Geology along a Margin of the Colorado Plateau and Rio Grande rift, north-central New Mexico: roadlog and field-stop discussions to accompany Field-trip #3 of the Rocky Mountain/South-Central sections annual meeting of the Geological Society of America in Albuquerque, New Mexico, April 20-27, 1991

prepared by

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ABSTRACT

Geomorphic and neotectonic features in the northwestern part of Española basin and Abiquiu embayment provide evidence of the long-term (past 8 m.y.) evolution of the Rio Chama/Rio Grande drainage system, and provide evidence that constrains the timing, magnitude, rate and kinematics of movement on rift-margin structures. Geomorphic evidence indicates that two periods of large-scale (hundreds of meters) base-level rise occurred within the study area (one coincident with the progradation and aggradation of the Pliocene Puye Formation; the other coincident with deposition of the Bandelier Tuff (1.5-1.1 Ma)). Periods of base-level rise alternated with three periods of large-scale fluvial incision (one during the late Miocene through Pliocene; another prior to deposition of the Bandelier Tuff (about 1.7-1.5 Ma); and the most recent during the mid- to late Quaternary (1.1 Ma to the present)). At least 6 inset Quaternary alluvial units, representing smaller-scale (tens of meters) cycles of aggradation and degradation, are superimposed on the mid- to late Quaternary period of incision.

Neotectonic analyses indicate that two general fault sets have formed since the late Miocene in the Abiquiu embayment. One fault set trends about N 15-32° E, the other N 68-75° E. Well-preserved fault-plane slickenlines indicate that the primary movement on most faults has been dip slip (average rake angle of slickenlines is 77-86° NE on fault plane) with only a minor component of left-lateral slip. However, one fault zone (Garcia) has a very small component of right-lateral slip (average rake of slickenlines is 84° SSW). On another fault zone, the Embudo, the low-angle rake of slickenlines (average of 33° NE) indicates predominantly strike-slip motion with relatively minor dip-slip motion on the NNE-trending segments of the Embudo fault zone. The Embudo fault zone is a major rift structure (accommodation zone) that

decouples the Española basin to the south from the Abiquiu embayment and San Luis basin to the north. Vertical displacement produced by faulting on the Embudo fault zone has a profound influence on the spatial distribution of erosion surfaces, rift sedimentation, and rift drainage evolution.

Tectonism appears to affect the formation and distribution of some geologic features (such as erosion surfaces and rift-sediment depots), particularly along the Cañones fault zone, which separates the Colorado Plateau from the Rio Grande rift, and across the Embudo fault zone. Volcanism appears to have initiated one period of base-level rise (deposition of the Puye Formation--although climate may have driven processes responsible for sediment production and transport), and been entirely responsible for a second period of base-level rise (coincident with deposition of the Bandelier Tuff). The role of climatic change on landscape evolution cannot be addressed fully owing to an absence of relevant paleoclimatic data for the region. However, we hypothesize that climate change accompanying Quaternary glaciations and deglaciations produced conditions that promoted episodic down-cutting by the Rio Chama, as expressed by the sequence of mid- to late Quaternary inset alluvial units. The inset alluvial units traverse major rift structures with no apparent change in their grade, indicating the inset units are not tectonic in origin.

INTRODUCTION

The Rio Grande rift in general and the Española basin in particular have been the focus of numerous field trips. Outstanding geologic exposures, a dynamic earth history, and a diversity of geologic processes and phenomena have made it an appealing place for geologists of varied backgrounds and interests to visit. Consequently, this trip retraces the routes of several field trips from which we have incorporated some information (duly noted) to augment this trip. In particular we have borrowed from the Guidebook to the Rio Grande rift of New Mexico and Colorado (J.W. Hawley (ed.), 1978); the 1979 and 1984 New Mexico Geological Society field conference guidebooks (Ingersoll et al. (eds.), 1979, and Baldridge et al. (eds.), 1984, respectively); road log of the Central Region Cluster Meeting of 1983 (J.W. Hawley, 1983); the 1987 Friends of the Pleistocene (Rocky Mt. Cell) field trip (C.M. Menges et al. (eds.), 1987); the 1989 field excursions run in conjunction with the General Assembly of the International Association of Volcanology and Chemistry of the Earth's Interior (Chapin and Zidek (eds.), 1989); and the scenic roadlog, <u>Española-Chama-Taos: A Climb Through Time</u> (Muehlberger and Muehlberger, 1982).

This field-trip log is a companion piece to an earlier manuscript (Gonzalez and Dethier, 1991), which represents our synthesis and geologic interpretations of geomorphic and neotectonic evolution along a margin of the Colorado Plateau and Rio Grande rift. This margin separates geologic provinces of distinctly different neotectonic history: the Colorado Plateau experiencing regional uplift and clockwise rotation (Aldrich and Laughlin, 1984; Zoback et al., 1981) while the Rio Grande rift has undergone regional uplift and crustal extension during the late Cenozoic. Along the Rio Chama valley and within the Abiquiu embayment, exposures of rift-margin structures, preservation of geomorphic surfaces, and intercalation of isotopically-dated volcanic rocks provide the means to unravel evolution of the Rio Chama/Rio Grande drainage system and the formation of this part of the rift.

This log provides directions to several localities where we found especially intriguing, puzzling, or illuminating features that figured heavily in our geologic interpretations. Our intent is to encourage future investigators to study these key localities and to relate them to geologic evidence garnered elsewhere in the rift.

Parts of this trip traverse privately-owned land. Access to stop 2 requires permission from the land-owner, who presently (1994) is Mr. Phil V. Sanchez of Española (telephone number (505)753-4828). Directions to the Sanchez residence appear in the roadlog between stops 2 and 3. In addition, the location of the Sanchez' residence is indicated in Figs. 1 and 7.

Ghost Ranch is owned and operated by the Presbyterian Church. Overnight accommodations and meals are available at Ghost Ranch with prior arrangements (telephone number (505)685-4333). Finally, stop 8, is located on a land grant, now subdivided into parcels of one or more acres. The features described at stop 8 are visible from public-domain roadways. Nevertheless, visitors should remember that property along the roadways is privately owned.

GEOLOGIC SETTING

The Rio Grande rift in northern New Mexico comprises four prominent, *en echelon*, asymmetric half-graben basins: the San Luis basin to the north, the Española basin, and the northern and southern Albuquerque-Belen basins to the south (Fig. 2). The San Luis and northern Albuquerque-Belen basins are eastward-dipping half grabens, whereas the Española basin and southern Albuquerque-Belen basins are westward-dipping half-grabens. Precambrian cored mountains (Sangre de Cristo and Sandia Mountains) with Paleozoic sedimentary rocks bound these basins to the east. The Colorado Plateau, consisting of upper Paleozoic through Mesozoic sedimentary rocks, bound these basins to the

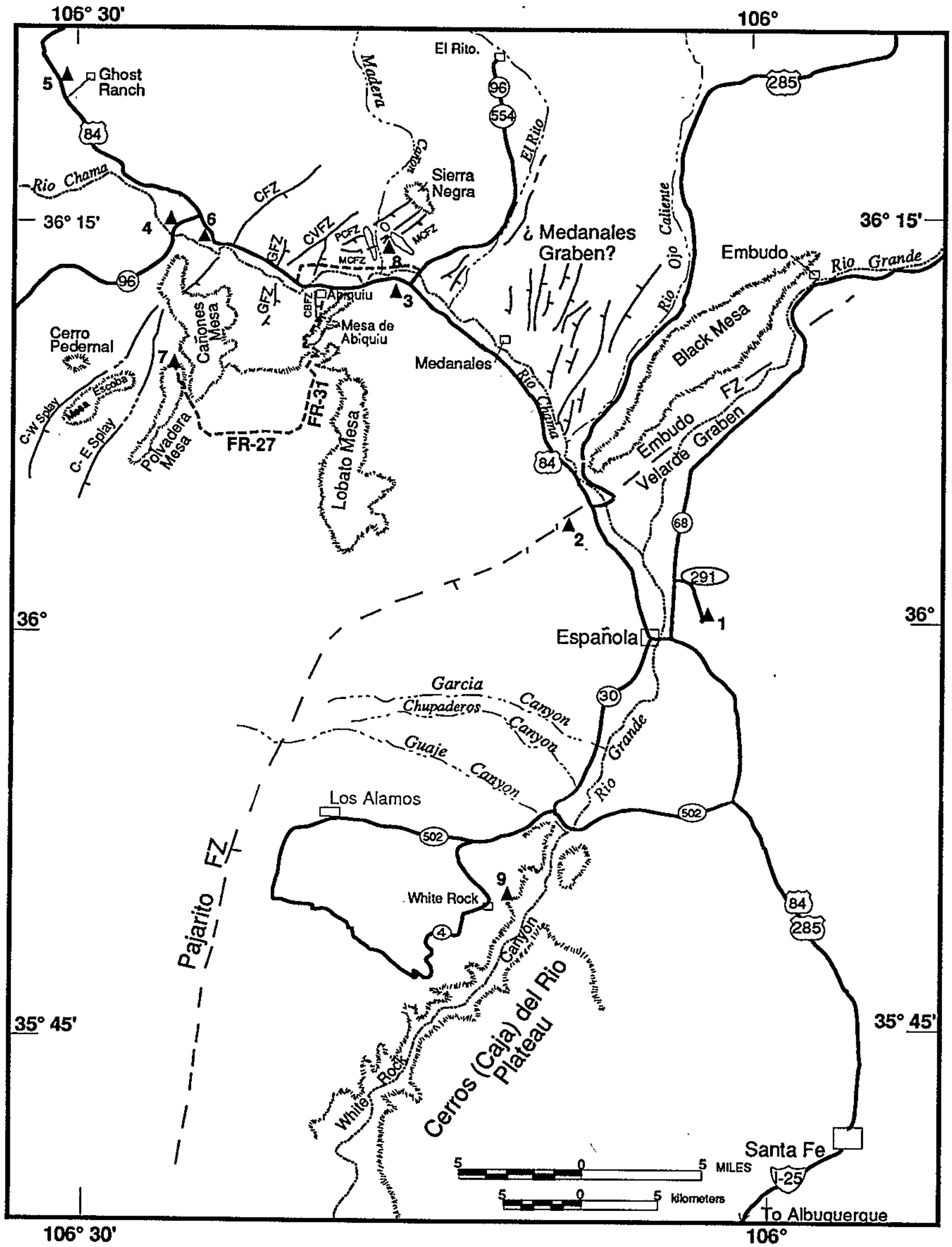
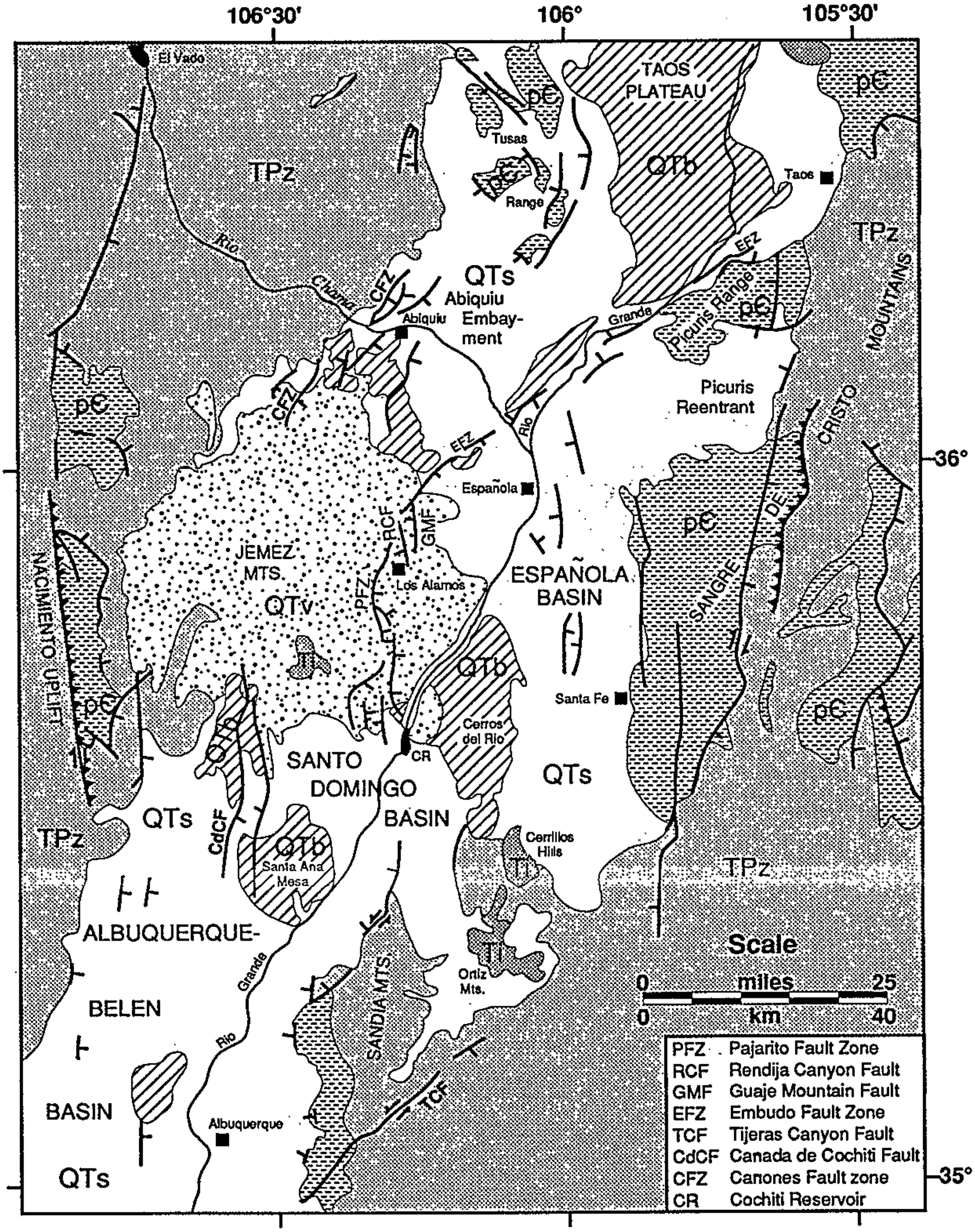


Figure 1. Location map showing the location of roadways, field-trip stops, and physiographic and geologic features found in the Española basin and Abiquiu embayment study area and cited in the text.

Figure 2. Generalized geologic map of the central Rio Grande rift of northern New Mexico (modified from Baldridge et al., 1983).



QTs — Miocene (24 Ma) and younger sedimentary rocks with Quaternary alluvium along streams and fan deposits near mountain fronts.

QTv — Miocene (24 Ma) and younger, silicic to intermediate, volcanic rocks and volcaniclastic deposits.

QTb — Miocene (24 Ma) and younger tholeiitic and alkali basalts.

Ti — Tertiary Intrusions.

TPz — Oligocene and older Phanerozoic sedimentary rocks.

pЄ — Pre-Cambrian crystalline rocks.

Thrust fault with barbs on upthrown side.

High-angle fault with ticks on downthrown side

Fault with transcurrent motion

west, except where the Jemez volcanic field defines the western border for much of the Española basin. The Precambrian cored Tusas Mountains (Brazos uplift) form the northwestern boundary of the Abiquiu embayment. The Abiquiu embayment has been treated as sedimentary and topographic parts of the northwestern Española basin, but in a tectonic sense serves as the southwestern hinge of the San Luis basin, separated from the adjacent Española basin by the Embudo fault zone (e.g., Muehlberger, 1979). The Embudo fault zone acts as an intra-continental transform fault between the San Luis and Española basins (Muehlberger, 1979) with a scissors-like motion accommodating change between the eastward and westward dipping basins (Kelley, 1978).

The stratigraphy of the Española basin, Abiquiu embayment, and the adjacent part of the Colorado Plateau is summarized in Fig. 3. Early Tertiary sediment comprises the Eocene El Rito Formation (Laramide basin fill?) and Oligocene to early Miocene Abiquiu Formation (earliest rift-fill sediment?; Abiquiu Tuff of Smith, 1938). Later rift-fill sedimentary strata include the Miocene Chama-El Rito and Ojo Caliente Sandstone (of Galusha and Blick, 1971) of the Tesuque Formation, the Miocene Chamita Formation, and Pliocene Puye Formation. Volcanic rocks emanating from the Jemez volcanic field include the Miocene Lobato and Pliocene El Alto basalts, the upper Miocene to Pliocene Tschicoma Formation (primarily dacite); the Pliocene Cerros del Rio flows (intermediate to mafic lavas), and the early Quaternary Bandelier Tuff, subdivided into lower (Otowi) and upper (Tshirege) Members (Doell el al., 1968; Bailey et al., 1969; Smith et al., 1970; Baldridge et al., 1980; Gardner and Goff, 1984; Fig. 3). Seminal sedimentary/stratigraphic studies in the Española basin include Galusha and Blick (1971), Manley (1976a, 1979), May (1980), and Ingersoll et al. (1990).

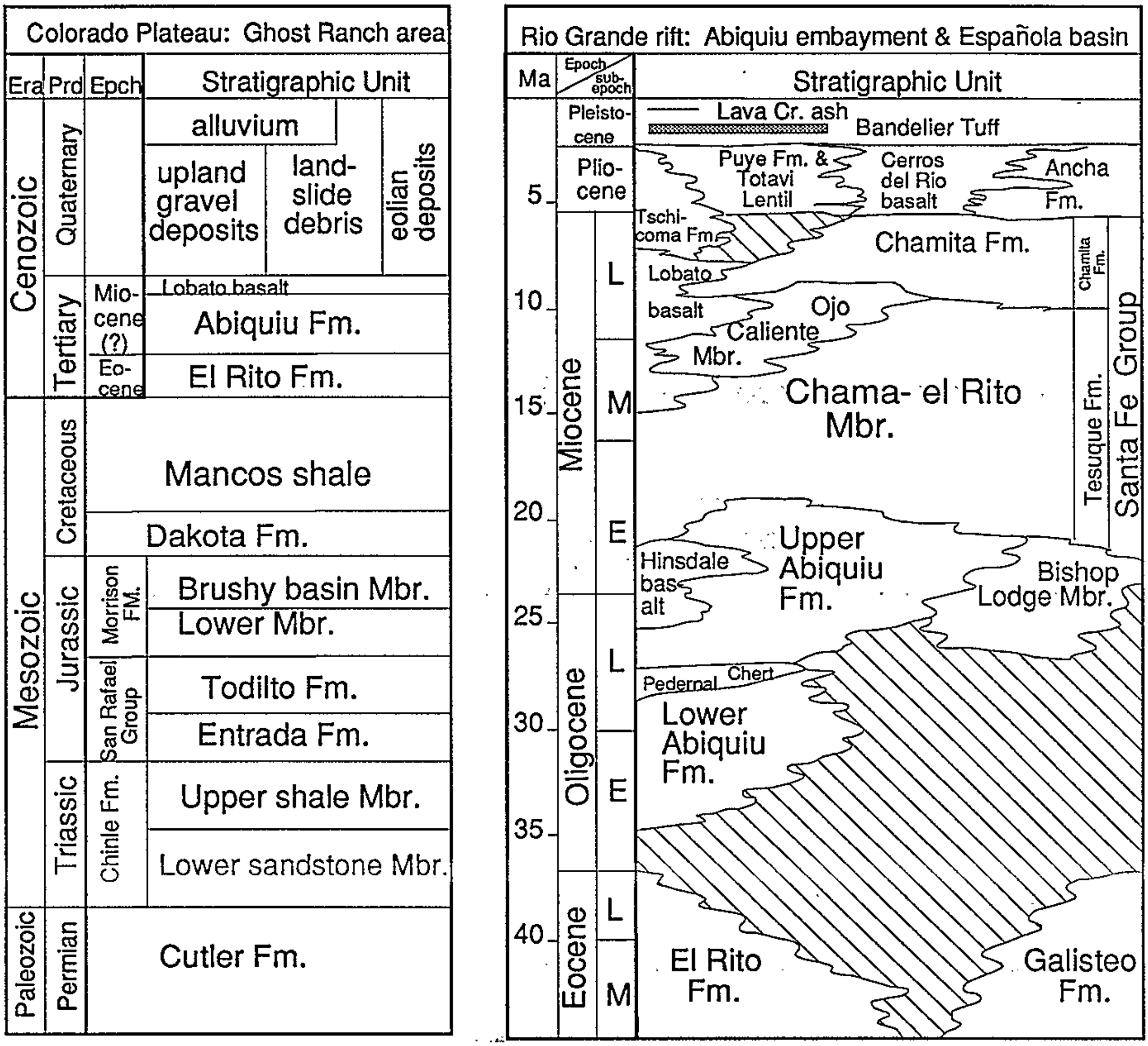


Figure 3. Generalized stratigraphic columns of the southeast margin of the Colorado Plateau (after Smith et al., 1961), the Abiquiu embayment, and the eastern and northern flank of the Jemez Mountains of the Española basin (after Ingersoll et al., 1990; Gardner and Goff, 1984; Aldrich and Dethier, 1990).

The study area spans a 100-km reach of the Rio Chama and Rio Grande valleys, extending from Ghost Ranch on the Rio Chama, past the confluence of the Rios Chama and Grande and downstream through White Rock Canyon and the Pajarito Plateau. The Rio Chama and Rio Grande valleys, situated on the north and east flanks of the Jemez Mountains, contain a wealth of geomorphic information, providing a basis for reconstructing the evolution of these drainages. Isotopically-dated volcanic rocks, intercalated with alluvium or burying ancient geomorphic surfaces, provide a valuable temporal framework for this reconstruction. Rift-margin faults, exposed at the earth's surface in many places, contain kinematic information about rifting. Topographic offset of strata across faults provides information on the timing, rate and magnitude of rift faulting in the area. This roadlog provides directions to some of the localities we have studied to reconstruct the geomorphic and neotectonic history of this rift-margin.

Mile-age	Roadlog
000.0	Begin mileage in Española at the intersection of U.S. Highways 84 and 285 **(US-84/285)** and **US-64** and New Mexico State Highway 68 **(NM-68)**. Proceed north on **US-64/NM-68** towards Velarde and Taos. **1.5**
1.5	Fairview: intersection with **NM-584** to the left (west) and **NM-583** to the right (east). Continue straight ahead (north) on **US-64/NM-68**. **1.25**
2.75	Ranchitos: turn right (east) onto **NM-291**. Follow **NM-291** for 1.8 miles, at which point you will find some low hills to the left (east) of the road. The tops of these hills are composed of Pleistocene age Rio Grande axial-stream deposits with overlying eolian sediment and soil profiles. **1.8**
4.55	Turn left onto a <u>gravel</u> road, which veers off of **NM-291** and heads straight towards a large round water tank located at the base of some hillslopes. **0.3**
4.85	Arrive at water tower (City of Española, New Mexico, written on the side). Park here (or drive along earthen roads to the higher water tank) and set out on foot to explore exposures of the Española Forma-

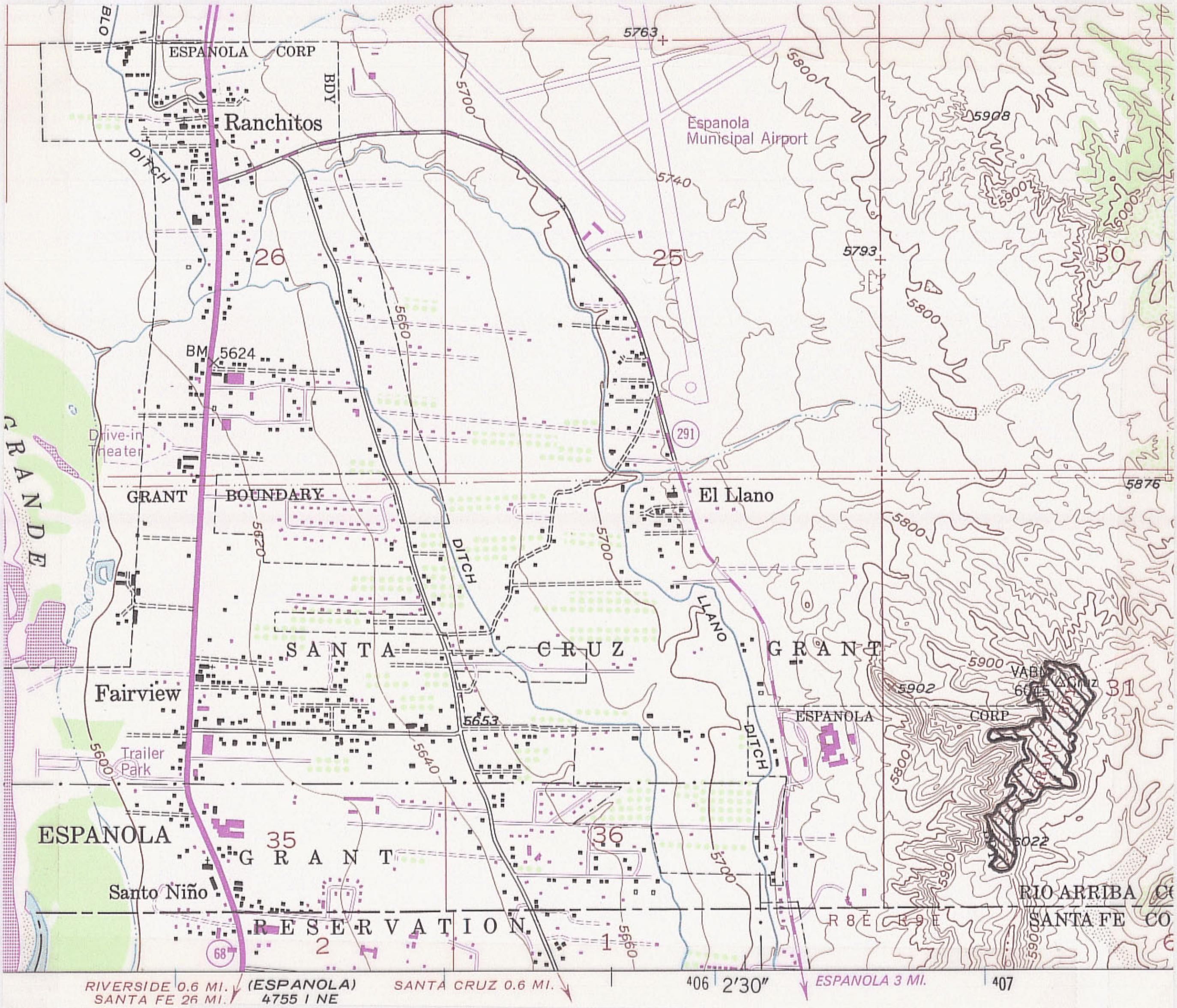
tion of Galusha and Blick (1971). Climb to the crest of the ridge east of the higher water tank and then hike 300 m to the east along a series of small crests and troughs cut across sediment of the Santa Fe Group. The Española Formation is exposed best on a north-trending ridge that separates the Española valley from Arroyo del Llano (see Fig. 4).

Stop 1: Española Formation east of Española High School

At this locality fluvial and eolian deposits that compose the Española Formation of Galusha and Blick (1971) unconformably overlie upper Miocene rocks (Tesuque or Chamita Formation). We have not mapped the Miocene rocks here, but they consist mainly of thick-bedded to massive silty sand and sand, thin beds of gravelly sand, and beds of altered tephra, including one basaltic ash bed. Love et al. (1987) mapped these rocks in nearby areas and provide detailed lithologic descriptions of the unit and of the local geology.

The Española Formation forms a cap 5 to 13 m thick on this and nearby mesas and consists of a lower fluvial and colluvial unit separated by a buried soil from overlying eolian dune deposits (Fig. 5). Vertebrate remains (Canus dirus and others reported by Love et al., 1987) in the fluvial unit suggest a middle or late Pleistocene age. We have not described the buried soil, but its carbonate morphology (Stage III in non-gravelly parent material) suggests several tens of thousands of years, at least, to possibly a few hundred thousand years of carbonate accumulation (Gile et al., 1981).

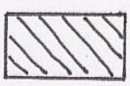
The eolian unit consists of dune sand and inter-dune silty sand enclosing buried A-C soil profiles. Coarse silt and very-fine sand comprise 10% to 30% of the dunes and 25% to 45% of the inter-dune deposits (D.P. Dethier, unpublished data, 1988). The silty sand contains relatively abundant gastropod (Succinea and Vallonia) and vertebrate remains. We have dated the gastropods at 19.1 ± 0.2 ka (University of Toronto, TO-1474) using



Scale: 1:24,000 (1 inch = 2000 feet)

Contour Interval 20 feet

Figure 4. Detailed map indicating the location of deposits examined at stop 1. Base map is the southeast corner of the San Juan Pueblo quadrangle.



Location of Quaternary deposits examined at stop 1

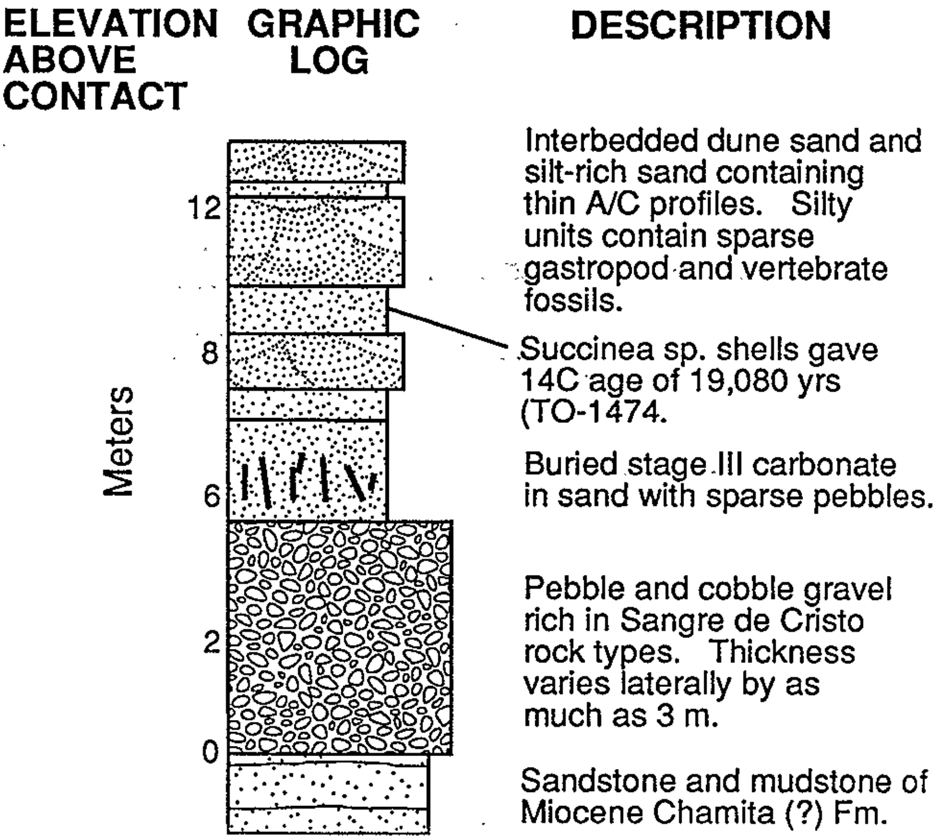


Figure 5. Generalized stratigraphic column depicting the late Pleistocene deposits located near the Española high school (stop 1).

accelerator-mass spectrometry techniques and have analyzed the isoleucine/alloisoleucine content (amino-acid D/L ratio) of Succinea and Vallonia shells from several different collection sites. The D/L ratios give an average value of 0.14 for the free fraction and 0.10 for the hydrolysate, both typical of ratios from latest Pleistocene deposits (McCoy, 1987; Dethier and McCoy, 1993). These data demonstrate that dunes were active at about 19 ka, suggesting that vegetative cover was sparser, winds stronger, and sediment supply closer than at present. The relative abundance of fine material indicates that löess was deposited during and between dune-building events. None of these data suggest whether the eolian deposition occurred during a cold, hot, or transitional climate. They are consistent with inferences about a broad meander belt (braid plain?) along the Rio Grande during the latest Pleistocene period of high discharge (Love et al., 1987). We interpret this evidence to suggest that the upper Española Formation was deposited during or soon after a period of high water and sediment discharge in the Rio Grande at about 19 ka.

4.85 Retrace route back to Fairview via Ranchitos. Begin with return to NM-291. **0.3**

5.15 Turn right (north) onto **NM-291** and head for Ranchitos. **1.8**

6.95 Turn left (south) onto **NM-68** and head for Fairview. **1.25**

8.2 Fairview: Turn right (west) onto **NM-584**. This road will cross the Rio Grande on the Phil I. Valdez bridge. **0.4**

8.6 Highway crosses the Rio Grande. Continue ahead on **NM-584**. **0.85**

9.45 At stoplight turn right (north) onto **US-84/285** toward Ojo Caliente and Chama. The highway passes through a series of roadcuts that expose the alluvial stratigraphy beneath the Q4 surface of Dethier and Harrington (1987) and Dethier et al. (1988). **1.2**

10.65 Highway passes through the biggest of the roadcuts, providing the best exposure of Q4 sediments. This roadcut was a field stop during the 1987 Friends of the Pleistocene field trip. Uranium-series disequilibria, amino acid and varnish-cation ratio data have been collected from this roadcut and are reported in Dethier and Harrington (1987) and Dethier et al. (1988). **2.2**

12.85 **Milepost 194**: Black Mesa is visible at 1:00 to 2:00. Black Mesa is capped by a basalt flow (2.78 ± 0.44 Ma; Manley, 1976b), which appears to have flowed down an ancestral channel of the Rio Grande. The basalt flow buries alluvial deposits and the T4 surface (Fig. 6B). **0.25**

13.1 School crossing. Please observe the traffic lights when they are operating. **0.25**

13.35 Turn left (west) onto a paved, blacktop road leading to the San Jose Church. View to the east was made famous by Ansel Adam's 1943 photograph--"Moonrise over Hernandez". **0.1**

13.45 Enter the parking lot of the church and turn right (north). Cross parking lot and enter an earthen roadway. Follow the earthen roadway as it makes a sharp left and proceed west along the north side of the San Jose Church and the San Jose Cemetery. The road ends at a locked gate. To continue on to stop 2 obtain permission to enter private land from Mr. Phil V. Sanchez, telephone number (505)753-4828. Mr. Sanchez also has the key to open the locked gate. The Sanchez residence is indicated in Figure 7. **0.2**

13.65 Pass through the gate, turn left (south), and continue along parallel to the overhead powerlines. **0.5**

14.15 Road way approaches an arroyo and turns to the right (west) to follow the left bank (as judged by looking downstream) of the arroyo. **0.2**

14.35 Road makes a horseshoe turn to the right and begins to climb out of the valley and onto remnants of Q3 and Q2 erosion surfaces (of Dethier et al., 1988). **0.2**

14.55 Road reaches the Q3 erosion surface and turns left (west). **0.5**

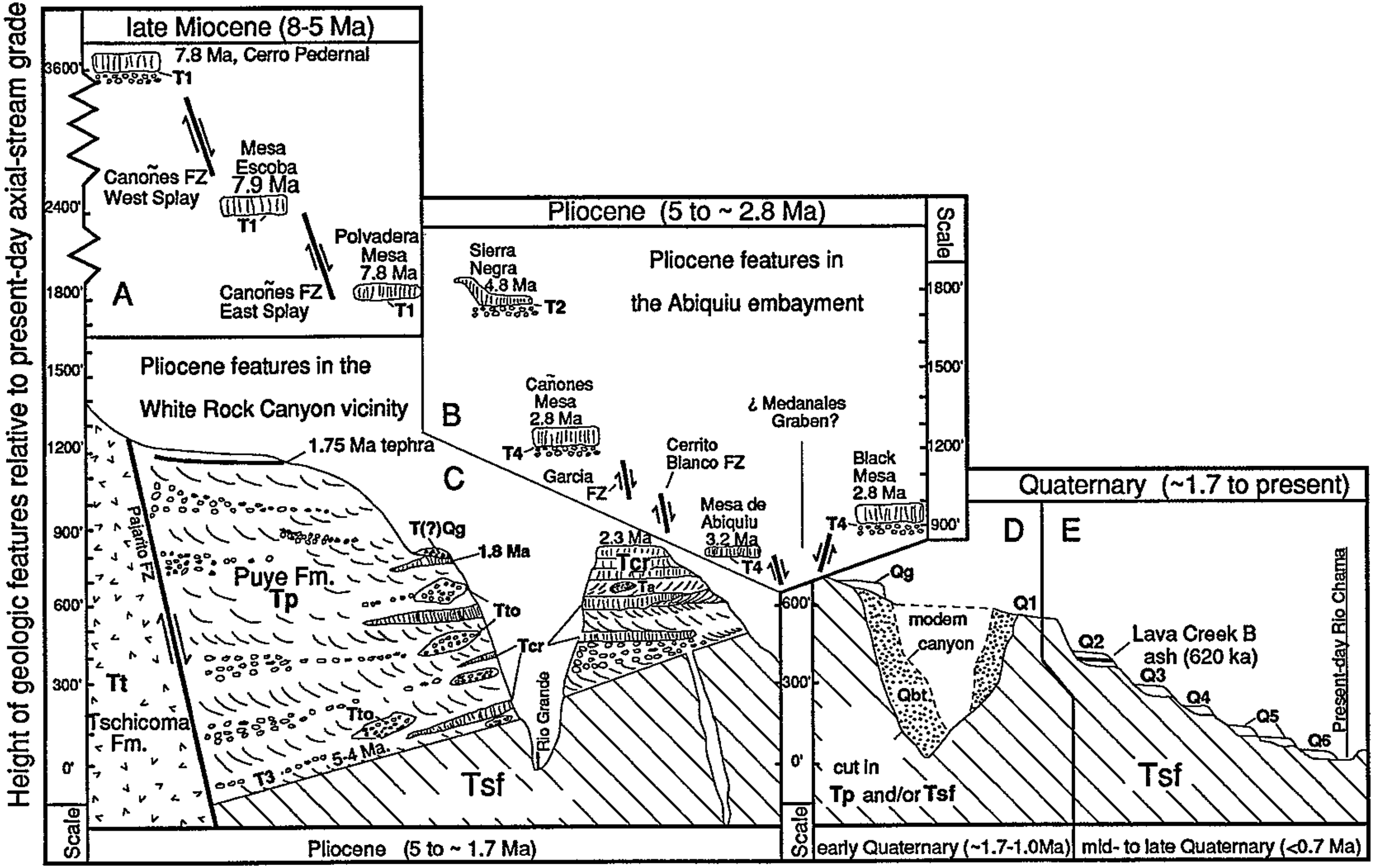
15.05 Begin climb up from the Q3 to the Q2 erosion surface. **0.5**

15.55 Roadway reaches its highest point on the Q2 erosion surface, although there are remnants of the Q1 erosion surface another 20-30 m (60-100 ft) higher in elevation on the left (south) side of the road. **0.1**

15.65 Faint wheel tracks diverge to the left. Stay straight on the main path. **0.7**

Figure 6. A schematic diagram illustrating the position (relative to present-day axial-stream base level) of late Cenozoic features found along the margin of the Rio Grande rift from Ghost Ranch to White Rock Canyon. **Panel A** depicts features formed during the late Miocene and subsequently offset by faulting. Note the break in scale for panel A. **Panels B and C** depict geologic features formed during the Pliocene and subsequently offset by faulting and tilting. **Panel B** highlights paleo-base-level features in the Abiquiu embayment, while **panel C** illustrates those features in the western Española basin, including (i) burial during the Pliocene of unit T3 (basal Totavi Lentil) by progradation of the Puye fan; and (ii) west-tilting of rift-fill sediment in the Española basin by Pliocene (and Quaternary) faulting along the Pajarito fault zone. The contrast between Pliocene base-level fall in panel B and overall Pliocene base-level rise in panel C illustrates the control of intra-rift tectonism (i.e., movement on the Embudo and Pajarito fault zones) on the geomorphic evolution of the Española basin. **Panel D** shows early Quaternary geomorphic evolution in the study area, specifically a period of early Quaternary (pre-Bandelier) incision to form canyons, and the period of early Quaternary (Bandelier) aggradation to back-fill the recently-carved canyons. **Panel E** illustrates a mid- to late Quaternary period of incision, which re-excavated canyons to form the present-day system of drainages along the flanks of the Jemez Mountains, and the flight of mid- to late Quaternary terraces, Qg, Q1-Q6, found along the axial and tributary drainages (revision of Gonzalez and Dethier, 1991).

Symbol	**Unit/Formation**	**Symbol**	**Unit/Formation**
Q6	inset alluvium	T4	Neogene alluvium
Q5	inset alluvium	Tp	Puye Formation
Q4	inset alluvium	Tto	Totavi Lentil
Q3	inset alluvium	T3	Neogene alluvium
Q2	inset alluvium	Ta	Ancha Formation
Q1	inset alluvium	Tcr	Cerros del Rio basalt
Qg	upland gravel	T2	Neogene alluvium
Qbt	Bandelier Tuff	T1	Neogene alluvium
T(?)Qg	upland gravel	Tsf	Santa Fe Group



Height of geologic features relative to present-day axial-stream grade
late Miocene (8-5 Ma)
7.8 Ma, Cerro Pedernal
T1
Cañones FZ
West Splay
Mesa
Escoba
7.9 Ma
T1
Polvadera
Mesa
7.8 Ma
Cañones FZ
East Splay
T1
A
3600'
2400'
1800'
1500'
1200'
900'
600'
300'
0'
Scale
Pliocene (5 to ~ 2.8 Ma)
Pliocene features in
the Abiquiu embayment
Sierra
Negra
4.8 Ma
T2
B
Cañones
Mesa
2.8 Ma
T4
Garcia
FZ
Cerrito
Blanco FZ
Mesa de
Abiquiu
3.2 Ma
T4
¿ Medanales
Graben?
Black
Mesa
2.8 Ma
T4
Pliocene features in the
White Rock Canyon vicinity
1.75 Ma tephra
C
T(?)Qg
1.8 Ma
Tto
Tcr
Puye Fm.
Tp
Pajarito FZ
Tt
Tschicoma
Fm.
Tto
5-4 Ma.
T3
Rio Grande
Tsf
2.3 Ma
Tcr
Ta
Pliocene (5 to ~ 1.7 Ma)
Quaternary (~1.7 to present)
D
E
Qg
Q1
modern
canyon
Qbt
cut in
Tp and/or Tsf
Q2
Lava Creek B
ash (620 ka)
Q3
Q4
Q5
Q6
Present-day Rio Chama
Tsf
early Quaternary (~1.7-1.0Ma)
mid- to late Quaternary (<0.7 Ma)

16.30 Cross an open grassy area and park in the saddle between two low hills. Follow the large-scale location map (Fig. 7) to stops 2A-2D. 2A is another 20-30 m farther down the road. The first roadcut to the left (south) side of the road contains a well-developed soil with Stage III+ carbonate. A NNE-trending segment of the Embudo fault zone crosses the roadway in this vicinity. For the remainder of stop 2, follow the large-scale map (Fig. 7) to localities discussed in the ensuing text.

Stop 2: Mid-Quaternary surfaces and faults along the Embudo fault zone, Arroyo de la Presa

The Embudo fault zone is most clearly exposed along the south side of the Arroyo de la Presa within about 3 km of US-84. Miocene sedimentary rocks and basalt flows and Pliocene (?) rocks south of the fault zone dip steeply to the south or west and are overturned locally. The Ojo Caliente Sandstone of the Tesuque Formation and the lower Chamita Formation crop out north of the fault zone (Dethier and Manley, 1985; Aldrich and Dethier, 1990), but are not exposed to the south.

Two basalt flows are intercalated with beds of the Chamita Formation. The stratigraphically lower flow, near the base of the Chamita Formation has yielded potassium-argon dates of 12.4 ± 0.4 Ma (UAKA 85-07) and 11.9 ± 0.3 Ma (UAKA 85-09; Dethier et al., 1986; Aldrich and Dethier, 1990). The younger flow has yielded potassium-argon dates of 9.93 ± 0.20 Ma (UAKA 85-06; Dethier et al., 1986; Aldrich and Dethier, 1990) and 9.9 ± 1.0 Ma (Manley and Mehnert, 1981). These flows appear in outcrops north of the Embudo FZ, but not to the south. Also, the attitude of these flows provides a valuable reference to measure tilting and deformation along the Embudo FZ.

The Embudo FZ appears to be an accommodation zone running along the trace of the Jemez Lineament from the Jemez volcanic field to the Taos Plateau. It is an important fault that:

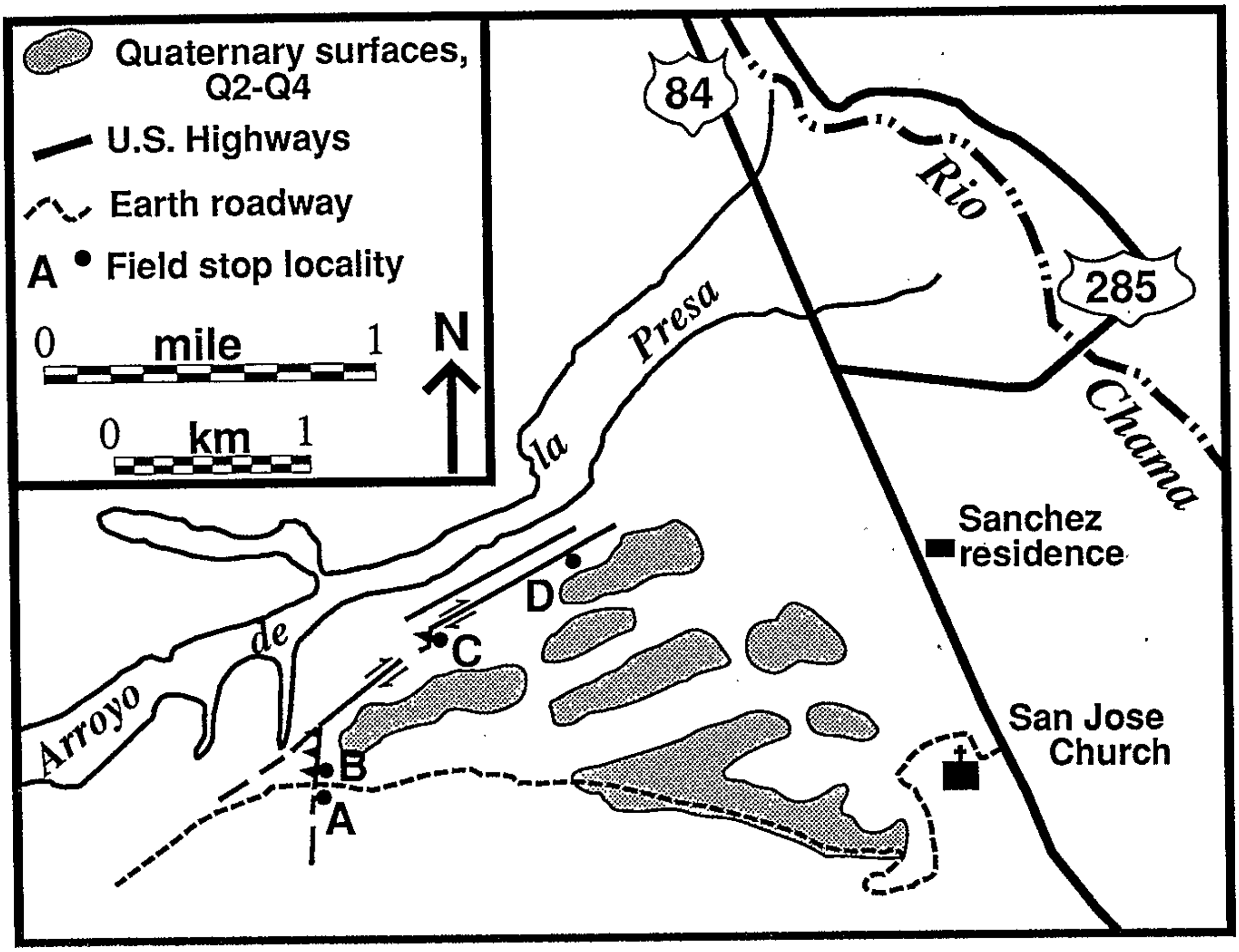


Figure 7. Sketch map indicating the location of outcrops and geologic features examined at field-stop 2 along the Embudo fault zone in Arroyo de la Presa.

(1) Bounds, in part, the Velarde graben, the deepest part of the Española basin (Manley, 1979).

(2) Appears to connect to the Pajarito FZ, which is the present, tectonically-active western-margin of the Española basin (cf. Gardner and Goff, 1984).

(3) Structurally divides the Española basin to the southeast from the shallower Abiquiu embayment (southwestern hinge of the San Luis basin?) to the northwest (cf. Baldridge and Jiracek, 1992).

(4) Accommodates the right-echelon step between the Española and San Luis basins of the Rio Grande rift (Muehlberger, 1979), and perhaps differences in extension rates north and south of the Jemez Lineament (Aldrich, 1986).

A diversity of fault types, including high-angle normal, high-angle reverse, and oblique- or strike-slip faults compose the Embudo FZ along Arroyo de la Presa. Fault segments occur in two general sets: a main set trending ENE with left-stepping *en echelon* segments, linked by a set of right-stepping *en echelon* NNE-trending fault segments (Fig. 7). Stratigraphic relations of Miocene and Pliocene sedimentary strata indicate that the area south of the fault has moved downward relative to the area north of the fault. However, this vertical offset **may** be minor relative to lateral or oblique slip although we have not identified piercing points to calculate horizontal and vertical amounts of movement on these fault segments.

Besides normal dip-slip, and strike-slip faulting, some evidence exists of local compression along this zone (also see Aldrich, 1986). NNE-trending fault segments generally have high-angle reverse faults bordered by a zone of steeply-dipping to overturned bedding that is tens to hundreds of meters wide.

Some beds contain discontinuous parasitic S and Z folds, which indicate NNE vergence in strata north or west of fault segments, and SSW vergence in units south or east of fault segments. Steeply-dipping beds (>70° to overturned) are also found on the south side of ENE-trending fault segments in some places. Immediately north of ENE-trending segments, the bedding dips less steeply to the southeast (approximately 8-30° SE; Dethier and Manley, 1985).

Alternatively, these features may have formed from extension. R.M. Chamberlin (pers. comm., 1991) suggested that tilting of footwall (in present-day orientation) sediment may have resulted from large-scale drag produced by hundreds of meters of throw on the Embudo FZ. Rotation of normal faults to and beyond vertical by such footwall deformation would then make some normal faults appear to have reverse sense of motion.

Resolution of these alternative hypotheses may require: (1) geophysical exploration of the subsurface through seismic profiles to determine the subsurface geometry of the Embudo FZ, and the amount of structural relief between the Abiquiu embayment and the Española basin; and/or (2) analysis of mesoscopic structural features that distinguish footwall deformation through extension (i.e., drag folding) from footwall deformation through compression (i.e., reverse faulting, and tilting of sedimentary beds to 70° and even overturned in places).

The geometry of the few, discontinuous fault exposures visible suggests that the ENE-trending segments of the Embudo FZ through the Arroyo de la Presa watershed may be a dextral strike-slip (or oblique-slip) fault with discreet areas of compression (Fig. 7). The low-angle rake (about 33° from the NE) of slickenlines (aligned mineral growths, grooves) suggests left-lateral slip on NNE-trending fault segments.

Arroyo walls at stops 2B and 2C (see location map, Fig. 7) contain exposures of these apparent high-angle reverse faults. High-angle normal faults occur within several meters on both sides of the apparent reverse fault at stop 2B. At stop 2C the apparent high-angle reverse fault truncates a paleo-channel containing imbricated gravel and cobble clasts of the Puye Formation, indicating Pliocene (or younger) activity on this segment of the fault zone (Aldrich, 1986). At stop 2D steeply dipping beds (> 70° near an ENE-trending fault gradually shallow within tens of meters distance to the south of the fault.

The sequence of deformed rocks south of the fault is truncated by an apparently undeformed bed of Rio Chama cobble gravel, which is overlain with a section of fluvial sand containing nearly pure lenses of the Lava Creek B tephra. Most of the tephra, erupted from the Yellowstone caldera at 620 ka (Sarna-Wojcicki et al., 1987), occurs within the basal 3 m of the sand, which is 6 to 12 m thick here and capped with a boulder gravel rich in basaltic clasts. We interpret the sand as a section of an alluvial fan that prograded across 300 m of the Rio Chama floodplain soon after deposition of the Lava Creek B tephra at 620 ka. Two lithologically similar fan/floodplain sequences are exposed at lower elevations between this location and the modern Rio Chama. At least one similar sequence is exposed at higher elevations to the west.

The top of the gravel deposited by the ancestral Rio Chama is at an elevation of about 110 m above the modern floodplain here and lies beneath the Q2 erosion surface (of Dethier et al., 1988). Deformation of the paleo-surface defined by the Lava Creek B tephra cannot be documented in this area. The nearest exposures of the tephra are 3 km to the south and more than 10 km to the north (Dethier et al., 1990). North-trending faults cut the Chamita Formation beneath the ancestral Rio Chama gravel, but apparently do not deform the gravel.

At this location, the Lava Creek B tephra is almost a pure glass that consists mainly of bubble-wall fragments between 50 and 300 microns in diameter. The grayish-white tephra is locally cemented with $CaCO_3$, and most exposures are riddled with modern burrows, making it difficult to collect "pure" samples. Electron microprobe analysis (Table 1) shows that the Lava Creek B ash bed in the Española basin is chemically distinct from other widespread ash beds. Calcium content and stratigraphic position distinguish the Lava Creek B from the Huckleberry Ridge ash bed that was also erupted at Yellowstone, but at 2.2 Ma (Table 1). We have not found the Huckleberry Ridge ash locally but have mapped the Lava Creek B at some two dozen locations between this site and Abiquiu (Dethier et al., 1990).

16.30 Turn around and retrace the route back to San Jose Church and US-84. **2.65**

18.95 Gate behind San Jose Church. **0.3**

19.25 Turn left (north) onto **US-84/285**. **0.65**

19.9 Driveway to the Sanchez' residence (marked by black wrought-iron gate with the name Sanchez). The Sanchez own the property which must be crossed to visit stop 2. **0.5**

20.4 Routes of **US-84/285** bifurcate. Continue straight ahead (north) on **US-84**. **0.65**

21.05 Bridge over Arroyo de la Presa; Black Mesa looming in near horizon at 2:00. **1.35**

22.4 Roadcut exposes a basalt flow. This flow is intercalated with the basal Chamita Formation. Samples collected from the west side of the roadcut yielded K-Ar dates of 8.3 ± 2.4 Ma (USGS-77-9-30-1; Manley and Mehnert, 1981) and 9.6 ± 0.2 Ma (UAKA-77-81; Baldridge et al., 1980). **1.05**

TABLE 1: Comparison of major-element chemistry of glass from the Rio Chama tephra to the chemistry of some other widespread tephra layers by means of electron microprobe (from Dethier et al., 1990).[1]

Tephra	SiO_2[2]	Al_2O	Fe_2O_3	MgO	MnO	CaO	TiO_2	Na_2O	K_2O	Total
Rio Chama[3]	76.63	12.30	1.56	0.02	0.03	0.53	0.12	3.54	4.97	93.11
ash bed	0.09	0.04	0.04	0.01	>0.01	0.01	0.01	0.05	0.02	0.25
Lava Creek B[4]	76.60	12.41	1.57	0.02	0.03	0.54	0.11	3.57	5.16	94.28
ash bed	0.32	0.19	0.05	0.01	0.02	0.02	0.01	0.10	0.15	0.33
Huckleberry	76.45	12.33	1.76	0.02	0.04	0.61	0.13	3.49	3.16	94.55
Ridge ash bed[4]	0.24	0.12	0.07	0.01	0.01	0.05	0.01	0.14	0.15	0.51
Bandelier Tuff	72.70	12.80	1.47	0.05	0.08	0.33	0.08	3.08	5.36	95.95
Upper	73.60	11.90	1.40	0.10	0.07	0.24	0.04	4.36	4.61	96.32
Lower										
Bishop ash bed	77.55	12.64	0.74	0.04	0.03	0.45	0.06	3.70	4.78	94.02
	0.20	0.22	0.03	0.01	0.01	0.03	0.01	0.18	0.24	0.75
A.E.[5]	1.3%	2.2%	6.4%	6.6%	15.0%	6.2%	17.4%	3.9%	4.2%	

1 From Sarna-Wojcicki et al. (1987), except for Bandelier Tuff analyses, which are from Gardner et al. (1986). Values given are in weight-percent oxide, recalculated to 100% on a fluid-free basis. Original oxide totals before recalculation are given to indicate the approximate degree of hydration of glass. Approximately 15 individual shards were analyzed for each sample, except for Bandelier Tuff, C.E. Meyer, analyst.

2 Values in percent ±1 st.dev., except for Bandelier analyses, which do not include 1 sigma values.

3 Mean of samples from 4 sites.

4 Average of 7 samples.

5 Average analytical error, calculated from average of concentrations of the shard population (except Bandelier Tuff), expressed as a percentage obtained by dividing standard deviation for each element by the average concentration of that element, multiplied by 100.

23.45 **Rio del Oso bridge**: To the right are two fins or ridges composed of a well-cemented Ojo Caliente Sandstone. The cement appears to have come from groundwater that ascended along fracture and/or fault zones, percolated into the surrounding country rock, and precipitated cementing minerals in the porous rock. With subsequent valley incision and erosion, the cemented zones have been exhumed and stand in relief. **0.7**

24.15 Remnants of units Q2 to Q5 are abundant and well expressed to the left (west) of the roadway for the next 10 miles. **3.55**

27.7 Junction with **NM-233** to Medanales, continue straight ahead on **US-84**. Across the Rio Chama to the right (north) is the region studied by S.J. May (1980) as part of his dissertation research completed at the University of New Mexico.

Note to the left a remnant of unit Q2 in which an erosional scarp has exposed a deposit of Lava Creek B ash (a Yellowstone-derived ash dated at 620 ka). The hillsides in this area comprise the Ojo Caliente Sandstone, a porous unit on which Ponderosa pines have colonized. Conventional paleoecological arguments have maintained that the Ponderosa pine is found at 7000 feet elevation or higher under the present climatic conditions (e.g., Martin, 1964). The presence of these Ponderosa pines at 6000 feet elevation indicates that geologic factors that can affect soil moisture content can greatly control the distribution of vegetation, making such general paleoecological inferences suspect. **1.65**

29.35 Bridge crossing La Madera Arroyo. **1.8**

31.15 The highway roadcuts for the next 0.5 miles provide excellent exposures of inset axial-stream (Rio Chama) sediment that compose units Q4 and Q5. **1.6**

32.75 Junction with **NM-554** (marked as NM-96 on older maps). Continue west on **US-84**. **1.35**

34.1 Turn left (south) into the parking lot and the trailhead to Poshuouinge, an archeological ruin. A short walk of a few hundred meters takes one up the hillside to the surface of unit Q5 where there are remnants of a ruin occupied by the Tewa people from 1400-1500 A.D. Follow the trail for another few hundred meters, climbing onto a remnant of unit Q3 from where there is a commanding 360° view of Tertiary and Quaternary surfaces of the lower Rio Chama valley.

Stop 3: Examination of Quaternary erosion surfaces, deposits, and the Lava Creek B ash

Arroyos draining the northeastern flank of Lobato Mesa expose as many as five inset mid- to late Quaternary deposits above the Rio Chama (Fig. 8). A

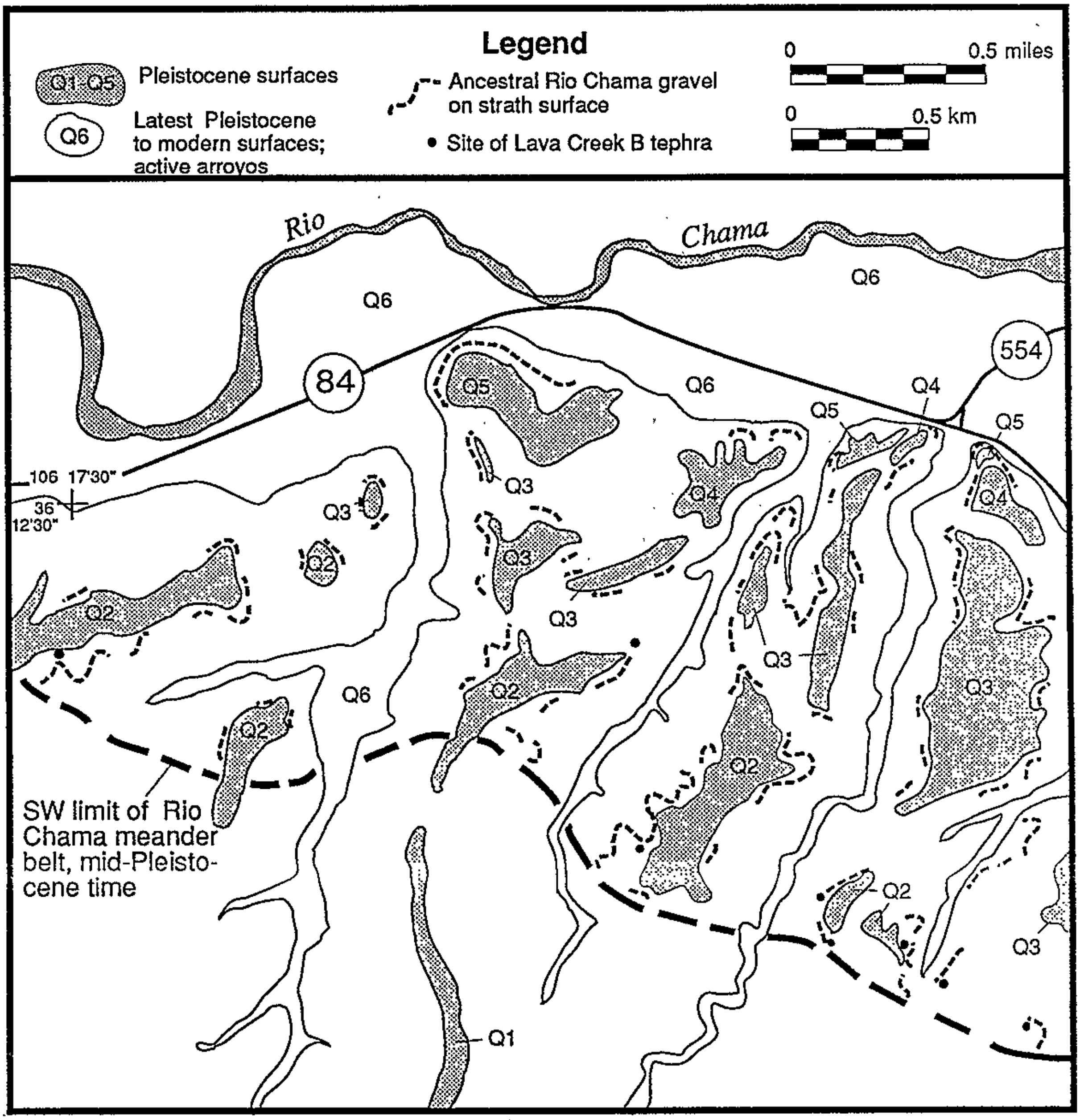


Figure 8. Sketch map indicating the location of mid- to late Quaternary inset units, ancestral Rio Chama axial-stream gravel deposits, and Lava Creek B tephra sites in the northeast quarter of the Abiquiu quadrangle (U.S. Geological Survey topographic map, scale 1:24,000).

short hike here traverses remnants of these inset deposits, which are exposed along arroyo walls, as well as a chance to examine the erosion surfaces cut across the deposits. The basal-cobble gravel in each inset deposit rests on a strath terrace cut across the Miocene Tesuque Formation (Fig. 9). In this area local base level lies near the contact between the Chama-El Rito Member and the Ojo Caliente Sandstone. The Chama-El Rito Member consists mainly of massive, buff-colored beds of arkosic silty sandstone and interbedded gray conglomerates composed of volcanic clasts. The Ojo Caliente Sandstone is an arkosic eolian sandstone that displays prominent cross beds at many locations. Fluvial deposits of the Chama-El Rito Member interfinger with the overlying Ojo Caliente dunes over a vertical distance of 10 to 30 m. This contact zone is probably time-transgressive, but the top of the Chama-El Rito Member is thought to be about 14 million years old here, whereas the Ojo Caliente Sandstone is between 14 and 12 million years old (Ekas et al., 1984). In most exposures between Lobato Mesa and the Rio Chama, the Chama-El Rito strikes NNE and dips 5° to 10° to the west. Near N- and NE-trending faults, bedding dips of 40° are common. Quaternary deposits that cover the eroded Tertiary strata are as thick as 40 m.

In the vicinity of stop 3, a layer of ancestral Rio Chama gravel, almost 700 m wide in places, marks the position of the Rio Chama at the time of the eruption of the Lava Creek B tephra. The tephra, slightly to completely reworked by fluvial processes, lies approximately 110 m above the modern Rio Chama. At most exposures, tephra lenses are surrounded by ancestral slack-water deposits and appear to have been deposited on the floodplain (Fig. 9). The fine-grained deposits are covered by or grade up into alluvial fan deposits. At one site a lens of pure tephra is preserved about 4 m above the

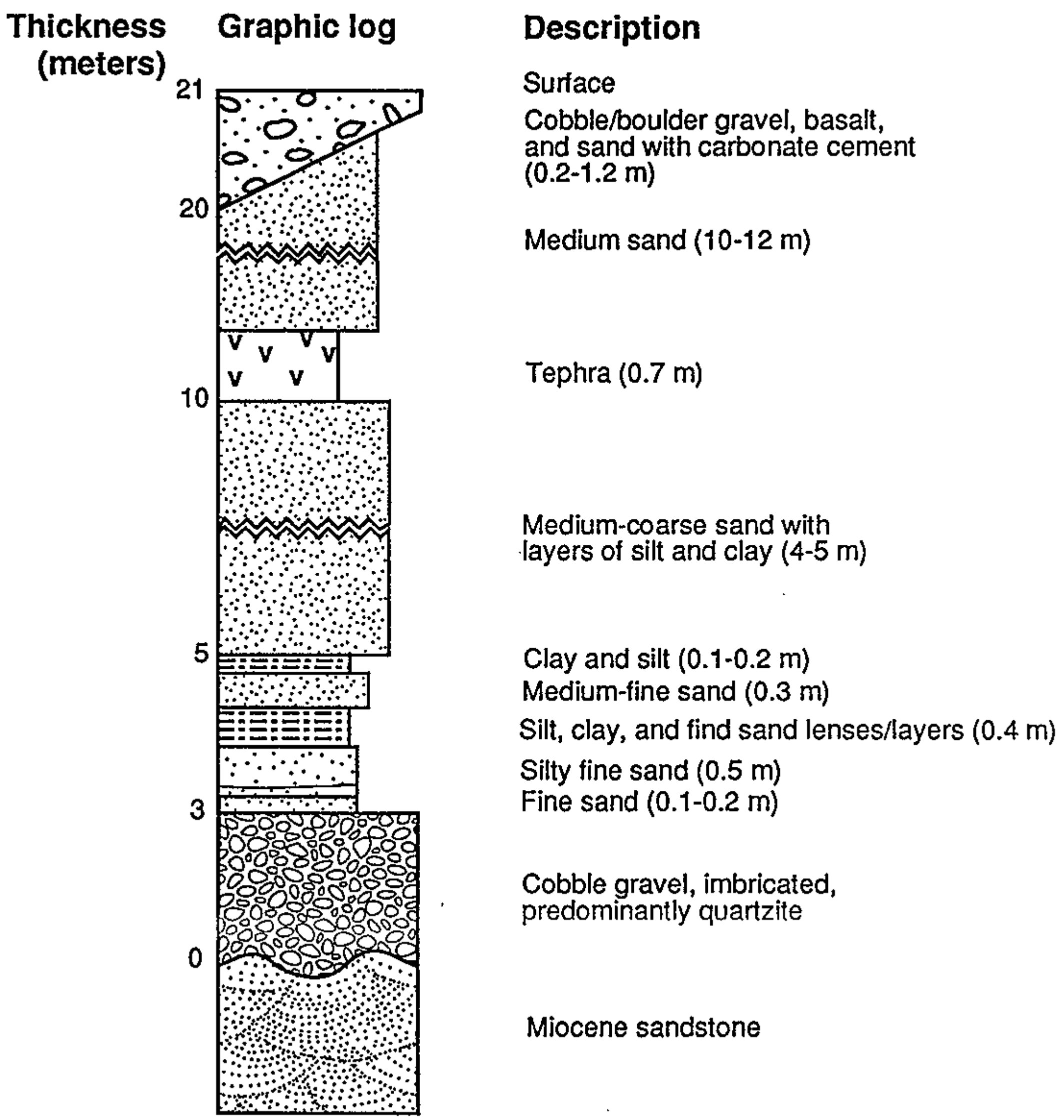


Figure 9. Typical stratigraphic sequence of mid- to late Quaternary inset alluvial units found in the Abiquiu embayment south of the Rio Chama. This particular example includes a deposit of Lava Creek B tephra, which is intercalated with sediments of unit Q2 in many places. Gastropods are found in the finer-textured strata in other localities (from Gonzalez and Dethier, 1991).

base of alluvial fan deposits, demonstrating that, at least locally, fans were already building across the floodplain during the period of tephra deposition. At several other sites, a second layer of Rio Chama gravel occurs 2 to 5 m up-section from the basal gravel and is covered by alluvial-fan deposits. We interpret these sequences as demonstrating that some aggradation took place on the Rio Chama as it was forced north and northeast by expansion of the alluvial fans.

A sketch map of the area east of Mesa de Abiquiu (Fig. 8) shows the relation between ancestral Rio Chama deposits, erosion surfaces cut across those deposits, and locations where we have mapped the Lava Creek B tephra layer. A composite cross-section from the area (Fig. 10) suggests the relationship between the elevation of deposits and D/L ratios in gastropods from those deposits. The D/L ratios demonstrate a progressive increase with elevation above the modern Rio Chama. Ratios at the lowest sites, which are about 28 m above present grade, are similar to those found at a site dated by radiocarbon method at 25.8 ka. Ratios at the highest sites are typical of those found with the Lava Creek B tephra (620 ka). The age of the four buried surfaces between the highest and lowest is probably middle Pleistocene, but the lowest of the four could be earliest Wisconsinan in age. These data demonstrate the utility of amino-acid ratios in stratigraphic correlations and suggest that deposit age can be estimated from such ratios, even in fluvial deposits.

We have not studied the soils, rock varnish, or other aspects of the surfaces cut across the Quaternary deposits in this area. Latest Pleistocene/Holocene (?) dune and local fluvial activity have covered or reworked large areas of each of the surfaces. Stage III+ carbonate is common in

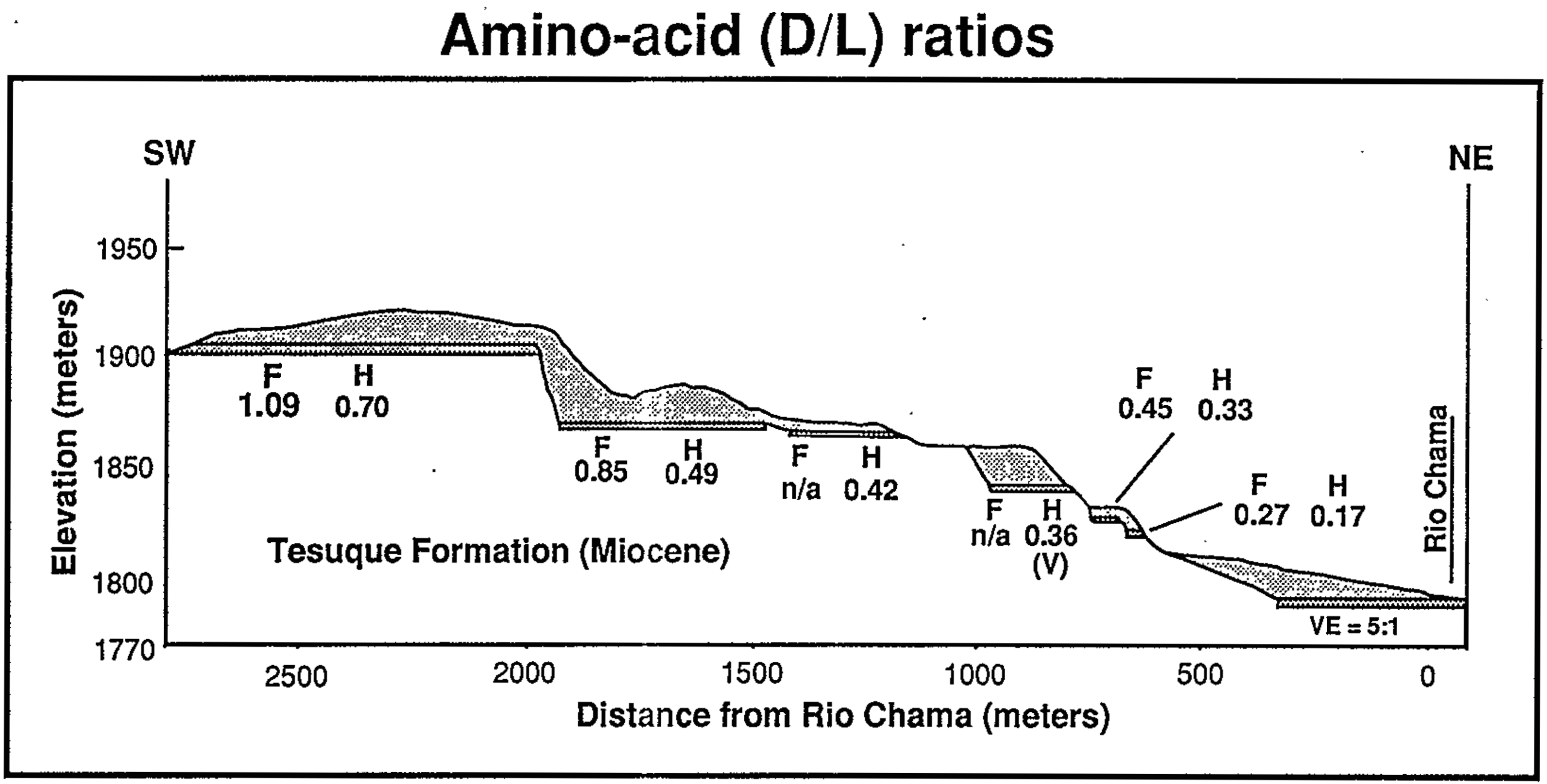


Figure 10. The schematic topographic cross-section of the Rio Chama valley depicts the relative position of mid- to late Quaternary inset alluvial units southeast of Abiquiu. The listed numbers are typical amino-acid (D/L) ratios in the free (F) and hydrolysate (H) fractions of gastropods from the Quaternary units. Ratios are from Succinea sp., except where noted by (V) for samples of Vallonia sp. (35 of 39 samples collected by D.P. Dethier in 1989-90. 4 samples collected by M.A. Gonzalez in 1990. Analysis complete by W.D. McCoy in 1990-91; cf. Dethier and McCoy, 1993).

exposures beneath the Q2, Q3, and Q4 surfaces, and well-developed rock varnish is present on large clasts near the edge of some surfaces, and on the Q1 surface.

Most of the prominent erosion surfaces in the Abiquiu-Medanales area cap alluvial fans that cover the ~620 ka Rio Chama gravel. These fans prograded at least 700 m laterally, probably in a relatively short time, since there are no significant buried soils within the fan deposits. Present day interfluves represent inverted arroyos and alluvial fan segments active at ~620 ka and are covered with basaltic boulder gravel derived from Lobato Mesa and capped by dunes that probably were active during the late Pleistocene/Holocene transition. None of the older and few younger surfaces that cap only <u>one</u> sequence are as extensive or as well preserved. These observations suggest that the climatic episode that took place after 620 ka was unusual. The episode produced a large volume of sediment, including significant amounts of coarse material, and forced the Rio Chama to migrate at least one kilometer. When such migrations took place during younger episodes of climate change, they apparently were for shorter distances, and the Rio Chama soon migrated back toward the west, removing large amounts of the newly stabilized alluvial fans.

34.1 Exit the parking lot and turn left (west) onto **US-84** heading towards Abiquiu. Straight ahead in the skyline is Mesa de Abiquiu, a mesa capped with a flow of El Alto basalt. The mesa is approximately 170 m (at its terminal end) above the present-day grade of the Rio Chama. The basalt on Mesa de Abiquiu has been K-Ar dated at 3.2 ± 0.1 Ma (UAKA-77-85; Baldridge et al., 1980). The flow has a narrow sinuous, relatively gentle slope (2.2% in the initial reaches, and decreasing to 0.7% in more distal segments), and is aligned at an acute angle to the present and presumed ancestral course of the Rio Chama. These facts suggest that the flow coursed down the floor of an ancestral valley, tributary to the Rio Chama. The floor of the former valley is correlated as a T4 (pre-Quaternary) surface (Fig. 6B). **0.75**

34.85 On the right (north) side of the highway are the ruins of the Santa Rosa de Loma de Abiquiu, a Franciscan mission established in 1773 (Muehlberger and Muehlberger, 1982, p. 33). The mission was on a route which eventually evolved into the famous Spanish Trail, linking Santa Fe with California and the Pacific Coast (Muehlberger and Muehlberger, 1982, p. 33). Fathers Dominguez and Escalante visited this mission during their epic exploration of the region in 1776. **1.7**

36.55 **US-84** passes through Abiquiu. The modern site of Abiquiu was colonized in 1754. The renowned artist, Georgia O'Keeffe, had residences in Abiquiu and near Ghost Ranch, drawing upon the striking images of the Abiquiu area for many of her remarkable works. **0.3**

36.85 Cross the Rio Chama bridge. Due north at 3 o'clock, is a ridge of well-cemented Ojo Caliente Sandstone. The Cerrito Blanco fault zone is exposed along this ridge, separating Upper Abiquiu Formation (white-colored strata) to the west from the younger Ojo Caliente Sandstone (tan-colored strata) on the east. **1.1**

37.95 Abiquiu Elementary School located to the right (north) side of the road. To the south and along the skyline are a series of Lobato basalt flows capping the Abiquiu Formation. **0.35**

38.3 Roadcut exposes a dike on the north side of the highway. The ridge held up by the dike is locally called Cerrito de la Ventana. The dike disappears from view below the alluvium of the Rio Chama valley to reappear on the south side of the river. Local inhabitants refer to the black fin of the dike south of the Rio Chama as the Creston (translated as the cockscomb). Two fault traces intersect at this roadcut. One trends NE along the outcrop of the dike and herein is called the Cerrito de la Ventana fault zone. The other trends due north from the roadcut. In addition, we believe it continues south of the Rio Chama valley and can be traced to its intersection with Lobato basalt flows approximately 3 km south of the Rio Chama. This fault zone passes within meters of the Garcia residence on the south side of the Rio Chama. For this reason and an absence of nearby geographic place names, we informally name this the Garcia FZ. A Lobato flow is offset approximately 250 feet (80 m) above the trace of the Garcia FZ. However, we have not inspected this topographic escarpment to determine if the 80 m of relief has resulted from flow over a paleo-escarpment, from post-flow fault offset, or from landsliding along an edge of the basalt flow. **0.1**

38.4 Lower Abiquiu Formation outcrops on right (north) side of the roadway for the next 2 miles. **2.1**

40.5 The outcrop on the right (north) side of the highway contains two angular unconformities: one between the Jurassic Entrada Formation (an eolian sandstone) and the overlying Eocene El Rito Formation (brick-red sandstone unit with a basal conglomerate bed), and the other between the El Rito Formation and the overlying Oligocene Lower Abiquiu Formation (conglomerate with a salmon-red to chalky-colored matrix). This outcrop was described by H.T.U. Smith (1938), a Harvard Ph.D. student studying under Kirk Bryan. Recent roadwork has modified the original features described by Smith. Smith mapped the Abiquiu 15 minute topographic sheet as part of his dissertation. **0.15**

40.65 **Milepost 216**, highway crosses the Cañones fault zone, the western morphotectonic limit of the present-day Rio Grande rift. The valley to the right (north) side of the highway contains the Cañones fault zone, the rift-bounding structure which separates Mesozoic and upper Paleozoic rocks on the west from Cenozoic sediment to the east. Stratigraphic offset indicates that there has been at least 400 feet (120 m) of vertical displacement along this fault. Subsurface seismic data corroborates this estimate (W.S. Baldridge, pers. comm., 1990; Baldridge and Jiracek, 1992). **0.2**

40.85 Roadway begins to climb out of the rift and into the Chama basin of the Colorado Plateau. The purple, ribbed rocks at the base of the fault scarp belong to the Cutler Formation (lower Permian). The Cutler Formation comprises alternating beds of mudstone and cross-bedded stream channel sandstones. Farther up the roadway, massive, buff-colored sandstone crops out. This massive sandstone is the basal Chinle Formation (upper Triassic). As indicated by the time intervals between the Cutler and Chinle Formations, these strata are separated by a disconformity. **0.8**

41.65 Picnic tables on the right. At 9:00 the red-, white-, and yellow-colored beds of the Entrada Formation are downfaulted to the east. Notice that the Lobato basalt capping this mesa is not faulted, indicating that this fault has not been active during approximately the last 10 million years. Elsewhere, however, nearby splays of the Cañones fault zone appear to have offset 8 Ma Lobato basalt flows by tens to hundreds of meters. **0.5**

42.15 The roadcut exposes the Chinle Formation and Quaternary alluvium derived from tributary streams emanating from Comanche Cañon. **1.05**

43.2 Turn left onto **NM-96** toward Abiquiu Dam. **1.0**

44.2 Roadcut exposes deposit of Quaternary-age Rio Chama axial-stream gravel with fine-grained eolian mantle and a Stage II+ to III carbonate soil horizons. **0.6**

44.8 Turn right into dam headquarters, continue for approximately 0.1 mile to the picnic grounds and overlook of Abiquiu Reservoir. **0.1**

Stop 4: Inset Quaternary Deposits in the Colorado Plateau

The overlook at Abiquiu dam affords a view of some inset Quaternary units found along the Rio Chama in this part of the Colorado Plateau. These inset Quaternary deposits generally comprise a basal axial-stream gravel (1-3 m thick), overlain by an eolian mantle of irregular thickness (0-2 m; Fig. 11). Adjacent to and below degrading terrace risers, a colluvial deposit may be intercalated between the basal gravel and eolian mantle. The colluvium generally consists of reworked gravel and eolian sediment, shed off the older, superjacent Quaternary terrace, forming a wedge that thins away from the riser. The colluvial wedge and eolian mantle may have more complex interfingering relations than depicted schematically in Fig. 11.

These inset Quaternary deposits differ in several ways from similar units found within the Rio Grande rift (e.g., deposits viewed at stop 3). Recall that at stop 3, the inset Quaternary units south of the Rio Chama are characterized by a depositional sequence that begins at the base with axial-stream gravel unconformably overlying Santa Fe Group sediment with overbank deposits, prograding fan and/or arroyo deposits (primarily sand) shed from the adjacent Jemez highlands above, and a coarse, gravel to boulder clast deposit capping the sequence. On the Colorado Plateau, we rarely find tributary deposits above the axial-stream deposits. We speculate that tributary streams could more easily switch channel position and form inverted topography in the easily eroded Tertiary strata of the Rio Grande rift. In contrast, the position of tributary streams is confined by the more resistant strata of the Colorado Plateau. Therefore, as base-level fell, tributary streams in the Colorado Plateau became entrenched, cut deeper valleys and eroded most pre-existing tributary deposits. In contrast, many Quaternary-age tributary stream deposits in the Rio Grande Rift are of larger caliber, and hence more difficult to erode, than the Tertiary rift-fill strata. Consequently, tributary streams shifted position to incise through less resistant Tertiary strata, leaving behind nearly intact remnants of Quaternary tributary or

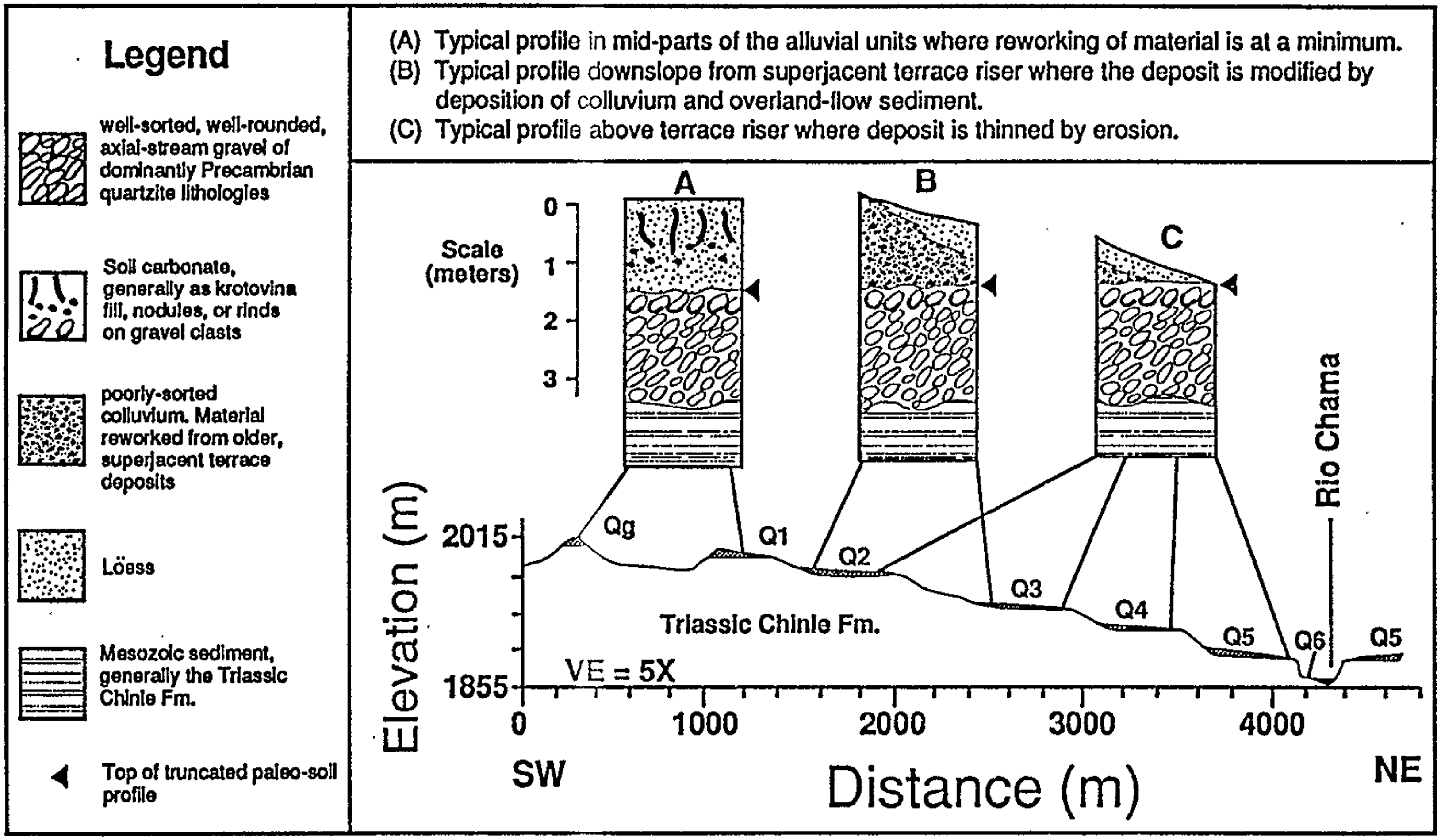


Figure 11. The schematic topographic cross-section of the Rio Chama valley depicts the relative position of mid- to late Quaternary inset alluvial units in the Colorado Plateau near the Abiquiu dam. Unit Q6 is usually and unit Q5 is sometimes inundated by water in the reservoir. The stratigraphic profiles schematically illustrate the types of deposits found in these Quaternary units, and how they change laterally with respect to distance above or below adjacent terrace risers.

piedmont deposits along many ridges.

In the Colorado Plateau, the absence of an erosion-protecting cap of coarse-grained tributary and/or piedmont deposits precludes preservation of any underlying fine-grained overbank axial deposits. It is the fine-grained overbank deposits that generally contain gastropods. Consequently, amino-acid racemization ratios, a dating technique used successfully in the Rio Grande rift (Dethier and McCoy, 1993), are not readily available for axial-stream deposits in the Colorado Plateau. It is possible that tributary-stream deposits close to mountain fronts may have stratigraphic sequences more conducive to preservation of gastropod-bearing strata.

As the provenance for the axial-stream gravel deposits was constant throughout the Quaternary, each inset unit is lithologically indistinct from other inset units. Correlation of axial-stream gravel deposits is based primarily on their height above the modern stream gradient. Fortunately, remnants of most inset Quaternary deposits are abundant enough to trace their longitudinal profiles for 40 miles (60 kilometers) from Ghost Ranch to the confluence of the Rio Grande and Rio Chama.

Figure 11 is a geologic cross-section through several inset Quaternary units visible from the Abiquiu dam overlook. Table 2 provides an estimation of the height of these units above the modern stream gradient. (Note: the 1945 edition of the 1:24,000 scale topographic map shows the position and elevation of the Rio Chama, prior to construction of the Abiquiu dam and reservoir. The height of the inset Quaternary units above the Rio Chama grade is relative to the pre-dam path of the Rio Chama.)

44.9 Exit Abiquiu Reservoir overlook and picnic grounds, and return to NM-96. **0.1**

Table 2: Age and height of inset Quaternary alluvial units

Alluvial Unit	Height of gravel[1] above axial channel (in meters)	Age Estimate	Dating Method(s)
T(?)Qg	230	> 1500 ka *ca* 1700 (?) ka	stratigraphic position underneath Guaje Pumice
Qg	160-180	1500-620 ka	stratigraphic
Q1	130-150	1500-620 ka	stratigraphic
Q2	110-125	≥ 620 ka	Lava Creek B tephra
Q3	75-90	620-130 ka (350-220(?) ka	tephrochronology and amino-acid ratios
Q4	40-50	150-60 ka	tephrochronology and amino-acid ratios
Q5	20-30	80-20 ka	radiocarbon dates and amino-acid ratios
Q6	0-12	≤ 20 ka	radiocarbon dates

[1]The height of the Quaternary units is measured from the top of the gravel bed to the modern-day channel of the Rio Chama. Irregular scour relief precludes use of the base of the Quaternary units. Variable thickness of overbank deposits or eolian mantles precludes use of the top of the depositional surface. The top of the gravel is more uniform in longitudinal profile and has less variation due to erosion than due the other surfaces or depositional contacts.

45.0 Turn left onto **NM-96**. Retrace route back to junction with **US-84**. **1.6**

46.6 Turn left (west) onto **US-84** towards Ghost Ranch and Tierra Amarilla. **0.35**

46.95 Roadcut exposes Quaternary tributary-stream gravel with Stage II+ carbonate soil horizons, overlying the Triassic Chinle Formation. **1.4**

48.35 **Milepost** 221. At 12:00 one can see the Mesozoic strata dominating this part of the Colorado Plateau. The basal Chinle Formation forms a broad lithologic bench here, over which there are thin Quaternary fan (and eolian?) deposits. Above this is the red-, white-, yellow-banded Entrada Formation, and the gray Todilto Formation The variegated Morrison Formation generally forms alternating slopes and benches above the Todilto/Entrada cliffs and below the cliff-forming Dakota Sandstone that caps many of the mesas in this area. **3.0**

51.35 Roadside picnic tables on the left (south) side of the road. The varicolored badlands to the right and straight ahead are composed of the Chinle Formation. **1.6**

52.95 Ghost Ranch Road turn-off on the right (north) side of highway. **0.2**

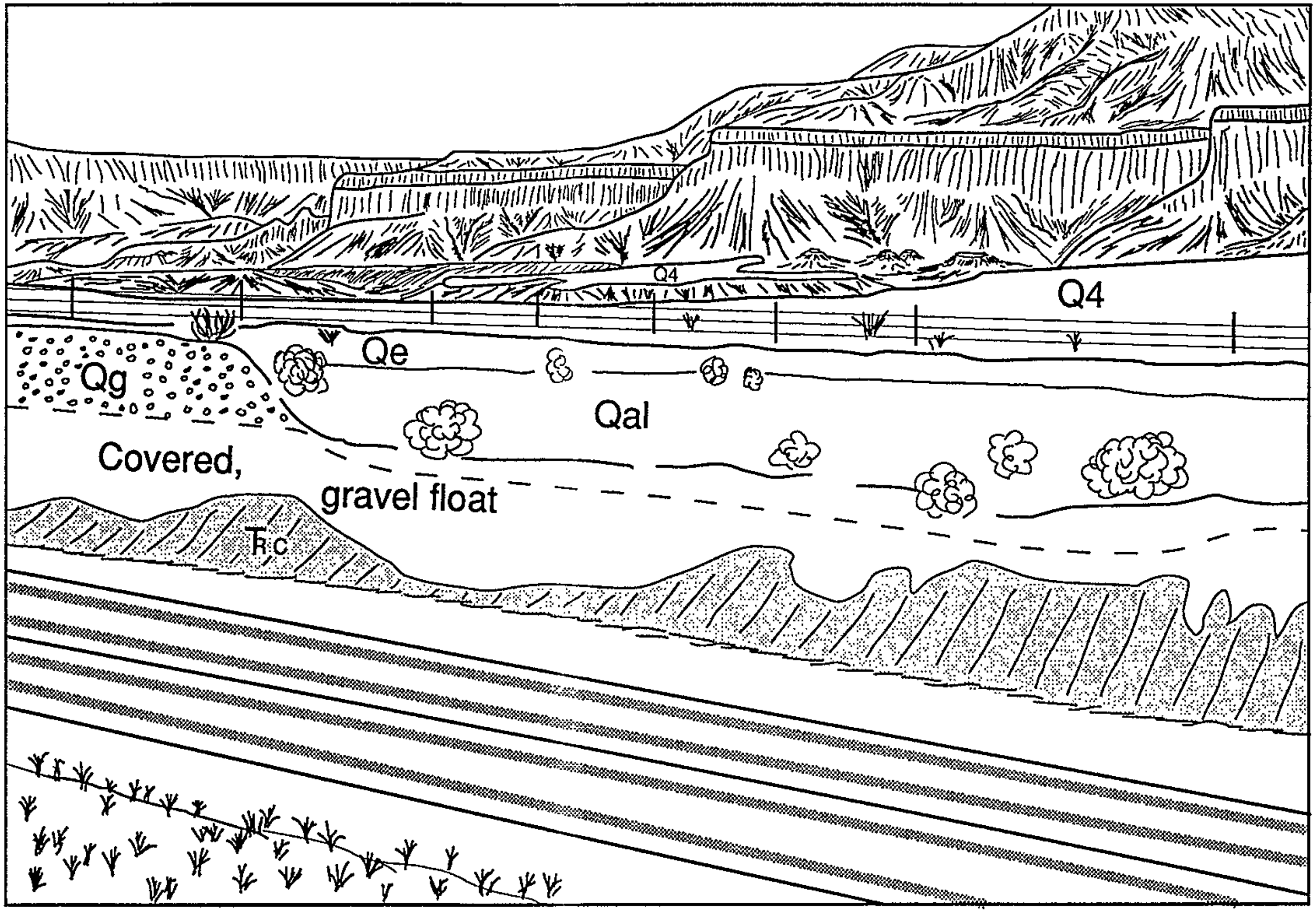
53.15 Bridge over Arroyo Seco. **0.1**

53.25 Pull over onto right (north) side of highway and park.

Stop 5: Overview of Pre-Quaternary and Quaternary surfaces

The roadcut on the north side of US-84 exposes Quaternary-age fluvial sediment overlying the Triassic Chinle Formation (Fig. 12). The fluvial gravel was deposited by the Arroyo Seco during the late Pleistocene. The top of the gravel deposit is scalloped, demarcating the position of a paleo-channel that has subsequently back-filled with finer-grained (sand and silt dominantly) sediment. The channel-fill sediment is replete with various fresh-water gastropods, including _Vallonia_, _Succinea_, _Pupilla_; _Gastrocopta_; _Vertigo_, and _Zonitoides_. Samples of _Vallonia_ and _Succinea_, collected at this locality, have given amino-acid ratios typical of snails from the late-Pleistocene (about 15-20 ka; W.D. McCoy, written communication, 1990; Dethier

Figure 12. This roadcut, along US-84 approximately 0.2 mile west of the turnoff to Ghost Ranch, exposes piedmont deposits of unit Q4, tributary-stream and eolian deposits, overlying the Triassic Chinle Formation. The cobble-gravel deposit is bedload sediment of the ancestral Arroyo Seco, a tributary to the Rio Chama. The surface of the cobble-gravel deposit is scalloped and buried by fine-grained channel-fill and overbank deposits. The channel-fill deposits contain gastropods which have been used for amino-acid racemization ratios. D/L ratios (for isoleucine/alloisoleucine content) obtained here are 0.21-0.25 (free fraction) and 0.13-0.14 (hydrolysate fraction; W.D. McCoy, written comm., 1990), typical of ratios from Wisconsinan-age deposits (20-40 ka (?); McCoy, 1987). A blanket of eolian sediment mantles the fluvial strata.


Q4
Q4
Qe
Qg
Qal
Covered,
gravel float
TRc

and McCoy, 1993; Table 3).

From the top of the roadcut, one gains a vantage of the surrounding geology (Fig. 12). The cliffs to the north comprise Mesozoic strata, including from bottom to top, the Triassic Chinle Formation, the red-, yellow-, and white-banded Entrada Formation (an eolian sandstone with large-scale cross stratification), the gray-colored Todilto Formation (a gypsum-rich stratum), the variegated Morrison Formation (alternating slope and bench former), and the Cretaceous Dakota Sandstone, the top cliff-forming stratum. To the south is the Jemez volcanic field. Volcanic domes, composed of the Tschicoma dacite and lava-capped mesas dominate the skyline (Fig. 13). Cerro Pedernal, Mesa Escoba, and Polvadera Mesa are capped by late Miocene Lobato basalt flows approximately 8 Ma. Below the Lobato basalt on Cerro Pedernal are Tertiary sedimentary units, including the Eocene (?) El Rito Formation and the late Oligocene to early Miocene (?) Abiquiu Formation (Abiquiu Tuff of Smith, 1938, Fig. 3 therein).

Finally, the panorama afforded at this stop provides an opportunity to review the evidence of pre-Quaternary base-level position. Between Española and Ghost Ranch are several remnants of pre-Quaternary base-level position. The evidence is found where late-Miocene to Pliocene lava flows buried ancestral drainage segments and now have formed inverted topography. The lavas flowed down ancestral river valleys, constraining base-level elevations at 4 times during the last 8 m.y. Where the lava buries axial-stream deposits, paleo-base level is precisely constrained. Where lava buries tributary valleys, we estimate axial-stream paleo-base level from projection of the buried valley gradients, or at least constrain axial-stream base-level to an elevation below that of the buried tributary remnant. The oldest stream

Table 3A: Typical amino-acid ratios for the lower Rio Chama valley

Alluvial Unit	Elevation above grade (m)	Typical (average) D/L values Succinea Free	Succinea Hydr	Vallonia Free	Vallonia Hydr
Q2	110-120	1.09	0.70	----	----
upper Q3	90	0.85	0.49	----	----
lower Q3	80	----	0.42	----	----
Q4	55	----	----	----	0.36
upper Q5	35-40	0.45	0.33	----	----
lower Q5	30	0.27	0.17	0.25	0.13

Table 3B: Amino-acid racemization data from gastropods in unit Q5, stop 5

Site #	Genus	Lab #[1]	Run	D/L[2] Free[3]	D/L[2] Hyd[3]
713-A	Succinea	AGL 1512	A	0.190	0.124
			B	0.228	0.149
			C	----	0.136
			Ave.	0.209	0.136
			S.D.	±0.027	±0.013
713-A	Vallonia	AGL 1513	A	0.242	0.136
			B	0.260	0.134
			Ave.	0.251	0.135
			S.D.	±0.01	±0.001

[1]Analysis performed by W.D. McCoy, University of Massachusetts, on November 9, 1990.

[2]D/L ratios are calculated from the amino acids alloisoleucine and isoleucine.

[3]Values are for free and hydrolysate fractions.

Figure 13. Sketch of the skyline of the northern Jemez Mountains from stop 5, view to the south. Distinct physiographic features visible in the southern skyline include *Polvadera Peak, Cerro Pedernal, Mesa Escoba and Polvadera Mesa. The Miocene Lobato* basalt flows on the three mesas appear to have buried segments of ancestral tributary streams to the Rio Chama. If the assumptions are valid that each tributary-stream segment was buried at approximately the same time; and that at the time of burial, all the tributary segments were graded to the same axial-stream grade, then their positions above the modern Rio Chama grade provide topographic evidence of neotectonic movement on rift-margin faults such as the East and West Splays of the Cañones fault zone.

valleys found in the area are the T1 surfaces, buried by an approximately 8 Ma Lobato basalt flows (Fig. 6A). The T1 surface is found beneath the basalt that caps Cerro Pedernal, Mesa Escoba, and Polvadera Mesa. The surface rest approximately 570-1150 m (1800-3600 ft) above the present-day gradient of the Rio Chama (Fig. 6A).

Another buried stream valley, herein identified as the T2 surface is found in only one locality in the area, beneath the 4.8 Ma basalt flow found on Sierra Negra, northeast of Abiquiu (Fig. 6B). Gravel lithologies, found beneath the Sierra Negra flow, indicate the buried stream valley or piedmont channel transported sediment from the southern Tusas Mountains. The tributary channel is now approximately 520-550 m (1700-1800 ft) above the modern grade of the Rio Chama.

Additional remnants of buried stream segments, identified as the T4 surface, are found beneath approximately 3.2-2.8 Ma El Alto flows that cap the lower part of Cañones Mesa and Mesa de Abiquiu, and a Servilleta flow atop Black Mesa (Fig. 6B). The T4 surface is now approximately 220-370 m (750-1250 ft) above the present-day gradient of the Rio Chama. The range of heights for each surface above grade may reflect: (1) imprecise projection of tributary remnants to axial-stream grade, and/or (2) tectonic evolution of the Rio Grande rift with offset of stream segments located across rift-margin faults (see discussion accompanying field-stop 6).

53.25 Make a U-turn and head back to the Ghost Ranch Road turn-off. **0.3**

53.55 Turn left (north) onto **Ghost Ranch Road** (gravel). Proceed north toward Ghost Ranch headquarters. **1.1**

54.65 Ghost Ranch road bifurcates: Turn left to headquarters and visitor center. **0.35**

55.0 Ghost Ranch visitor center. End of day one.

Day 2: Neotectonism and ancestral drainage of the rift margin

Assemble at the Ghost Ranch headquarters to begin the roadlog for Day 2.

0.0 Retrace route of the **Ghost Ranch road** to **US-84**. 1.7

1.7 Turn left (east) onto **US-84** proceeding towards Abiquiu. 6.3

8.0 Junction with NM-96: continue straight on **US-84**. 1.6

9.6 Turn right (south) off of the highway and onto an earthen road across from the picnic tables. Park off the highway and walk along the earthen road for about 200 m to the east where you will arrive at some sandstone cliffs (Lower Member of the Chinle Formation) and a vantage point overlooking the Rio Chama valley and the Cañones FZ.

Stop 6: Cañones Fault Zone and other rift-margin structures

The Cañones fault zone is the most prominent fault zone in the Abiquiu embayment. It juxtaposes Tertiary basin-fill sedimentary units on the east against older Mesozoic and Paleozoic rocks to the west. The Cañones FZ is defined by high-angle normal faults that generally trend NNE to NE (Table 4). The main fault plane on which most of the vertical offset has occurred, dips approximately 67° SE. Slickenlines on this plane have an average rake of 79° NE, suggesting that a small component of left-lateral slip accompanies primarily dip-slip motion (Table 4). High-angle normal faults, dipping to the NW, occur tens to hundreds of meters east of the main fault plane. These antithetic faults demarcate small grabens that form along some segments of rift-margin fault zones.

Where US-84 crosses the Cañones FZ there is approximately 120 m (400 ft) of stratigraphic offset, juxtaposing upper Paleozoic and Mesozoic strata (Cutler and Chinle Formations) on the west against the Eocene El Rito Formation (Laramide basin fill?) and the Lower Abiquiu Formation (earliest

Table 4: Summary of fault zones characteristics

Fault Zone	Trend	Dip Angle	Ave. Rake of Lineations on Main Plane	Minimum Slip-Rate (cm/yr)
Cañones	N32°E	67°SE	79°NE (Sinistral sense)	0.011 (570 m/5 m.y.)+
Garcia	N27°E	64°SE	84°SW (Dextral sense)	0.003 (80 m/3 m.y.)
Cerrito Blanco	N15°E	70°SE	83°NE (Sinistral sense)	0.003 (90 m/3 m.y.)
Plaza Colorado	N75°E	68°SE	77°NE (Sinistral sense)	N.A.
Madera Cañon	N46°E	62°SE	86°NE (Sinistral sense)	0.007-0.010 (10 m/80-150 ka)
Embudo				
Main segment ENE-trending	N68°E	65°SSE	N.A.	N.A.
cross segment NNE-trending	N20°E	74°ESE	32°NNE (Sinistral slip)	N.A.

+Calculated slip rate assumes Cañones FZ was active from 8 to 3 Ma, and has been inactive since 3 Ma.

rift-fill sediment?) on the east. This estimate of stratigraphic throw at the surface is in good agreement with subsurface seismic imaging of the fault done by the 1990 SAGE (Summer of Applied Geophysical Experience) field class (W.S. Baldridge, pers. comm. 1990; Baldridge and Jiracek, 1992).

Vertical motion along the Cañones FZ appears to increase to the south where the fault zone bifurcates into the West and East splays (Gonzales and Cañones faults, respectively, of Kelley, 1978). The T1 surface, preserved beneath the 8 Ma late Miocene Lobato basalt flows on Cerro Pedernal, Mesa Escoba and Polvadera Mesa, appears to have 570 m (1870 feet) of vertical offset across the West and East splays of the Cañones FZ (Fig. 6A). However, a younger 3 Ma El Alto flow crosses the trace of, but is not offset by the Cañones FZ. Therefore, the Cañones FZ appears to have had an average slip rate of 0.011 cm/yr (570 m/5 m.y), as constrained by topographic relations between Lobato and El Alto basalt flows.

Because the buried T1 surfaces at Cerro Pedernal, Mesa Escoba and Polvadera Mesa are part of a tributary paleo-drainage, the exact amount of offset is difficult to constrain, due to inaccuracies associated with projection of tributary longitudinal profiles. In addition, the time when the Cañones FZ was active is debated by rift investigators. For example, Manley and Mehnert (1981) believe motion on the Cañones FZ post-dates the 8 Ma Lobato basalt flows on Cerro Pedernal, Mesa Escoba and Polvadera Mesa. Baldridge and Jiracek (1992) believe faulting ceased on the Cañones FZ prior to eruption of the 8 Ma Lobato basalt flows.

Smith (1938) first described the geology of the Cañones FZ where it is exposed in the roadcut on the north side of US-84 approximately 5 miles (8 km) west of Abiquiu. He stated, "Evidence that the Cretaceous and older rocks were faulted and tilted prior to deposition of the El Rito [Formation] is particularly well displayed at two places. On the north bank of the Chama about 5 miles west of Abiquiu, the El Rito [Formation] dips 18° to the east, whereas the underlying Morrison [Formation] dips 21° to the west (Fig 6 [of Smith, 1938]). This indicates that tilting in pre-El Rito and in post-El Rito time took place in opposite directions and that the dip of the Morrison [Formation] as a result of the first deformation must have been steeper than at present."

We do not observe westward tilting of the Morrison Formation at this locality. Instead, our observations and the geologic mapping of Manley (1982) indicate that the Jurassic Entrada Formation is situated between the Morrison and El Rito Formations at this roadcut. Perhaps Smith mistook the large eolian crossbeds of the Entrada sandstone for primary bedding in the Morrison Formation. Alternatively, he may have described an outcrop that has eluded our field investigations thus far. Indeed, this roadcut has been substantially altered by recent road construction and road widening. Parts of the road cut have also been covered with mesh and concrete to stabilize the surface and safeguard travellers.

9.6 Return to pavement of **US-84** and head east toward Abiquiu. **0.85**

10.45 **Milepost 216**. Highway crosses the Cañones fault zone. **2.15**

12.6 Roadcut exposes the dike of Cerrito de la Ventana and the Garcia fault zone (informal name appearing in Gonzalez and Dethier, 1991). **1.65**

14.25 Cross Rio Chama bridge. **0.15**

14.4 Turn right (south) onto Forest Service Road 31 (**FR-31**). **0.3**

14.7 To the left (at about 9:00) is a coarse boulder deposit on the right bank (looking downstream) of the Abiquiu Creek. Some of these boulders have intermediate-axis diameters well in excess of 1 meter. This extremely coarse deposit is not found in the Q4 (or Q5?) deposits in adjacent arroyos, suggesting that it represents an isolated phenomenon and not a widespread feature related to past climatic conditions. **0.75**

15.45 Cross cattle guard. To the right (west) is a remnant of unit Q1, approximately 150 m (500 ft) above the floor of Abiquiu Creek. To the left is the 3.2 Ma Mesa de Abiquiu. **2.0**

17.45 Ford Abiquiu Creek. **0.55**

18.0 Ford Abiquiu Creek again. **0.3**

18.3 Ford Abiquiu Creek and follow road to the left. Santa Fe Group sediment is exposed along the sides of the canyon with Lobato basalt capping the mesa to the left and El Alto basalt capping Mesa de Abiquiu on the right (Goff et al., 1989). **0.75**

19.05 Roadway crosses a cattle guard and flattens onto the top of the El Alto flow. This flow extends 6 km to the northeast. The sinuous, narrow flow path, the relatively gently gradient (0.7% in the lower reaches) suggest that the Mesa de Abiquiu flow followed an ancestral channel of Abiquiu Creek. This flow buried the T4 surface which rests approximately 170 m (at its terminal end) above the modern stream grade. Baldridge et al. (1980) have obtained a K-Ar date of 3.2 ± 0.1 Ma for this flow. Polvadera Peak is visible at 1:00. **2.8**

21.85 Junction with **FR-27**. Turn right (west) onto **FR-27**. **1.15**

23.0 The road crosses a thin deposit of Pliocene gravel. Smith et al. (1970) have mapped this deposit as the Puye Formation. This Puye outcrop is just meters thick in comparison to deposits tens to hundreds of meters thick south of the Embudo fault zone. We hypothesize that south of the Embudo FZ the Puye Formation is a thick, tectonically-controlled deposit, formed by coalescing fans, or bajada, bounded in most part by the Embudo and Pajarito FZs. North of the Embudo FZ, the Puye Formation is laterally discontinuous, relatively thin (a few to a couple tens of meters thick), and confined to Pliocene and early Quaternary stream channels. This pattern of Puye sedimentation across the Embudo FZ indicates that the northwestern part of the Española basin has been a subsiding depocenter, in contrast to the adjacent part of the Abiquiu embayment, which appears to have been tectonically uplifted over the same time interval. In the uplifted rift margin, Puye-like sediment was predominantly transported away from the Jemez volcanic field to the ancestral Rio Chama. In the subsiding Española basin the Puye sediment was stored in a large volcaniclastic fan. **1.6**

24.6 **FR-27** winds between two dacite domes. Cerrito Chato to the left (south) has been dated at 3.8 ± 0.19 Ma (Goff et al., 1989), and Cerro Pelon to the right (north) is a younger (2.96 ± 0.27 Ma) dacite vent (Goff et al., 1989). **1.4**

26.0 Junction with **FR-427**. Bear right, remaining on **FR-27**. **1.7**

27.7 Junction with **FR-422**. Bear right, remaining on **FR-27**. **2.1**

29.8 Turn right onto a faint tire-tracked earthen path. **0.8**

30.6 Follow tracks for 0.8 miles to end of a mesa underlain by the Bandelier Tuff.

Stop 7: Tectonic control on paleo-topography and volcanogenic sediment distribution

The northern end of Polvadera Mesa affords a panoramic view of the margin between the Colorado Plateau and the Rio Grande rift. The exposed stratigraphy of the Colorado Plateau comprises (from oldest to youngest) the Triassic Chinle Formation, a continental red bed deposit of intercalated conglomeratic sandstones, sandstones, mudstones and siltstones (Smith et al., 1961); the Jurassic Entrada Formation, a massive, cross-bedded eolian sandstone; gypsum of the Todilto Formation, marked by a very prominent white marker unit; the Jurassic Morrison Formation, consisting of variegated mudstones, siltstones, and sandstones, which form the broad slopes and benches above the Todilto; and the Cretaceous Dakota Sandstone, which in many places appears as a cliff-forming unit that caps many of the surrounding mesas (Smith et al., 1961; Goff et al., 1989).

Below the Lobato basalt on Cerro Pedernal are Tertiary sedimentary units, including the Eocene (?) El Rito Formation and the late Oligocene to early Miocene (?) Abiquiu Formation (Abiquiu Tuff of Smith, 1938, see Fig. 3 therein). Previous investigators (e.g., Wood and Northrop, 1946; Smith et al., 1970; Baltz, 1978; Baldridge et al., 1980, 1984; May, 1980, 1984) have suggested that these basin-fill sediments, found west of the western-most rift-margin fault zone, accumulated on the broadly-warped eastern limb of the Nacimiento uplift (a Laramide structure on the eastern edge of the Colorado Plateau) and the western margin of the ancestral Española basin. This Laramide (?) basin controlled sediment dispersal in this area until late Miocene and Pliocene faulting created a morphologically-distinct rift basin (Baltz, 1978; Baldridge et al., 1980, 1984; Manley and Mehnert, 1981).

Apparent offset of the 8 Ma Lobato basalt flows between Cerro Pedernal, Mesa Escoba, and Polvadera Mesa indicates that faulting may have occurred since the late Miocene on the East and West Splays of the Cañones FZ (Fig. 14). These faults are also zones of weakness that ancestral streams, such as Cañones Creek to the west, could exploit to carve large, deep canyons. The canyons subsequently back-filled with Bandelier Tuff from 1.5 to 1.1 Ma (Fig. 14; also Figs. 6D, 15B, and 15C). Relief on the contact between the Otowi and Tshirege Members of the Bandelier Tuff suggest that streams had begun to incise between eruptions of the two members. Since 1.1 Ma streams have re-excavated parts of the paleo-canyons (Fig. 15D). Valley incision has progressed to a point almost as deep as to deeper than the canyons in pre-Bandelier time.

Tsiping, a prehistoric Tewa pueblo, is visible on the mesa to the northwest. Tsiping was occupied during the 13th and 14th centuries A.D. The ruins of the pueblo contains over a hundred ground-floor masonry rooms built of blocks cut from the Bandelier Tuff, and over 15 ceremonial kivas excavated into the tuff (Goff et al., 1989). Tsiping was a well-fortified village, protected by the mesa's vertical escarpments on the north, east and west, and by a high masonry wall to the south (Goff et al., 1989).

30.6 Retrace route back to **FR-27**. **0.8**

31.4 Junction with **FR-27**. Turn left (east) and retrace route back to **FR-31**. **7.9**

39.3 Junction with FR-31. Turn left (north) onto **FR-31** and retrace route back to Abiquiu and the intersection with **US-84**. **7.6**

46.9 Junction with US-84. Turn left (west) on **US-84**. **0.1**

47.0 Cross Rio Chama bridge. **0.4**

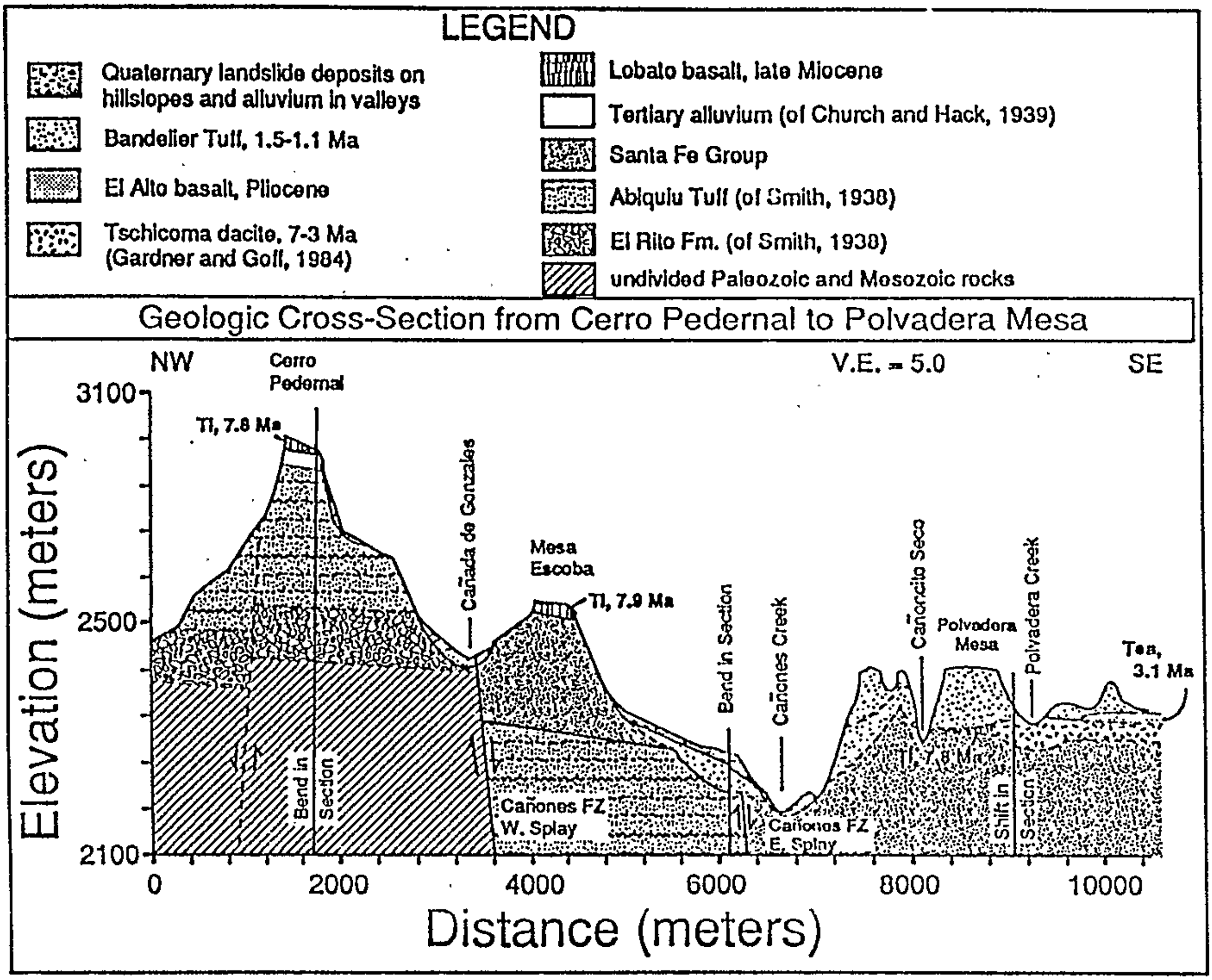
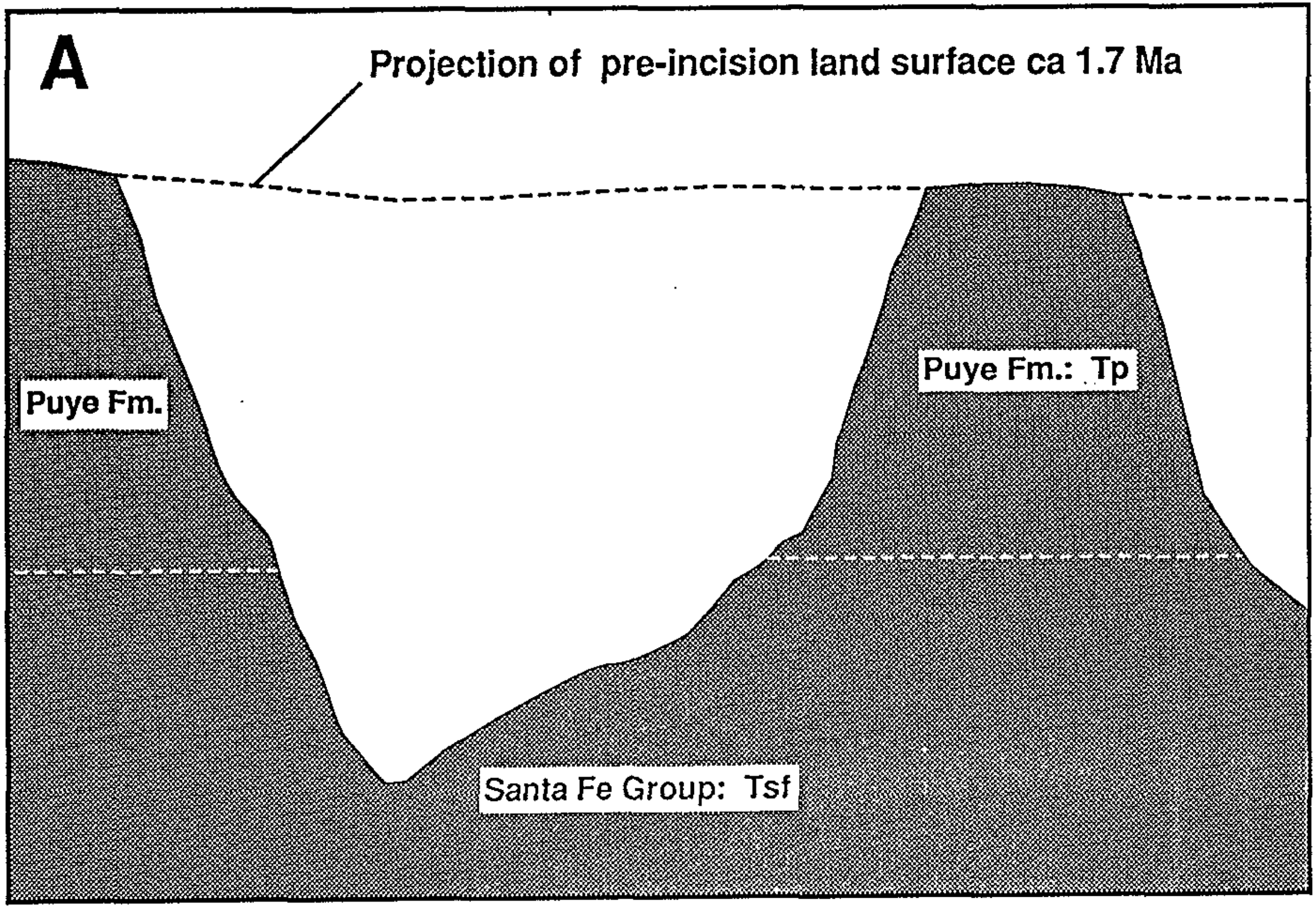


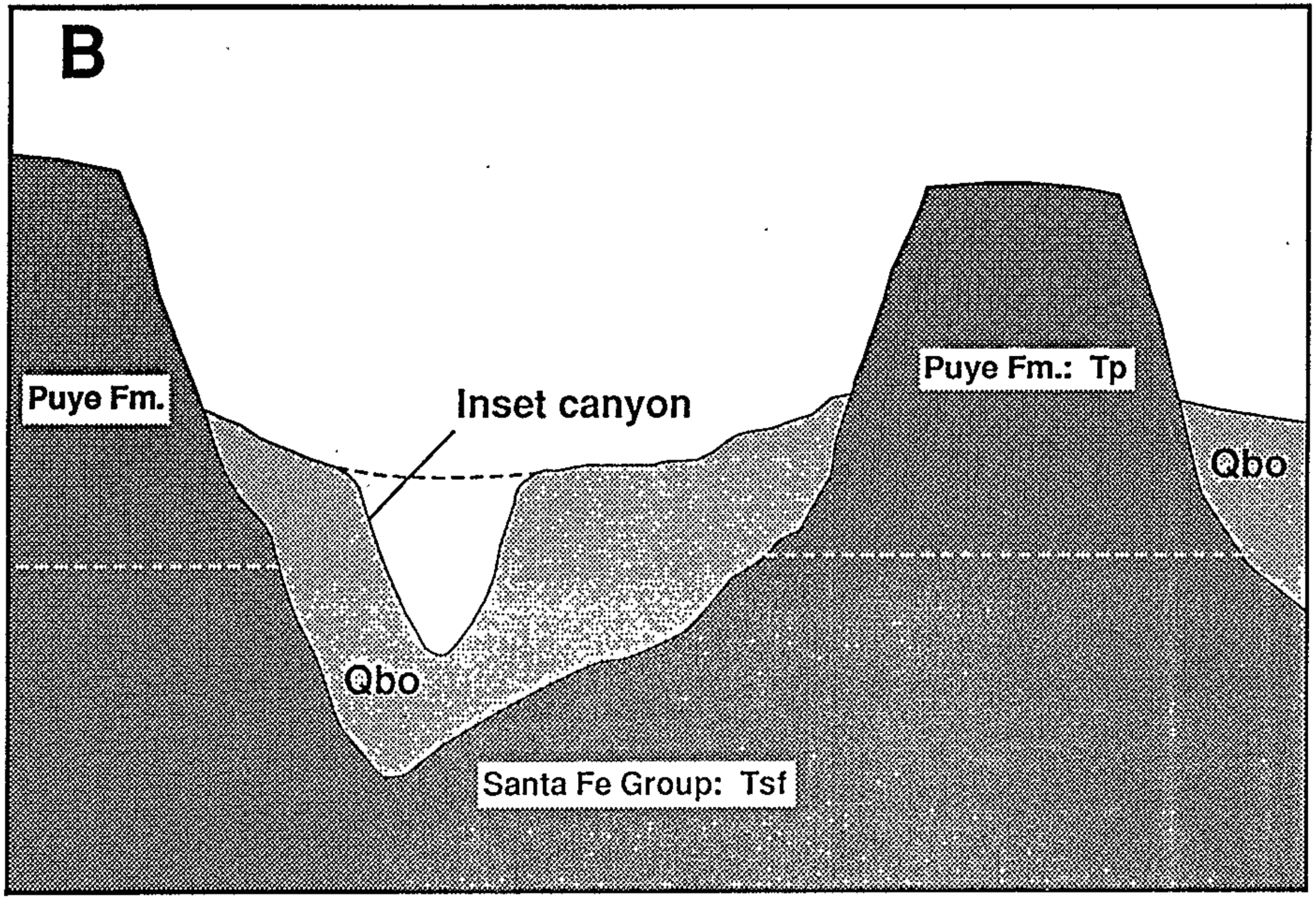
Figure 14. Geologic cross-section from Cerro Pedernal to Polvadera Mesa.

Figure 15. The schematic diagrams portray the evolution of canyons on the flanks of the Jemez Mountains from 1.7 Ma to the present. **(A)** Period of early Quaternary canyon cutting from about 1.7-1.5 Ma. **(B)** Period of early Quaternary (Bandelier) base-level rise begins with eruption of the Otowi Member at 1.5 Ma. **(C)** A hiatus in Bandelier volcanism occurs between eruptions of the Otowi and Tshirege Members. During this hiatus small, inset paleocanyons are carved into the Otowi Member as the streams of the Pajarito Plateau attempt to re-equilibrate with their pre-eruption base level and gradient. Early Quaternary (Bandelier) base-level rise resumes at 1.1 Ma with eruption of the Tshirege Member. In places, the Tshirege ejecta are so deep that canyons fill completely, many ancestral drainage divides are buried, and the once deeply dissected pre-Bandelier landscape is transformed into a gently-dipping planar one. **(D)** A period of large-scale fluvial entrenchment re-excavates the canyons in the Jemez Mountains after 1.1 Ma. A veneer of Bandelier Tuff is left plastered along the contemporary canyon walls as streams cut new canyons in approximately the same location as pre-Bandelier canyons.

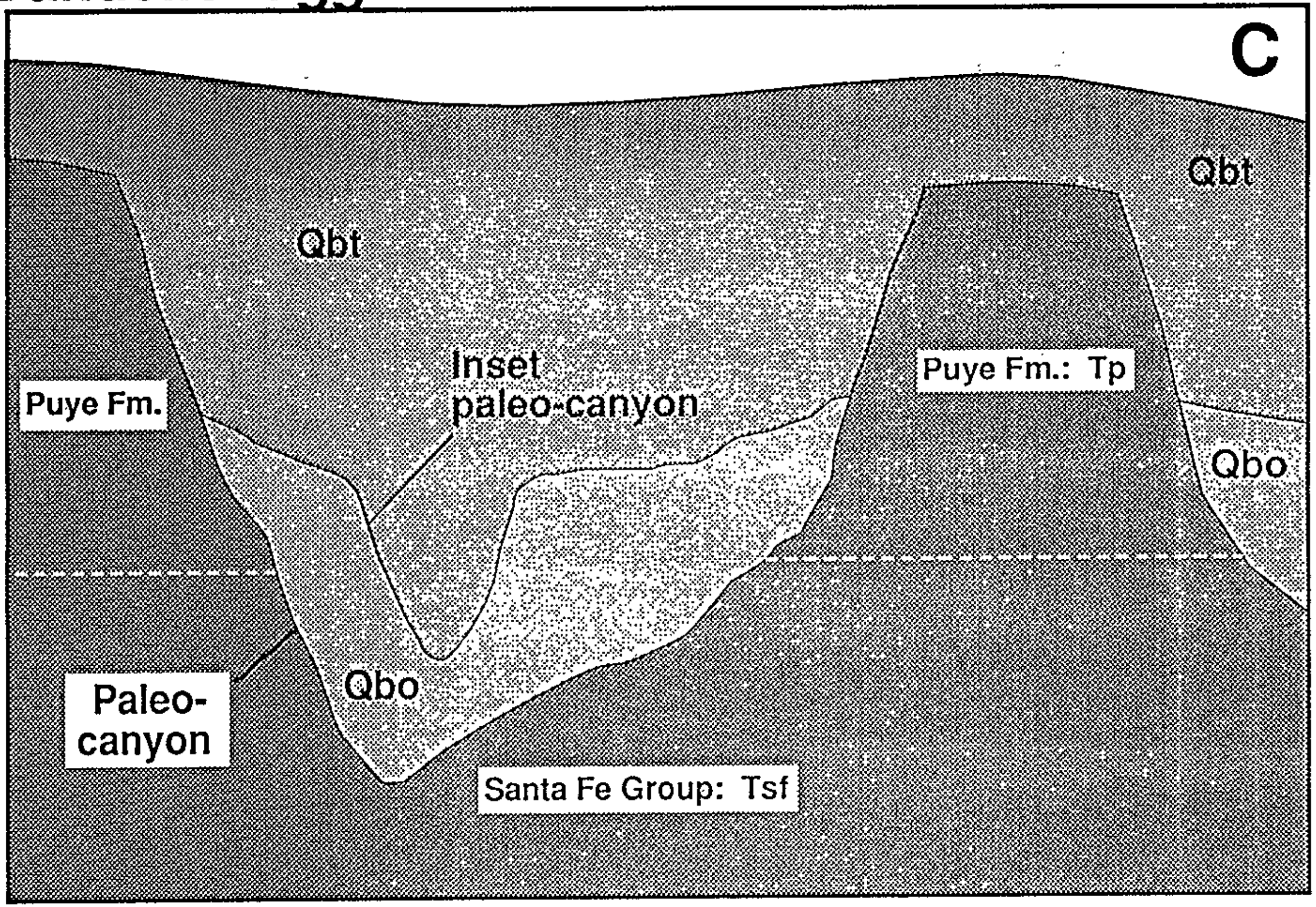
Pre-Bandelier period of incision: 1.7-1.5 Ma



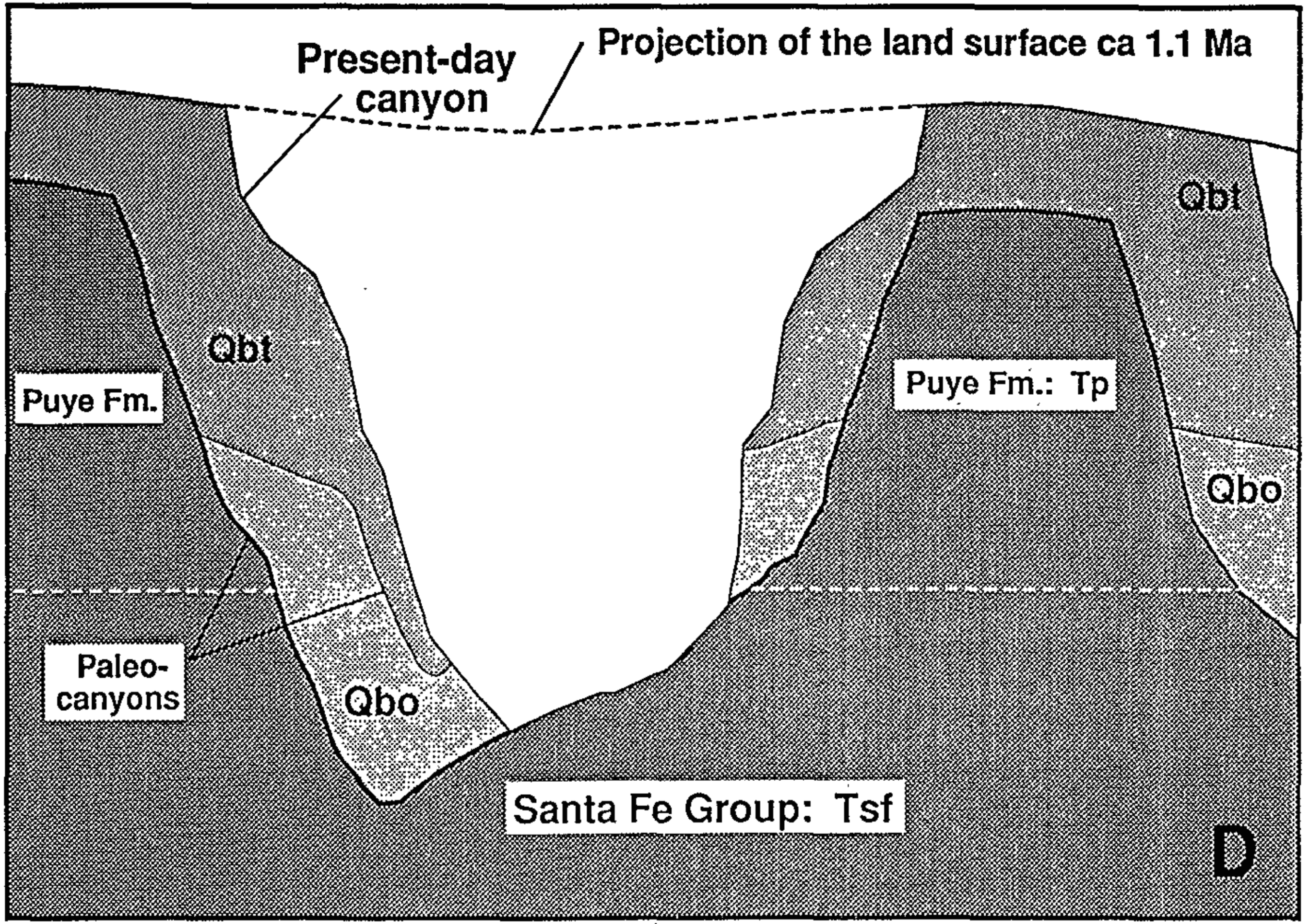
Period of Bandelier aggradation begins ca. 1.5 Ma



Bandelier aggradation continues from 1.5-1.1 Ma



Canyon cutting: 1.1 Ma to present



47.4 Turn right (north) onto graded, earthen road (herein called the **River Road**). **0.1**

47.5 Cross Arroyo del Cobre wash. **0.1**

47.6 Right turn in roadway. Straight ahead is the white, Upper Abiquiu Formation (Miocene), a fluvially reworked tuff. **0.1**

47.7 **River Road** crosses an irrigation ditch. The Cerrito Blanco fault zone, juxtaposing Abiquiu Formation (white) against the Ojo Caliente Sandstone (tan), is visible at 10:00 to 11:00. **2.25**

49.95 **River Road** crosses wash. **0.05**

50.0 Rio Chama axial-stream deposits and overlying tributary-stream deposits are preserved in the low hills just left (north) of the roadway for the next 0.4 miles. The axial deposits comprise well-rounded, dominantly Precambrian quartzite clasts, in contrast to tributary deposits that comprise subrounded to sub-angular quartzite and foliated metamorphic (schists and gneisses primarily) clasts. In addition, the axial deposits have a gray color overall; the tributary deposits a red to rusty appearance. **0.85**

50.85 Road crosses another wash. **0.25**

51.1 Veer left (north) onto **gravel roadway** about 20-30 m before reaching Madera Cañon wash. The gravel road ascends the hillside onto a deposit of unit Q5. **0.15**

51.25 Roadcut exposes Quaternary gravel deposited by the ancestral Madera Cañon wash. A Stage II+ carbonate soil horizon is preserved in the fluvial gravel. **0.05**

51.3 Road gradient flattens out temporarily atop the surface of unit Q5, passing momentarily beneath powerlines. **0.1**

51.4 Road cut exposes piedmont gravel of unit Q4. Stage II+ carbonate soil horizon preserved in the gravel. **0.05**

51.45 Road gradient flattens out onto the surface of unit Q4, and then turns abruptly to the right (north). **0.65**

52.1 Road bends to the left, crosses Madera Cañon fault zone, and begins to ascend across the fault scarp. **0.1**

52.2 Top of fault scarp and entrance to a private driveway. Park and walk down the fault scarp along the roadway.

Stop 8: Late-Quaternary faulting (?) along the Madera Cañon Fault Zone

The Madera Cañon FZ comprises high-angle normal faults that generally trend N45°E. The main fault plane dips an average of 62°SE, and an antithetic normal fault trends sub-parallel to the main fault plane with a dip of 66°NW. Together these faults define a small graben, several tens of meters wide at the earth's surface, along this segment of the Madera Cañon FZ.

The stratigraphy of Madera Cañon comprises two Tertiary units, the Upper Abiquiu Formation (white-colored, well-bedded, fluvially-reworked tuff), exposed in the valley sides at the fault zone and to the north, and the Chama-El Rito Member (variegated fluvial beds of tan-, gray-, brown-, and buff-colored sediments) of the Tesuque Formation, exposed farther south and east along faults that parallel the Madera Cañon FZ. Quaternary piedmont sediment transported by the ancestral tributary drainages from the Precambrian cored highlands to the north unconformably overlie the Abiquiu and Tesuque Formations.

This locality is one of the few places within the Abiquiu embayment (besides the Embudo FZ, see for example Harrington and Aldrich, 1984; Harrington, 1986; Harrington and Dethier, 1987) where there appears to be mid- to late Quaternary fault movement. Movement is suggested by: (1) a 10-m high scarp perfectly aligned on the trace of the Madera Cañon FZ (Fig. 16); (2) accumulation of fine-grained sediment at the base of the scarp, presumably from degradation of a fault scarp (though this could be degradation of a terrace riser as well); (3) evidence of small offsets (less than 1 m) of the Quaternary sediment by fault splays, however the majority (about 9 more meters) of the offset is obscured by colluvium; and (4) orientation of cobble-sized clasts in the fluvial deposit at the base of the scarp that suggests

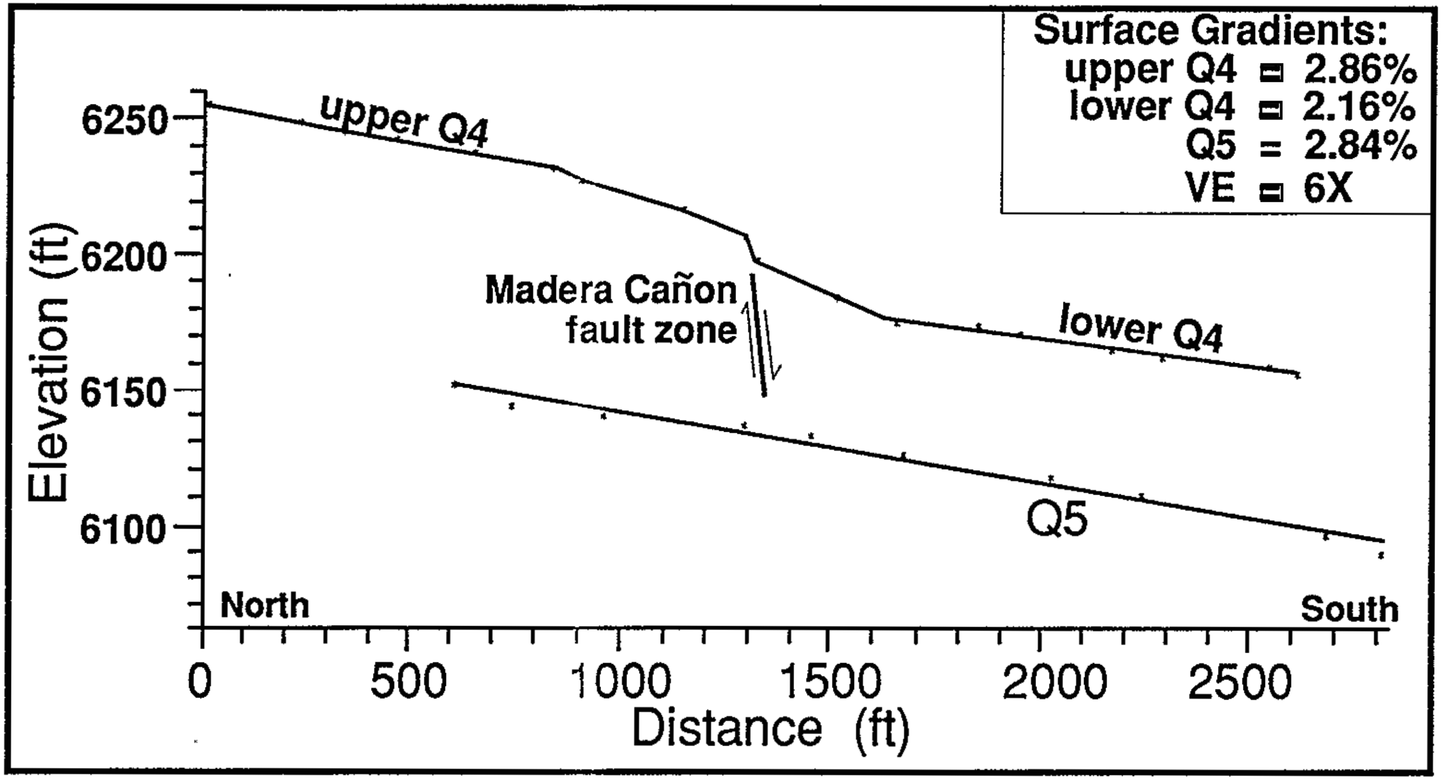


Figure 16. Longitudinal profiles along a piedmont surface of unit Q4 and the surface of inset tributary terrace Q5 across the Madera Cañon FZ in the Madera Cañon drainage. Vertical displacement of the surface of unit Q4 indicates an episode of faulting post-dating unit Q4 and pre-dating unit Q5.

stream transport was transverse to the scarp, and not parallel to the scarp, suggesting that the scarp is tectonic in origin and not a terrace riser.

Other similar and older piedmont surfaces east and west of this locality are not ostensibly offset by the Madera Cañon FZ. It is difficult to explain why older surfaces that traverse the FZ are not offset while unit Q4, west of Madera Cañon apparently is. Maybe the Madera FZ is segmented into short strands (1 km or less in length), each of which has unique slip histories.

52.2 Turn around and retrace route down piedmont surface to River Road. 1.1

53.3 Junction with River Road. **Turn left (east)** onto **River Road**, cross the Madera Cañon wash, and proceed toward **NM-554**. **1.9**

55.2 Junction with NM-554. **Turn right (south)** onto **NM-554**. **0.05**

55.25 Cross the Rio Chama. **0.55**

55.8 Junction with **US-84**. **Turn left (east)** towards Española. **3.4**

59.2 Roadway crosses the La Madera Arroyo bridge. **1.65**

60.85 Junction with **NM-233** (road to Medanales). **Continue straight** on **US-84**. **4.3**

65.15 Bridge over Rio del Oso. **1.05**

66.2 Roadcut with basalt flow. **1.35**

67.55 Bridge over Arroyo de la Presa. **0.7**

68.25 Junction with **US-285**. Routes merge, **continue straight**. **1.15**

69.4 Entrance to San Jose Church on the right (west). **3.85**

73.25 Enter Española at junction with **NM-584**. **Continue straight** through stoplight. **0.9**

74.15 Road descends off an axial-stream (Rio Grande) deposit. **0.35**

74.5 First stoplight. **Continue straight** ahead on **US-84/285**. **0.05**

74.55 Second stoplight. **Turn right** onto **NM-30** toward Los Alamos. **0.2**

74.75 Third stoplight. **Proceed straight** ahead on **NM-30**. **0.35**

75.1 Large boulders, reworked by debris flow from deposits of the Puye Formation (?), and gravel of the ancestral Rio Grande appear in the Quaternary units located on the right (west) side of **NM-30** for the next 0.4 miles. **1.0**

76.1 Erosional surfaces Q1-Q4 (of Dethier et al., 1988) are visible to the right for the next 6 miles. **2.3**

78.4 Turn off on the right to Puye Cliff ruins. The roadside historic marker reads:

> This spectacular site on the Pajarito Plateau is located in the reservation of Santa Clara Pueblo. It includes a pueblo on the mesa top and rooms cut from the volcanic rock. Puyé, occupied from about 1250-1550 [A.D.], is considered the ancestral home of Santa Clara and other Tewa-speaking pueblos.

0.6

79.0 Black Mesa (not the same as that near Hernandez) appears at 10:00. At 2:00 are cliffs composed of the Puye Formation. Straight ahead at 12:00 is La Mesita and basalt flows of the Cerros del Rio volcanic field. Many of these flows formed during the Pliocene and early Quaternary. Some flows are found on both sides of the modern Rio Grande, indicating that White Rock Canyon had either back-filled, or had not yet been carved, when these flows crossed the present position of the Rio Grande. **4.2**

83.2 **Turn right (west)** at the junction with **NM-502**, and proceed towards Los Alamos. **0.3**

83.5 Roadcut to the right exposes Quaternary stream deposits overlying Santa Fe Group sediment. **0.35**

83.85 On the right is the turn-off to Guaje Canyon where some of the most spectacular outcrops of the Puye Formation occur. A basaltic andesite flow is visible on the skyline, across the canyon to the left (south). This is the Otowi flow of Galusha and Blick (1971). It has a potassium-argon date of 2.5 ± 0.1 Ma (UAKA 86-65; Dethier, in press). **1.45**

85.3 Entrance to a gravel operation on the right. The gravel mine provides outstanding exposures of the Puye Formation. Road now begins to climb up-section through the Puye Formation, a Cerros del Rio flow and Bandelier Tuff. **0.5**

85.8 Lacustrine deposits of the Puye Formation, indicative of intermittent damming of the Rio Grande by landslides in Pliocene canyons, are exposed in the roadcuts just before and throughout the large, horseshoe turn. **0.2**

86.0 Roadcut exposes for the next 0.35 miles a tholeiite flow (2.4 ± 0.3 Ma; Luedke and Smith, 1978), which flowed east from sources near Los Alamos. Phreatomagmatic features suggest this unit flowed into a lake (note underlying lacustrine deposits at mile 85.8). **0.35**

86.35 A buried soil (?) appears in the roadcut for the next 0.05 miles. **0.05**

86.4 Roadcut now exposes the Guaje Pumice, basal unit of the Otowi Member of the Bandelier Tuff. **0.5**

86.9 Roadway expands to 3 lanes, **move to the right lane** and take the White Rock/Bandelier National Monument **exit to NM-4**. **1.65**

88.55 Roadway bifurcates with the right lane becoming the truck route to Los Alamos. **Move to the left lane and continue toward White Rock on NM-4.** To the left (east) is the Tsankawi unit of the Bandelier National Monument. **0.95**

89.5 A number of pockmarks are visible in the cliffs of Bandelier Tuff to the left (east) side of the road. These holes were carved by early native inhabitants and served as caches and living spaces. **1.75**

91.25 **Take the first left into White Rock (Rover Road).** Follow the signs to White Rock Overlook Park. **0.15**

91.4 **Turn left** onto **Meadow Lane.** **1.15**

92.55 **Turn left** onto **Overlook Road.** Thin (less than 3 m) Pleistocene fluvial deposits mantle basalt in this area. Upper Bandelier Tuff is exposed in the mesa to the left (north). **0.7**

93.25 Overlook parking area. Park and assemble on cliff edge for stop 9.

Stop 9: White Rock Canyon formation and large-scale cycles of base-level change

" White Rock Overlook provides a spectacular view of White Rock Canyon, rocks of the Santa Fe Group (buff arkose), Pliocene flows and volcanic centers of the Cerros del Rio field, and massive Pleistocene slumps that affect most of the stratigraphic column. The Rio Grande, visible some 200 m below, has apparently flowed within 6 km of its present location since mid-Pliocene time. The tholeiitic basalt which caps the plateau here flowed east from now-buried vents and entered a lake at about 1.8 Ma (D.P. Dethier, unpublished data, 1987). Pillow basalt and palagonitic breccia are exposed next to the waterfall west of the Overlook, and similar exposures are found in each canyon north to Los Alamos Canyon (see Road log, mile 86.0). Upper and Lower Bandelier Tuff (locally) and Rio Grande cobble gravel lie on the basalt surface.

" Interlayered basalt flows and phreatomagmatic, lake and fluvial deposits underlie the capping flow. These rocks record growth of the northern Cerros del Rio volcanic field and episodic damming of the Rio

Grande between about 2.7 and 2.3 Ma (Aubele, 1979). La Mesita, located to the NNE of the Overlook, consists of a phreatomagmatic sequence capped by a cinder cone and flows apparently derived from the same magma. The gently sloping basalt (hawaiite) directly east of the Overlook is about 2.3 Ma and lies above the Ancha Formation, which is thought to be a time-stratigraphic equivalent of the volcaniclastic Puye Formation. To the south a thick exposure of Bandelier Tuff fills a deep paleocanyon cut into basalt east of the White Rock Canyon. At this location and at several other, landslide debris lies beneath the tuff. More commonly, the slides incorporate Bandelier Tuff. Most of the massive slumps visible from here appear to be of early or mid-Pleistocene age.

" The brownish yellow deposit beneath the power line (E. bank of the Rio Grande) consists of 30 m of laminated to thin-bedded silt, clay and fine sand. This lacustrine sequence lies above a Rio Grande boulder gravel and records a transition from "normal" discharge to ponded conditions in mid[-] (?) Pleistocene time. Galusha and Blick's (1971) suggestion that a Pleistocene glacier dammed a lake in White Rock canyon seems unlikely, but a dam generated by a massive slump or hydraulic damming could explain the deposit. The top elevation of the lacustrine sediment (1715 m) suggests that the lake extended north to Española, but we have not recognized similar deposits in that area." (Dethier, 1987 in C.M. Menges et al., eds., 1987, pp. 34-35).

Stratigraphic relations of Pliocene and Quaternary deposits and the paleo-topographic relations identified from paleo-canyons in the vicinity of White Rock Canyon provide evidence of large-scale cycles of fluvial base-level rise and fall during the past 5 m.y. During this interval 2 large-scale cycles (hundreds of meters) of aggradation and incision have occurred (Fig. 6C-6E). At least 6 smaller-scale (tens of meters) cycles of aggradation and incision are superimposed on the mid- to late Quaternary period of large-scale incision, indicating that progressive base-level fall was episodic during that time (Fig. 6E).

Aggradation began in the White Rock Canyon area about 5-4 Ma with progradation of the Puye Formation, a large volcaniclastic fan deposited primarily on the east flank of the Jemez volcanic field (Waresback, 1986; Waresback and Turbeville, 1990). Growth of the fan seems to be coincident with active movement on the Pajarito and Embudo fault zones (Gardner and Goff, 1984), which created a depocenter for sediment shed from the adjacent volcanic pile. The basal Totavi Lentil, an axial-stream gravel deposited by an ancestral Rio Grande (Fig. 6C), is found approximately 100 m (350 feet) above the present-day grade of the Rio Grande in Los Alamos Canyon (whose confluence with the Rio Grande is approximately 7 km upstream of White Rock overlook); less than 90 m (<300 feet) above grade in Sandia Canyon (about 2 km upstream of White Rock overlook); and approximately 30-40 m (120 feet) above grade in Ancho Canyon (approximately 7 km downstream from the White Rock overlook; Dethier, in press). The Pajarito and Embudo fault zones demarcate the boundaries of this tectonic fan unit (Puye Formation). North of the Embudo fault zone the distribution of Puye deposits is restricted to a few Pliocene (and early Quaternary?) stream channels. These northern, outlying deposits are laterally discontinuous and only a few meters thick at most.

Aggradation of the Puye fan seems to have continued to at least 1.8 Ma, based on the date (1.75 ± 0.08 Ma; Spell in Waresback and Turbeville, 1990) of a tephra deposited near the top of the Puye Formation. Soon after deposition of the tephra (about 1.7 Ma to 1.5 Ma) large-scale incision occurred in many canyons draining the Pajarito Plateau and Jemez Mountains. In many places hundreds of meters of incision occurred with some paleo-canyons cut nearly as deep or even deeper than modern canyons (Dransfield and Gardner, 1985; Figs. 6D and 15A).

From 1.5 to 1.1 Ma there was large-scale base-level rise, produced by eruptions in the Jemez Mountains and deposition of the Bandelier Tuff (Fig. 15B-C). The Bandelier Tuff comprises two members, the lower Otowi and upper Tshirege Members. In addition to filling paleo-canyons, the Otowi Member is cut by smaller, inset paleo-canyons, indicating that drainage systems of the

Pajarito Plateau had already begun to incise in an effort to re-equilibrate with pre-eruption base levels before the upper Tshirege Member of the Bandelier Tuff was deposited (Fig. 15C; Dransfield and Gardner, 1985). The outline of one paleo-canyon, in-filled with sediment of the Tshirege Member, is visible across the Rio Grande approximately 6 km downstream from White Rock overlook.

Fluvial entrenchment has occurred since 1.1 Ma with at least 6 smaller-scale cycles of fluvial cut-and-fill superimposed on the mid- to late Quaternary period of fluvial entrenchment (Fig. 6E). Although the cause of the mid- to late Quaternary large-scale fluvial entrenchment is somewhat enigmatic, we hypothesize that the smaller-scale cycles of aggradation and incision are related to Quaternary climatic fluctuations. Similar Quaternary deposits are found elsewhere in the Rio Grande rift of northern New Mexico (Wells et al., 1987; Kelson, 1986; Pazzaglia, 1989). The persistence of the deposits on both sides of major rift structures along with the consistency of their elevation above modern grade, indicates that their origin is more probably related to regional climatic factors. Tectonism would create discontinuities or displacements in ancestral river grades across fault zones.

In summary, the stratigraphic relations and paleo-topographic features of the White Rock Canyon area indicate the following chronology of events: (1) aggradation of the Puye Formation and burial of the basal Totavi Lentil indicates base-level rise beginning around 5-4 Ma; (2) aggradation ceased soon after the deposition of a 1.75 Ma tephra; (3) fluvial incision of 100s of meters occurred from 1.7-1.5 Ma; (4) base-level rose following deposition of the Bandelier Tuff, which filled paleo-canyons in many places and overtopped interfluves in many other places, particularly the Pajarito Plateau. The lower member of the Bandelier Tuff has in some localities, canyons preserved within itself, indicating that short-lived, but rapid base-level fall interrupted the episode of Bandelier deposition; (5) from 1.1 Ma to the present the streams of the Española basin have been incising. At least 6 cycles of smaller-scale cut-and-fill are superimposed on this larger-scale period of incision.

This concludes the field trip and formal examination of the geomorphology and neotectonic features along the western margin of the Rio Grande rift through the Española basin. Several return routes to Albuquerque are possible. First, retrace route through White Rock back to the intersection of Rover Road and NM-4.

Alternate Route 1: The quickest way back to Albuquerque follows NM-4 East to NM-502 East, to Pojoaque. At Pojoaque, take US-84/285 South to Santa Fe. From Santa Fe take I-25 South to Albuquerque.

Alternate Route 2: Take NM-4 West through the Valles Caldera and Jemez Mountains to La Cueva. At La Cueva, turn left, following NM-4 through Jemez Springs to San Ysidro. At San Ysidro turn left onto NM-44 South to Bernalillo. Follow I-25 South from Bernalillo to Albuquerque.

Alternate Route 3: Take NM-4 West to FR-289. Follow FR-289 to FR-268. Turn left on FR-268 and proceed southeast towards Cochiti and NM-22. Turn left, taking NM-22 east to I-25. Take I-25 South to Albuquerque. Parts of this route are closed during winter and early spring for as long as the forest service roads are wet and/or thawing. FR-289 is well-maintained in its northern reach, but deteriorates further south. Vehicles with four-wheel drive or adequate clearance are recommended, and travellers unfamiliar with current road conditions are advised to contact the Jemez Springs district office of the Santa Fe National Forest (telephone number 988-6988 for residents of Santa Fe and Los Alamos; and 1-(505)-829-3535 from other telephone districts) for a road status report.

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