Read, 1959) for strata equivalent to the Summerville Formation on the Colorado Plateau. We now assign these strata at Romeroville Gap to the Summerville Formation because the name Bell Ranch is superfluous and the base of the Morrison Formation is properly correlated as the base of the sandstone complex above the Summerville shales/siltstones (Anderson and Lucas, 1992, 1994; Steiner et al., 1994). Summerville strata extend up the Front Range into Colorado where these strata have been termed Ralston Creek Formation and eastward onto the Southern High Plains as far east as western Oklahoma (Anderson and Lucas, 1992, 1994).

The Morrison Formation at Romeroville Gap consists of a lower sandstone-dominated unit about 165 ft thick and an upper mudstone-domi-

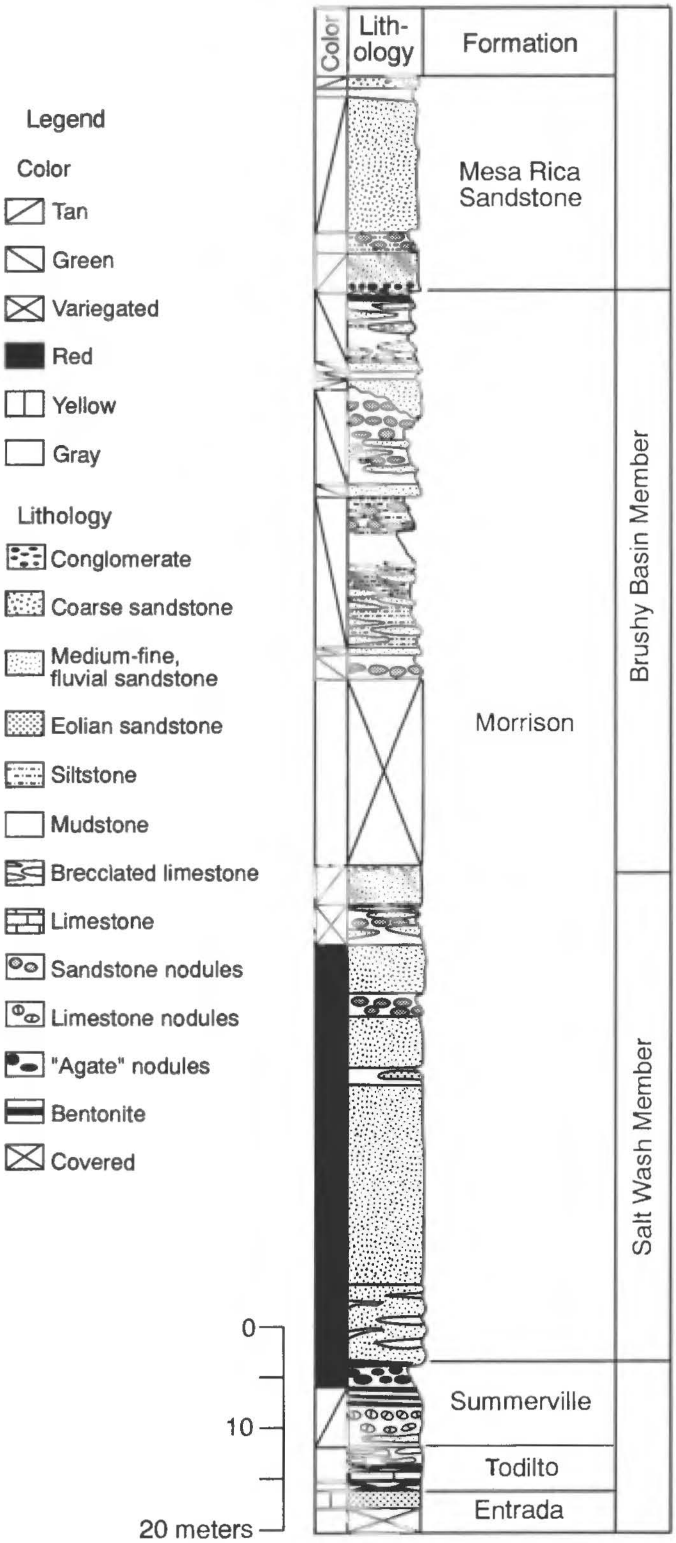

FIGURE 2.26. Measured Jurassic section at Romeroville Gap, Stop 5.

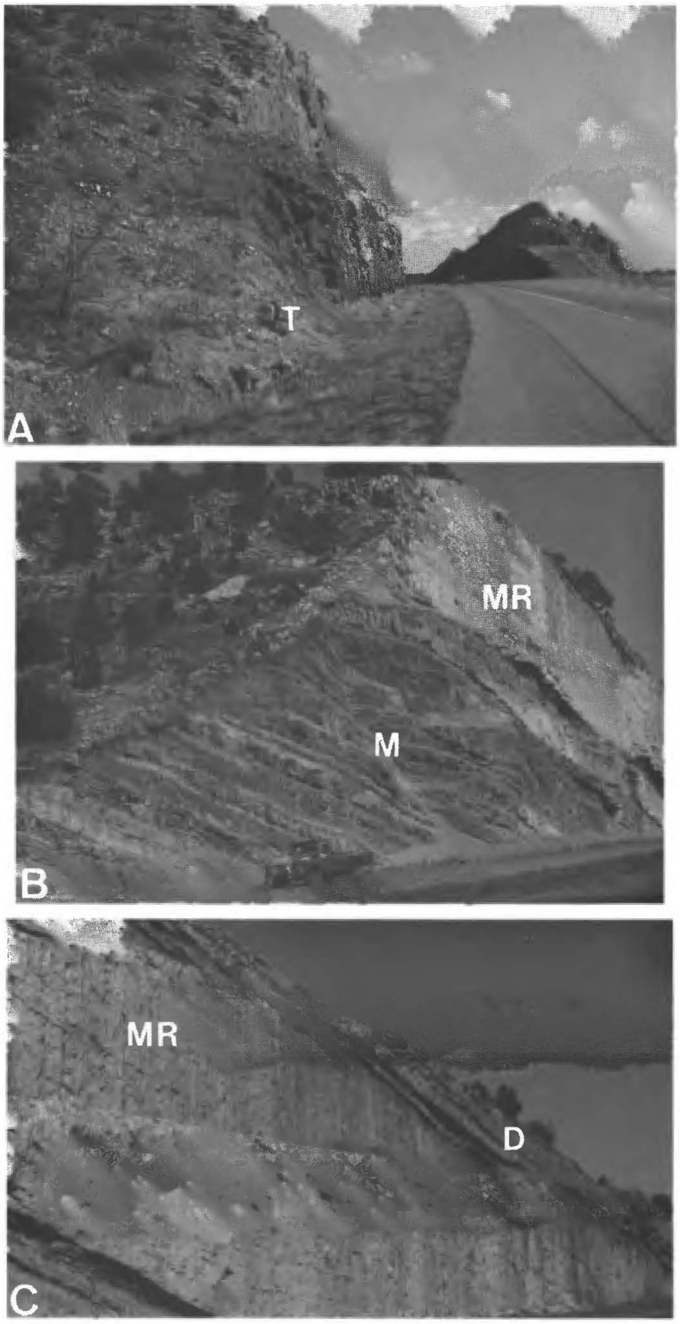

FIGURE 2.27. Jurassic and Cretaceous strata at Romeroville Gap, Stop 5. A, view NE, Todilto Formation (T). B, view NW, Morrison Formation (M) overlain by Mesa Rica Sandstone (MR). C, view NW, Mesa Rica Sandstone (MR) overlain by Dakota Sandstone (D). From 1985 NMGS Guidebook, p. 51.

nated unit about 310 ft thick. The lower sandstones are mostly grayish, yellow and green, laminar and quartzose. Their magnetic polarity stratigraphy (Steiner et al., 1994) confirms a correlation also supported by stratigraphic position and lithology: the lower sandstone-dominated interval of the Morrison Formation at Romeroville Gap is equivalent to the Salt Wash Member of the Morrison on the Colorado Plateau. We therefore assign these strata at Romeroville to the Salt Wash Member.

Overlying mudstones of the Morrison Formation at Romeroville Gap are brown, green and gray, bentonitic and contain numerous thin sandstones and silcretes. We assign these strata to the Brushy Basin Member because of their stratigraphic position and lithology. This assignment is supported by magnetostratigraphy at Trujillo Hill, about 30 mi to the east of Romeroville Gap, which indicates the upper mudstone-dominated interval of the Morrison in this region correlates to the Brushy Basin Member on the Colorado Plateau. Stratigraphic sequence, lithology and magnetostratigraphy thus enable a secure correlation of Morrison strata between Romeroville Gap and the Colorado Plateau. At Romeroville, the Lower Cretaceous (upper Albian) Mesa Rica Sandstone of the Dakota Group disconformably overlies the Morrison Formation.

After stop **continue north** on frontage road. **0.1**

96.7 Base of Mesa Rica Sandstone exposed in roadcut on far side of I-25; overlying carbonaceous strata are Pajarito Formation. **0.5**

97.2 On left are dark gray shales of nearly flat-lying Upper Cretaceous Graneros Shale. Light-colored limestones of the Greenhorn Formation (Bridge Creek Member) overlie the Graneros here and are also visible. We are now in the Laramide Las Vegas sub-basin of the Raton Basin. **1.1**

98.3 Overpass on I-25 on left; continue north on frontage road. To right, in canyon cut by the Gallinas River, is flat-lying Dakota Sandstone. **0.5**

98.8 Dakota Sandstone exposed on right. **0.2**

99.0 **Turn left** and drive over I-25, continue west on NM-283 towards Mineral Hill and San Geronimo. **0.4**

99.4 At 3:00, the round hill is capped by Greenhorn Limestone. The main Santa Fe Trail from Las Vegas joins our route just ahead. **0.3**

THE SANTA FE TRAIL

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The Santa Fe Trail was founded in September, 1821, when William Becknell and his mules left Old Franklin, Missouri for points west. Two and a half months later, after nearly 1000 miles of travel, Becknell arrived in Santa Fe, where, after easily selling his wares, he hastened back to Missouri for another load. That same year, Mexico had won independence from Spain, and eastern traders were now welcomed into Santa Fe. On Becknell's second trip the following spring, his packed wagonloads turned a 2000% profit in Santa Fe, and a new era of commerce, emigration, racial strife, and American expansion and prosperity began. For New Mexicans, the freight trail provided relatively inexpensive goods from the eastern U.S., as well is an influx of people with different skills and customs. For easterners, it provided the opportunity to search westward for a better life. For the Plains Indians, it forebode a cruel and devastating future. Immigration became more appealing when, in August of 1846, General Stephen Watts Kearny and the Army of the West marched into Santa Fe to claim New Mexico for the United States. In the following years, as commerce grew, the U.S. government built several forts to protect the wagon trains.

The Santa Fe Trail crosses the prairies, deserts, and mountains of five states--Missouri, Kansas, Oklahoma, Colorado and New Mexico. In Fort Dodge, Kansas, the trail split into the Mountain Branch, which crossed the Arkansas River near Bent's Fort and entered New Mexico over Raton Pass, and the Cimarron Cutoff, which travelled southwest through the Oklahoma panhandle. The two branches rejoined at Wagon Mound, near Fort Union, a major garrison built in 1851. Travelers on the Mountain Branch enjoyed the advantages of circumventing the heat of the waterless Cimarron Desert and avoiding many of the hostile, nomadic Indians. But the Mountain Branch was longer and, most importantly, crossed Raton Pass, which, prior to construction of a toll road in 1866, was a dangerous and torturous climb, and commonly snow-covered.

In 1866, traffic along the trail peaked at about 5000 wagons; each merchant risking accidents, disease, drought, storms, floods, robbery and hostile attacks. But as the railroad lines expanded westward across Kansas and Colorado, trail traffic dwindled. In 1878, the Santa Fe Railroad tracks crossed formidable Raton Pass into New Mexico. In 1880, the first locomotive steamed into Lamy outside of Santa Fe, and the Santa Fe Trail began a decline into history. The story of the trail would have ended there if not for the hard work of a small group of trail devotees who lobbied to add the Santa Fe Trail to National Historic Trail status. They succeeded, and in 1987, after the trail had been abandoned for over 100 years, President Reagan signed into law an amendment assuring preservation of the trail by the National Park Service.

99.7 Sawmill on left. Ahead is the Creston anticline, the same NW-trending hogback that we saw at Stop 5 at Romeroville. We will be passing down-section from Cretaceous shales to the Pennsylvanian-Permian Sangre de Cristo Formation, and eventually into the Proterozoic basement several miles ahead. The Creston anticline is coincident here with the Pedernal uplift, an Ancestral Rocky Mountain (Penn-Permian) structural high that extends southward into southernmost New Mexico. The Pedernal uplift may have controlled the later, Laramide development of the Creston anticline. **0.2**

99.9 The water gap ahead, Kearny's Gap, was the main route of the Santa Fe Trail, and was used by General Kearny and his army in August, 1846. Prior to Kearny's incursion, the gap was known as Puerto del Norte. **0.1**

100.0 Milepost 1. Outcrops of E-dipping sandstone. **0.6**

100.6 Notice the old iron bridge on the left. Just past the bridge, an old road climbs a low ridge upon which was built a torreon (small, round Spanish fort) for defending the pass. The stone remains of the Kearny Gap stage station lie just southeast of the road. From here, the Santa Fe Trail divided into three routes towards Santa Fe (north, middle, south). Wagon ruts from the middle and south branches are still visible. The southern route was probably the main route of the Trail. See Marc Simmons' (1986) excellent book *Following the Santa Fe Trail* for more details on Trail landmarks and history. **0.4**

101.0 Milepost 2. **0.1**

101.1 Good roadcut exposures of Triassic strata of Chinle Group for next 0.5 mi. **0.9**

102.0 We now enter a second hogback with Santa Rosa Formation sandstone dipping moderately westward. **0.3**

102.3 On left, along Agua Zarca creek, are ancient river terraces with a strongly incised modern channel. **0.7**

103.0 Milepost 4.0. Madera Group limestone exposed in roadcuts. **0.2**

103.2 Crossing from Paleozoic sedimentary strata to metamorphosed Proterozoic rocks. Ridges to the north are mantled by a high, old terrace deposit that contains well-rounded Proterozoic and Paleozoic clasts. No fault is seen along the creek, but exposures are poor and the rocks are highly fractured. Quite likely, the two alluvial-covered drainages north and south hide a high-angle fault. Small magnitude,

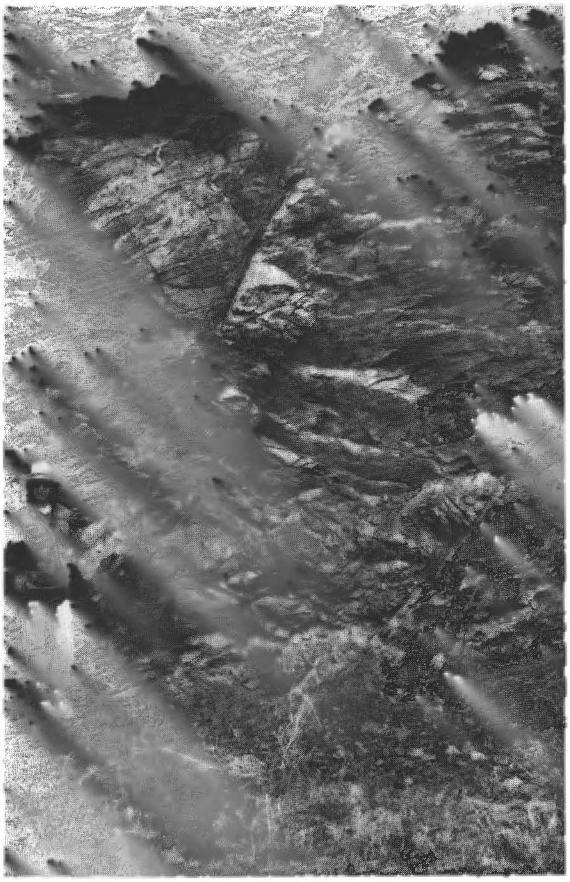

FIGURE 2.28. Roadcut at mile 103.2 consists of folded Proterozoic quartzofeldspathic gneiss that is highly fractured and cut by steeply W-dipping reverse faults.

FIGURE 2.29. Close view of drag folded foliation indicating reverse movement on this Laramide (?) W-dipping fault in Proterozoic gneiss.

W-dipping reverse faults in the roadcuts have the appropriate slip to bring Proterozoic up against Paleozoic here (Figs. 2.28, 2.29).

South of the creek, excellent exposures of basement reveal well-layered mafic schist and amphibolite with a shallowly dipping foliation and extension lineation. Locally are interlayered quartzofeldspathic, muscovite, sillimanite(?) gneisses. Granitic pegmatites are typically deformed within the foliation. The foliation is folded disharmonically by upright folds. **0.1**

103.3 Proterozoic schist and gneiss are crosscut by granitic pegmatites in these roadcuts. Both country rocks and pegmatites are deformed. Folds are upright and north-trending. Small W-dipping (60°) faults cut the Proterozoic rock. Some late, thin, undeformed, steeply W-dipping pegmatite veins crosscut the folds. **0.2**

103.5 Amphibolites exposed on right are cut by pegmatite veins which contain large feldspars. The blue color and fine lamellae indicate that the feldspars are Ca-rich (labradorite). Just ahead we cross back from basement to sedimentary rocks. **0.2**

103.7 Flat-lying limestone exposed in roadcuts to right. Notice the superb exposure of the upper level of a carbonate solution collapse feature (Fig. 2.30). Presumably, dissolution below road level has caused collapse of the road level limestone beds. Above the limestone is a small pocket of layered alluvium which accumulated in the surface karst. If you look to the right, on the east end of the outcrop, the limestone layers terminate against similar, poorly sorted alluvial layers. This might be the western edge of a similar, but larger, collapse feature. **0.3**

104.0 Milepost 5.0. **0.6**

104.6 More flat-lying Madera Group limestone in roadcuts. **1.3**

105.9 **STOP 6. Mineral Hill Overlook - Rowe-Mora Basin. Pull off on right shoulder.** From this location we have an excellent overview of the eastern flank of the southern Sangre de Cristo Mountains. The conspicuous rounded monolith on the northwest skyline is Hermit's Peak. Elk Mountain is on the far skyline to the left of Hermit's Peak. The high skyline ridge southward from Hermit's Peak, called Barillas Ridge, is the drainage divide between the Pecos River to the west and the Gallinas river to the east. The low relief plain in front of us is Madera Formation, and the slightly higher hills in the middle northwest foreground are Sangre de Cristo Formation. An impressive set of Laramide structures parallel the western mountain front, separating the sedimentary rocks of the lowlands from Proterozoic and overlying sedimentary rocks in the uplands.

Hermit's Peak is a massif of Proterozoic granites and gneisses with screens of amphibolite. The Hermit's Peak thrust fault (Baltz and O'Neill, 1986) is located at its base. Capping the Proterozoic rocks is a thin layer of Mississippian and Pennsylvanian carbonates. A cave near the top of Hermit's Peak was one of several inhabited by the mystic Geovanni Maria Augustini, reportedly the son of an Italian nobleman. In 1863 he walked the Santa Fe Trail from "Hermit's Cave" in Council Grove, Kansas to Las Vegas,

FIGURE 2.30. Roadcut at mile 103.7 in Madera Formation limestone displays the upper level of a paleosinkhole. Dissolution below road level has caused collapse of the road level limestone beds. Above the limestone is a small pocket of darker-colored, horizontally bedded alluvium that accumulated in the surface karst.

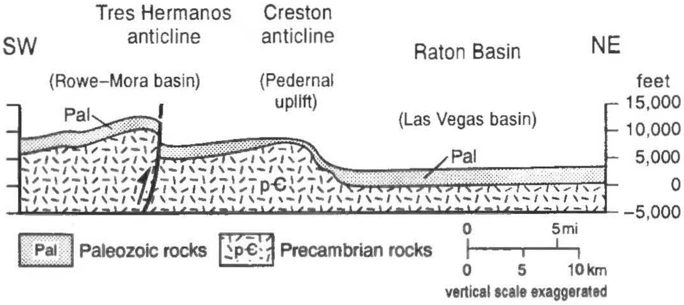

FIGURE 2.31. Generalized southwest-northeast cross section at the latitude of Mineral Hill showing major structural features. Modified from Baltz (1956).

where he supposedly performed miracles. He was later killed in southern New Mexico.

This part of the range is characterized by megascopic asymmetrical folds and imbricate thrust faults that increase in intensity from south to north (Fig. 2.31). The area contains two large, asymmetrical, SE-plunging anticlines, the Tres Hermanos anticline to our west, and the Creston anticline to our east (we have crossed this structure twice, once at Stop 5 near Romeroville and again at mile 101 on this road). Both folds have steeply dipping northeast limbs and gently dipping southwest limbs. The axis of the Tres Hermanos anticline coincides with the crest of the mountain divide to the west. The Chapelle syncline lies just to the east of the divide. High-angle, west-side-up faults locally parallel northeast fold limbs, especially to the north of here. These faults contain as much as 5000 ft of throw. At this latitude, about 3 mi west, approximately 3000 ft of throw on the Blue Canyon fault has placed Proterozoic rocks over the Pennsylvanian Sangre de Cristo Formation. As we trace the Tres Hermanos anticline northward, it terminates along a system of NE-striking tear faults which have contributed to the uplift of several large basement-cored blocks, including the Hermit's Peak block.

End of Second-day Road Log. Return to I-25 for return trip to Santa Fe.

This view of the original Hot Springs Hotel (rt, ctr.) on Gallinas Creek six miles northwest of Las Vegas, NM, is notable in that the famed "Great Montezuma" hotel should also be visible. And it is, more or less (mostly less): it was destroyed by fire on 17 January 1884 shortly before the photo was taken. Its remains can be seen in the rubble and ashes just above and to the right of the passenger coaches. The ornate railroad depot (left, ctr) miraculously survived the fire, which must have been intensely hot—note the badly charred pine trees on the first terrace to the right. The two-story structure is the stone bathhouse; livery stables to the right of the Hot Springs Hotel. The new Montezuma would be built on the hill to the far right (out of the photo) only to be consumed by flames within four months of opening. The Montezuma No. 3 (locally known as the "Phoenix" for obvious reasons) is built upon the foundation of No. 2 and remains today as an outstanding example of the great resort hotels of the previous century. NMBM&MR photo collection, #1319, courtesy Kansas State Historical Society, Topeka.