Second-day trip 1 road log: From Albuquerque to Tijeras, Cedar Crest and Sandia Crest

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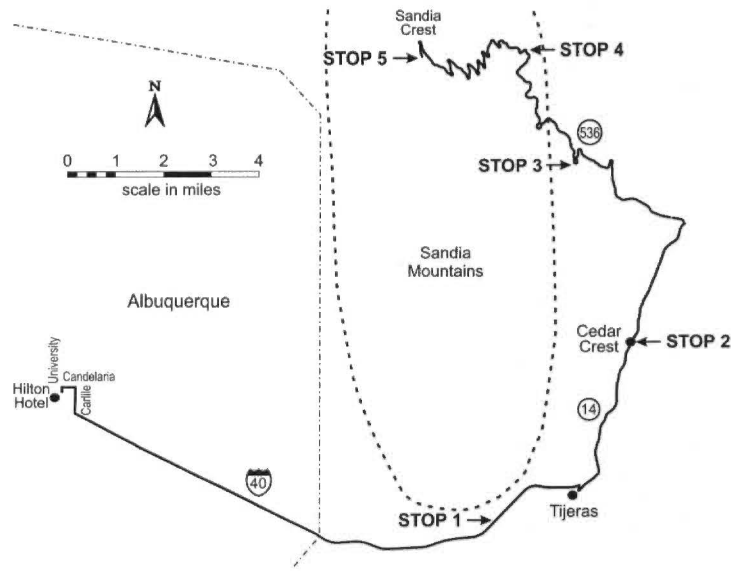
SECOND-DAY TRIP 1 ROAD LOG, FROM ALBUQUERQUE TO TIJERAS, CEDAR CREST AND SANDIA CREST

SPENCER G. LUCAS, ADAM READ, KARL E. KARLSTROM, JOHN W. ESTEP, BARRY S. KUES, ORIN J. ANDERSON, GARY A. SMITH, and FRANK J. PAZZAGLIA

FRIDAY, SEPTEMBER 24, 1999



Assembly point: South end of parking lot of Hilton Hotel, Menaul and University, Albuquerque.
Departure time: 7:30 a.m.
Distance: 35.4 mi.
Stops: 5

SUMMARY

Today's route ascends Sandia Crest, some 5000 ft above the City of Albuquerque, to take in what has to be the most extensive geologic vista in New Mexico. To reach it, we leave the city on old US-66, heading east through Tijeras Canyon. Stop 1, in the Canyon, examines the southern contact (and inferred base) of the Sandia Granite, where we discuss the tectonic and thermal setting of its emplacement. Stop 2, on the eastern flank of the Sandia uplift, is in the Tijeras syncline at Cedar Crest. Here, we compare the exposed Jurassic strata to the Jurassic section seen in the Hagan basin on the first day's tour. This leads us into broader issues of changes in tectonic style, sedimentation and climate in the Southwest during the transition from Middle to Late Jurassic.

At Stop 3, we examine the profound nonconformity (the so-called "great unconformity") between Proterozoic granites and Pennsylvanian sedimentary rocks, a hiatus of more than one billion years. Models of glacioeustatically driven Pennsylvanian sedimentation and local Laramide faults also are prominent issues at this stop. Stop 4 presents us with a rare opportunity to examine quartzite of probable Mississsippian age exposed in the Sandia uplift and pursue broader issues of what exactly happened in north-central New Mexico during the "great unconformity" hiatus.

The last stop, at Sandia Crest, gives us an areal view of about 10% of New Mexico. Here, we focus on the age of the Sandia uplift, a controversial and unresolved problem. Discussion will also range across the geologic features in our field of view, from the Colorado Plateau edge and Rio Grande rift to the west and south, to the southern High Plains and Sangre de Cristo Mountains to the east and north.

Mileage

0.0 Start at Hilton Hotel. **Turn left** onto University Blvd., heading north. **Move to right lane. 0.1**

0.1 **Turn right** at Menaul Ave., heading east. **0.7**

0.8 Cross North Diversion Channel. **Move to right lane. 0.4**

1.2 **Turn right** onto Carlisle Blvd. **Immediately get into left lane as preparation to enter I-40 eastbound. 0.3**

1.5 **Turn left** at I-40 east entrance ramp. Note Sandia Crest at 10:00, South Sandia Peak at 11:00 and Tijeras Canyon at 1:00 in distance. The Sandia mountain front is an imposing geomorphic escarpment that reflects a complicated history of rock-uplift and erosion. Rincon Ridge has an apparent concordance with a prominent bench in the Sandia mountain front. Above the bench rises a cliff face embayed by numerous drainages with narrow, rib-like interfluves. Smooth triangular facets extend below the bench, dissected only by major streams such as La Cueva Arroyo. These geomorphic features might best be explained by at least two phases of rock uplift, one before creation of the bench, and one following it, with the bench representing a period of tectonic quiescence and mountain front pedimentation between the two. The timing of these periods of rock uplift is poorly known, and some of the discussion surrounding this trip will explore the arguments for and against the older of these uplift periods having occurred during Laramide (Late Cretaceous–Paleogene) time. In any case, there are several additional unresolved issues regarding the genesis of the Sandia mountain front, not the least of which is the fact that the mountain front does not closely coincide with the known locations of large, rift-bounding faults. **4.5**

6.0 Pass under Eubank Blvd. It is at about this location that the Santa Fe basin fill begins to thin significantly as you cross large, down-to-the-west faults. **1.0**

7.0 Pass under Juan Tabo Blvd. bridge. Get into right lane as preparation to exit I-40. East of Juan Tabo there is little more than a thin (~100 ft) Quaternary alluvial fan cover over pedimented granite. **1.0**

8.0 **Leave I-40 at Exit 167** (Tramway Blvd. exit), bearing right on exit ramp. **0.2**

8.2 **Turn right** onto Tramway Blvd. **Immediately get into one of leftmost two lanes. 0.1**

8.3 **Turn left** on Central Ave., heading east; **get into right lane. 0.1**

8.4 Go straight at the light at Four Hills Road, heading east on NM-333 (old US-66). **0.4**

8.8 Note on left Precambrian Sandia Granite outcrops in road cut. Similar outcrops occur in next few road cuts. The Sandia Granite in this area is typically quartz monzonite containing large (0.4–1.5 in.) microcline megacrysts. U-Pb zircon and titanite dates indicate a crystallization age of about 1.44 Ga (Steiger and Wasserburg, 1966; recalculated by Kirby et al., 1995). Ar-Ar dates on hornblende and muscovite from the pluton are 1.42 Ga (Kirby et al., 1995), indicating rapid cooling from 930 to 570ºF at this time. Along its southeastern margin, the Sandia Granite intrudes country rock consisting of quartzite and a granitic orthogneiss (the Cibola granite of Kirby et al., 1995; see discussion at Stop 1, below). **0.3**

9.1 Leaving Albuquerque city limits; enter Tijeras Canyon. Note spheroidal weathering of Sandia Granite to left in roadcut.The distinct weathering of the Sandia granite is called corestone weathering. This predominantly chemical weathering process commonly occurs in compositionally homogeneous, jointed granitic rock types under a wide range of climates. Corestone formation is strongly favored by hydrolysis in the phreatic zone, which alters the biotite and feldspars adjacent to a joint, producing grus. Subsequent exposure of the weathering profile washes the grus from the joints, exposing the distinct, rounded, corestone-littered hillslopes. There is a paucity of regolith on granitic hillslopes in the Sandias today, reflecting their decidedly weathering-limited character. But, the ubiquitous corestones attest to an ancient, perhaps pre-Quaternary weathering regime when there was much regolith production on transport-limited hillslopes. The thick accumulations of grus and gravel atop the piedmont west of the Sandia mountain front and in the alluvial fans and axial fills of Tijeras Arroyo we will pass over in the next few miles are strong stratigraphic evidence for this pronounced transition in hillslope processes. A simple, but unproven, explanation of the change in hillslope process is to attribute it to the major changes in climate associated with the Quaternary. **0.5**

9.6 On left in roadcut note the prominent dike cutting the Sandia Granite; note pegmatite east of I-40. **0.3**

9.9 Cross over I-40 on bridge, note pegmatite to left here; also note prominent jointing in Sandia Granite. Note thick alluvial fan, composed almost entirely of grus, that was used as road metal in the construction of I-40. **0.4**

10.3 Enter greater Carnuel; also called Carnue, this settlement has existed since at least the early 1800s (Pearce, 1965). **0.8**

11.1 Note spheroidal weathering of granite outcrops in large roadcut. To the north (left) are the Sandia Mountains; to the south (right) are the Manzanita Mountains.

The Pennsylvanian strata in the Sandia and Manzano Mountains disconformably overlie Precambrian units in most places (remnants of Mississippian rocks are also present locally) and reach a thickness of nearly 1860 ft. These strata represent deposition during Middle–Late Pennsylvanian (Atokan through Virgilian) time (about 311 to 290 Ma on the Gradstein and Ogg [1996] timescale). Regionally, the succession consists of a basal, relatively thin, predominantly clastic unit (Sandia Formation), overlain by the very thick Madera Group (Myers, 1973).

The lower part of the Pennsylvanian Madera Group in the Manzanita and Manzano Mountains is mainly composed of thick, massive, gray, marine limestone (Los Moyos Limestone), with an increasing proportion of gray, black, green, and red shale and mudstone and brown-to-red sandstone in the upper half (Wild Cow Formation), representing a wide variety of marine and nonmarine depositional environments (Myers, 1973). Upper Madera rocks display high variability in road cuts along I-40 to the east; near Tijeras they have been covered to prevent erosion. The lithologies, age, and relationships with the underlying Precambrian displayed by the Madera Group in Tijeras Canyon are typical of the Pennsylvanian over most of central and northern New Mexico, although different lithostratigraphic names are used elsewhere (Fig. 2.1.1).

The stratigraphic nomenclature applied to subdivisions of the Madera Group in the Manzanita and Manzano Mountains to the south by Myers (1973) has not been formally extended to the Sandia Mountains. Kelley and Northrop (1975) used an informal division of the Madera Formation into a lower limestone member and an upper arkosic limestone member that had been applied widely by earlier workers to many of the Pennsylvanian sequences in northern and central New Mexico. The units to which Myers (1973) applied the names Los Moyos Limestone ("lower limestone member") and Wild Cow Formation ("upper arkosic limestone member") to the south are doubtless present in the Sandias, although

age/	lith.	Kelley & Wood (1946)		Read &Wood (1947)		Myers (1973)	
Missourian-Virgilian		MADERA FORMATION	Atrasado Member	MADERA FORMATION	upper arkosic member	MADERA GROUP	Wild Cow Formation
Desmoinesian			Gray Mesa Member		lower limestone member		Los Moyos Limestone

FIGURE 2.1.1. Three sets of nomenclature have been proposed for most of the Middle-Upper Pennsylvanian strata (Madera Group or Formation) in north-central New Mexico.

the subdivisions of the Wild Cow Formation (Sol se Mete, Pine Shadow, and La Casas members) may be more difficult to identify away from the Manzanos because of lateral facies changes. Careful stratigraphic study and correlation of the Sandia Mountains Pennsylvanian section with that of the Manzanita and Manzano Mountains are needed to extend definitely Myers' names into the Sandias. Nevertheless, we provisionally use the formation names of Myers for Madera units in the Sandias in this guidebook, for example referring to the massive limestones on Sandia Crest as the Los Moyos Limestone.

We also note that the names established by Myers (1973) for the "lower limestone member" and "upper arkosic limestone member" (Los Moyos Limestone and Wild Cow Formation) in the Manzano Mountains were preceded by the names Gray Mesa and Atrasado members of the Madera Formation in the Lucero uplift area to the southwest (Kelley and Wood, 1946) (Fig. 2.1.1). Further work is needed in order to assess the similarities between the Los Moyos Limestone and Gray Mesa Limestone, and between the Atrasado and Wild Cow Formation, but we suspect that these may be the same units. If true, because of long priority, the names of Kelley and Wood (1946) should supplant those of Myers (1973) in the Manzano, Manzanita, and Sandia Mountains.

Deposition of these Pennsylvanian units occurred in subsiding, generally north–south-trending shallow elongate basins adjacent to intermittently rising uplifts (Fig. 2.1.2). In the Sandia-Manzano Mountains area, most nearshore, shallow-marine deposition occurred in relatively unstable, restricted belts between basin and uplift, resulting in some abrupt local facies changes, especially in the upper part of the Madera Group. Near the end of the Pennsylvanian, renewed uplift to the north increased

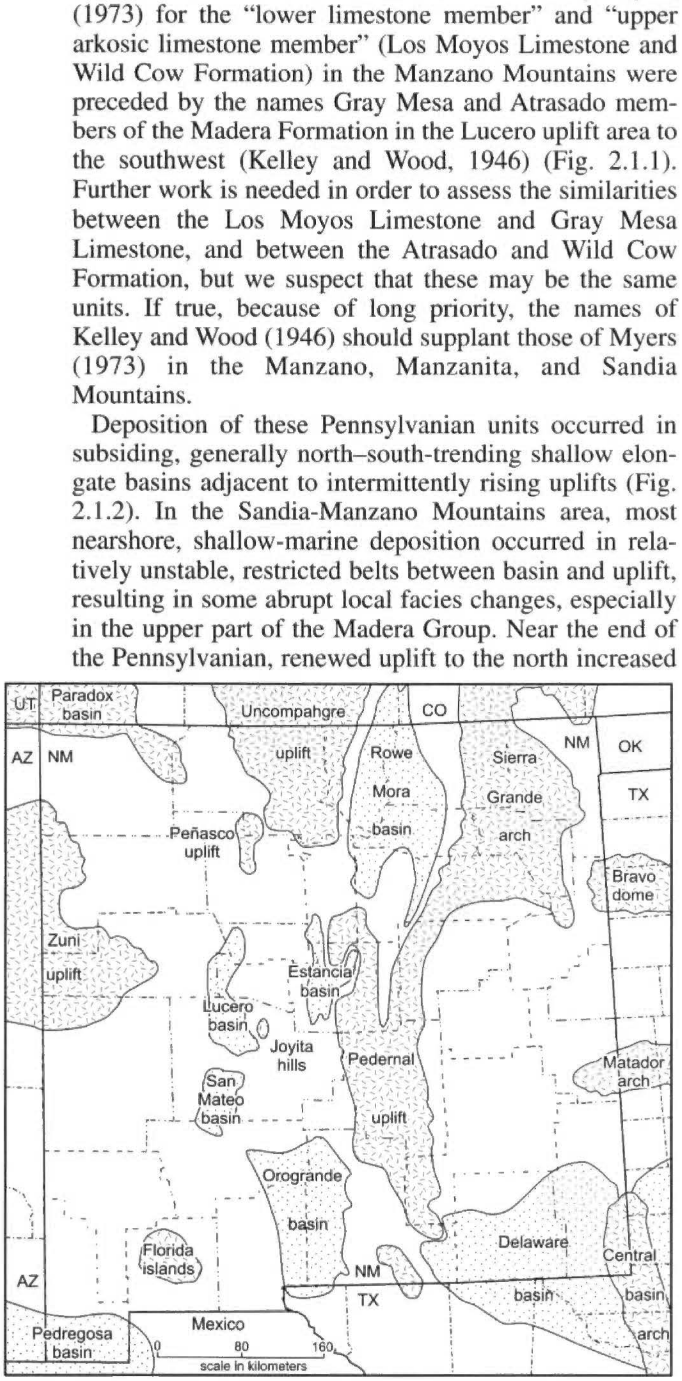


FIGURE 2.1.2. Paleotectonic map of Late Pennsylvanian New Mexico (after Kottlowski and Stewart, 1970).

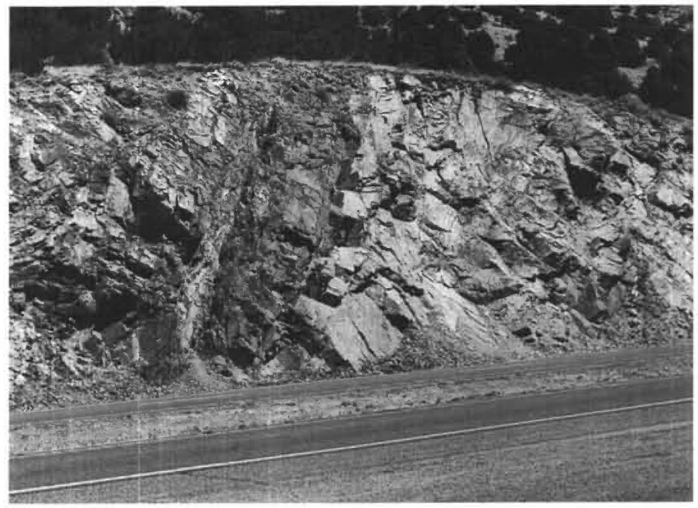


FIGURE 2.1.3. Outcrop of part of Seven Springs shear zone of granitic gneiss cut by dikes and aplites at Stop 1.

the volume of terrigenous sediments shed into the basins. Alternating red shales and sandstones and marine limestones characterize the uppermost part of the Madera Group, with the overlying Lower Permian Abo Formation documenting the final inundation of marine environments in this area by southward prograding alluvial plain sediments. **0.2**

11.3 Pass exposures of grus-dominated alluvial fan exposed in roadcut on left. **0.9**

12.2 **Pull off road to right** onto broad shoulder for **STOP 1.** This stop examines the southern contact (and inferred base) of the Sandia Granite (also see the following mini-paper). We traverse from the contact between weakly deformed Sandia Granite, structurally down through an extensional shear zone at the base of the pluton and into the Cibola Granite—which contains 1.65-Ga zircons (Dan Unruh, unpublished data) and is likely part of the aureole of the pluton. The main questions we address concern the tectonic and thermal setting for emplacement of the Sandia Granite. A color geologic map encompassing the area of this stop and much of Tijeras Canyon is in the separate color insert section of this guidebook.

The roadcut across from our parking area is a cross section of the base of the pluton and the upper part of the shear zone (Fig. 2.1.3). About 650 ft west of the eastern end of the outcrop is a small drainage that allows access to outcrops on the ridge above the roadcut. Just east of this drainage is a transitional contact between biotite-rich, moderately sheared granites interpreted to be part of the base of the Sandia Granite (on the west) to sheared leucocratic gneisses of the Cibola Granite below. This contact is also well exposed on the bouldery outcrops above the roadcut where megacrystic, variably sheared Sandia Granite overlies mylonites of the Seven Springs shear zone.

Walking east along the roadcut, the Seven Springs shear zone consists of granitic gneiss, cut by leucocratic dikes and aplites. Average foliation strikes NE and dips moderately (30–40°) NW; stretching lineation plunges to the northwest. K-feldspar phenocrysts are dynamically recrystallized into augen, many of which are symmetrical, but some of which record top-to-the-south/dextral oblique shearing. Melt-filled shear bands of several different orientations are observed; these accomodated rotation of blocks within the ductile shear zone. Aplite dikes are variably sheared and interpreted to be syntectonic with respect to shearing. At the eastern end of the roadcut, a pegmatite dike cross cuts the mylonitic foliation of the shear zone and indicates that the last liquids (probably from the Sandia pluton) crystallized after the shearing in this region. Later (Phanerozoic) brittle faults are present, some parallel to foliation and some high angle.

SOUTHERN MARGIN OF THE SANDIA PLUTON AND THE "CIBOLA PROBLEM"

Karl E. Karlstrom

Department of Earth and Planetary Sciences, University of New Mexico, Albuquerque, New Mexico 87131

The Sandia pluton is an important example of one of the ca. 1.4-Ga granitoids that perforate older (1.8–1.6 Ga) crust in the southwestern United States. This enigmatic event has been interpreted in terms of "anorogenic" magmatism (Windley, 1993) versus intracratonic transpressive tectonism (Nyman et al. 1997). This paper discusses new advances in our understanding of the age, tectonic significance, and thermal history near the southern margin of the Sandia pluton.

Age—The Sandia Granite has yielded a U-Pb zircon date of 1.44 Ga (Steiger and Wasserburg, 1966, recalculated by Kirby et al., 1995). Recent attempts to redate the pluton from outcrops 1 mi to the west yielded 1.446 ± 0.026 Ga, with evidence for xenocrystic (older) zircon grains and possibly cores (Dan Unruh, unpublished data). Ar-Ar hornblende dates from the pluton, and mica dates from the southern aureole, are both about 1.42 Ga (Kirby et al., 1995). The 1.44-Ga date may be closer to the crystallization age, although small amounts of inheritance may make this date a bit older than emplacement. The Ar–Ar dates represent rapid cooling through about 500ºC (hornblende) and 350ºC (muscovite) after emplacement.

Petrogenesis—This is an A-type granite, high in alkalies and silica, anhydrous, and with low f_{O2}. It contains numerous elliptical diorite enclaves that show evidence of mingling and mixing of mafic magma with the granite during emplacement (note the large K-feldpar megacrysts within enclaves and cuspate margins). These enclaves are interpreted to represent modified remnants of mantle-derived (basaltic) magma that underplated and caused partial melting of lower crust.

Thermal setting—Metamorphic geological studies in the aureole suggest a depth of emplacement of 7–10 km (2.5 kbars). This is based on the presence of andalusite and K-feldpsar in the northern aureole, plus quantitative thermobarometry. The country rock was likely already very hot, as the aureole temperatures of 650ºC and the zone of penetrative deformation (migmatization) are unusually wide for a pluton at these shallow depths. Sedimentary layers in the southern part of the aureole, within the Seven Springs shear zone, contain andalusite and sillimanite and record conditions of about 600–650ºC and 2–3 kbars (Andronicos et al., in press). There is a strong metamorphic field gradient in Tijeras Canyon, from upper amphibolite grade near the pluton to greenschist grade to the southeast. This gradient is believed to be a contact aureole around the Sandia pluton, and it seems to go across the Tijeras fault, indicating that Phanerozoic cumulative displacements on the Tijeras fault were not enough to remove the aureole.

Emplacement—The southern half of the Sandia Granite (~1 km) consists of shallow, north-dipping sheets of magacrystic granite, with numerous zones of mafic enclaves, subtle compositional layers, and magmatic layering defining the sheets. Kirby et al. (1995) interpreted the granite to have been emplaced as a 5–7-km-thick tabular sheet parallel to an active extensional/dextral shear zone at the base of the pluton. The extension may have made space for the granite. The roof of the pluton is exposed on the east of the Sandia Mountians (see Stops 3, 4) and also in the Monte Largo Hills (Timmons at al., 1995). Thus, the Cenozoic-age Sandia structural block seems to coincide with the areal distribution of the Sandia Granite.

Seven Springs Shear Zone—This shear zone is defined at its NW side by a 10–100-m-wide gradation between unsheared Sandia Granite and variably sheared Sandia Granite, with melt-filled shear zones and high-T, dynamically recrystallized feldspars attesting to continued movement during and after pluton crystallization. Shear zone movement was top-north, sometimes with a dextral component. Melt-filled shear bands, variably deformed aplites and pegmatites suggest that shearing took place during emplacement of the Sandia Granite (Kirby et al., 1995). Melt-filled shear bands have variable orientations and appear to have accommodated minor block rotations within the wider deforming zone.

Cibola "problem"—Structurally downward (southeast) from rocks that are clearly the deformed equivalent of the Sandia pluton is the 1–2-km-wide Seven Springs shear zone that deforms a more leucocratic (less biotite) granite and granitic gneiss called the Cibola Gneiss (Kelley and Northrop, 1975). This rock is also variably sheared (top-north) and contains lenticular screens and thin but laterally continuous layers of quartzite. Earlier workers considered the whole package to be a paragneiss (Lodewick, 1960) based on the presence of "rounded" zircons interlayered with quartzite. However, homogeneity, lack of bedding, petrology, and geochemistry of the Cibola suggest it is a granitoid, and Kirby et al. (1995) referred to it as Cibola Granite. In several locations, the quartzites can be seen to be intruded by the Cibola, and they are interpreted as metasedimentary screens intruded by granite.

New U-Pb dating of zircons from the Cibola Granite give dates of 1653 ± 21 Ga (Dan Unruh, unpublished data). However, zircons are rounded and cracked and may be inherited zircons. Nevertheless, the zircons do not show a range of ages, as do inherited zircons, for example, in the Priest pluton to the south. Thus, this age is provisionally taken as the age of emplacement of the Cibola Granite. This age is broadly similar to the date of 1645 ± 15 Ga from the Manzanita Granite to the south (Brown et al., this volume).

In contrast, Kirby et al. (1995) considered the Cibola Granite to be 1.4-Ga leucocratic granites that were drawn down into the active shear zone during crystallization of the Sandia pluton. This was based on the presence of mylonitic fabrics, melt-filled shear bands, and deformed dikes in the Cibola Granite with similar orientations and kinematics to sheared Sandia Granite, and the gradation between the sheared Sandia and Cibola granites within the Seven Springs shear zone (as seen in Stop 1). This may still be true, if the zircons were inherited from a single source. However, similar sheared granites are found in the Manzanita shear zone to the south (Brown et al., this volume) and in the Monte Largo Hills, and it seems most likely that the Cibola Granite is part of a 1.65-Ga country rock package to the Sandia pluton, and that it was deformed (and partially re-melted) at the base of the 1.4-Ga Sandia pluton.

After Stop, continue east on NM-333. **0.2**

12.4 "Deadman's Curve" and Tijeras fault—north-dipping Cibola Granite is faulted against metavolcanics of the Tijeras Greenstone. This fault likely had numerous movement times (see below), but it truncates Proterozoic foliation at high angle on both sides of the fault and hence is not simply a reactivated pre-1.4-Ga fault. However, the fault does generally follow the southern margin of the Sandia pluton and is parallel to the dominant, NE-trending foliation in the region. On right, note alluvial fan cobbles on gneiss. **0.1**

12.5 Pass under I-40 bridge. **0.3**

12.8 To right, note alluvial deposit of poorly sorted fan breccias and exposure of axial alluvial deposits of Tijeras Arroyo. The Quaternary stratigraphy of this portion of the Tijeras drainage was described in a minipaper in the 1982 NMGS guidebook (Smith et al., 1982). In summary, there are axial facies that interfinger with three alluvial fan deposits. Tijeras Arroyo has been through several cut-and-fill cycles during the Quaternary, but has accomplished little actual net incision into bedrock. As a result, the Quaternary deposits are complexly juxtaposed atop one another rather than preserved as a flight of inset terraces. **0.2**

13.0 Road continues through outcrop belt of Cibola Granite to left, above I-40. Tijeras Arroyo visible at 1:00. **0.1**

13.1 Green-colored Tertiary dike crops out above I-40. **0.3**

13.4 Quarry in alluvial fan gravel unit of Tijeras Arroyo at 3:00. **0.3**

13.7 To right, note large bluff of Pennsylvanian limestone above Seven Springs (defunct gas station). Several canyons on the northern side of the Interstate provide excellent cross sections across the Seven Springs shear zone (access under the Interstate is provided by concrete tunnels). The Pennsylanian Sandia Formation and Madera Group can be seen to crop out on either side of the Tijeras fault zone in Tijeras Canyon. Remarkably, the "great unconformity" and unit contacts are at about the same elevation across the fault and have a similar, shallow south-dip of about 20° (see the Tijeras map in the color insert in this guidebook). In spite of repeated movements on this fault zone (see Stop 2 and paper by Karlstrom et al., this volume), net dip slip was negligible. Net strike slip is unknown.

The Tijeras fault zone in this area forms a complex intersection of fault systems: (1) the north–south Flatirons-Cañoncito and San Antonio reverse faults and associated east-facing monoclines; (2) the northeast-striking Tijeras-Gutierrez fault system and associated northwest-facing monoclines; and (3) the north–south Otero Canyon fault system and associated east-facing monoclines that represent a northern branch of the Montosa fault system (see Karlstrom et al., this volume, fig. 4). To the southeast, this fault zone truncated the Seven Springs shear zone and its quartzite screens. While large (several-miles scale) strike-slip displacements on the Tijeras fault zone are possible, there is no direct evidence of the magnitude of such displacements in the Proterozoic or lower Paleozoic strata (Kirby et al., 1995).

The Pennsylvanian limestones in this area of Tijeras Canyon were initially believed to be Lower Carboniferous by Jules Marcou, the first geologist to view and describe the geology of Tijeras Canyon. Marcou, a member of the Whipple Expedition, explored this area in October 1853, camping on 8 October just north of the village of Tijeras, and ascending to the crest of the Sandias two days later. Blake (1856), using Marcou's field notes, and Marcou (1858), noted elements of the geology that can be readily identified today. Passing eastward through Tijeras Canyon, Marcou recorded "blackish-grey granite, with hornblende and large crystals of white feldspar" (Sandia Granite); "rose-colored granite, with but little feldspar" (Cibola Granite); "green serpentinoid trap"(Tijeras Greenstone); and the "Mountain Limestone" (Madera Group). Numerous fossils were collected from the Madera here, and from the crest of the Sandias (see Sutherland and Harlow, 1973; Kelley and Northrop, 1975, for extended discussion of Marcou's Pennsylvanian fossil collections, which were among the earliest New Mexico fossils to be described and illustrated in publications).

In and a little beyond Tijeras village, Marcou noted the "Trias, with all of its divisions," which included, near Antonito, white gypsum. Marcou thus lumped all of the exposed strata in this area, from the Permian Abo red beds through the gypsum of the Jurassic Todilto Formation (seen at Stop 2) into the Triassic. On a quick reconnaissance trip, with no fossils from these strata to help him out, we should not fault Marcou for not distinguishing rocks of three different geological periods (actually four; he missed the Cretaceous strata along this route, too, although he did recognize the Cretaceous in the Hagan basin and along the Rio Puerco, to the west).

Marcou (1858) produced a geologic map of the areas in New Mexico that the Whipple Expedition passed through (roughly through central New Mexico from Tucumcari on the east to Zuni Pueblo on the west). The part of his geologic map for the Albuquerque area and Tijeras Canyon (see Kelley and Northrop, 1975, for a reproduction) is a good first effort to portray the geology of the area of this field conference. **0.2**

13.9 The little hill at 12:30 immediately south of and adjacent to the highway is a colluvial/alluvial fan deposit unconformably overlying greenstone bedrock. The top of this deposit displays a well-developed, red calcic soil with a silty, eolian-derived A horizon. Sitting on top of this soil are car-sized boulders of granite, derived presumably from some hillslope to the north. Transportation of the boulders to their present location by some fluvial or debris flow process that also did not remove the underlying well-developed soil is highly improbable. It is more likely that the large boulders were emplaced by a rockfall process, perhaps generated during ground accelerations accompanying an earthquake. Indeed, several paleoseismic studies, some in progress, have demonstrated Quaternary ruptures on the Tijeras fault system. **0.7**

14.6 Rio Grande Portland Cement plant at 3:00, quarrying limestone of Madera Group. **0.3**

14.9 Enter Tijeras, note Village limit sign. It has been suggested that the name Tijeras (Spanish for scissors) refers to the open scissors shape of crossing canyons at the site of the village. However, according to Pearce (1965), Tijeras is actually a family surname. There has been a settlement here since at least 1856. **0.2**

15.1 Four-way stop sign at junction with "S-14;" post office on left. Go straight on NM-333, heading east. Abo Formation here is unconformably overlain by alluvial/colluvial deposits. **0.2**

15.3 Go under I-40 bridge, note red bed road cuts in nonmarine Lower Permian Abo Formation. **Get into left lane. 0.4**

15.7 Road forks, **bear left on NM-14**; go under I-40 bridge. **0.1**

15.8 Excellent road cuts in Abo Formation red beds with probable pedogenic calcretes. (Fig. 2.1.4).

A substantial tectonic event took place in the western U.S., including northern New Mexico—between Mississippian and Early Permian time—the ancestral Rocky Mountain (ARM) orogeny. During the Mississippian, deposition across New Mexico took place in shallow marine and supratidal environments during a time of relative tectonic quiescence (e.g., Armstrong and

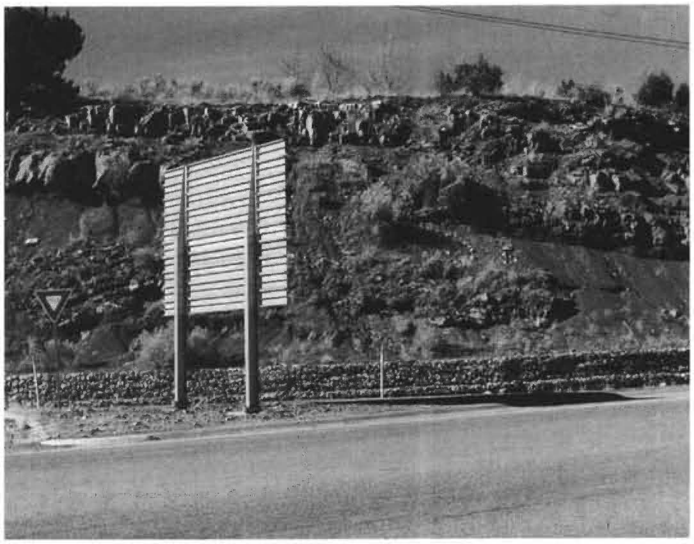


FIGURE 2.1.4. Roadcuts in Abo Formation at Mile 15.8 are characteristic of the unit—red-bed mudstones with probable pedogenic calcrete nodules and thin, sheet-like fluvial sandstones.

Holcomb, 1989). However, beginning in Pennsylvanian time, a series of north- and northwest-trending uplifts formed in New Mexico during the first phase of the ARM orogeny (Fig. 2.1.2). By latest Pennsylvanian (Virgilian) time, they formed a huge, north-trending massif (the Uncompaghre uplift), which, connected to the Pedernal uplift to the south, nearly divided the state into eastern and western halves. Marine deposition took place in the basins of the Late Pennsylvanian ARM uplifts (Fig. 2.1.5). However, by Early Permian (Wolfcampian) time, regional sea level had fallen and most of the state was a large, nonmarine fluvial basin of deposition with a paleoslope down to the south (Fig. 2.1.5).

The cause of ARM deformation remains poorly understood, although it seems clear that this was a major intracratonic shortening event that unroofed Precambrian-cored uplifts. One model of the tectonics of the ARM is that of Kluth and Coney (1981) and Budnik (1986). They proposed that the late Paleozoic, basement-cored uplifts and adjoining basins formed in response to northwest–southeast crustal shortening and sinistral strike-slip faulting caused by the Ouachita collision of North America with South America-Africa during the amalgamation of Pangea. In contrast, Ye et al. (1996) recently proposed that a northwest-trending subduction zone on the southwest margin of North America may have driven the ARM orogeny, in a style similar to that of the later (Cretaceous–Paleogene) Laramide orogeny. **0.3**

16.1 Hogback at 10:00–12:00 is Cretaceous Mesaverde Group, and next few roadcuts are Cretaceous. **0.3**

16.4 Continue north on NM-14 as road cuts through Cretaceous Mesaverde Group hogback; enter Tijeras syncline; road to left to Hobbies. Just above Hobbies is a well-exposed, overturned section of the Middle Triassic Anton Chico Member of the Moenkopi Formation, the oldest Mesozoic strata along the flanks of the Tijeras syncline. Here, the Moenkopi is 35 ft of grayish-red siltstone and sandstone between the Permian San Andres Formation and the Upper Triassic Agua Zarca Formation

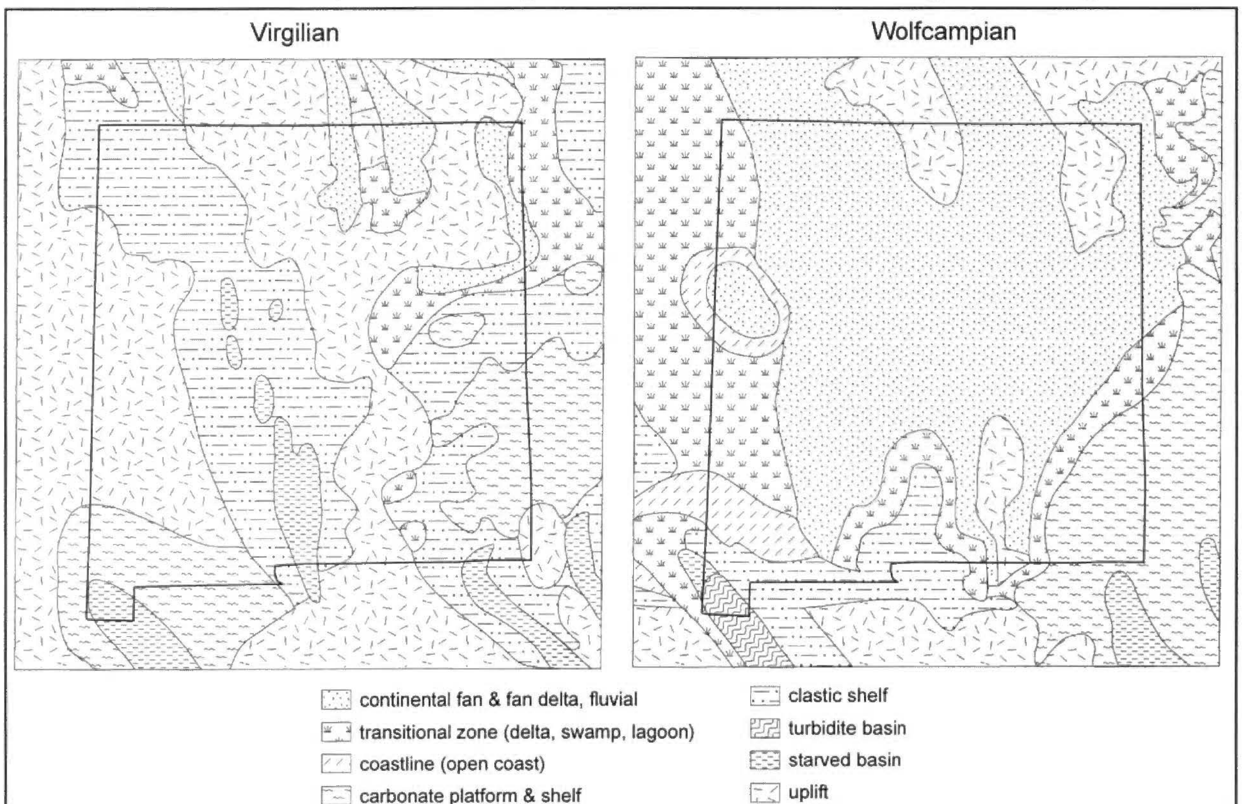


FIGURE 2.1.5. Paleogeographic maps of New Mexico during the two phases of the ancestral Rocky Mountain orogeny. On the left, during Late Pennsylvanian time, marine deposition took place in basins bounded by north- and northwest-trending, basement-cored uplifts. By Wolfcampian time (right), nonmarine red-bed deposition dominated the New Mexican landscape.

of the Chinle Group (Lucas and Heckert, 1995, section I). **0.4**

16.8 Enter greater Cedar Crest. Road cuts on left for next 0.3 mi are vegetated slopes of Cretaceous Mancos Shale. **0.6**

17.4 Alluvial/colluvial deposits with calcic soil development exposed to the left. There are several of these deposits within the Tijeras drainage basin on the eastern side of the Sandia Mountains. The deposits are composed almost entirely of subrounded Madera Group rock types and lesser amounts of red Abo Formation sandstone clasts. This petrography and texture suggest original deposition as alluvial fans. Numerous buried calcic soils in the deposit argue for several periods of colluvial reworking of the alluvial deposits. The soils and elevation of the deposits above the modern Tijeras Arroyo valley bottom suggest a middle Pleistocene or older age. **0.3**

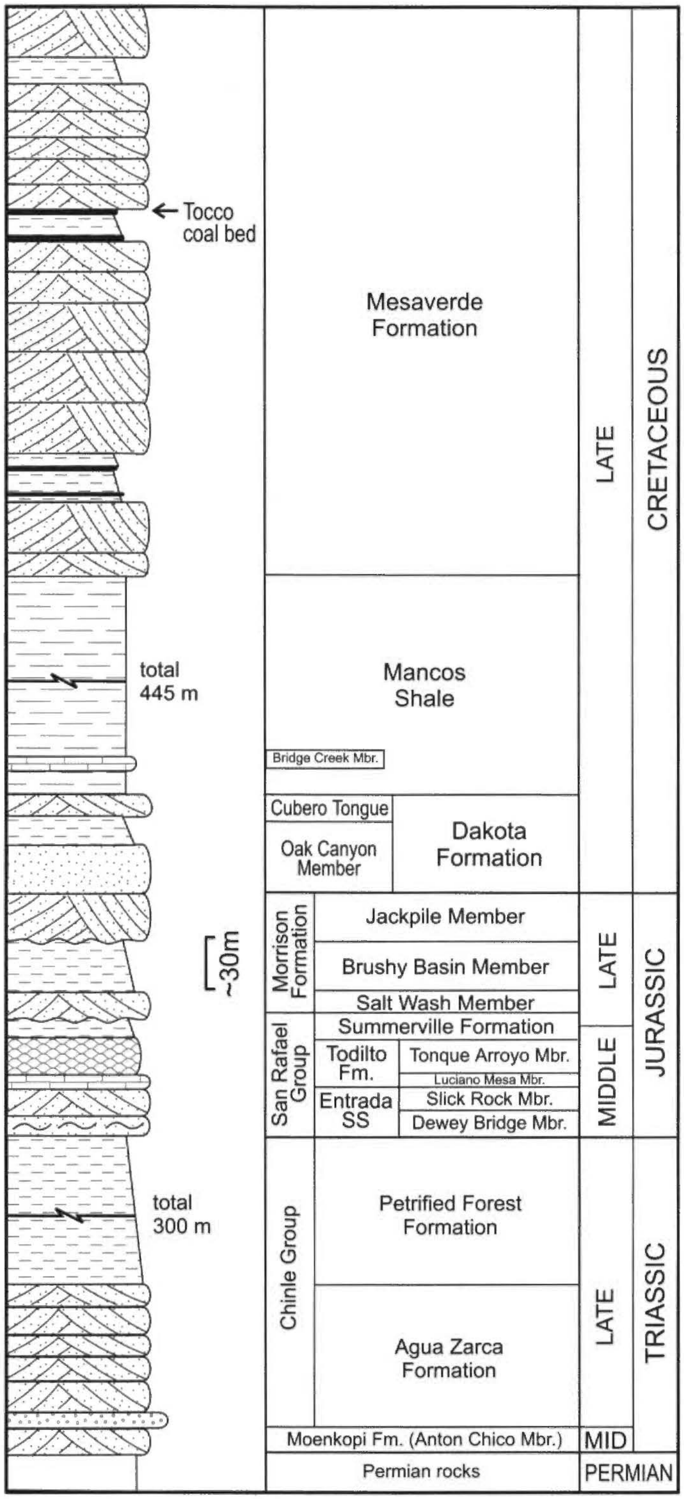


FIGURE 2.1.6. Summary of the Mesozoic stratigraphy at Cedar Crest (based on original data, Kelley and Northrop, 1975 and Lucas and Heckert, 1995).

17.7 On right, Cretaceous hogback is a sandstone of the Mesaverde Group. A thick, but relatively unstudied Mesozoic section is exposed here at Cedar Crest (Fig. 2.1.6). Triassic rocks belong to the Middle Triassic Moenkopi Formation and Upper Triassic Agua Zarca and Petrified Forest formations of the Chinle Group (Lucas and Heckert, 1995). Jurassic strata, to be examined in some detail at Stop 2, belong to the Entrada, Todilto, Summerville, and Morrison formations. The Cretaceous section is the least studied and consists of the Dakota Formation, Mancos Shale, and Mesaverde Group.

The Tijeras syncline contains one of only two coal fields in Bernalillo County. The other field lies along the western side of the Rio Puerco in the extreme western part of the county. Neither field contains coal of commercial interest or in minable beds given the current economic conditions, and neither area is likely to see coal production except for small-scale, local use. A coal field, incidentally, is defined as a discrete area underlain by strata containing one or more coal beds (Wood et al., 1983), and implies no production, past or present. It thus contrasts with the term "oil field," which does carry the expressed condition of production.

The Tijeras coal field, as the local field is known in the literature, lies on the eastern slope of the Sandia Mountains and is of added interest because the associated outcrops of Upper Cretaceous rocks represent the southeasternmost occurrence of the intertongued Dakota-Mancos section originally described by Landis et al. (1973) in the southern San Juan Basin. The coal-bearing rocks occupy the center of a syncline approximately 5 mi long and 2 mi wide. It is defined on the west by the Tijeras fault and on the east by the Gutierrez fault, both of which form the local segment of the more extensive, northeast-trending Tijeras-Cañoncito fault zone.

Beds dip moderately to steeply around the perimeter of the syncline but flatten and become nearly horizontal toward the center. The structure is modified slightly by two relatively minor anticlinal folds as shown on the detailed geologic map by Ferguson et al. (1996). Coal occurrence and outcrops within the field do not appear to be influenced by these minor structures. The following discussion is taken from Elston (1967):

"Small amounts of bituminous coal have been mined in the past for consumption in Albuquerque. Lee (1912) described the Holmes mine in SE 1/4, SE 1/4, sec. 1, T. 10 N, R. 5E., which worked a bed 12–30 inches thick, and the Tocco mine in the center of sec. 31, T. 11 N, R. 6 E, which mined a bed 18 inches thick. A 30-inch bed was said to be present in the Tocco mine 25 feet below the 18-inch bed. Not only are the beds thin, but they are also badly fractured."

The two areas probed two distinct coal zones separated stratigraphically by about 500 ft; the Tocco Mine worked the upper zone. Using only beds thicker than 14 in., Read et al. (1950) stated that measured and indicated coal resources in the two zones totaled 1.6 million st.

Lee and Knowlton (1917) measured a detailed section across the margins of the Tijeras syncline and into the center. They assigned all post-Mancos strata to the Mesaverde Formation (now Group). This is accurate for the most part, however, a finer designation is now possible (Fig. 2.1.7). We tentatively concur with Molenaar (1983) in regarding the lower part of the section to be the Crevasse Canyon Formation, and the upper part to be Mancos Shale through Menefee Formation. In ascending order, the basal crossbedded sandstone, as much as 115 ft thick, is assigned to the Dalton Sandstone Member; the overlying coal-bearing section to the Crevasse Canyon Formation (possibly the Gibson Coal Member?) while at the same time recognizing marine strata within it; the Hosta Tongue of the Point Lookout Sandstone, as much as 55 ft thick; the Satan Tongue of the Mancos Shale, an interval which Lee and Knowlton (1917) reported to be as much as 390 ft thick; and the Point Lookout Sandstone(?) and Menefee Formation at the top of the section (Fig. 2.1.7). If the correlations are correct, then the Tocco mine is developed in Menefee Formation strata, which could be considered equivalent to the Cleary Coal Member. Thus, the two coal zones in the Tijeras field are in separate formations, as the lower zone is in the Crevasse Canyon Formation. Lee and Knowlton were nevertheless correct in assigning all to the Mesaverde Formation (Group).

Equivalent strata to the north and on the northwestern side of the Tijeras-Canoncito fault have a more marine aspect. As Molenaar (1983) illustrated, the regressive Dalton Sandstone and the Hosta Tongue (associated with the subsequent transgression) merge seaward in the Placitas-Hagan basin area. In that area, the Dalton-Hosta Sandstone has been referred to as the Cano Sandstone (Stearns, 1953). The name Cano has never gained widespread usage and for that and other reasons we tentatively prefer to use the compound term Dalton-Hosta in those areas where the two units cannot be distinguished.

Before World War I, some coal was mined here from the Mesaverde Group in what Lee (1912) referred to as the "Tijeras coal field." However, production from the structurally controlled, relatively thin coal beds was limited, and as Lee (1912, p. 577) noted, "The economic importance of these beds is yet to be demonstrated." **0.2**

17.9 Enter Cedar Crest; note alluvium in roadcut on left. **0.5**

18.4 On left, behind U-Haul dealership, are red beds of Petrified Forest Formation of upper Chinle Group. **0.5**

18.9 On right in road cut, strata of the Jurassic Summerville Formation and Salt Wash Member of the Morrison Formation are disrupted by the Tijeras fault. At its northern end, this outcrop preserves pebbly beds of sandstone typical of the Salt Wash Member, which contrast with underlying fine-grained sandstones, siltstones, and limestones of the Summerville Formation. **0.2**

19.1 On right, post office. **0.2**

19.3 **Turn right** at Mountain Christian Church into large graveled parking lot for **STOP 2.** Here, we will examine the Jurassic section exposed in the abandoned gypsum quarry that is now the parking lot of the Mountain Christian Church (Fig. 2.1.8). The section here is very similar to that seen yesterday in the Hagan basin at Stop 3. However, here we have an opportunity to examine a somewhat younger interval of the Jurassic section than was exposed at yesterday's stop.

The Jurassic section here has been tectonically thinned

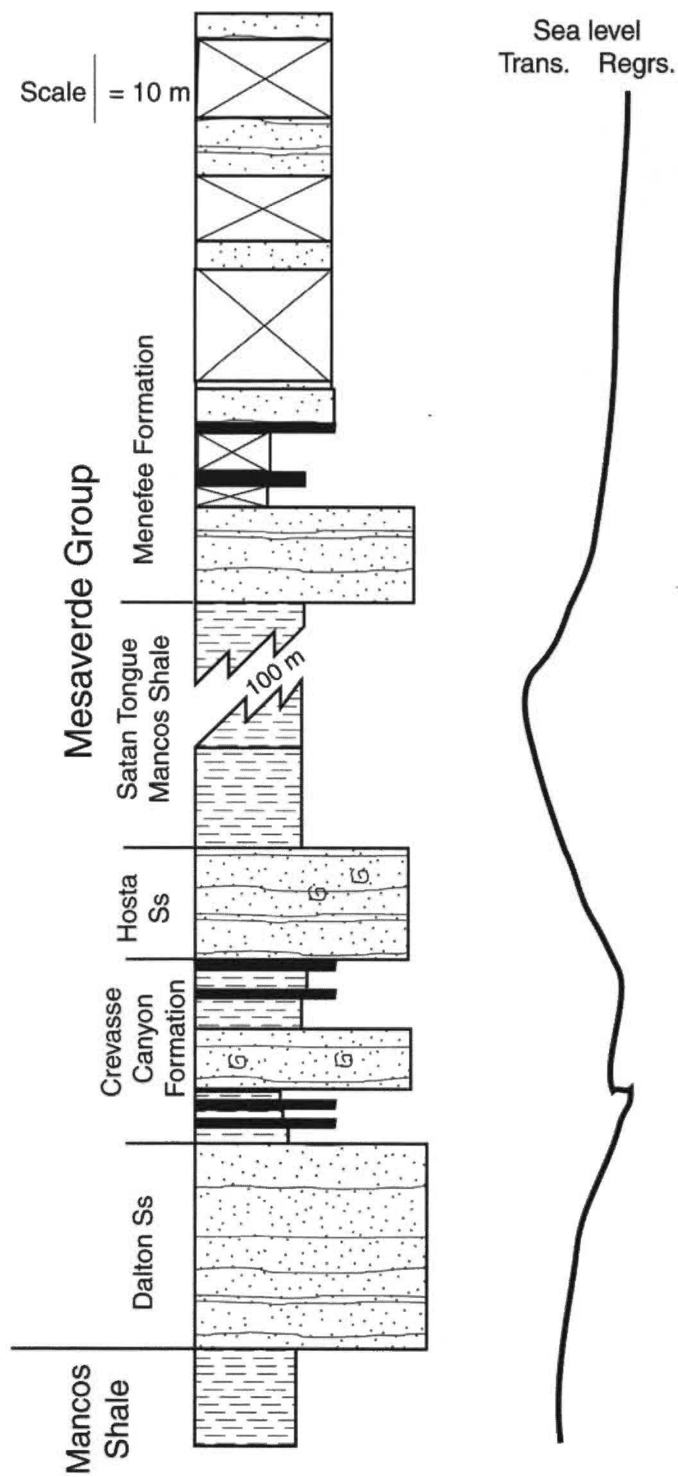


FIGURE 2.1.7. Measured section of the Mesaverde Group in the Tijeras syncline (Modified from Lee, 1912; Lee and Knowlton, 1917).

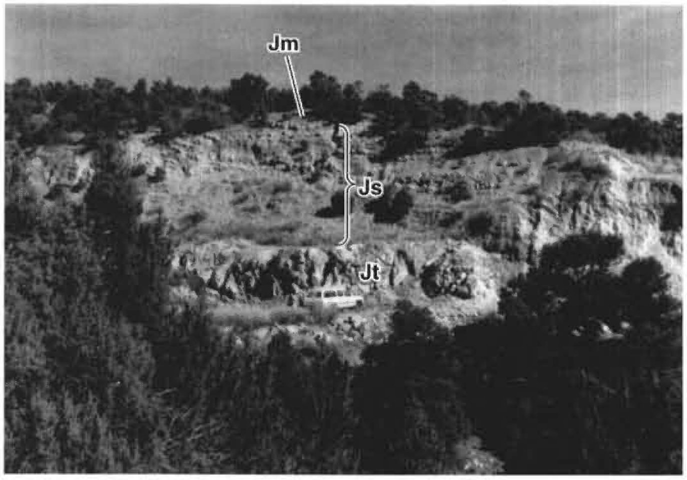


FIGURE 2.1.8. Photograph of the Jurassic section exposed at Stop 2. JM = Morrison Formation, JS = Summerville Formation, JT = Todilto Formation.

and begins at the highway, dips eastward (~40°) and encompasses the abandoned gypsum quarry, the first cuesta east of the quarry and the strike valley and next cuesta to the east. The section (ascending: Fig. 2.1.9) is: (1) Dewey Bridge Member of Entrada Sandstone, 37.7 ft thick and mostly ripple-laminated, very fine-grained, red-bed sandstone; (2) Slick Rock Member of Entrada Sandstone, trough-crossbedded, medium-grained, yellowish-gray sandstone about 35 ft thick; (3) Luciano Mesa Member of Todilto Formation, 7.2 ft of dark gray kerogenic, finely laminated limestone; (4) Tonque Arroyo Member of Todilto Formation, massive white gypsum about 102 ft thick; (5) Summerville Formation, 82 ft thick and mostly ripple-laminated red bed sandstone and variegated siltstone, shale, and nodular limestone; (6) Salt Wash Member of Morrison Formation, 69 ft thick and mostly trough-crossbeddded, medium- to coarse-grained and locally pebbly sandstone; (7) Brushy Basin Member of Morrison Formation, a mostly covered slope underlain by green smectitic mudstone about 103 ft thick; and (8) Jackpile Member of Morrison Formation, about 105 ft thick and mostly trough-crossbedded kaolinitic sandstone.

walker N to contact of Entrada over Chinle Grp

The Entrada–Todilto part of this section is very similar to the section we saw yesterday at Stop 3, and can be interpreted in a similar fashion. The focus here will be on the well-exposed Summerville section in the quarry high wall, and the Summerville-Morrison contact at the top of the cliff. Note the following:

1. Summerville deposition took place in quiet, ephemeral, shallow water on a coastal plain of low relief (e.g., Kocurek and Dott, 1983; Peterson, 1988; Lucas and Anderson, 1997). The basin of deposition extended from the shoreline of the Curtis-Sundance seaway in Utah–Wyoming southward to central New Mexico and western Oklahoma (Fig. 2.1.10). Summerville strata exposed here—ripple-laminated fine sandstones, shales and ledgy, nodular limestones—fit this overall model of the depositional system.

2. The Summerville-Morrison contact is picked at a significant lithologic change—coarse-grained and locally pebbly, trough-crossbedded sandstones mark the base of (and constitute much of) the Salt Wash Member of the Morrison Formation. Previous workers, however, often overlooked this change, and included Summerville strata in the Morrison (e.g., Kelley and Northrop, 1975). Sometimes the name "Recapture Shale Member" was erroneously applied to the Summerville strata. At this location, Ferguson et al. (1996) erroneously assigned the Salt Wash strata to the Bluff Sandstone (see the accompanying minipaper).

3. The Summerville-Morrison contact is the J-5 unconformity of Pipiringos and O'Sullivan (1978), a tectonosequence boundary. This boundary corresponds to a significant tectonic reorganization of the Late Jurassic Western Interior basin, where shallow water Summerville deposits with source areas to the southeast and southwest are succeeded by Morrison fluvial deposits derived from a volcanically active uplift to the west (Fig. 2.1.10).

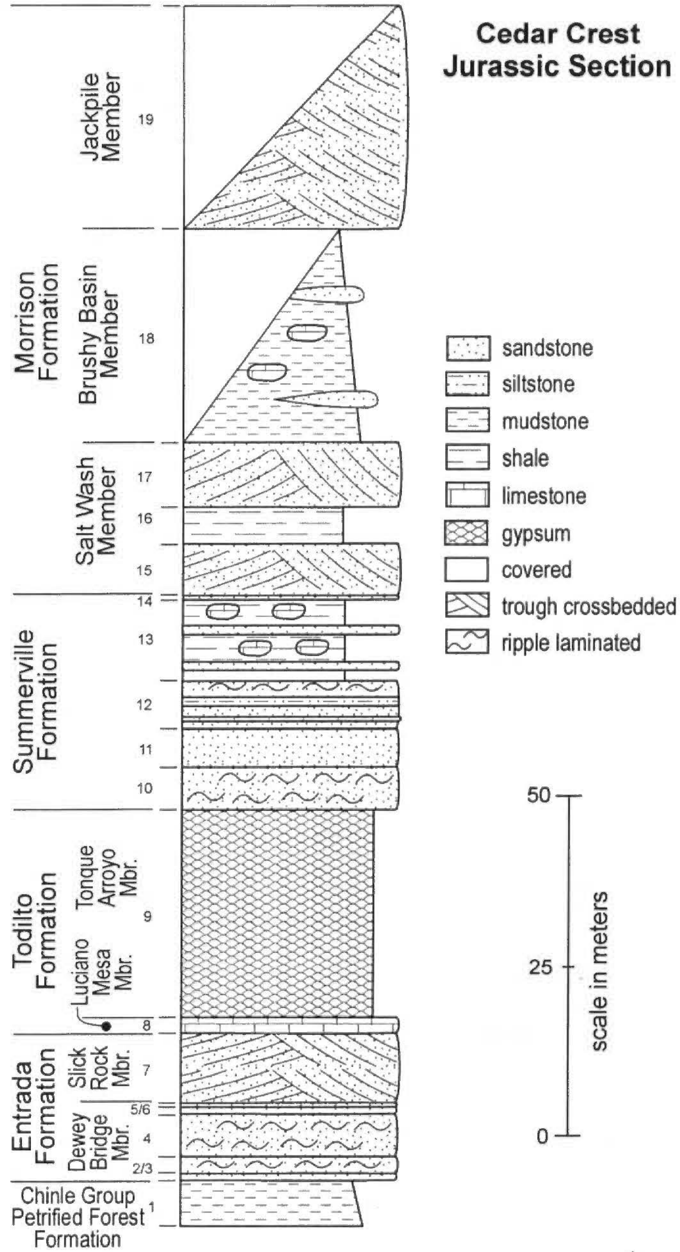
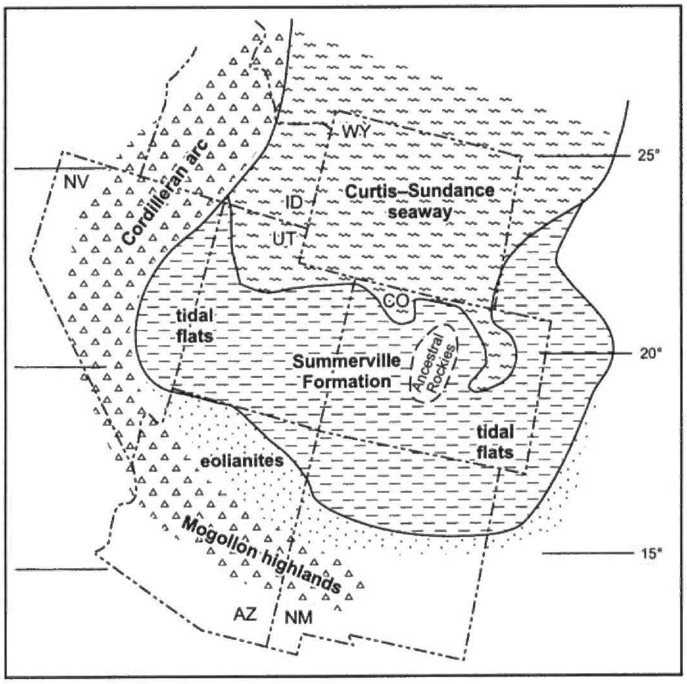


FIGURE 2.1.9. Measured section of Jurassic strata exposed at Stop 2.



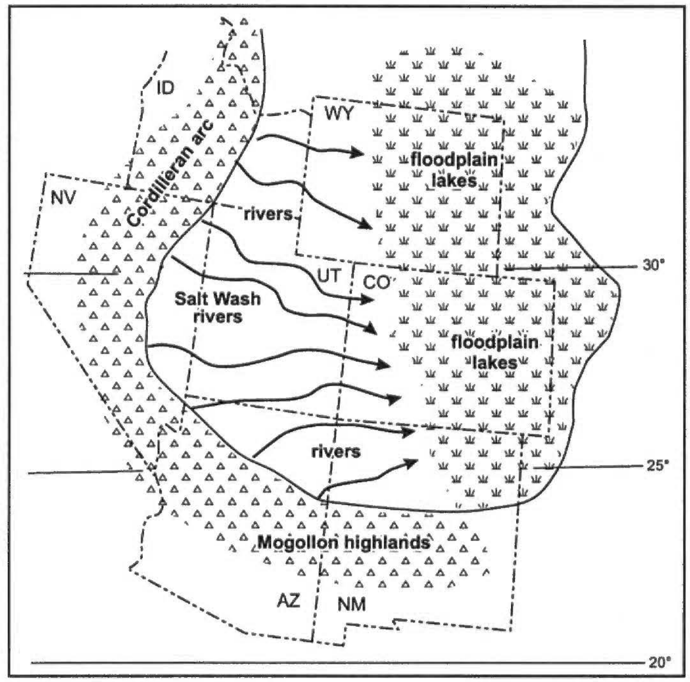


FIGURE 2.1.10. Paleogeography of the west-central United States during deposition of the Summerville Formation (left) and at the onset of Morrison Formation deposition (right).

If time permits, we will also examine exposures of the Tijeras fault zone just south of the quarry. Take the footpath that exits the quarry area on its south side. Walk about 100 yards, then leave the trail where it bends east and (instead) walk south on a strike ridge of sandstone (Dakota Formation). Where the ridge intersects a small drainage, the Tijeras fault can be seen to juxtapose Dakota Formation (on the NW) with folded shales of the Mancos Shale. This zone contains several fault slices and highly fractured rocks. Slickenlines in the Dakota are dominantly low angle, compatible with strike slip. Numerous steeply plunging tight folds in the Mancos Shale (e.g., plunge of 52° toward 075°) also lend support to interpretations of a component of stike slip on this fault (Ferguson et al., 1996). The dip-slip component of deformation is north side up, but stratigraphic separation is not great here. A short traverse south along the drainage reveals numerous high angle faults.

MIDDLE AND UPPER JURASSIC ROCKS AT CEDAR CREST, NEW MEXICO

Orin J. Anderson, Spencer G. Lucas, and John W. Estep

New Mexico Museum of Natural History and Science,
1801 Mountain Road NW, Albuquerque, New Mexico 87104

Middle and Upper Jurassic (Callovian through Kimmeridgean) rocks of the eastern Sandia Mountains block are not as well exposed as we are accustomed to seeing them on the Colorado Plateau to the west. However, along and between the northeast-trending faults that form the local segment of the Tijeras-Cañoncito fault zone, there are areally restricted exposures that offer a glimpse of much of the Jurassic section. Such an exposure is present along the eastern side of NM-14 approximately 3 mi north of I-40 at Cedar Crest, New Mexico. This section has been recognized as Jurassic at least since Darton (1928). More recently, field work and sample analysis supported by the New Mexico Museum of Natural History and Science, and geological mapping by Ferguson et al. (1996), have provided additional detail on the lithology and local relationships of these rocks.

While the mapping and interpretation of Ferguson et al. (1996) does not differ substantially from previous mapping (e.g., that of Kelley, 1963 and Kelley and Northrop, 1975), their recognition and placement of the basal Morrison Formation contact does differ from ours. The difference pertains specifically to the light-colored sandstone unit, as much as 72 ft thick, overlying typical Summerville strata at the top of the local outcrop. Ferguson et al. (1996) mapped this sandstone as the Bluff Sandstone, a dominantly eolian unit near the top of the San Rafael Group, and widely recognized across the eastern and southeastern portions of the Colorado Plateau. We, on the other hand, regard this unit to be the basal Morrison interval, namely the Salt Wash Member of the Morrison Formation. The placement of this contact carries with it the added significance that it also defines the top of the San Rafael Group, and the position of the regionally extensive J-5 unconformity (Lucas and Anderson, 1997; Anderson and Lucas, 1997).

Our reasons for placing the 72-ft-thick sandstone unit in the Morrison Formation are as follows. Basal Morrison strata (Salt Wash Member) from the type area in Grand County, Utah, and southward into the southern San Juan Basin consist of fine- to coarse-grained, pebbly, trough-crossbedded sandstone, with abundant rip-up clasts, and locally well-developed burrowing (trace fossils). Additional features are a very light-gray to pinkish-gray coloration, relatively thin interbeds of maroon mudstone or siltstone, eastward and southeastward paleoflow indicators, a distinctly scoured base, commonly with pedogenic carbonate development as much as 3 ft thick (but generally less), and a blocky weathering pattern that results from the prevailing 1.5–6-ft-thick sandstone beds collapsing as overhang above the fine-grained interbeds.

Not all of these characteristics will be observed at every locality. Enough, however, are observed here to permit assignment of this sandstone to the Morrison Formation. The trough-crossbedding, rip-up clasts, and modestly scoured base identify this as a fluvial unit. The Bluff, in contrast, is generally, but not entirely, an eolianite. Most significantly, the Bluff does not contain rip-up clasts or clay clasts, and where present has a gradational or intertonguing relationship with the underlying Summerville Formation. Accordingly, we recognize no Bluff Sandstone at this locality. Indeed, the Bluff is similarly missing or unmappable at other nearby localities such as the Hagan basin (Lucas et al., 1995) and at Galisteo Dam (Lucas et al., this volume).

The variation in thickness and lithology of the Salt Wash Member of the Morrison on a regional scale is due to a variety of factors. The generally eastward flowing streams of the lower Morrison depositional systems were distal in this area, and, accordingly, pebbly or conglomeratic facies are not as common here as they are in more proximal localities to the west and northwest. We have, however, recognized conglomeratic sandstones in the Salt Wash Member at Placitas, just 15 mi northwest of here. Paleotopography is responsible for the considerable thickness variation with distal (eastward) thinning superimposed on those criteria. Pedogenic carbonate preservation at the J-5 unconformity was dependent on the extent of local scouring as the Morrison fluvial system established itself, as well as the original thickness of the carbonate bed. No pedogenic carbonate is present at the basal Morrison J-5 unconformity in the local section. It should be further noted that dense gray carbonate beds as much as 7 in. thick are present in the Summerville Formation to within 3 ft of its upper contact. These carbonate beds probably represent lacustrine deposition during late Summerville time. Other criteria pertaining to lower Morrison stratigraphy are: (1) provenance varied, where extrabasinal input was minimal, the Salt Wash streams were reworking the fine-grained substratum (Summerville and Bluff deposits), so local facies will be fine grained; and (2) sand/shale ratios vary considerably, reflecting depositional settings that ranged from major channel systems to distal floodplain with silt and clay predominant.

Reconnaissance work in the area immediately to the northeast (near San Antonito) suggests that locally a Bluff Sandstone lithology (grayish-red, fine-grained sandstone) may be present beneath the Salt Wash Member. Nonetheless, it would appear from the limited outcrop that most of what has been recently mapped as Bluff Sandstone in this area by Ferguson et al. (1996) is in reality Salt Wash Member of the Morrison.

The upper part of the Morrison, the Brushy Basin Member, is not well exposed at this locality. It does, however, appear to be a variegated, smectitic claystone, with thin beds (<1 ft thick) of dark, fine-grained, very well-indurated (siliceous) sandstone. At the very top of the Morrison section we recognize, as did Kelley (1963), the light-colored Jackpile Sandstone, a prominent unit in the southeastern Colorado Plateau section. The recent mapping by Ferguson et al. (1996) makes no reference to the presence of the Jackpile Sandstone.

After Stop, **turn right onto NM-14** continuing north. **0.2**

19.5 On right in road cut is the Entrada-Chinle contact. The Chinle Group section here is very similar to that exposed in the Hagan basin and seen by us yesterday. The only significant difference appears to be the lack at Cedar Crest of the fluvial sandstone and conglomerate of the Correo Member at the top of the Chinle section (Lucas and Heckert, 1995). **0.2**

19.7 We are driving in a strike valley of red-bed mudrocks of the Petrified Forest Formation of the Chinle Group—Chinle is intermittently exposed in roadcuts for next 2 mi. **0.9**

20.6 Cross the drainage divide separating Tijeras Arroyo to the south and Frost Arroyo to the north. **1.2**

21.8 **Turn left** at junction with NM-536 (Sandia Crest Road). Note the Ortiz Mountains to the north, which are formed largely on middle Cenozoic sills, stocks and laccoliths. Gold-bearing placers, skarns, veins, breccias and Cu-Mo porphyries have been the focus of varied mining activities in the Ortiz Mountains. Indeed, about 350,000 oz of gold have been produced here (Maynard, 1989). **0.2**

22.0 To the left is hogback of tan sandstone of the Upper Triassic Agua Zarca Formation of Chinle Group; in strike valley beyond are Moenkopi red beds and underlying Permian strata. **0.4**

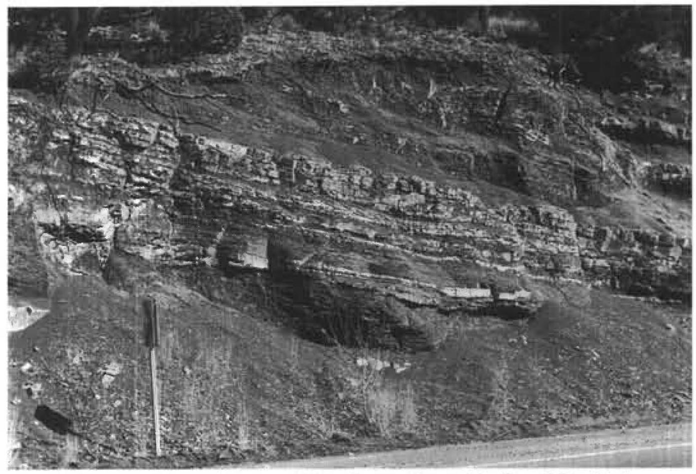


FIGURE 2.1.11. Outcrop of Abo Formation red beds at Mile 22.4.

22.4 Entering Abo-Yeso strike valley. To left is small hogback of Glorieta Sandstone. Low ridges flanking highway are southeast-dipping cuestas of Permian Glorieta Sandstone. **0.4**

22.8 To right, in road cuts are easterly dipping, mudstone-dominated redbeds of Abo Formation, with small faults (Fig. 2.1.11). **0.1**

22.9 Roadcut on right in Lower Permian Abo Formation red beds composed of tabular fluvial-channel sandstone interbedded with mottled floodplain mudstone. **0.5**

23.4 On left are limestones of Madera Group. **0.1**

23.5 Enter Cibola National Forest, note sign on right. This is the approximate location of a northeast-striking, down-to-the-west normal fault that juxtaposes Abo Formation and Madera Group. On right is a good outcrop of Madera Group limestones above the Sandia Formation and tan Sandia Granite with pegmatites. **0.1**

23.6 Passing outcrops of lower Madera Group. The Madera Group here is an approximately 1300-ft-thick succession of Middle and Upper Pennsylvanian (Desmoinesian–Virgilian) strata divided by Read et al. (1944) into a lower gray limestone member (about one third of the formation) and an upper arkosic limestone member, the latter composed of intimately interbedded limestone, arkosic sandstone, and shale. As mentioned earlier, Myers (1973) redefined the same strata in the Manzanita and Manzano Mountains (south of I-40) as the Madera Group, composed of the Los Moyos Limestone and Wild Cow Formation, as equivalents of the gray limestone and arkosic limestone members, respectively. **0.1**

23.7 Entrance to Sulfur Springs picnic area on left. The springs, about 800 ft west of the road, are along the north-striking Barro fault, a down-to-the-west normal fault that controls the location of this segment of Tejano Canyon, along which the road grade is constructed. **0.2**

Turn left into Doc Long Picnic Area parking lot for **STOP 3**. Here, we will look at Madera Group cycles, the Sandia Formation and the Precambrian and discuss the ancestral Rockies, "great unconformity," uplift history and evidence for 1.1(?)- and 0.7-Ga tectonism.

The "great unconformity" is well displayed here (Fig. 2.1.12), with Sandia Formation strata of Pennsylvanian age resting directly on Precambrian granite. Figure 2.1.13, a geologic map and cross section of the Doc Long

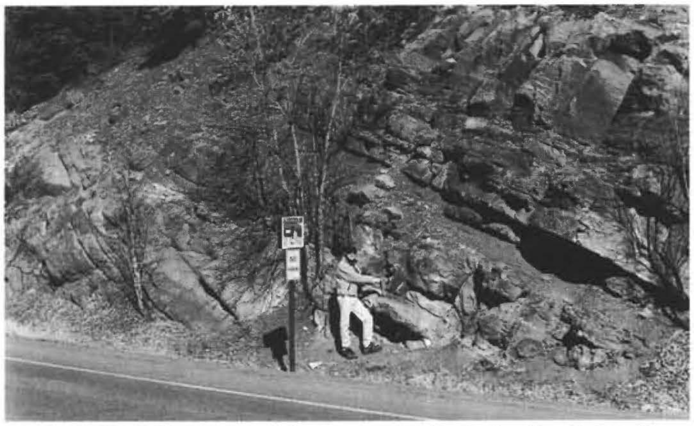


FIGURE 2.1.12. Photograph of the "great unconformity" at Stop 3. John Estep is standing on weathered Proterozoic granite and his hand points to its contact with overlying strata of the Pennsylvanian Sandia Formation.

area, shows locations of some points of interest at this stop. On the eastern side of the road **(be careful—fast traffic here has limited visibility due to curves in the road),** is an excellent exposure of the "great unconformity" between the 1440-Ma Sandia Granite and the coarse sandstone of the ~300-Ma Sandia Formation. Note the weathered and crumbly nature of the 1.44-Ga granite beneath the unconformity that represents 1.14 Ga of missing geologic history and the similarity of the weathering to the more recent corestone weathering seen earlier in Tijeras Canyon. Also note that Mississipian strata (to be discussed at Stop 4) are not present here. Farther down the road and overlying the Sandia Formation are good exposures of the limestones and shales of the lower part (Los Moyos Formation) of the Madera Group.

The west-side-down Barro and Doc Long faults are responsible for the basement exposure here in Barro Canyon. The Doc Long fault juxtaposes the Permian Abo Formation against the Sandia Granite—just up the hill and north of the bathrooms at the entrance to the Doc Long Picnic area, west-dipping fault planes with slickensides can be examined. Note the steep east-dip of the Paleozoic section west of the fault (Fig. 2.1.13). This geometry, shown on an E–W cross section, is antithetic to what is expected for drag on a west-dipping normal fault, suggesting a Laramide ancestry for these structures.

The east-tilted Sandia Formation (Atokan) rests on weathered granite along a low-angle contact overlain by reworked granitic regolith rich in pink microcline megacrysts. The uppermost granite contains remnants of a late Paleozoic weathering profile with conspicuous corestones representing incipient stages of spheroidal weathering. The coarse-grained granite contains abundant pink microcline megacrysts, white plagioclase feldspar, light-gray vitreous quartz, thin books of biotite, and scattered magnetite. Progressing northward along the roadcut, xenoliths of gneissic country rock can be seen together with white quartz veins and fractures coated with small, pale-green fluorite cubes. The grus accumulating in the roadside ditch provides an interesting comparison to the basal clastic layer of the overlying Sandia Formation. Strata of the Sandia Formation are present as alternations of sandstone, shale, and limestone, possibly

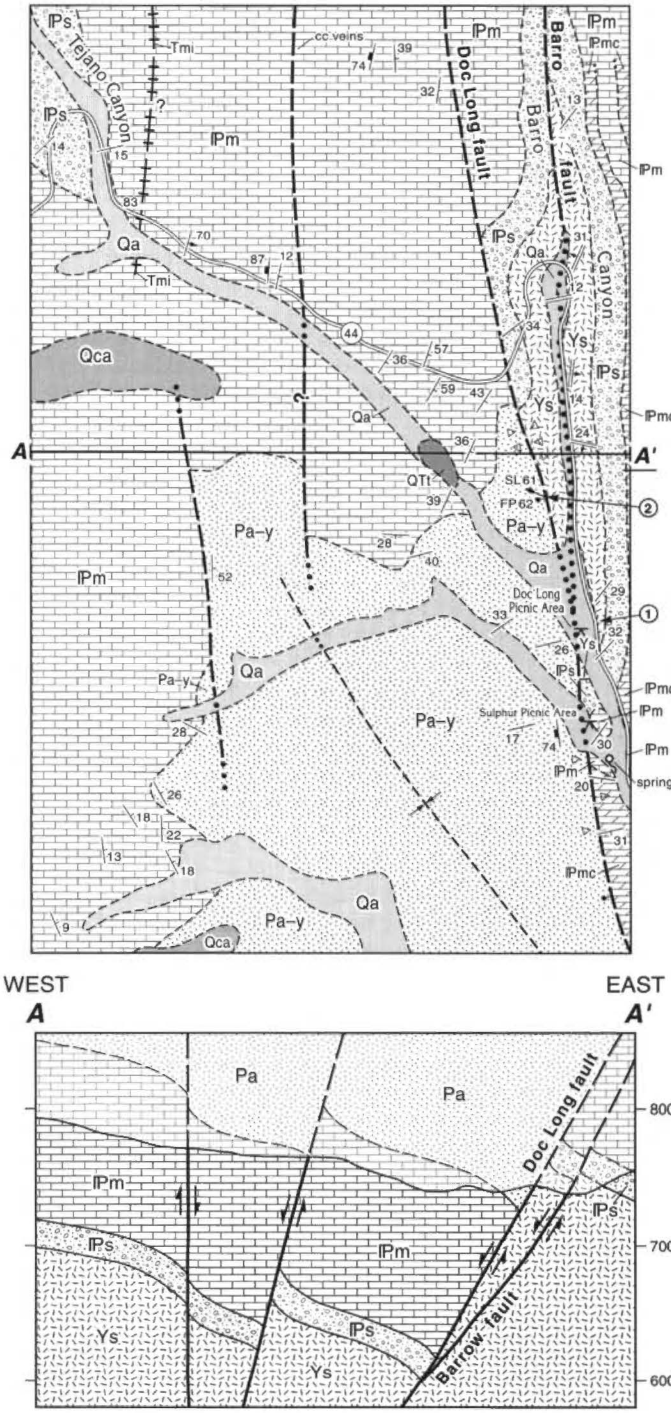


FIGURE 2.1.13. Geologic map and cross section of the area around Stop 3 (by Adam Read). Map units are: Pa-y = Abo Yeso undifferentiated; Pm = Madera Group undifferentiated; Pmc = ledge forming limestone layer in Pm (marker unit); Ps = Sandia Formation; Qa = alluvium (modern stream deposits); Qca = colluvium/alluvium; QTt = travertine deposit; Tmi = Tertiary mafic intrusive (weathered dike visible in roadcut and mentioned in log); Ys = Sandia Granite.

recording high-frequency eustatic, sea-level fluctuations in response to glaciation in distant Gondwana (cf. Wiberg and Smith, 1994). Prominent fossils seen in the lowest limestone include brachiopods (spirifers, productids, and compositids are most evident), crinoid ossicles, fenestrate bryozoans, molds of gastropods, and rare rugose corals.

LATE PALEOZOIC REMAGNETIZATION OF PRECAMBRIAN CRYSTALLINE ROCKS, SANDIA MOUNTAINS AND ELSEWHERE: RELATIONSHIP TO ANCESTRAL ROCKY MOUNTAIN DEFORMATION AND SEDIMENTATION

John Geissman

Department of Earth and Planetary Sciences, University of New Mexico, Albuquerque, New Mexico 87131

Over three decades ago (Irving and Parry, 1963), paleomagnetists recognized that the late Paleozoic, specifically most of the Pennsylvanian and at least half of the Permian, was characterized by a constant, reverse-polarity geomagnetic field. Today, it is well-accepted that this interval of geomagnetic field time, referred to as the Kiaman superchron, started in the earliest Pennsylvanian and ended about 258 Ma, in the Late Permian. The consequences of about 60 Ma of constant polarity, together with an unusual plate configuration and likely climatic consequences, have been extreme, in the sense that many pre-existing rocks, notably lower to mid-Paleozoic sedimentary sequences in many parts of the world, were partially to completely remagnetized during this time period. Recognition of the existence of such a late Paleozoic secondary magnetization in rocks from North America is relatively straightforward. The magnetization is, by implication, exclusively of reverse polarity and of south-southeast declination and shallow negative to shallow positive inclination. For North America, this direction gives rise to paleomagnetic poles in northwest Siberia, a position on the North American apparent polar wander path that is unique to Phanerozoic time for this craton. Examples of well-documented cases of remagnetization in New Mexico and nearby areas include the Cambro–Ordovician Bliss Formation in southern New Mexico (Romano, 1998), the Cambro–Ordovician Ignacio Formation in the San Juan Mountains (Geissman, 1991), the Mississippian Leadville Formation in central Colorado (Horton et al., 1984), and the Cambrian Tapeats Sandstone in the Grand Canyon area (Elston and Bressler, 1977). In addition, Precambrian crystalline rocks in several areas of the central and southern Rocky Mountains have yielded secondary magnetizations of late Paleozoic affinity. These are relatively special cases in that the rocks yielding such magnetizations are found at or just below the regional nonconformity, developed in the late Paleozoic ancestral Rocky Mountain deformation, between Precambrian crystalline rocks and upper Paleozoic sequences, typically dominated by mixed continental and shallow marine sequences.

Harlan and Geissman (1989) interpreted these magnetizations as originating from either surface weathering or, preferably, in response to subsurface brine migration along and near the regional nonconformity. As part of a study of the regional distribution of late Paleozoic magnetizations in Precambrian crystalline rocks, we have obtained small paleomagnetic collections from the Sandia Mountains, at two localities. The first is the exposure of the nonconformity between the Sandia Granite and overlying lowermost Pennsylvanian Sandia Formation, across from Doc Long Picnic Grounds. Few of the samples from the Sandia Granite yielded an interpretable magnetization in progressive demagnetization, and the entire collection from the granite failed to yield any internally consistent magnetization. Similarly, the samples from the Sandia Formation failed to yield a magnetization that could have been interpreted as Pennsylvanian in age. The second locality, near Seven Springs in Tijeras Canyon, yielded more interpretable results. Mafic metaigneous rocks within 6 ft of the nonconformity with the Sandia Formation yield relatively well-defined magnetizations in progressive demagnetization that are of southeast declination and shallow negative inclination, after correction for slight east-side down tilting of the range (Fig. 2.1.14). Response to demagnetization is not completely straightforward, in that above about 580ºC, the remanence-carrying magnetic mineralogy begins to alter, and spurious behavior characterizes response above this temperature. Demagnetization behavior is interpreted to indicate that much of the magnetization resides in high laboratory unblocking temperature hematite, and that some phase is breaking down above about 580ºC to create new magnetic phases. Metaigneous rocks 3.6 m or more below the nonconformity, on the other hand, have their magnetization dominated by magnetite and show no indication of the late Paleozoic remanence and in fact do not contain any internally coherent magnetization. The late Paleozoic magnetization in the metaigneous rocks immediately below the nonconformity in Tijeras Canyon is interpreted as either a weathering-related remanence, acquired before deposition of Sandia Formation strata or burial, fluid-flow-related remanence acquired over a prolonged period of time in the late Paleozoic during deposition of Sandia, Pennsylvanian Madera, and Lower Permian Abo/Yeso strata.

After Stop **turn left** and continue up Sandia Crest road (NM-536). **0.1**

24.0 On right, excellent road cuts in highly weathered granite.

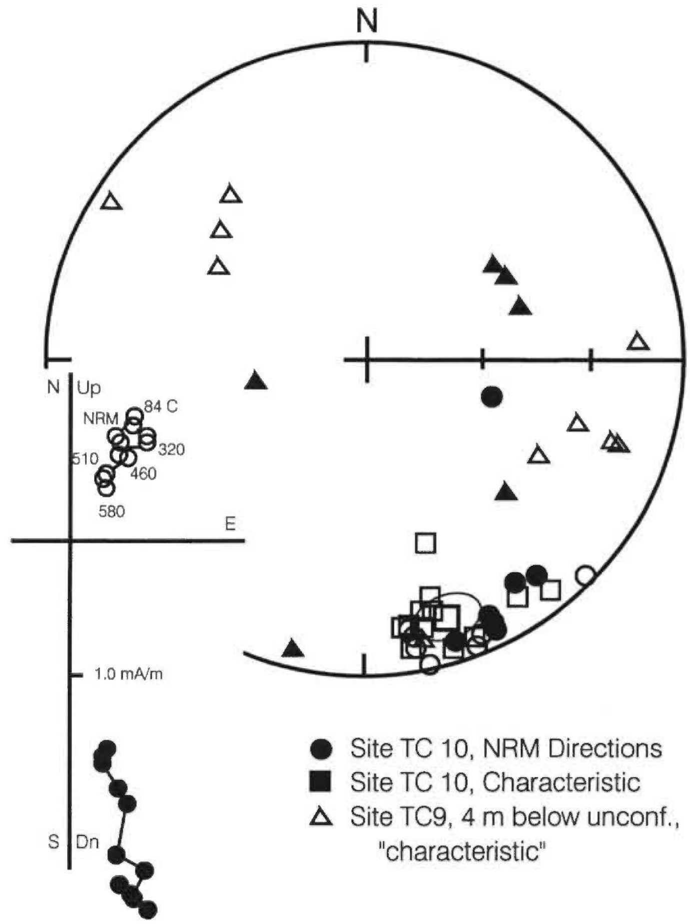


FIGURE 2.1.14. Equal-area projection of in situ (geographic coordinates) paleomagnetic data from two sites in metaigneous Proterozoic rocks sampled above Seven Springs, Tijeras Canyon. Site TC10 is in metaigneous rocks sampled immediately below the nonconformity with Lower Pennsylvanian Sandia Formation strata. Site TC9 is in metaigneous rocks about 12 ft below the nonconformity. Circles show NRM directions from 14 samples at site TC10. Squares show directions of magnetization for samples at site TC10 isolated in progressive thermal demagnetization. Large square and associated ellipse are the site mean direction and associated projected cone of 95% confidence about the estimated mean direction for samples from site TC 10. Triangles show directions of magnetization isolated in either progressive alternating field or thermal demagnetization from site TC9. Closed (open) symbols refer to lower (upper) hemisphere projections. Inset shows the typical example of progressive thermal demagnetization of sample TC10E, to 580ºC, prior to the acquisition of a spurious magnetization. Standard Zijderveld (1967) type projection showing the projection of the endpoint of the magnetization vector onto two simultaneous planes, the horizontal by the solid symbols and the vertical-E/W plane by the open symbols.

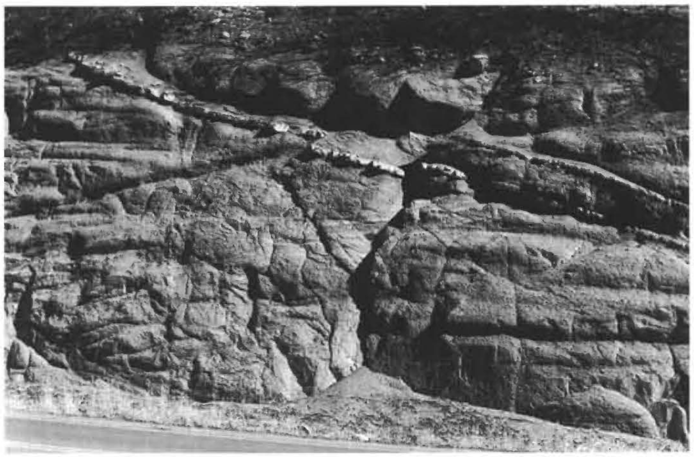


FIGURE 2.1.15. Pegmatized dikes and veins in Sandia Granite at Mile 24.3.

Road is aligned north–south along Barro Canyon, a tributary to Tejano Canyon that is eroded along the Barro fault zone. **0.3**

24.3 On right, note prominent, shallowly dipping pegmatite dikes and veins in the granite roadcut before the Barrow Canyon hairpin turn (Fig. 2.1.15). These features suggest that the least-compressive stress (σ_3) was subvertical near what is inferred to be the roof of the Sandia pluton (supracrustal rocks are seen to be intruded by the granite near the confluence of Barrow Canyon and Madera Canyon drainages to the north). **0.1**

24.4 Rounding switchback coincident with Barro fault; entering outcrops of upper Madera Group. Cross Barrow fault, then pass great unconformity and into Sandia Formation. **0.1**

24.5 Doc Long fault in Madera Group. **0.1**

24.6 Road returns to upper slopes of Tejano Canyon. Outcrops of limestone and reddish mudstone on left have traditionally been mapped as part of the upper Madera Formation in this area but may be equivalent to the Bursum Formation farther south (Kelley and Northrop, 1975). **0.1**

24.7 Excellent roadcuts for the next mile through faulted Pennsylvanian section described by Smith (this volume). Interbedded limestone and clastic rocks typical of Wild Cow Formation of the Madera Group are exposed here. Some limestone beds are richly fossiliferous, with the most common taxa being brachiopods, bryozoans, and crinoids. **0.4**

25.1 East-dipping fault of uncertain displacement sense, cutting Madera Group on right. **0.1**

25.2 Highly weathered green, biotite-latite(?) dike of probable middle Cenozoic age cutting Madera Group on right. At road level, this dike is intruded into strata that Wiberg and Smith (1993) correlate to the lowermost Madera Group (Los Moyos Limestone of Myers, 1973). A fault is obscured by colluvium a short distance west of the dike, and the section that follows along the road is the lower part of the Sandia Formation. **0.1**

25.3 View up Tejano Canyon of lower Madera Group outcrops; enter Sandia Formation. **0.1**

25.4 Hairpin curve across Tejano Canyon drainage; Sandia Granite is poorly exposed below the highway in the drainage to the right. Note exposures here of Sandia Formation sandstones and limestones. **0.3**

25.7 On left, poorly sorted colluvial hollow fill is exposed above the Sandia Formation. **0.3**

26.0 Wide pullout on right provides an overview of the Tejano Canyon Pennsylvanian section and the plains east of the Sandia Mountains. Natural outcrops along the eastern side of Tejano Canyon emphasize the distinction of the cliff-forming limestone of the lower Madera Group in contrast to the mostly slope-forming Sandia Formation. Looking southeastward across the sprawling East Mountain residential area and Estancia basin one can see Pedernal Mountain (7010 ft) on the skyline, 56 mi distant. Precambrian rocks exposed on Pedernal Mountain are an exhumed remnant of the extensive late Paleozoic Pedernal uplift, which was the source of clastic sediment in the Sandia Formation and Madera Group (Fig. 2.1.2). A deep, overfilled basin formed under the present Estancia basin (as much as 7925 ft of Pennsylvanian and Lower Permian strata: Broadhead, 1997) and was flanked to the west by a west-sloping ramp on which the Sandia Formation and Madera Group were deposited.

Outcrops across the road are typical of the alternating clastic and carbonate sediment of the Pennsylvanian section. Nonmarine sandstone and shale rest sharply on marine limestone and are abruptly overlain by an upward-deepening (grainstone to thin-bedded wackestone) sequence of limestone facies. **0.2**

26.2 Cliff-forming limestone of the lower Madera Group visible across Tejano Canyon to right. On left, good exposures of Madera Group. **0.2**

26.4 On left, Sandia Formation overlies granite; note minor relief beneath the "great unconformity;" note clastic-dominated Sandia Formation resting nonconformably on Sandia Granite in roadcuts on left. **0.5**

26.9 Milepost 5; just beyond is faulted block of Madera dipping to west. Colluvial hollow fill exposed to left. **0.1**

27.0 Highway turns southwestward away from Tejano Canyon along a tributary drainage following a northeast-striking fault. Anomalously west-dipping outcrop of Madera Group is a response to a complex fault junction between this fault and the northwest-striking Lagunita fault, which is just east of the highway (Kelley and Northrop, 1975). **0.2**

27.2 On left, Sandia Formation is faulted against Madera Group. **0.3**

On left, Tree Spring trailhead. Tree Spring is one of the rare sites in New Mexico (there are only four) that have yielded fossils of the American mastodon, *Mammut americanum*. Part of an upper jaw with two molars was collected from Quaternary soil near Tree Spring at an altitude of 7870 ft (Kelley and Northrop, 1975; Lucas, 1987; Lucas and Morgan, 1997). These extinct proboscideans were forest browsers, in contrast to their much more common contemporaries, the mammoths, who were grazers.

Numerous springs in this area are along fault traces that disrupt the east-dipping limestone layers. Infiltrated water flows largely downdip along bedding and is locally forced upward to the surface where faults juxtapose limestone against less permeable rocks on the downslope side of the fault or where gouge in the fault zone forms a permeability barrier. **0.5**

FIGURE 2.1.16. View to northeast near Mile 28.3 of Ortiz Mountains beyond the Hagan basin.

28.0 On right, Dry Camp Picnic Area; on left, arkose-rich Madera limestone in roadcuts. **0.3**

28.3 Fossil locality on left in green shale roadcut in Madera; view to northeast of Ortiz Mountains beyond the Hagan basin (Fig. 2.1.16). **0.1**

28.4 Interbedded limestone and shale typical of the Los Moyos Formation of the Madera Group. Indeed, the highway from here to Sandia Crest is largely a series of switchbacks up a long dipslope developed on the Los Moyos Limestone. **0.4**

28.8 On left is Sandia Peak Ski Area. **0.2**

29.0 Roadcuts in limestone, shale, and fine-grained sandstone of the Madera Group. View to right of Ortiz Mountains and southern end of the Sangre de Cristo Mountains. **0.2**

29.2 Madera Group in roadcut to left displays rapid changes in dip and discontinuous beds consistent with a deep-seated landslide deposit. **0.2**

29.4 Junction with NM-165 to Placitas. **Turn to right** into Balsam Glade for **STOP 4**, to examine a quartzite of probable Mississippian age (Fig. 2.1.17). Buses park in lot, and participants **walk down road about 1 mi** to Stop. The accompanying minipaper addresses the age of the quartzite we will examine here.

MISSISSIPPIAN DEL PADRE SANDSTONE OR PROTEROZOIC QUARTZITE?

Adam S. Read[1], Karl E. Karlstrom[2], and Brad Ilg[3]

[1]New Mexico Bureau of Mines and Mineral Resources, Socorro, New Mexico 87801; [2]Department of Earth and Planetary Sciences, University of New Mexico, Albuquerque, New Mexico 87131; [3]Victoria University, Wellington 6000, New Zealand

Enigmatic exposures of white quartzite crop out throughout the Sandia Mountain region along the great unconformity. Some workers have suggested that this generally white quartzite is Paleoproterozoic metaquartzite (e.g., Kelley and Northrop, 1975); others have considered similar rocks nearby to represent orthoquartzite of the Lower–Middle Mississippian Del Padre Sandstone (e.g., Armstrong and Mamet, 1974). An easily accessible outcrop of this quartzite, and the contact between it and the Sandia Granite is the site of Stop 4 (Fig. 2.1.18). Confusion exists because these rocks can look either sedimentary or metamorphic, even in the same outcrop. The stratigraphic position of these rocks (along the Proterozoic/Paleozoic unconformity), their lack of obvious foliation, and their occasionally pebbly texture indicate that they are unmetamorphosed sedimentary rocks. However, even the most

FIGURE 2.1.17. Outcrop of quartzite of probable Mississippian age at Stop 4.

sedimentary-looking parts of these rocks are strongly silicified and have quartz microstructures such as strongly recrystallized interlobate grain boundaries and undulatory extinction that suggest at least weak metamorphism took place. New geologic mapping and petrographic study of these rocks shows that some are Paleoproterozoic metamorphic rocks (with garnet, cordierite, and biotite), and some are pre-Pennsylvanian sedimentary rocks (but highly silicified, fractured, and recrystallized). The age of these sedimentary rocks is known only to be post-Paleoproterozoic and pre-Pennsylvanian. If these rocks are indeed Mississippian, hot mineralizing fluids apparently affected these rocks during Late Mississippian tectonism. Alternatively, these rocks may be Neoproterozoic. A brief review of Mississippian geology in the region follows, setting the stage for a discussion of the rocks at Stop 4.

In north-central and northern New Mexico, pre-Pennsylvanian Paleozoic strata are generally thin and poorly exposed and were first recognized in 1940 (Northrop, 1961; Kelley and Northrop, 1975). Armstrong (1955) discovered Mississippian megafossils of Meramacian age in the southern Nacimiento Mountains and proposed the name Arroyo Peñasco Formation for a locality just east of the type section (this discovery and paper began a lifelong career of research on Mississippian rocks for Gus Armstrong). Mississippian sections were measured in the Placitas area by Toomy (1953) and Armstrong (1955) and in Tijeras Canyon by Szabo (1953). Catacosinos (1962) attempted to find Mississippian rocks along the unconformity beneath Sandia Crest, but only found blocks of what he considered pre-Pennsylvanian limestone enclosed within the Sandia Formation.

In northern New Mexico, Baltz and Read (1960) proposed two formation names for pre-Pennsylvanian rocks, the Espiritu Santo Formation (a basal quartzite, limestone, and dolomite) and the overlying Tererro Formation (a series of limestones and dolomites divided into three members separated by disconformities). Sutherland (1963)

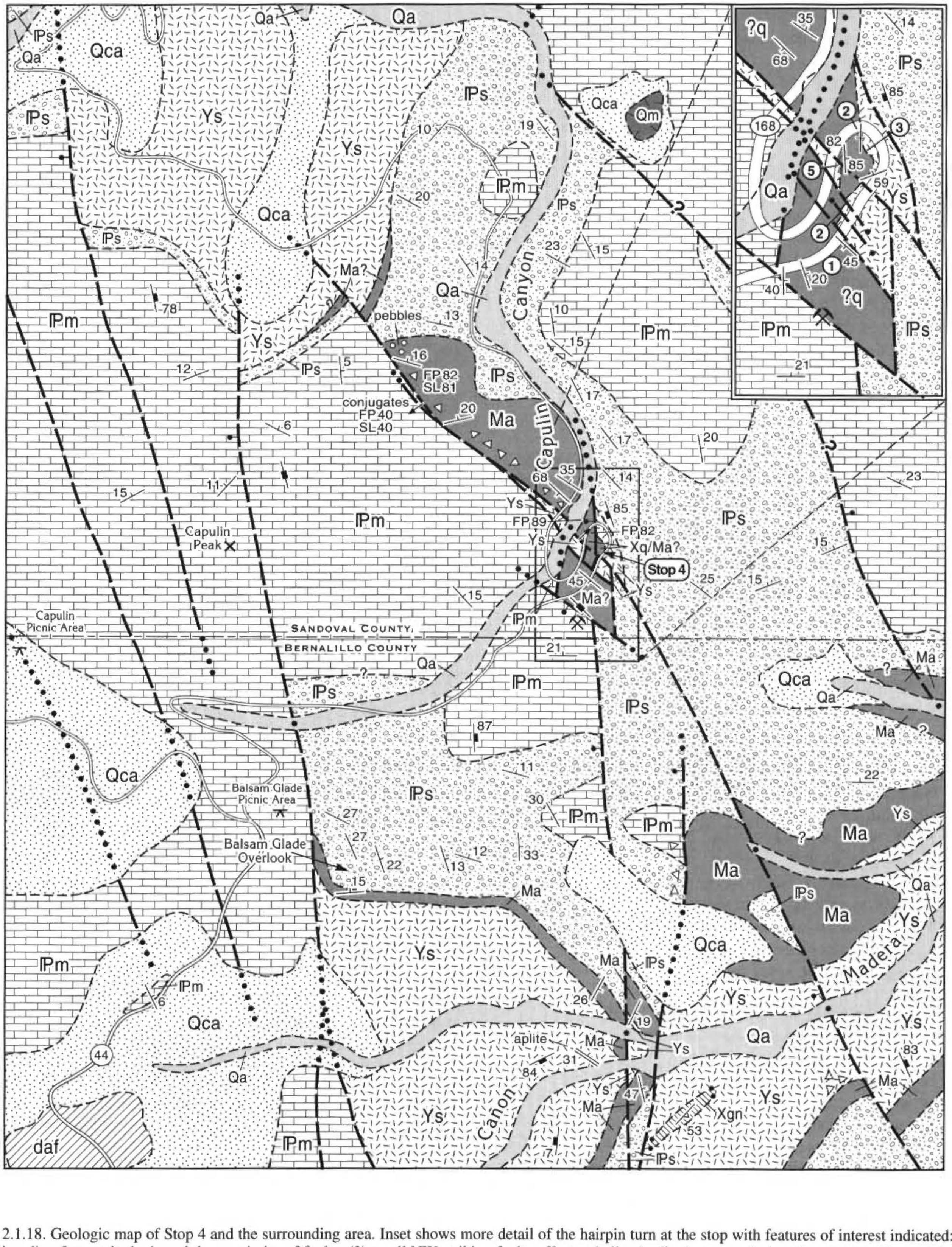


FIGURE 2.1.18. Geologic map of Stop 4 and the surrounding area. Inset shows more detail of the hairpin turn at the stop with features of interest indicated: (1) note the changing dip of quartzite beds and the proximity of faults; (2) small NW-striking faults offset a shallowly dipping quartzite/granite contact; (3) quartzite appears to be enclosed in granite, suggesting an intrusive contact; (4) note vertical quartzite bedding parallel to the quartzite/granite contact; quartzite samples taken 3 ft from the contact contain garnet and biotite; and (5) note slickensides along this NW-striking fault and the trace of the fault across the canyon. Map units are: daf = disturbed land/artificial fill; Ma = basal Mississpian Arroyo Peñasco Group (Del Padre Sandstone/Proterozoic quartzite?); Pm = Madera Group undifferentiated; Ps = Sandia Formation; ?q = Ma or Proterozoic quartzite?; Qa = alluvium (modern stream deposits); Qca = colluvium/alluvium; Qm = small marshy closed basin; Xgn = Paleoproterozoic banded gneiss; Ys = Sandia Granite.

removed the basal orthoquartzite from the Espiritu Santo Formation and called it the Del Padre Sandstone, referring to a thick type section (93 ft) exposed along the Rito del Padre near Beatty's Cabin in the Pecos Wilderness. Thicker sections of the Del Padre Sandstone (up to 754 ft) appear just east of the Pecos-Picuris fault and probably are related to accomodation space provided by pre-Pennsylvanian movement along the fault (Sutherland, 1963). The Del Padre Sandstone is commonly white, well indurated, and may locally contain pebbles near its base. This sandstone, although often thin (and sometimes absent), is found over much of northern New Mexico where Mississippian rocks are exposed (Sutherland, 1963; Armstrong and Mamet, 1990). It is generally silica cemented and is easily mistaken for a Precambrian rock, as noted by Sutherland (1963). Due to a lack of fossils, Sutherland (1963) considered the age of the Del Padre Sandstone to be between Neoproterozoic and Early Mississippian. However, field relationships suggest that the Del Padre interfingers with the overlying Espiritu Santo Formation, implying a probable mid-Mississippian age (Sutherland, 1963). Because of this reported relationship, Armstrong and Mamet (1974) considered the Del Padre Sandstone to be Osagean, added it back into the Espiritu Santo Formation of Baltz and Read (1960) as an additional member, and included both the Espiritu Santo and Terrero formations within a newly defined Arroyo Peñasco Group.

Quartzites east of the Sandia Peak Ski Area in La Madera Canyon were mapped and described by Phillips (1964). He considered the entire package beneath the Sandia Formation to be Precambrian and reported the presence of quartzite, little-altered sandstone, greenstone, and schist. The sandstone was described by Phillips (1964) as an unfoliated rock that breaks along grain boundaries and is composed principally of quartz with minor biotite and rock fragments. He regarded this apparently unmetamorphosed sandstone as a mystery, particularly due to its close association with other metamorphic rocks. The quartzite is described as weakly foliated and intercalated with coarse biotite schist locally. Phillips (1964) noted that the contact between the Sandia Granite and the quartzite is a gently east-dipping surface (parallel to the Paleozoic dip slope). He considered and rejected the possibility that this contact represents a low-angle fault, as no brittle structures were seen in that orientation.

The map of the Sandia Mountains and vicinity produced by Kelley and Northrop (1975) only included Mississippian rocks from two localities in the Placitas area because other exposures were very thin or equivocal. They chose to consider the entire Mississippian section as the Arroyo Peñasco Formation rather than subdivide units into formation names within an Arroyo Peñasco Group. The mapping of Phillips (1964) in Madera Canyon was incorporated into the Kelley and Northrop (1975) map, with the sandstones and quartzites shown as undifferentiated Precambrian metamorphic rocks.

Recent workers have discovered that Mississippian strata in the Sandia Mountains are more widespread. In 1997, Read and Ilg completed detailed mapping along the great unconformity from Placitas to Sandia Crest (Read et al., 1999). They traced pre-Pennsylvanian quartzites and carbonates exposed along the unconformity to just north of Sandia Peak. Differentiating lithologic units within the Mississippian section proved difficult at a map scale of 1:12,000, so the exposures were assigned to the undifferentiated Arroyo Peñasco Group. The quartzites are strongly silicified and locally mineralized by barite, fluorite, and magnetite along predominantly NW-striking joints and faults. Some of these NW-striking faults appeared not to offset the Madera Group, which was only very rarely seen to be mineralized. A similar NW-striking fault (Fig. 2.1.18) bounds the eastern edge of quartzite exposure at Stop 4 and is clearly visible on the flanks of Capulin Peak just to the northwest of the hairpin turn. Such faults may be remnants of Early Pennsylvanian tectonism (Armstrong and Mamet, 1990) that were, in most cases, reactivated by later deformation.

During recent mapping in Madera Canyon (Read et al., 1999; Fig. 2.1.18), as well as along Sandia Crest and in the Sedillo quadrangle, unfoliated quartzites were mapped along the unconformity between the Sandia Formation and Proterozoic basement (granite, or supracrustal rocks). In Las Huertas Canyon east of Placitas, exposures of similar quartzites that lie unconformably above metarhyolite contain a basal conglomerate. Directly overlying the quartzite are the Mississippian carbonates described in Armstrong (1955) and later papers. These outcrops in Placitas are clearly the Del Padre Sandstone (Armstrong and Mamet, 1974) and are, in places, very similar to the quartzites found along the regional unconformity from Placitas to Sandia Crest. In thin section, both pebbles and matrix grains are strongly recrystallized and show evidence of both brittle and ductile deformation (Fig. 2.1.19A). Most grains have moderate to strongly developed undulatory extinction and sutured grain boundaries. In addition, numerous microfractures, often defined by fluid inclusion planes, cut across grain boundaries. These microtextures are thought to form in quartz aggregates at temperatures of up to 300°C (Passchier and Trouw, 1996). No obvious foliation is present, but the outlines of relict sedimentary grains are not visible petrographically. These microtextures are surprising for a rock that looks so much like a pebble conglomerate in hand sample and is thought to be Mississippian in age. The long history of faulting and fault reactivation in the vicinity of the Crest of Montezuma clearly resulted in brittle deformation of these rocks, but such extensive ductile deformation is surprising for rocks that presumably remained at relatively shallow crustal levels since their deposition.

In and near Madera Canyon, the quartzite exposures show characteristics of both Paleoproterozoic supracrustal rocks and of younger sedimentary rocks. As observed in the Placitas area, the quartzite appears to follow the great unconformity. At one locality deep in the canyon, rounded and weathered granite (~12-in. diameter) was found entirely enclosed within the quartzite, suggesting that the sandstone/quartzite was deposited on an unconformity rather than being intruded by granite. The quartzite sometimes appears to have a granular texture and rounded grains that look detrital. However, in other places, pegmatite veins appear to have intruded some of the overlying quartzite, but only within tens of centimeters of the contact. The quartzite is often locally strongly quartz veined and is occasionally mineralized along some of these veins. At Stop 4, some irregularly shaped quartzite bodies are enclosed within the Sandia Granite, suggesting that either contacts are intrusive or (less likely) represent fault slivers.

Petrographic study suggests that both sedimentary and metamorphic quartzites are present. Just below the Sandia Formation beneath the Madera Canyon overlook southeast of the Balsam Glade picnic area (where the fieldtrip buses will stop for the walk to Stop 4), the unfoliated quartzite looks very much like an orthoquartzite (i.e., sedimentary) in thin section (Fig. 2.1.19B). On the left side of Figure 2.1.19B, rounded grains of quartz within a silicified matrix appear to be only weakly deformed and have only weak undulatory extinction. However, on the right side of the photomicrograph (and across a microfault), the quartz grains appear to have more sutured grain boundaries. The microtextures seen in Figure. 2.19B are very similar to a sample of the Del Padre Sandstone from the Picuris Mountains (Fig. 2.1.19C), where grains have very weak to absent undulatory extinction but variably sutured grain boundaries. One lone, highly strained grain on the photomicrograph shows evidence of dynamic recrystallization and probably represents detritus from the deformed quartzite of the Paleoproterozoic Ortega or Rinconada formations. These textures are similar to those described by Sutherland (1963) for the Del Padre Sandstone in the Sangre de Cristo Mountains. Closer to the granite contact in Madera Canyon, just below the site of the sample seen in Figure 2.1.19B, samples of a darker banded quartzite are unequivocally metamorphic rocks in thin section (Fig. 2.1.19D) with poikiloblastic garnet texures and cordierite. Thus, microtextural evidence suggests that locally some quartzites are Paleoproterozoic metamorphic rocks and some are variably recrystallized pre-Pennsylvanian sedimentary rocks.

Samples from the vertical beds on the northern side of the hairpin turn and just west of the vertical granite contact at Stop 4 appear to be metamorphic rocks, as they contain garnet and biotite. However, the whiter quartzite at the stop was not sampled, and in thin section may look like the nearby and identical looking quartzite from the overlook at Balsam Glade (Fig. 2.1.19B). Also, quartzite containing quartz pebbles crops out nearby on the east flank of Capulin Peak and the west side of

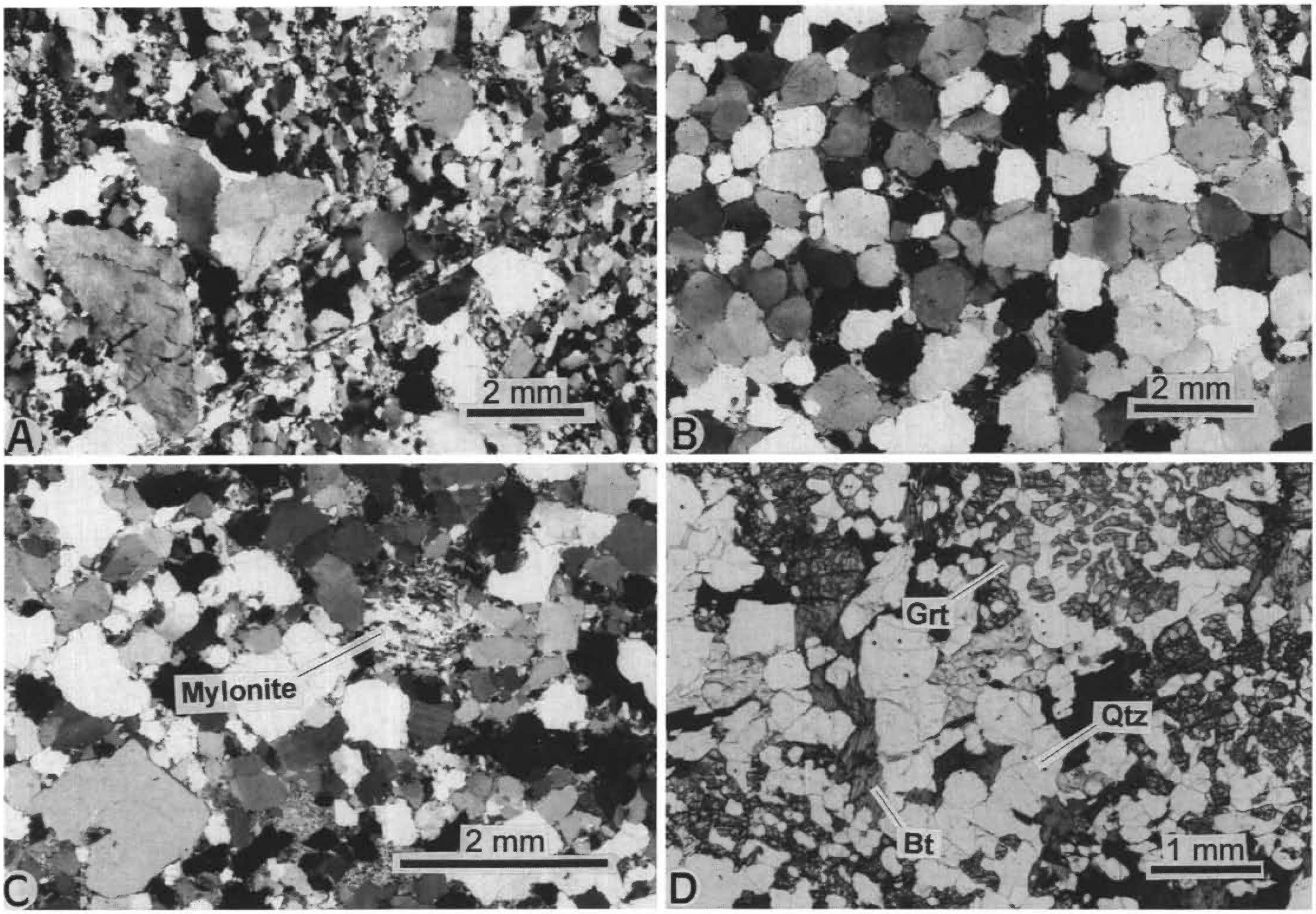


FIGURE 2.1.19. Thin sections relevant to the identification of probable Mississippian-age quartzites in the Sandia uplift. **A**, XPL, Sample KS 999, pebble conglomerate from the Del Padre Sandstone in Las Huertas Canyon east of Placitas looks unmetamorphosed in hand sample. Ductile deformation is evident with sutured grain boundaries and patchy to undulatory extinction. Note the lack of foliation, the quartz-pebble clasts, and microfaults. **B**, XPL, Sample KS 995, well indurated quartzite from just beneath the Sandia Fm. near the Balsam Glade overlook into Madera Canyon. Note the rounded quartz grains cemeted by quartz left of the microfault and the more sutured grains to the right of the microfault. **C**, XPL, Sample HC 430, Del Padre Sandstone from the Picuris Mountains (thin section courtesy of Paul Bauer). Note minor suturing of grain boundaries in addition to the lone highly strained quartz mylonite grain. Static recrystallization would have eliminated this evidence for a provenance from a highly strained source (probably quartzite from the Hondo Group). **D**, PPL, Sample KS 993, Metamorphic rock from beneath the Balsam Glade Madera Canyon overlook is beneath sample KS 995 and above the Sandia Granite. Assemblage includes quartz-garnet-biotite-cordierite. Note the poikiloblastic garnet texture.

Palomas Peak to the north.

The vertical bedding and apparently intrusive granite contact at Stop 4 may represent the initial geometry during intrusion. However, this area is also near the trace of a major NW-trending fault that may record ancestral Rockies and/or Laramide deformation. Some of the numerous faults at Stop 4 are very likely related to the reverse faults seen to the north along the base of the Crest of Montezuma, where a Laramide monocline is present.

The sedimentary origin of the Del Padre Sandstone in the Sangre de Cristo Mountains is well documented, and the age is bracketed between Paleoproterozoic and Late Mississippian. However, the strong silicification and microtextural evidence for ductile deformation observed in these rocks, particularly in the Sandia Mountains and vicinity, suggests an age older than Mississippian is possible. The metamorphic rocks that are also present are of high grade and, although recrystallized, are strongly foliated. These rocks represent roof pendants of the Sandia pluton in the vicinity of Madera Canyon, as suggested by Phillips (1964) and Kirby et. al. (1995). Apparently high-grade metamorphic rocks are in some places unconformably overlain by younger rocks that, while they look similar in many cases, were not subjected to intense metamorphism and deformation.

This seems to be the case in the vicinity of La Madera Canyon and perhaps is the case for the rocks at Stop 4. It is possible that the relatively low-temperature microtextures seen in the Del Padre Sandstone/quartzite may partly be a consequence of extensive silicification of a sandstone composed of grains derived from strongly deformed basement rocks (as suggested by Fig. 2.1.19C). Ulmer and Laury (1984) documented extensive diagenetic changes within the Arroyo Peñasco Group above the Del Padre Sandstone in the Sangre de Cristo Mountains, including dolomitization, dedolomitization, chertification, silicification, and pyritization. The overlying basal Pennsylvanian strata appear, in some places, to have also been affected by mineralizing fluids that may be related to this silicification. If the silicification and microtextural evidence for ductile deformation indicate Late Mississippian to Early Pennsylvanian tectonism, then we may need to reevaluate our view about the extent and degree of deformation and mineralizing fluid flux during the development of the ancestral Rocky Mountains. If the deformation seen in the Del Padre Sandstone is not Mississippian, the next logical possibility is that these rocks could be Neoproterozoic and correlative with the Apache Group or Grand Canyon Supergroup in Arizona and similar age sediments in the Sacramento Mountains of southern New Mexico (Pray, 1961). In summary, some of these quartzites in New Mexico are demonstrably Paleoproterozoic, some are post-Paleoproterozoic and pre-

Pennsylvanian, and many are of uncertain age. Conclusive evidence for the age of the Del Padre Sandstone is lacking, but Ar^{40}/Ar^{39} thermochronology of mica and K-spar found in some quartzite samples may help resolve this problem.

Sandia Cave, a famous archeological site, is near this Stop. In 1936, Frank Hibben, then an Anthropology Professor at UNM, uncovered fossils in the cave of late Pleistocene mammals in association with spearpoints, scrapers, and other tools (Hibben, 1940, 1941). These "Sandia points" provided *prima facie* evidence of "Sandia Man," so Hibben had discovered some of North America's oldest inhabitants. Furthermore, the Sandia spearpoints had a single notch ("shoulder") flaked on one side, and thus bore a striking resemblance to spearpoints found in France and Spain that archeologists termed Solutrean. This similarity supported the idea that European hunters had emigrated across Beringia, thus peopling the New World during the late Pleistocene (Hibben, 1946). Furthermore, the Sandia points had been found beneath a layer with Folsom points, making "Sandia Man" older than "Folsom Man" and thus the oldest evidence of humans in North America.

Sandia Man entered the textbooks, but over the 60 years since its discovery, little more of the Sandia Man tool culture has been discovered. Recently, Preston (1995) has alleged that Hibben made the Sandia points himself and "salted" the site. If true, Sandia Man would become one of the greatest archeological hoaxes. What is certain though, is that Sandia Cave is an important paleontological site for late Pleistocene mammals, including a rare record of the American mastodon in New Mexico (Lucas and Morgan, 1997).

After Stop, continue on Sandia Crest road (NM-536) toward Sandia Crest. **0.5**

29.9 Milepost 8. **0.1**

30.0 On right, turnoff for Capulin Spring recreation area. Capulin Spring is along one of numerous northwest-striking faults that interrupt the east-dipping Madera Group between here and Tejano Canyon, to the east. From here, the highway begins a steep ascent, with many switchbacks, toward the crest of the Sandia Mountains. **0.1**

30.1 Pass roadcuts of jumbled blocks of the Madera Group. This deposit has a linear topographic extent reminiscent of a large, debris-flow levee. It also resembles a moraine, but no other glacial features have been described in the Sandia Mountains, and they are generally held to have been ice free in the Pleistocene. **0.1**

30.2 First of many crossings of the Bernalillo-Sandoval County line. **0.1**

30.3 Bernalillo County line. **0.5**

30.8 Madera Group crops out in roadcuts for next 5 mi of winding road to Sandia Crest. **0.1**

30.9 On left is turnout for Nine Mile Picnic Area. **1.0**

31.9 Milepost 10. **0.2**

32.1 On right, mixed limestones and clastics of Madera Group with average dip of ~15°. **0.2**

32.3 On left, in road cut, more limestones of Madera Group. **0.3**

32.6 On right, in road cut, limestones of Madera Group. Note again that road is switchbacking up the Madera dip slope. **1.5**

34.1 To left, Ellis trailhead. **0.2**

34.3 Sign on left marks our ascent above 10,400 ft elevation. **1.2**

35.0 On right in road cut, note cyclically bedded Madera limestones. View to left (east) and behind (north) of the mountains of the Ortiz porphyry belt including, from the south, South Mountain, San Pedro Mountain, Ortiz Mountains, and the Cerrillos Hills. Intrusive rocks of late Eocene to late Oligocene age underlie these ranges and are associated with coeval volcanic rocks of the Espinaso Formation near Cerrillos. Precious-metal mineralization is associated with epithermal veins and skarns and has been exploited since at least the 16th Century. **0.4**

35.4 End of Sandia Crest road. **Turn left** into lower lot of Sandia Crest for **STOP 5**. The summit of Sandia Crest provides a remarkable overview of about 10% of New Mexico (Fig. 2.1.20), from the Colorado Plateau on the west to the Estancia basin to our east. Here we will discuss the age of the Sandia uplift, the La Luz Mine, and the formation of the Rio Grande rift.

The Sandia Mountains form the east flank of the Rio Grande rift and have long been viewed as a classic example of a rift-flank uplift, where surface uplift was driven by isostatic unloading of the footwall during Tertiary normal faulting associated with the Rio Grande rift (e.g., Kelley, 1982). However, these mountains are aligned with the eastern front range of the Rocky Mountain uplift that extends from Wyoming to New Mexico. For the Sandia Mountains, like the Rocky Mountains themselves, there is uncertainty whether uplift of rocks from sea level (at the end of the Cretaceous) to high elevations was mainly in the Laramide, mainly in the Neogene or some of each (Pazzaglia and Kelly, 1998). The origin of the "ramp" structure of Paleozoic and Mesozoic strata at the north

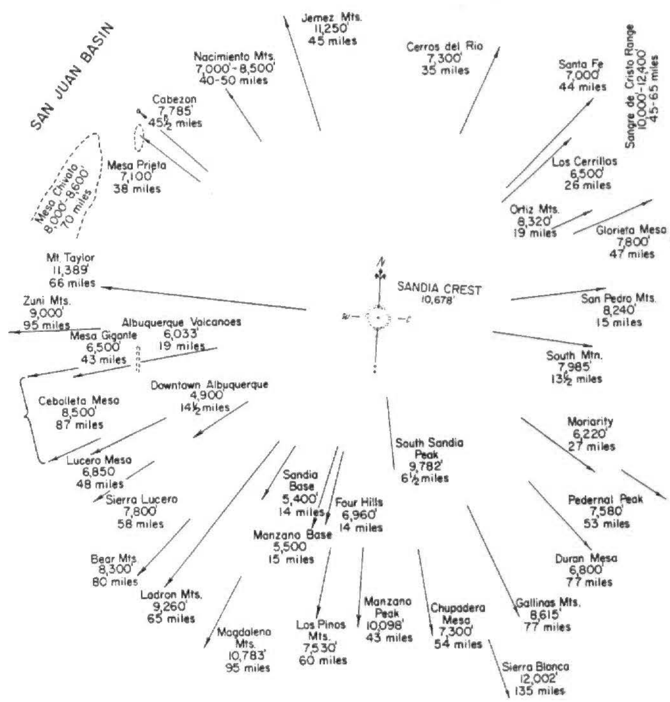


FIGURE 2.1.20. Panoramic index from Sandia Crest (from Kelley, 1969).

end of the Sandia Mountains also has similar uncertainty. Kelly (1982) proposed that it was middle Tertiary in age and formed as a relay ramp, due to transfer of extensional slip from the Rincon to San Francisco faults. This is a viable hypothesis, and it seems consistent with the interpretation of the low-angle nature of transfer faults and with the usual interpretation of the Sandia fission-track dates of 25 Ma as the time of uplift of the rift flank.

However, a second model is also possible whereby the ramp represents a preserved part of a north-plunging Laramide anticline analogous to the northern Nacimiento Mountains. In this model, the NE-trending Placitas (and related) faults are interpreted to initially have been right-steps (extensional jogs) in a Laramide right-lateral strike slip system, the "ramp" is a faulted anticline, and the fission-track ages record denudation and exhumation of the uplift out from under >1.8 mi of Mesozoic and Tertiary sediment at about 25 Ma. To resolve which of these models is correct, we need better evidence for the time(s) of movement on faults and for the original thickness, configuration, syntectonic(?) histories, and denudation histories of the sedimentary basins that are now only preserved as remnants in the Hagan, the San Juan, and related Rocky Mountain Laramide basins.

Unfortunately for this model, current understanding of Laramide sedimentation in north-central New Mexico does not support—indeed, it tends to refute—the presence of a Laramide high in the present location of the Sandia Mountains. Particularly significant is the basin analysis of the Galisteo Formation in the Hagan basin-Espinaso ridge area north of the Sandia Mountains (Gorham, 1979; Gorham and Ingersoll, 1979). Paleocurrent azimuths from the Galisteo indicate southerly (Sangre de Cristo source) and southeasterly (Nacimiento uplift source) paleoflow until uppermost Galisteo strata, when flow to the northwest began off of the rising Ortiz-Espinaso volcanic field. No paleoflow northward from a Laramide Sandia uplift is indicated by the Galisteo Formation. Thus, those who envision a Laramide Sandia uplift must ignore the evidence from nearby synorogenic sediments and build the uplift based on structural models and hypothetical fault movements.

The La Luz trail, which begins in Juan Tabo Canyon northeast of Albuquerque, ends here on Sandia Crest. The La Luz mine just south of Sandia Crest at 10,040 ft, was discovered in 1887 and produced lead and silver (with minor gold and copper) from a vein along a fault between the Sandia Formation and the Sandia Granite. The fault vein strikes N 23°W (Kelley and Northrop, 1975). This is one of several, mineralized, NW-striking structures present in the Sandia Mountains. Access to the mine was via a trail similar to the La Luz trail. Apparently the mine was originally named the Ruppe mine but was renamed the La Luz mine after the present trail was built.

The Rio Grande rift is the N–S graben exposed below us. The basal Paleozoic unconformity exposed near the crest of the Sandia Mountains (elevation of about 10,000 feet) is also exposed: (1) on the east Albuquerque bench at the foot of the mountains (in Juan Tabo and south of Embudo Canyon; elevation 6000 ft); (2) in Shell Santa Fe #1 drill hole, near Bernallio at minus 6000 ft; and (3) at depths of >25,000 feet in the southern Albuquerque (Shell Isleta #2). Thus, total throw on normal faults that bound the eastern part of the Rio Grande rift in the Albuquerque area exceeds 35,000 ft. The high elevation, pronounced tilt of the Paleozoic strata, and young fission-track ages of the Sandia Mountain segment of the rift shoulder all suggest that this segment has behaved differently than the Manzanita and Manzano segments to the south. May et al. (1994) suggest that this reflects enhanced isostatic rift flank uplift where the master extensional fault forms the east side of the Rio Grande rift.

End of Second-day Trip 1 road log.