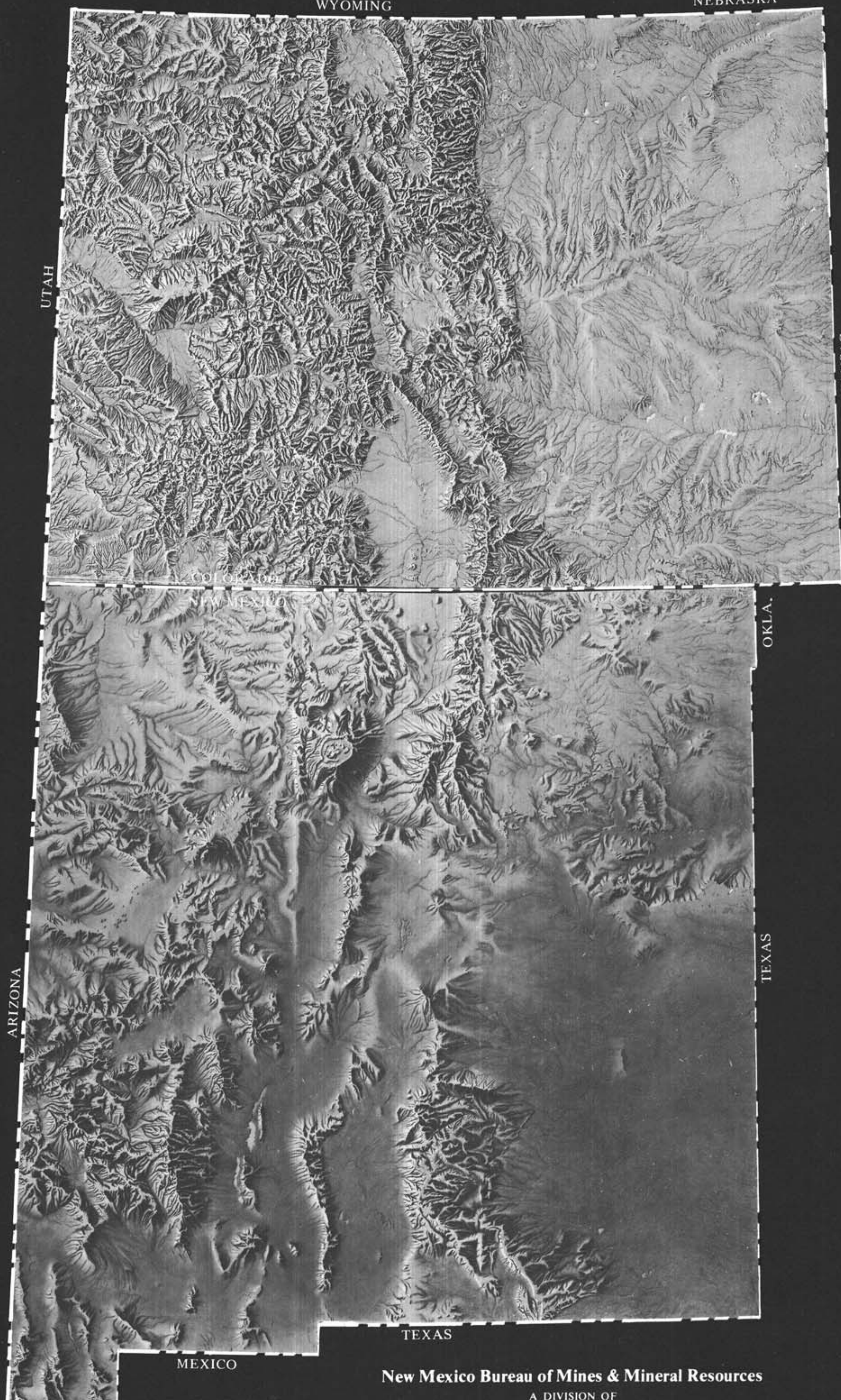
Guidebook to Rio Grande rift in New Mexico and Colorado

compiled by J. W. Hawley

1978



CIRCULAR 163

New Mexico Bureau of Mines & Mineral Resources
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The Rio Grande rift is one of the more significant structural and topographic features of the earth. To understand its geologic history is to begin to understand the geologic history of the western United States—including the Rocky Mountains, the Colorado Plateau, the Basin and Range province, and the Great Plains. In addition, the geologic, topographic, geophysical, magmatic, tectonic, and geomorphic features of the Rio Grande rift are similar to those of other rift zones of the earth. Evaluation of these facets will contribute to knowledge of all rift zones and their relationships to worldwide tectonics.

This guidebook is designed to acquaint those who take the field trips with the details of geologic features along the rift zone. Included are short papers on topics relative to the overall region. These papers and the road logs are of special interest to anyone pursuing further study of the rift. In its own way, the guidebook is a symposium volume on the field features of the rift and is, therefore, a companion to the many papers presented at the symposium *Rio Grande Rift: Tectonics and Magmatism* to be published by the American Geophysical Union.

As the New Mexico agency charged with the study of the state's geology and required to give scientific assistance in the exploration, development, and conservation of New Mexico's mineral wealth, we publish this guidebook to the landscape and geology of the heart of New Mexico—the Rio Grande rift.

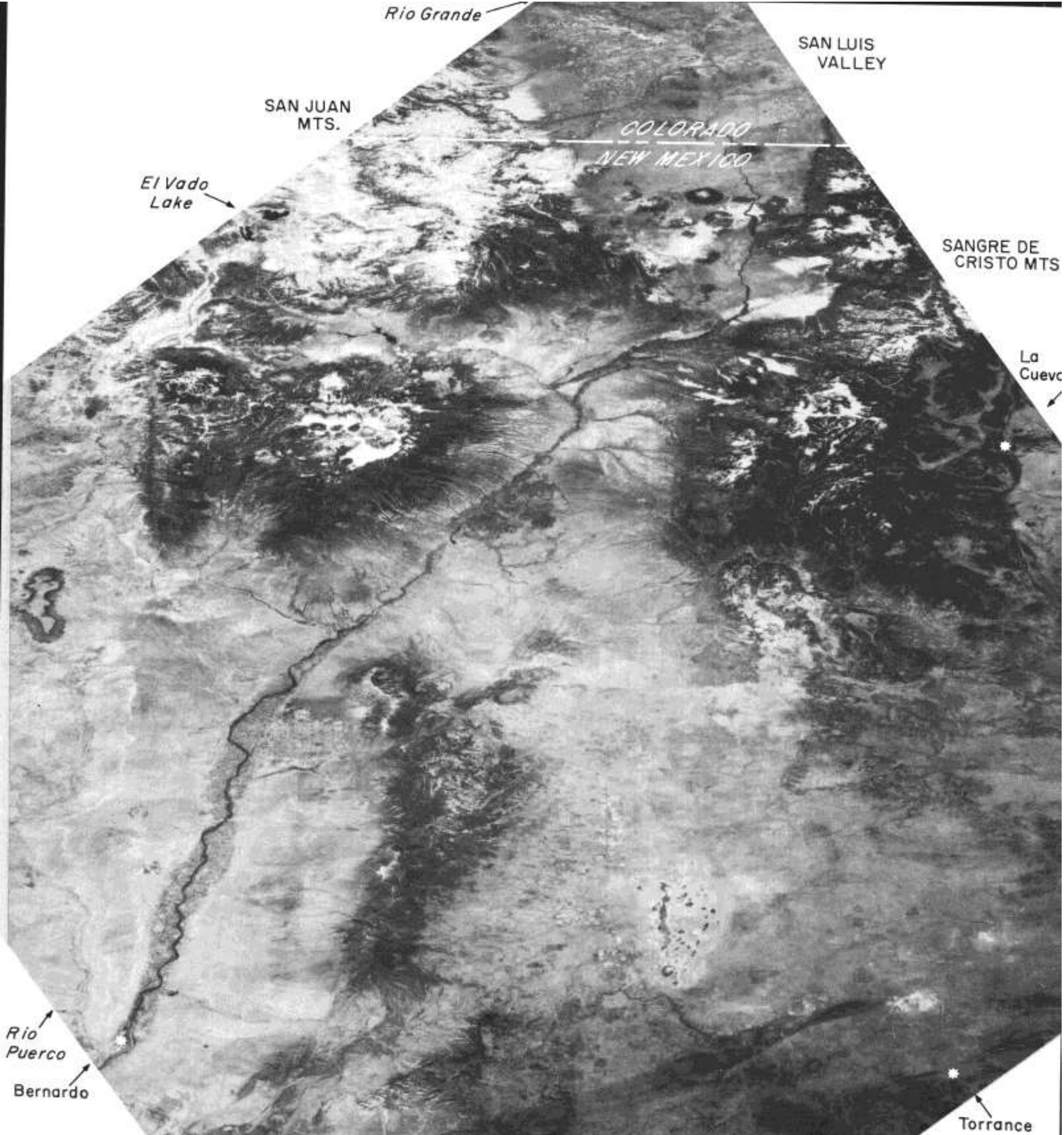
Many scientists have contributed their time and talents in the preparation of the road logs and articles, but major credit goes to John W. Hawley, who solicited papers and contributions, assembled the illustrations, wrote and rewrote most of the road logs, and who had full responsibility as compiler. The comprehensiveness and scientific excellence of this material are the result of John's efforts.

Frank E. Kottlowski
Director
New Mexico Bureau of Mines
and Mineral Resources

GUIDEBOOK TO RIO GRANDE RIFT IN NEW MEXICO AND COLORADO

And some rin up hill and down dale
knapping the chucky stanes to pieces
wi' hammers, like sae many road
makers run daft. They say it is to see
how the world was made.

—Sir Walter Scott



FRONTISPIECE—SKYLAB 4 PHOTOGRAPH, WITH VIEW TO NORTH UP THE RIO GRANDE RIFT FROM AN ALTITUDE OF 270 MI (432 KM) OVER CENTRAL NEW MEXICO. From lower left to top center, the Albuquerque, Santo Domingo, Española, and San Luis basins step over en echelon as the rift crosses a wide zone with strong, northeast-trending structural grain. The Estancia Basin, a shallow downwarp developing along the east side of the Albuquerque Basin and separated from it by the east-tilted fault-block uplifts of the Manzano and Sandia Mountains, is conspicuous in the center foreground. The Jemez lineament—one of the most active magmatic zones in the United States during the past 5 million years—trends northeastward from basalt-capped Mesa Prieta at left center margin, crosses the south end of Sierra Nacimiento, and passes beneath the Valles caldera at left center. Black Mesa, a prong of Servilleta basalt extending southwestward to the confluence of the Rio Chama and Rio Grande, lies along the Jemez lineament northeast of the Valles caldera. The Rio Grande Gorge and the scattered stratovolcanoes of the Taos Plateau volcanic field are prominent geomorphic features at the south end of the San Luis Basin (photo SL4-89-008 provided by the Technology Application Center, University of New Mexico).

Circular 163

New Mexico Bureau of Mines & Mineral Resources

A DIVISION OF
NEW MEXICO INSTITUTE OF MINING & TECHNOLOGY

Guidebook to Rio Grande rift in New Mexico and Colorado

compiled by J. W. Hawley
in cooperation with 42 other coauthors

prepared especially for

Symposium on Tectonics and Magmatism of Rio Grande Rift
Santa Fe, New Mexico, October 8-17, 1978

SOCORRO 1978

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Davis, G. H., and Keller, G. R., 1978, Subsurface structure of San Luis Valley, *in* Guidebook to Rio Grande rift in New Mexico and Colorado: New Mexico Bureau of Mines and Mineral Resources, Circ. 163, p. 28

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Preface

Many individuals and several organizations have assisted in compiling and editing this book. Early stages of work in 1977 were concerned with developing a guidebook concept that would best fit the International Symposium theme of *Tectonics and magmatism of the Rio Grande rift.* This effort included selection of tour-stop sites and routes of travel between Santa Fe and the starting points at Denver and E1 Paso. The following persons helped in this key phase of guidebook development: George Bachman, Elmer Baltz, Joe Bridwell, Chuck Chapin, Lindrith Cordell, Harold James, Wayne Lambert, Mike Machette, Kim Manley, Jacques Renault, Al Sanford, Glenn Scott, Bill Seager, and Ogden Tweto. Many of these persons have also contributed road-log and tour-stop entries. Information on formal contributions to the guidebook text, as well as names of individual contributors, is given in the Introduction. This assistance of 42 persons is gratefully acknowledged. In addition to the workers named above, the following individuals participated in the actual compilation and field checking of road-log and tour-stop entries: Roy Bailey, Richard Chamberlin, Ed Deal, Wolf Elston, Roy Foster, Ted Galusha, Vin Kelley, Frank Kottlowski, Bert Kudo, Pete Lipman, Bill Muehlberger, Bob Osburn, Jon Sandor, and Sam Thompson 1II.

The final and somewhat hectic stage of guidebook compilation involved a team of staff members of the New Mexico Bureau of Mines and Mineral Resources. This included not only routine, high-quality stenographic and cartographic work, but also much round-the-clock effort by the Bureau editorial staff, particularly Candace Merillat and Joan Pendleton. There is literally no way that the book could have been published without their help.

Special acknowledgment is due to Mike Inglis of the Technology Application Center, University of New Mexico, for assistance in selection of the Skylab photography used to illustrate this book. Photographs provided by the Technology Application Center and by Wayne Lambert, Bob Osburn, and Harold James are gratefully acknowledged.

The Geological Society of America and the New Mexico Geological Society allowed the use of a number of illustrations from their publications. Finally, assistance rendered by the U.S. Geological Survey during the course of guidebook preparation deserves special acknowledgment. This help included preparation of the cover map, editorial assistance, and most of all, enthusiastic support for this publication effort on the part of many members of the Survey staff.

John W. Hawley
Environmental Geologist
New Mexico Bureau of
Mines and Mineral Resources

Socorro
September 1, 1978

Abstract

This volume is a comprehensive field guide to the middle and late Cenozoic geology of the Rio Grande rift region extending from central Colorado south to the international boundary. Initially the book was used on field trips of the 1978 International Symposium on Tectonics and Magmatism of the Rio Grande Rift. Included are two multicolor tectonic maps (1:1,000,000) specially prepared for the symposium, one of Colorado and the other for the rift region of New Mexico, Texas, and Chihuahua. The road logs cover about 1,750 mi of a tour route from Denver to E1 Paso via Santa Fe. Logs are oriented for both northbound and southbound travel. Two additional logs cover the Jemez Mountain and Española Basin areas near Santa Fe. Detailed commentaries by 30 contributing authors on the geology and geophysics of 65 stops are included with the road logs. The volume also includes six invited papers on rift geology and geophysics, two correlation charts, selected data on deep drill holes in New Mexico, and heat-flow data for Colorado and New Mexico.

PUBL1SHER'S NOTE *to 2nd printing—In* the scramble to get the original edition into print within a drastically foreshortened lead time ensuring that conferees would have copies in hand during the field tours, a couple dozen errors found their way into print. Most were inconsequential relative to the total effort. All have been corrected in the present edition.

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Introduction

This book is a comprehensive guide to the middle and late Cenozoic geology of the Rio Grande region of Colorado and New Mexico. Though initially used on field trips for the International Symposium on Tectonics and Magmatism of the Rio Grande Rift, the guidebook will be useful to anyone interested in the Cenozoic history of the 600-mi-long area extending from central Colorado to E1 Paso, Texas.

Sheets 1 and 2 (in pocket) show the region covered by the tour guide, including the route traversed and the location of stops. The book was organized to coordinate with field trips and technical sessions of the International Rift Symposium. Road logs into Santa Fe from both Denver and E1 Paso (prior to formal technical sessions) were planned to introduce participants to geological and geophysical features and concepts related to the geodynamics theme of the symposium.

The guidebook comprises five major sections. Three consist of road logs, with comprehensive entries at individual tour stops; a fourth section has three invited papers pertinent to the rift region as a whole, and the fifth section is made up of special maps, tables, and charts also related to various parts of the rift region. Two tectonic maps (sheets 1 and 2) of the Colorado region and of the New Mexico-Texas-Chihuahua region are the basic illustrations for this guidebook and should be consulted during the tours.

The first two road log sections (Northern rift guides 1 and 2 and Southern rift guides 1 and 2) cover the routes to Santa Fe, New Mexico, southbound from Denver, Colorado, via Alamosa, and northbound from E1 Paso, Texas, via Socorro, New Mexico. Each section also contains a reverse route from Santa Fe to either Alamosa-Denver or Socorro-El Paso as well as a list of references cited. Road logs *to* Santa Fe contain complete tour text, including stop commentary, illustrations, and short technical papers pertinent to limited geographical features. Road logs *from* Santa Fe include only geologic and geomorphic features seen en route between formal stops; commentary is cross-referenced to the complete text and illustrations of the Santa Fe-bound logs.

Discussions at individual stops all relate to the central theme of rift dynamics in a geologic time frame covering the past 30 to 40 m.y. However, many discussions concern special themes, such as the Cenozoic evolution of individual range and basin blocks, case histories of local geophysical studies, or geomorphic expression of recent faulting.

The northern part of the field trip (Denver-Alamosa-Santa Fe) was chosen to be the first part of the book, because the structure of the rift in that region is quite well defined. Close spacing and prominent relief of the rift borders, particularly in the upper Arkansas Valley and San Luis Basin, provide better insight into the deep-seated processes involved in formation of the mountain and rift-basin terrain. Ogden Tweto, of the U.S. Geological Survey, concisely summarizes current knowlege of the structural evolution of the rift in Colorado. His contributions include the tectonic map of the rift region in Colorado (sheet 1) and commentary on features observed en route from Denver to Alamosa, via Climax, Leadville, Salida, Poncha Pass, and Mosca. This commentary includes short road-log entries and expanded discussions at stops.

The Alamosa to Santa Fe part of the northern tour guide emphasizes 1) volcanic rocks of the southern San Luis Basin, and 2) the nature of the boundaries between the basin and the San Juan Mountains on the west and the southern Sangre de Cristo-Picuris ranges on the east and southeast. The volcanic units include pre-rift rocks in blocks west of and within the rift as well as rocks contemporaneous with rifting—such as the extensive Pliocene basalt flows of the Taos Plateau. Contributors to the road logs and tour stops include R. H. Burroughs (pre-rift volcanics and structural evolution of the San Luis Hills area south of Alamosa), P. W. Lipman (southeastern San Juan Mountains and the Taos Plateau west of the Rio Grande Gorge), and W. R. Muehlberger and John Hawley (basin-fill stratigraphy and structure in the southeastern San Luis Basin adjacent to the Sangre de Cristo and Picuris Mountains). The northern rift guide concludes with road logs by Muehlberger and Hawley that cover the Rio Grande Canyon-Embudo constriction area (transitional between the San Luis and Española Basins) and the eastern Española Basin.

Southern rift guides 1 and 2 highlight features of the rift between E1 Paso and Santa Fe. The southern road log has more parts than does the northern guide, because 1) the basic physiography of the region is characterized by many individual (often isolated) range blocks and 2) the ongoing geological and geophysical research in the southern region represents the work of many different institutions and individuals.

The short Texas part of the tour offers a comprehensive review of work on the Franklin Mountain block and the adjacent bolson areas that extend from Texas and New Mexico into Chihuahua, Mexico. Major guidebook contributors for this area include E. M. P. Lovejoy, W. R. Seager, and J. W. Hawley on geology, and G. R. Keller, R. G. Graham, and R. F. Roy on geophysics.

Topics covered in the southern New Mexico segment of the tour guide, from near Las Cruces to Socorro, reflect the intensive field research during the past decade on 1) middle Cenozoic volcano-tectonic (cauldron) features and 2) the controls that these features as well as precursor Laramide structures have exerted on the late Cenozoic evolution of the rift. Guidebook entries also reflect current interest in geothermal resources and related geophysical studies. Commentary at stops includes discussions on geology of the Las CrucesCaballo Reservoir area by Seager and Hawley, geophysics and geothermal resources by Paul Morgan, history of the Elephant Butte Irrigation Project by Jerry Mueller, geology of the Fra Cristobal Range by Sam Thompson III, and geology of cauldron features in the San Mateo and Magdalena Mountain area by C. E. Chapin, E. G. Deal, and G. R. Osburn. Road logs from E1 Paso to Elephant Butte and from Elephant Butte to Socorro were contributed, respectively, by J. W. Hawley and W. R. Seager and by Hawley, C. E. Chapin, and G. R. Osburn.

The Socorro to Santa Fe segment of the southern tour guide is introduced by A. R. Sanford's paper on characteristics of the rift in the Socorro vicinity that are revealed from geophysical studies. The theme of middle Cenozoic cauldron features and their influence on rift tectonics is again emphasized with a short tour around the southern end of the Socorro-Lemitar uplift, followed by a trip in the Socorro Basin east of the uplift to near San Acacia. The road log for this part of the tour is contributed by C. E. Chapin, R. M. Chamberlin, and J. W. Hawley.

Emphasis of the tour guide north of San Acacia is on the geology and geophysics of the Albuquerque Basin. This is the area of recent COCORP seismic-reflection profiling and current investigations of basin-fill stratigraphy and soil geomorphology. The latter research is being applied in studies of faults that displace Quaternary geomorphic surfaces and associated deposits. Stop discussions also relate to the geology and geophysics of boundaries between the basin and the SandiaManzano-Los Pinos range (to the east) and the uplifts of the Colorado Plateau (to the west). Influence of Laramide precursors on evolution of basin-and-range structures is again noted. Two stops (near Los Lunas and Bernalillo) stress Pliocene and Pleistocene evolution of andesitic to basaltic volcanic fields within the rift depression. The road log from Rio Salado, near San Acacia, to south of Albuquerque is by Hawley, while the log of the Albuquerque-Bernalillo area is by P. W. Lambert. Tour-stop discussions on basin-fill geology and soil-geomorphic relationships are by M. N. Machette, P. W. Lambert, and J. W. Hawley. Geology of the ranges and structural evolution of the Albuquerque Basin is covered by V. C. Kelley, and Lindrith Cordell presents data from recent geophysical surveys in the Sandia Mountain-Albuquerque Basin area.

The Bernalillo to Santa Fe part of the southern rift tour covers an area, including the Santo Domingo subbasin, that is structurally transitional between the Albuquerque and Española Basins. Road logs and tour-stop discussions are by J. W. Hawley and F. E. Kottlowski, with contributions from V. C. Kelley on the northern Sandia Mountains and southern Santo Domingo subbasin. The northernmost stop is in the Santa Fe embayment, south of the Española Basin, where the middle to late Cenozoic history of the Santa Fe area is reviewed by F. E. Kottlowski.

The concluding part of the southern rift guidebook section covers the lower Jemez Valley area between Bernalillo and San Ysidro and includes a road log and a tour-stop discussion by Ted Galusha and J. W. Hawley. Work on basin-fill (Santa Fe Group) stratigraphy (starting with Kirk Bryan and associates) is reviewed, and the use of vertebrate faunas in dating a Miocene stratigraphic sequence is described. The log connects with the Jemez Mountain tour, included in the next section.

Two further road logs, with commentary, compose the third section of the guidebook. These guides cover two areas that can be conveniently reached on one-day trips from Santa Fe. The first road log is a guide to the geology of the Jemez Mountain-Valles caldera area by R. A. Bailey and R. L. Smith; this guide is followed by two short papers reviewing recent geological and geophysical research in areas near the Jemez Mountains and Española Basin. The first paper, by A. J. Budding, deals with the subsurface geology of the Pajarito Plateau (the eastern piedmont of Jemez Mountains) as interpreted from gravity data. The second paper, by Jayne Aubele, concerns the geology of the Cerros del Rio volcanic field, located across White Rock Canyon from the Pajarito Plateau. The second tour guide in this section of the book emphasizes the late Cenozoic geology of Española Basin and has been prepared by Kim Manley.

The fourth major section of the guidebook contains three invited papers of general interest. Elmer Baltz provides a historical review of the Rio Grande depression-rift concept from its early development, by Kirk Bryan, to the present. More importantly, Baltz also provides a broad geological perspective (in both a regional and historical sense) of the tectonic setting in north-central New Mexico, the core area of rift-related research. Joe Bridwell discusses physical behavior of the upper mantle beneath the northern rift. The overview of rift basalts by Jacques Renault contains information on many of the volcanic centers (most of Pliocene and Pleistocene age) seen on the tour. This paper concludes the text portion of the guidebook.

Included in the special maps and tables section are four maps, covering the entire field trip region, that should be consulted on a continuing basis throughout the trip. In great part these maps represent new compilations of data prepared especially for this guidebook; the Colorado data have not been previously published in this form. The key maps for the user of this guidebook are sheets 1 and 2 (in pocket). These are the tectonic maps of the rift system in Colorado (by Ogden Tweto) and in New Mexico, Chihuahua, and Texas (by L. A. Woodward, J. F. Callender, W. R. Seager, C. E. Chapin, J. C. Gries, W. L. Shaffer, and R. E. Zilinski). These two maps are supplemented by compilations of heat-flow data on a tectonic map base generalized from sheet 1 and the New Mexico part of sheet 2. The heat-flow data have been collected and compiled by M. A. Reiter, C. L. Edwards, A. J. Mansure, and C. Shearer.

Other information in the special maps and tables section includes a table of selected data on deep drill holes along the rift in southern and central New Mexico, by R. W. Foster. The selected data points on deep drill holes are keyed to wells plotted on sheet 2 and are cited in road log and tour stop entries for the E1 Paso to Santa Fe guidebook sections. Two correlation charts included in this final section are state-of-the-art compilations by Hawley of data on middle and upper Cenozoic units. They were prepared to assist guidebook users in wading through the sea of stratigraphic terms applied in the rift region extending from Colorado to Texas.

For additional details on the Rio Grande rift region, the following recent publications are recommended. They are available from either the New Mexico Bureau of Mines and Mineral Resources in Socorro or from the Geological Society of America.

Bachman, G. O., and Mehnert, H. H., 1978, New K-Ar dates and the late Pliocene to Holocene geomorphic history of the central Rio Grande region, New Mexico: Geological Society of America, Bull., v. 89, no. 2, p. 283-292

Cordell, Lindrith, 1978, Regional geophysical setting of the Rio Grande rift: Geological Society of America, Bull., v. 89, no. 7, p. 1073, 15 figs.

Kelley, V. C., 1977, Geology of Albuquerque Basin, New Mexico: New Mexico Bureau of Mines and Mineral Resources, Mem. 33, 59 p.

, 1978, Geology of Española Basin, New Mexico: New Mexico Bureau of Mines and Mineral Resources, Geol. Map 48, scale 1:125,000

Kelley, V. C., and Kudo, A. M., 1978, Volcanoes and related basalts of the Albuquerque Basin, New Mexico: New Mexico Bureau of Mines and Mineral Resources, Circ. 156, 30 p.

The following publications of the New Mexico Geological Society may also be consulted:

Field conference guidebooks

6th—South-central New Mexico, 1955
11th—Rio Chama country, 1960
12th—Albuquerque country, 1961
14th—Socorro region, 1963
16th—Southwestern New Mexico 1I, 1965
17th—Taos-Raton-Spanish Peaks country, 1966
20th—The Border region, 1969
22nd—San Luis Basin, 1969
25th—Ghost Ranch, 1974
26th—Las Cruces country, 1975

Special publications

5—Cenozoic volcanism in southwestern New Mexico, 1976
6—Tectonics and mineral resources of southwestern North America, 1977
7—Field guide to selected cauldrons and mining districts of the Datil-Mogollon volcanic field, New Mexico, 1978

Northern rift guide 1,
Denver-Alamosa, Colorado

by Ogden Tweto, *U.S. Geological Survey, Denver, Colorado*

The Denver-Alamosa leg of the northern-rift field trip begins in sedimentary terrane in the South Platte River valley, between the Front Range of the Southern Rocky Mountains to the west and the Great Plains to the east (sheet 1, in pocket). The route follows US-40 westward out of Denver for about 10 mi (16 km) and then passes onto 1-70 and crosses the Front Range. Except for scattered Quaternary deposits and Laramide intrusive rocks, the Front Range segment of the route is entirely in Precambrian rocks. These rocks are cut by many faults, most or all of which probably underwent some Neogene movements; but large-scale Neogene movements are reasonably established or inferred only near mile 23 and west of mile 57.3. At Idaho Springs the route enters the Colorado mineral belt and continues in or on the fringe of this belt almost to Salida. At Eisenhower Tunnel the route passes beneath the Continental Divide and enters the drainage of the Blue River, which is tributary to the Colorado River. Near the base of the long grade west of the tunnel, the route crosses the Williams Range thrust fault and enters a long narrow belt of sedimentary rocks between the Front and Gore-Tenmile Ranges (sheet 1).

Reactivated old faults bordering the Gore and Tenmile Ranges are major elements of the Neogene rift system, as discussed in the entry for Stop N1 at mile 67.9. After Stop N1, the route goes through Tenmile Canyon, which cuts through the Precambrian rocks of the Gore-Tenmile Range tectonic block. The route then parallels the Laramide and Neogene Mosquito fault, on the west side of the Tenmile and Mosquito Ranges, to beyond Leadville. At the head of Tenmile Canyon (at the pronounced loop in 1-70 southeast of Vail, sheet 1) the route passes onto Colo-91 (not shown) southward to Leadville and then continues from the site of the late Paleozoic Front Range highland of the Ancestral Rockies into Pennsylvanian rocks of the adjoining late Paleozoic sedimentary basin to the west.

Slices of the Dry Union Formation (Miocene and Pliocene) in the Mosquito fault zone near Climax, noted in the entry for Stop N2, mile 87.4, together with remnants near Stop N1 and elsewhere in the Blue River valley, indicate that the Dry Union was once continuous from the upper Arkansas Valley near Leadville northward to Kremmling (sheet 1) and beyond. At Climax and Fremont Pass, the route recrosses the Continental Divide and enters the Arkansas River drainage.

At Leadville the route passes onto US-24 and enters the upper Arkansas Valley graben (see Stop N3, mile 100.4). This is the northern end of more-or-less-continuous graben structure in the Rio Grande rift system, though faults with related movements continue northward to Wyoming. The only pre-Pleistocene Cenozoic unit exposed through most of the valley is the Dry Union Formation, but the presence of downfaulted Oligocene volcanic and volcaniclastic rocks beneath the Dry Union in the Salida area suggests that such rocks may be part of the deep fill elsewhere in the valley. A part of the graben at Leadville coincides with the deepest gravity low (-338 mgal) known in the conterminous United States. The anomaly is attributed in part to the valley fill but principally to the presence at shallow depth of a batholith that is inferred to underlie the Colorado mineral belt (Tweto and Case, 1972). As indicated on sheet 1, the bedrock surface beneath the upper Arkansas Valley slopes southward somewhat more steeply than the surface gradient; geophysical data suggest a bedrock elevation of 1,800 m west of Leadville, 1,200 m near Buena Vista, and 600 m near Salida.

At mile 115.4, an elective excursion to Twin Lakes (Stop N4) is posted in the log, to be taken if time permits. Thanks to abundant drill-hole data, this area affords considerable insight to the structural complexities at a major right-angle jog in the graben boundary. The graben constricts south of Twin Lakes and again at Clear Creek (mile 119.7). A few miles farther south, the graben begins to widen again. At Stops N5 and N6, evidence of Quaternary movements on western border faults of the graben, as well as the Quaternary stratigraphy, will be seen. Scott and others (1975) worked out this stratigraphy, which was used to date young fault movements. At a distance to the east are volcanic-filled paleovalleys transecting the Mosquito Range. The Oligocene volcanics in these valleys were derived from igneous centers in the Sawatch Range to the west, and the paleovalleys establish that the Arkansas Valley did not yet exist in Oligocene time (Epis and Chapin, 1975; Lowell, 1971).

At Stop N7, mile 166.4, and in the Salida area, extensive exposures of the Dry Union Formation can be seen. The Dry Union and underlying Oligocene volcanic rocks occupy a roughly triangular graben, the south side of which is a fault transverse to the northerly trend of the main rift system. This fault abruptly terminates the tectonic block of the towering Sangre de Cristo range, and it displaces, downward to the north, the north-trending graben connecting the Arkansas and San Luis Valleys in the Poncha Pass area (Van Alstine, 1968). Though a narrow graben extends through it, the Poncha Pass area is a horst with respect to the Arkansas and San Luis Valleys (Knepper, 1976). At Poncha Pass, mile 188.9, and on US-285, the route leaves the Arkansas River drainage and enters the Rio Grande drainage and San Luis Valley.

The San Luis Valley is one of the major basins in the Rio Grande rift system. Though there are some modifying structural features, the basin is essentially a half graben, whose bedrock floor dips eastward from the volcanic San Juan Mountains to the frontal fault of the Sangre de Cristo range (Stops N8 and N9, miles 214.5 and 245.2). The valley is a foundered segment of an area that was tectonically high in Laramide and late Paleozoic times. The Sangre de Cristo range is a remnant of the eastern flank of the Laramide uplift, elevated to its present great height in Neogene time. Near Villa Grove and Stop N8, late Quaternary fault scarps will be seen extending diagonally across the comparatively narrow northern end of the valley. The fill in the valley at a locality several miles west of Stop N9 is 10,000 ft (3 km) thick, as established by a drill hole to the Precambrian floor. A deep gravity low in the area between Stop N9 and the Sangre de Cristo range suggests a still greater thickness: about 30,000 ft (9 km) was estimated originally, but this figure is being reevaluated, and the thickness may be considerably less than that.

DENVER TO ALAMOSA, COLORADO

The following road log is concerned principally with faults that have had Neogene movements related to the Rio Grande rift and with the Neogene stratigraphy that documents those movements. Other aspects of the regional geology, such as Precambrian rocks, pre-Neogene stratigraphy, and Laramide structure, are treated in numerous other road logs, notably in Weimer and Haun (1960), Donnell (1960), Epis and Weimer (1976), and (for the San Luis Valley) James (1971). A few of the numerous geologic maps pertinent to the trip area (mainly those covering large areas) are cited below. A map by Scott (1972) shows geology in the vicinity of the route at the mountain front west of Denver, and this map also depicts Quaternary units generally recognized east of the mountains. Geology of the Front Range is shown on a map by Lovering and Goddard (1950). From near the west end of Eisenhower Tunnel to Clear Creek (mile 119.7), geology along the route is shown on a map of the Leadville 1 °x2° quadrangle (Tweto, Moench, and Reed, 1976, 1978). From Clear Creek to a point south of Alder Creek (mile 193.5), the route is through the Montrose 1 °x2° quadrangle (Tweto, Steven, and others, 1976). The Pueblo 1 °x2° quadrangle covers the Alder Creek area to Moffat (Scott and others, 1976). South of Moffat, the route is in the Trinidad 1°x2 ° quadrangle (Johnson, 1969). Geothermal features of the rift zone in the Arkansas and San Luis Valleys are discussed in Epis and Weimer (1976) and Pearl (1974). Heat-flow data are presented by Reiter and others (this guidebook).

Mileage

0.0 Intersection of Broadway and Colfax Avenue in Denver. *Go west on Colfax (US-40).* To South Platte River, route is over late Pleistocene gravel terraces; bedrock is Denver Formation (Paleocene and Upper Cretaceous). **1.8**

1.8 South Platte River. For several miles after crossing viaduct, route continues over dissected pediments capped by older Pleistocene alluvial deposits and younger Pleistocene eolian deposits. **5.7**

7.5 Intersection with Simms Street. **0.7**

8.2 Ahead on right is Table Mountain, capped by alkalic basalt (shoshonite) layer within the Denver Formation. Note nearly flat dip. **1.9**

10.1 *Turn onto 1-70.* **0.4**

10.5 Green Mountain at left, capped by Green Mountain Conglomerate (Paleocene) above Denver Formation. The even skyline ahead is truncated edge of Tertiary erosion surface on flank of Front Range-the Rocky Mountain peneplain of Lee (1923), now recognized as part of a very extensive late Eocene prevolcanic surface. Below skyline, hogback of Lower Cretaceous sandstone of the Dakota Group is just east of mountain front. **0.6**

11.1 The Golden reverse fault is in valley in front of hogback; fault cuts out several thousand feet of Cretaceous shales. Compare steep dips with flat dips at Table Mountain, 3 mi back. **0.3**

11.4 Deep cut through Dakota hogback and Morrison Formation (Upper Jurassic). **0.5**

11.9 Overpass. Valley is in Lykins Formation (Triassic and Permian) and Lyons Sandstone (Permian). **0.3**

12.2 Approximate contact of Fountain Formation (Permian and Pennsylvanian), largely covered, and Precambrian rocks. Precambrian rocks for next 25 mi are interlayered gneisses of various kinds, metamorphosed 1,700-1,775 m.y. ago. These are complexly folded and are intruded by many pegmatites and by small bodies of granitic rocks. They are cut by many faults, which range from Precambrian to Tertiary in age. For the next 4.8 mi, highway is in Mount Vernon Canyon, climbing toward level of prominent late Eocene erosion surface seen earlier in profile. Highway is also entering site of Front Range highland of late Paleozoic Ancestral Rockies. **4.8**

17.0 Mount Vernon summit (Genesee overpass). **1.0**

18.0 View northward (to right) across canyon of Clear Creek. Note generally accordant topography of late Eocene surface. 5.0

23.0 For next 1.2 mi highway follows old valley localized by a broad fracture zone, which is one of a northwest-trending series cutting Precambrian rocks of east flank of Front Range. These fracture zones were formed in Precambrian time and have been reactivated repeatedly since then. This one displaces the late Eocene surface 2,000 ft (600 m) on the west. **1.2**

24.2 Floyd Hill summit; steep descent to bottom of Clear Creek Canyon. The long ridge beyond canyon is capped by about 330 ft (100 m) of upper Tertiary boulder gravel deposited by ancestral Clear Creek. **2.4**

26.6 Junction of US-6 and US-40; *continue* on 1-70. **2.9**

29.5 Idaho Springs exit; *continue* on 1-70. At Idaho Springs, route enters the Colorado mineral belt, a northeast-trending belt 10-15 mi (15-25 km) wide characterized by mineralized areas, porphyry intrusions, and by a gravity low. The area between Idaho Springs and Central City, 5 mi (8 km) to the north, has produced about $200 million, mainly in gold and silver. First discovery of lode gold in Colorado was made in this area in 1859. **8.8**

38.3 US-40 exit; *continue* on 1-70. In valley bottom ahead is second Bull Lake moraine of South Clear Creek. In steep valley at right is first Pinedale moraine of West Clear Creek. For next 17 mi (to Eisenhower Tunnel), the Precambrian terrane consists of bodies of Silver Plume Granite in a matrix of metasedimentary gneiss. The Silver Plume is representative of the middle group of three age groups of Precambrian granites in Colorado, dated at approximately 1,700, 1,400, and 1,000 m.y. **4.5**

42.8 Georgetown at left. Chief production from the Georgetown-Silver Plume mining district was silver and lead, which occurred in veins. **2.2**

45.0 Silver Plume; many old mines high on steep slopes to right. **8.8**

53.8 Loveland Pass, elevation 12,000 ft (3,658 m), on skyline to left; ahead is US-6. The pass is on a major north-northeast-trending fault in the interior of the Front Range. **0.4**

54.2 US-6 exit; *continue* on 1-70. **0.8**

55.0 Approaching Eisenhower Tunnel; Loveland Pass ski area at left. Tunnel passes beneath Continental Divide in saddle area on skyline. Saddle site provided shortest tunnel route but also is site of a wide, faulted and crushed zone that greatly increased the difficulty and cost of the tunnel. To stabilize the ground for a second

FIGURE N1—WILLIAMS RANGE AND TOWN OF SILVERTHORNE; view northeast across Blue River Valley from point near mile 65.2. Lower slopes of Williams Range are Cretaceous shales; upper slopes and crest are Precambrian rocks above the Williams Range (Laramide) thrust fault (photo by Wayne Lambert, October 17, 1977, mid-morning).

bore, in progress, small tunnels are driven in advance on each side and are filled with reinforced concrete, making large dowels through the mountain. **0.6**

55.6 *Enter Eisenhower Tunnel,* elevation 11,013 ft (3,357 m). **1.7**

57.3 Exiting tunnel and starting down long steep grade in valley of Straight Creek. Many faults transverse to road occur in Precambrian gneisses; fracturing and alteration related to the faults account for great height of many roadcuts. Faults are in a north-northwest-trending zone of Precambrian origin, but late Tertiary movement is proved 20 mi (30 km) to the north, where the faults border a graben filled with Miocene sediments. As the route descends, Gore Range comes into view ahead, and Tenmile Range to left and ahead. Blue River fault, which had large post-Miocene movement, is at the foot of steep slopes of both ranges. **4.1**

61.4 Buffalo Peak in Gore Range is ahead. Blue River fault is in front of it, at the foot of a steep slope. **1.9**

63.3 Crossing Williams Range thrust fault, which brings Precambrian rocks over Pierre Shale (Upper Cretaceous). This fault extends north-northwest continuously for 60 mi (97 km), and a closely related echelon fault farther south, the Elkhorn thrust, extends another 25 mi (40 km). **1.9**

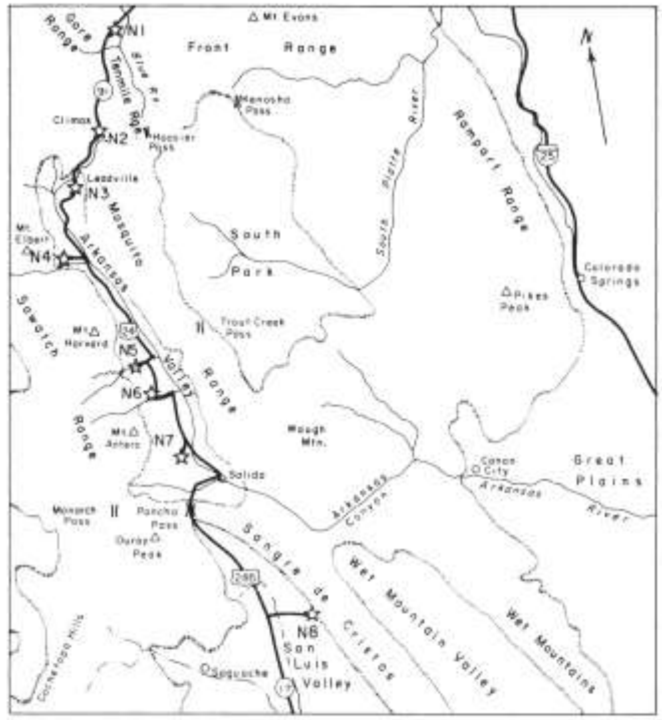
65.2 Colo-9 and Dillon-Silverthorne exit; *continue* on 1-70 across Blue River. Looking north, lower slopes of the Williams Range (east of Blue River valley) are Cretaceous shales; upper slopes and crest are Precambrian rocks above the Williams Range (Laramide) thrust (fig. N1). High earth-fill dam at left impounds Dillon Reservoir (fig. N2), which will be seen at Stop N1 . After crossing Blue River, highway climbs Bull Lake terminal moraine of Tenmile Creek drainage. At mile 66.8. glimpses of pre-Bull Lake moraine can be seen

FIGURE N2—DILLON RESERVOIR AND TENMILE RANGE NEAR STOP N1; view southwest across Blue River Valley from point near mile 65.2. Hoosier Pass in saddle area beyond upper end of reservoir. Valley is in Cretaceous and Upper Jurassic rocks; peaks of Tenmile Range are Precambrian rocks. Blue River fault with great Neogene displacement extends along front of Tenmile Range and through Hoosier Pass. Peaks to left of Hoosier Pass are upper Paleozoic sedimentary and Laramide intrusive rocks in spur of Front Range. Trip route (I-70) is through canyon to right of Tenmile Range (photo by Wayne Lambert, October 17, 1977, early morning).

through trees at the right, exposed in yellow placer cuts. Both moraines contain rocks and ores from Climax and Kokomo, 20 mi (32 km) ahead on route. **2.4**

67.6 *Exit* at scenic viewpoint. **0.3**

67.9 **STOP N1, Dillon Reservoir viewpoint.** Here the route enters the main area of rift-related structure at this latitude (figs. N3 and N4; sheet **1).** Mountains on the skyline eastward across reservoir are in the Front Range. To the northeast and nearer is the Williams Range. Blue River valley is west of the Front and Williams Ranges. West of the valley is the Gore Range, not visible from this point. Abrupt rocky slopes in the foreground south of this point are the north end of the Tenmile Range, which is part of the same tectonic block as the Gore Range but separated topographically by the deep canyon of Tenmile Creek. Blue River valley is a long structural low bordered on the east side by the Williams Range (Laramide) thrust fault, which brings Precambrian rocks of the Williams Range and of the west flank of the Front Range over generally east-dipping Cretaceous rocks. The west side of the structural low is bordered by the Blue River fault, a major element of the rift system at this latitude, at the base of steep slopes of the Gore Range. The fault is visible to the south of this point, at the base of the steep slopes of Precambrian rocks. The fault continues south-southeast along the steep flank of the Tenmile Range, toward Breckenridge. Patches of the Dry Union Formation (upper Tertiary) are brought against Precambrian rocks along the fault, and Quaternary movements are evident in several places. The Blue River fault is a Precambrian fault that was reactivated in late Paleozoic, Laramide, and Neogene times and is part of a fault system at least 155 mi (250 km) long. The Gore Range to the west of it is a fault block of Precambrian rocks 6-9 mi (10-15 km) wide and 47 mi (75 km) long that has a relief of 3,300-5,000 ft (1,000-1,500 m), largely owing to Neogene uplift. The Gore fault, on the west side of the fault block, is a part of the same ancient fault system as the Blue River fault and has had a similar history. The Gore fault was markedly active in late Paleozoic and early Mesozoic time, when it formed the border between a highland to the east and a sedimentary basin to the west. We are here on the highland, where in most places the Morrison Formation (Upper Jurassic) lies on Precambrian rocks. West of the Gore fault, the Morrison is separated from the Precambrian by 10,000 ft (3,000 m) of sedimentary rocks.



The part of the reservoir in view occupies the lower valley of Tenmile Creek; another major part is in the Blue River valley, beyond the low hills on the eastern shore. The arm of the reservoir visible here is enclosed behind great arcuate Bull Lake moraines of Tenmile Creek. The moraines form or cap the hills on the eastern shore, and we stand on one. The first (and possibly second) Pinedale moraines are largely below high-water level but protrude in places as islands and peninsulas. **2.1**

70.0 Frisco exit. *Continue* on 1-70; crossing Blue River fault and entering Tenmile Canyon, in Precambrian gneisses. Tenmile Range at east (left); Gore Range at west (right). **5.7**

75.7 Junction of US-6-I-70 and Colo-91. *Proceed south on Colo-91.* Valley here is in the Mosquito fault zone. The Mosquito fault is a north-trending Laramide or

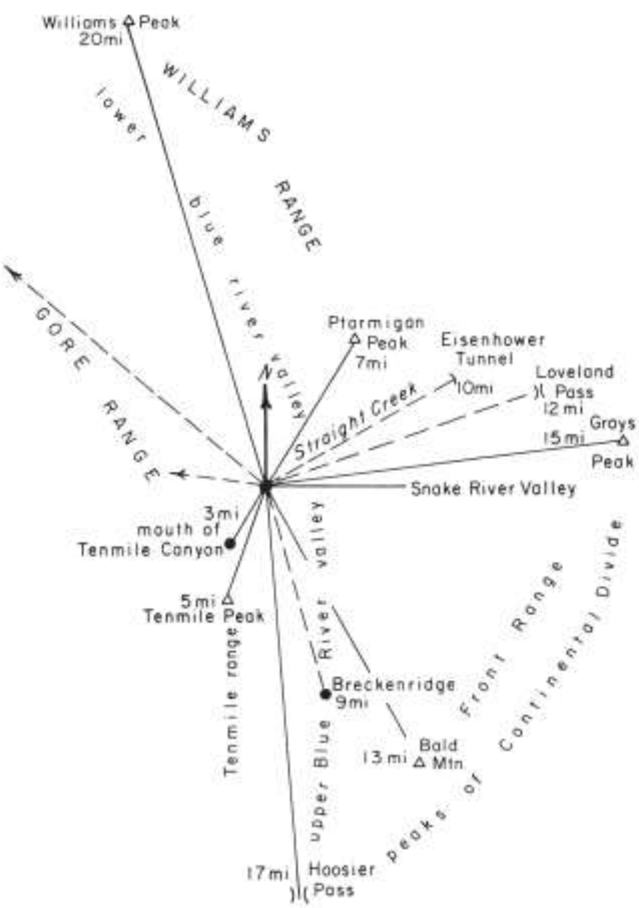


FIGURE N3—PANORAMIC INDEX OF FEATURES SEEN FROM STOP N1, DILLON RESERVOIR VIEWPOINT.

FIGURE N4—LANDSAT IMAGE **(a, above)** AND INDEX MAP **(b, at left)** OF THE NORTHERN RIO GRANDE RIFT AND ADJACENT PARTS OF NORTH-CENTRAL COLORADO; image scale approximately 1:1,000,000 (image E-1172-17141-7 transmitted January 11, 1973; courtesy of Technology Application Center, University of New Mexico).

older normal fault, downthrown to the west, that underwent major reactivation in Neogene time. From this vicinity southward, the fault borders the west side of the Tenmile Range. Northward, it extends acutely through the north-northwest-trending tectonic block outlined by the Gore and Blue River faults and ends against the Blue River fault. The Gore fault crosses the valley at right about 1.5 mi (2.5 km) west of Colo-91. It was the border of a late Paleozoic highland; reddish mountains beyond it are Pennsylvanian and Permian rocks. **4.1**

79.8 Gore fault joins Mosquito fault in this vicinity. Relations are obscured by a Laramide stock and extensive glacial cover. From this location onward to Leadville, the highway is in Pennsylvanian rocks that are extensively intruded by porphyry sills, dikes, and stocks. **1.2**

81.0 Structures at right are for extension of Climax tailings disposal system. The highway starts the long climb to remain above successive tailings ponds, which will be visible at right. **2.4**

83.4 Site of Kokomo town and zinc-lead mining area at right. The most productive part of the area is now beneath tailings, and the remainder will also be beneath tailings when they extend to structures noted above. **4.0**

87.4 **STOP N2, Climax.** On Continental Divide at Fremont Pass is Climax, elevation 11,318 ft (3,450 m), the world's largest molybdenum mine. The orebody is in Precambrian rocks above a concealed Oligocene stock on the upthrown side of the Mosquito fault. The huge hole in the side of the mountain was formed by caving as ore was drawn out from beneath; thus, it is not an excavation. The Mosquito fault is just in front of the cave hole, and its trace northward is marked by a break in the grassy slope above timberline. Looking southward across the intervening valley, the fault is in the grassy saddle area to the right of the high peak of Precambrian rocks (fig. N5). Just beyond the saddle, slices of the Dry Union Formation (upper Tertiary) are present in the fault zone. In front of and just below the saddle, high lateral moraines are faulted. Deep drilling has established that the Precambrian basement west of the Mosquito fault is 6,500 ft (1,975 m) below the surface at Climax. On the basis of a faulted orebody, Climax geologists have postulated 9,000 ft (2,740 m) of post-ore (post-30 m.y.) displacement on the fault. The fault continues southward to Leadville and beyond. On the route ahead, glimpses of its trace may be seen at the head of high benchy areas at or near the timberline. The mountain range on the left from here southward to Salida is called the Mosquito Range. **0.4**

87.8 Storke tunnel level of the Climax mine and coarse-crushing plant. Cirque beyond is the head of the East Fork of Arkansas River. On right, after making hairpin turn, is Chalk Mountain, an Oligocene rhyolite porphyry pluton. **1.1**

88.9 Gravel pits are in a filled basin behind the third Pinedale moraine, which forms the low hummocky area just ahead. Mountain slopes ahead and on right nearly to Leadville are intricately sliced by north-trending faults that, at Leadville, have been proved to have had major late Tertiary displacement. **3.9**

92.8 Second Pinedale terminal moraine of East Fork of Arkansas River, overlain on east side by younger alluvial fan. **4.2**

97.0 East Fork of Arkansas River here cuts through first Pinedale terminal moraine, remnants of which form low hummocky benches at each side. Ahead, highway climbs toward Bull Lake medial moraine formed at the junction of glaciers from East Fork and from Evans Gulch to the east. Beneath the highway and the medial moraine is a deep channel in the bedrock surface. This channel was the pre-Dry Union course of the East Fork of the Arkansas River. To the right on the skyline are Sawatch Range and Mt. Elbert, the highest point in Colorado, with an elevation of 14,433 ft (4,399 m). **1.6**

98.6 Junction of Colo-91 and US-24. *Proceed south on US-24; enter Leadville.* **0.3**

98.9 Pre-Bull Lake moraine in cuts behind Safeway store. **0.8**

99.7 Intersection, 9th Street and Harrison Avenue; *turn left and proceed south on Harrison Street* in downtown Leadville. **0.2**

99.9 Lake County Courthouse, Harrison Avenue and 5th Street; *prepare for left turn ahead.* **0.1**

100.0 *Turn left at 4th Street.* **0.3**

100.3 *Turn right on Hazel Street,* which leads into Toledo Street south of 3rd Street. 0.1

100.4 **STOP N3, Leadville.** On Toledo Street, just south of

FIGURE N5—HEAD OF ARKANSAS RIVER IN MOSQUITO RANGE; view southeast from Stop N2 at Climax and Fremont Pass (mile 87.4). Buildings are at mouth of Storke tunnel of Climax mine. Peak at right is Mt. Arkansas (elevation 13,795 ft) and at left, Mt. Democrat (elevation 14,148 ft), in Precambrian rocks. Mosquito fault with great Neogene displacement extends across lower right slope of Mt. Arkansas and through the area of the mine buildings. Area in front of the fault is in upper Paleozoic rocks heavily mantled by glacial drift (photo by Wayne Lambert, October 16, 1977, late afternoon).

3rd Street, we look westward across the valley of the upper Arkansas River to the Sawatch Range (fig. N6). The Sawatch Range is an enormous anticlinal structure, and the valley is a graben that slices longitudinally through the anticline, high on the east flank. The Mosquito Range, east of the valley, is a part of the anticline, capped at this latitude by east-dipping Paleozoic rocks. The graben seen here is the northern terminus of the more-or-less continuous graben structure in the Rio Grande rift zone, though related movements on faults occurred northward to the Wyoming boundary (sheet 1; fig. N4). In this area, the west side of the graben is essentially a single fault or fault zone at the foot of the slopes of the Sawatch Range. The east side is step-faulted by numerous north-trending normal faults that pass through the Leadville district; the final big step is at the Mosquito fault, high on the Mosquito Range to the east (fig. N7). The Mosquito and subsidiary faults are reactivated Laramide faults. Except for glacial cover, the graben is filled by the Dry Union Formation (upper Tertiary). The beds of this formation dip westward wherever seen in the valley and indicate that the western border fault flattens with depth. Similarly, beds of the Dry Union preserved in pockets along the step faults on the east side of the valley dip eastward toward the faults and indicate that these faults also flatten with depth.

The Leadville mining district has produced more than $500,000,000 in silver, lead, zinc, gold, and copper, as valued at the time of production. The ore deposits are principally replacement deposits in dolomites of Mississippian, Devonian, and Ordovician age, which are intricately intruded by Laramide and younger porphyries. The east-dipping sedimentary rocks are repeatedly stepped up to the east by the north-trending normal faults (fig. N7), thus making them accessible to mining through an east-west distance of about 3.7 mi (6 km). The district is traversed by two major glacial canyons and is widely covered with glacial deposits. The older glacial deposits are displaced by some of the north-trending faults. In unglaciated parts of the district, the ores are oxidized to depths of as much as 1,000 ft (300 m). The oxidation transformed pyrite-sphalerite-galena ores into the bonanza silver ores mined in the early days. The deep oxidation occurred before and during deposition of the Dry Union Formation, under conditions of a very low water table. This oxidation probably occurred at a time when the Arkansas Valley graben was sinking rapidly, older parts of the Dry Union were accumulating in the valley, and the Leadville mining area was a high pediment undergoing erosion. 0.2

100.6 *Turn right on Monroe Street to Harrison Avenue.* At mile 100.8, *turn left onto US-24.* **0.3**

100.9 Road makes sharp turn at south end of Harrison Avenue as route leaves Leadville. In next 3.5 mi (5 km), pediment at left (south) is cut on outwash of second pre-Bull Lake glaciation (Malta Gravel). Pediment at right is cut on first pre-Bull Lake till and Malta Gravel. **1.4**

102.3 Stringtown and, at right, former smelter. Water well at smelter bottomed in Dry Union Formation at depth of 600 ft (183 m). **2.0**

104.3 Route makes sharp turn at Malta railroad junction. Lowest gravity low (-338 mgals) in the conterminous

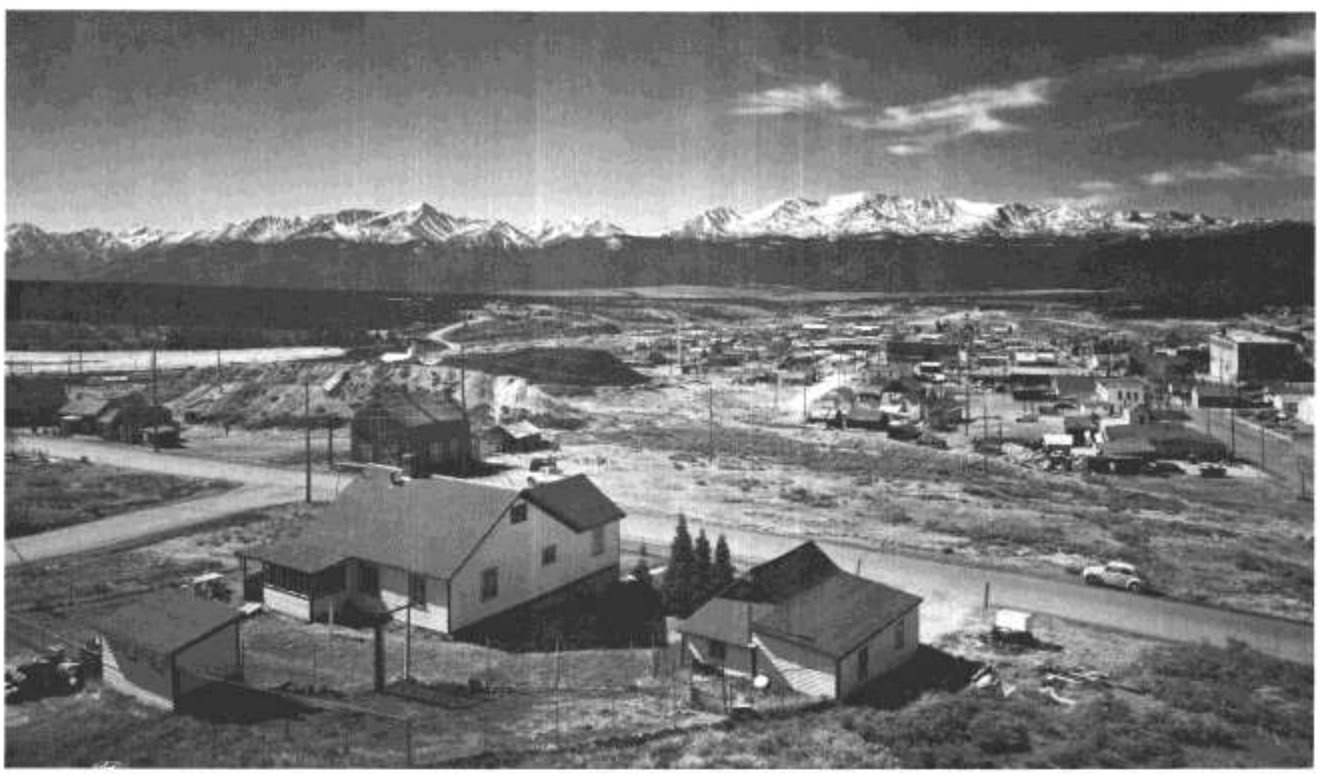


FIGURE N6—LEADVILLE, UPPER ARKANSAS VALLEY, AND SAWATCH RANGE; view southwest from Stop N3 (mile 100.4). Mt. Massive, elevation 14,421 ft (4,437 m), to right of center; Mt. Elbert, elevation 14,433 ft (4,440 m), to left of center; La Plata Peak, elevation 14,336 ft (4,411 m), at far left; all in Precambrian rocks. Neogene faults in timbered area near base of range. Valley is graben deeply filled by Dry Union Formation (Neogene) and glacial deposits (photo by Wayne Lambert, October 16, 1977, mid-day).

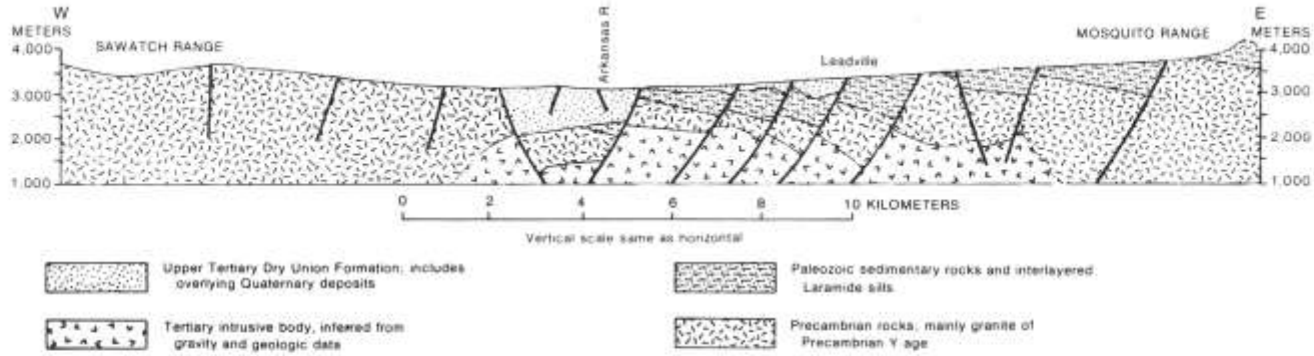


FIGURE N7—GENERALIZED GEOLOGIC SECTION ACROSS THE UPPER ARKANSAS VALLEY AT LEADVILLE, COLORADO.

United States is in valley bottom at right. On basis of gravity, Tertiary valley fill is estimated to be 3,000-4,000 ft (900-1,200 m) thick, placing the bedrock (Precambrian?) surface at an elevation of about 6,500 ft (2,000 m). The peaks of Precambrian rocks beyond the valley are at elevations of 14,100-14,433 ft (4,300-4,400m). **1.8**

106.1 Pediments ahead on left are cut on Dry Union Formation and, near their heads, on first pre-Bull Lake till. Both units are faulted against bedrock at the heads of the pediments. 2.6

108.7 Railroad overpass. **0.7**

109.4 Pediments ahead on right are cut on Dry Union Formation and pre-Bull Lake glacial deposits. Ridge rising to skyline above pediment is first Bull Lake moraine. Landslide in Dry Union at pediment front. **3.9**

113.3 Shallow canyon in Precambrian rocks. A thick prism of Dry Union Formation lies to west of a fault that is only 330-660 ft (100-200 m) west of canyon wall. Bedrock pediments on left are pre-Dry Union, covered in places by scabs of Dry Union, which in turn is pedimented to the same level. **2.1**

115.4 Junction of US-24 and Colo-82. *Optional excursion to Twin Lakes (Stop N4), via Colo-82.* Mileages from junction.

Twin Lakes excursion

0.0 Climbing second Bull Lake moraine upon leaving US-24. *Turn right onto Colo-82.* **1.0**

1.0 First Pinedale terminal moraine at left. Moraine is underlain by Bull Lake lacustrine deposits, as shown by several drill holes on the axis of a proposed dam on the moraine crest. **0.6**

1.6 Lower lake of Twin Lakes (fig. N8). The lakes serve as a reservoir, controlled by a small dam at outlet at left. The water released here supplies agricultural ditches east of Pueblo, Colorado, 125 mi (200 km) down the Arkansas River. **1.0**

2.6 Knob of Precambrian granite on lake shore. Several drill holes near highway were in Dry Union Formation beneath the glacial materials, to depths of at least 150 ft (45 m), suggesting a fault on north side of the knob. Near the shore on the west side of the knob, the granite is overlain by a few feet of silty volcanic ash identified as type-O Pearlette by Glen Izett. This anomalous occurrence requires either that the ash, protected by the knob, survived the Bull Lake and first Pinedale glaciers, or that it was derived from pre-Bull Lake deposits beneath the lake and was washed up by wave action in later time. **1.5**

4.1 *Turn left* to lower road. **0.4**

4.5 ***Turn sharp left at* lower road. 0.3**

FIGURE N8—LOWER LAKE OF TWIN LAKES AND SAWATCH RANGE NEAR STOP N4; view west from point near mile 1.6 of Twin Lakes optional excursion. Mt. Elbert at extreme right. Mountains are Precambrian rocks and Eocene granodiorite. Graben-border faults extend south across lower slope of Mt. Elbert and east near southern shore of lake. Morainal lake is underlain by Dry Union Formation (Neogene) (photo by Wayne Lambert, October 16, 1977, mid-day).

4.8 STOP N4, Twin Lakes (optional stop at recreation site). Twin Lakes are in a right-angle bend or jog in the western border of the Arkansas Valley graben. The main western fault of the graben extends northward along the base of Mt. Elbert from the upper end of the upper lake. The fault is intersected near the southwest corner of the upper lake by an arcuate, northward-convex, east-trending fault that probably lies beneath the lakes near their southern shores. The mountains south of the lakes consist of Precambrian rocks, which are overlain on their lower slopes by high Bull Lake lateral moraines. The angle between the north- and east-trending faults is filled primarily by Dry Union Formation, which is mantled by glacial deposits. Several large faults evidently are present in the area of Dry Union, as determined from numerous test holes drilled by the U.S. Bureau of Reclamation.

The ridge to the north of the lakes is a glacial valley wall excavated in the Dry Union Formation. This was admirably shown by a trench 75 ft (23 m) deep, now covered, excavated for the penstocks leading to the power plant at the northwest corner of the lower lake. Test holes drilled to a depth of 400 ft (122 m) at the power plant bottomed in Dry Union. The crest of the ridge is a moraine of the first stade of the Bull Lake glaciation. The moraine rests in places on Dry Union Formation and in other places on pre-Bull Lake till. The second Bull Lake and first Pinedale moraines form benches in front of the crest in places, but they have been extensively disrupted by landsliding. Most of the slope from here to the upper end of the upper lake is landslide. The sliding occurred between the first and second Pinedale glacial advances. The second Pinedale moraine separates the two lakes, and an outwash apron on its northern side lies on the landslide material. Geology of the lake bottoms is not known but may consist of fault blocks of Precambrian rocks, Dry Union Formation, and pre-Bull Lake tills. A drill hole near the outlet of the lower lake passed successively through 40 ft (12 m) of beach sand and post-first Pinedale lacustrine deposits, a few feet of first Pinedale till, 235 ft (70 m) of Bull Lake lacustrine deposits, and entered Precambrian granite at a depth of 271 ft (83 m). A drill hole beside the highway in the same area entered an early pre-Bull Lake till (or a mudflow?) at a depth of 70 ft (21 m) and bottomed in this same material at 503 ft (153 m). Drill holes immediately north of that hole entered Dry Union Formation beneath the surficial glacial deposits. From Stop N4 site, *turn right (east).* **1.3**

6.1 *Turn left* on road to Colo-82. **0.3**

6.4 Junction with Colo-82. *Turn right.* 2.3

8.7 Junction with US-24; end of Twin Lakes excursion.

115.4 Junction of Colo-82 and US-24. *Proceed south on US-24.* Old gold placer workings at right are in Bull Lake outwash. Ahead, highway and river are in Precambrian rocks, but a graben filled by Dry Union Formation and early glacial deposits is only 'a short distance to west. **4.3**

119.7 Low Pinedale moraine of Clear Creek between high Bull Lake lateral moraines. Here, graben defined by Dry Union and early glacial fill constricts to a few hundred meters in width. **2.0**

121.7 Terminal moraine of Pinedale glacier of Pine Creek. The glacier dammed and impounded the Arkansas River, and catastrophic floods were released at least twice when the ice dam was breached. Large boulders transported by the floods will be seen studding the Pinedale terraces southward to Salida. **2.0**

123.7 Landslide area at right (west) is underlain by Dry Union Formation at constriction in graben that widens southward in Arkansas Valley. **3.0**

126.7 On lower slopes at left and ahead, across river, remnants of pre-Dry Union pediment cut on Precambrian granite. **1.2**

127.9 Surface above terrace front at right is on middle Pleistocene alluvium (Kansan? of Scott, 1975) overlying Dry Union Formation. The alluvium contains a layer of type-O Pearlette volcanic ash 600,000 years old. Mt. Harvard, elevation 14,417 ft (4,394 m), on skyline at right. **3.5**

131.4 Highway climbs slightly to surface on lower Pleistocene alluvium (Nebraskan? of Scott, 1975). Outcrops of Precambrian rocks near highway; early Pleistocene valley axis was to west. 2.6

134.0 Buena Vista city limit. **0.7**

134.7 Intersection of US-24 and Colo-306 in Buena Vista. *Turn right on Colo-306*, which is on Pinedale and Bull Lake outwash to Stop **N5. 4.7**

139.4 **STOP N5, West of Buena Vista.** Cottonwood Creek at entrance to canyon and at front of Sawatch Range. Low ridge on south side of road is **Bull Lake till,** cut by a fault to be seen here. At the base of the slope, the till is in fault contact with outwash gravel. View northeast across valley to Mosquito Range. Precambrian rocks of the range are intensely sliced by north-northwest-trending faults of the graben or rift system. Locations of some of the faults are visible as benches and eroded scarps. The Quaternary deposits in the valley are underlain by the Dry Union Formation. Resistivity and gravity data indicate that the bedrock surface beneath the valley slopes sharply westward toward the Sawatch Range and that the valley fill southeast of this locality is about 4,000 ft (1,200 m) thick. The resistivity data also indicate step faulting in the basement surface near the east side of the valley.

Looking southeast of the highway leading into the valley of Trout Creek is a dark, forested east-west ridge. This ridge consists of Oligocene volcanic rocks that originated in the Sawatch Range and occupy a paleovalley transverse to the present Mosquito Range. This paleovalley and others funneled ash-flow tuffs eastward into South Park and even to the plains between Denver and Colorado Springs (Epis and Chapin, 1975). The paleovalleys establish that the Arkansas Valley did not yet exist in Oligocene time. Another paleovalley occupied by Oligocene volcanic rocks is at Buffalo Peaks, the highest summits in the Mosquito Range visible from here. The part of the Sawatch Range visible southward is an Oligocene intrusive complex that contains a deeply eroded caldera and was the evident source of the ash-flow tuffs in the paleovalleys. *Return toward Buena Vista.* **3.9**

143.3 At the outskirts of Buena Vista (city limit sign), *turn right on Chaffee County Road 321* (road to Chalk Creek). Area crossed en route between Buena Vista and Mt. Princeton Hot Springs, below Stop N6, is

FIGURE N9—SAWATCH RANGE AND UPPER ARKANSAS VALLEY BETWEEN BUENA VISTA AND MT. PRINCETON HOT SPRINGS; view west from near US-24–US-285. Border faults extend along base of mountains and cut basin-fill units ranging from Dry Union Formation (Miocene) to upper Pleistocene glacial deposits. Cottonwood Canyon below Mt. Yale (elevation 14,194 ft) to right of center is near Stop N5 where faulted Bull Lake till is seen. Mt. Princeton (elevation 14,197 ft) to left of center overlooks Stop N6 on high piedmont surface. Mt. Princeton Hot Springs at mouth of Chalk Creek Canyon at far left (photo by J. W. Hawley).

shown on fig. N9. The road is on second Bull Lake outwash for about 1.5 mi and then crosses low ridges capped by middle Pleistocene alluvium standing above outwash surface. Farther south, the road is on first Bull Lake outwash for 2 mi, then passes onto lower Pleistocene alluvium (Nebraskan? of Scott, 1975). **7.4**

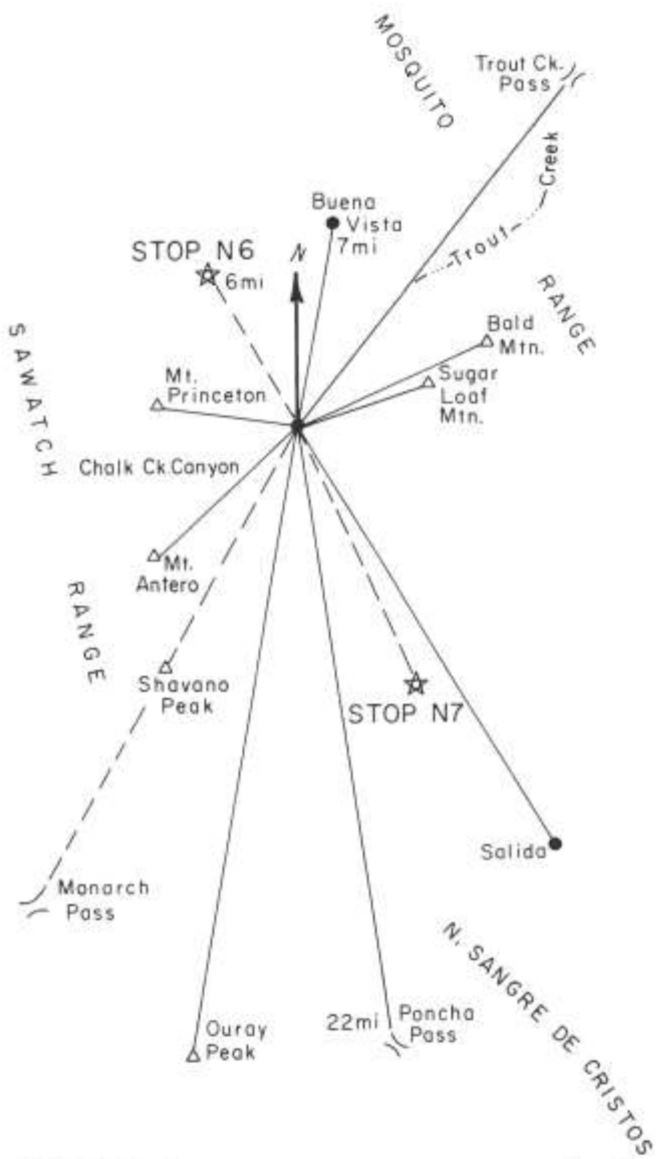


FIGURE N10—PANORAMIC INDEX OF FEATURES SEEN FROM STOP N6, CHALK CREEK OVERLOOK.

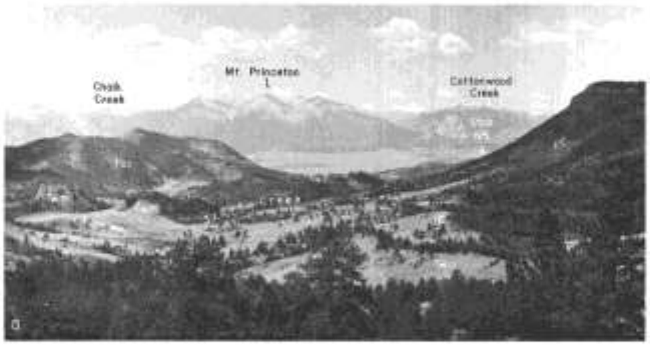
150.7 **STOP N6, Chalk Creek overlook.** On high surface of lower Pleistocene (Nebraskan?) alluvium overlooking valleys of Chalk Creek and Arkansas River above Mt. Princeton Hot Springs (fig. N10). The lower Pleistocene alluvium and underlying Dry Union Formation are faulted against Tertiary quartz monzonite at the steep front of Mt. Princeton to the west. The Colorado Geological Survey reports disruption of piping and structures installed within the last two decades in this fault zone. The fault zone contains hot springs and constitutes one of the most promising geothermal areas in Colorado. The quartz monzonite near the fault zone is intensely altered hydrothermally, accounting for the white color and the names Chalk Cliffs and Chalk Creek. Across Chalk Creek to the south, various Pleistocene units are faulted against bedrock at the mountain front.

Looking east, the highway parallel to Chalk Creek is on the oldest Pinedale outwash. The broad and next higher level to the south of that is the outwash terrace of the second stade of the Bull Lake Glaciation. Two higher terraces to the south are mantled, respectively, by middle and lower Pleistocene alluvium (Kansan? and Nebraskan? of Scott and others, 1975). The Kansan? alluvium contains type-O Pearlette ash (600,000 years), and the Nebraskan? is overlain by Bishop ash (700,000 years). These will be seen fleetingly in road-cuts on the main highway (miles 158.3, 159.8).

On the east side of the Arkansas River near the mouth of Chalk Creek are two brownish-gray rounded hills of Oligocene rhyolitic volcanics, and high on the slope to the northeast is a topographically prominent, truncated volcanic cone, which was the evident source (fig. N11). The volcanic rocks near the valley bottom dip steeply and have been let down to their present level by north-trending faults between them and the source cone. Looking southeast, the largest of the paleovalleys crossing the Mosquito Range may be seen, disrupted by many faults that are evident in the topography. These faults have dropped the volcanics to the level of the Arkansas Valley, where they are overlain by the Dry Union Formation, which in turn is faulted against volcanics and Precambrian rocks. **0.2**

150.9 On steep grade, at very small angle to road, contact between old alluvium with angular clasts and coarse glacial gravel with rounded clasts. **0.6**

151.5 Junction of Chaffee County Road 321 and Colo-162 at Mt. Princeton Hot Springs resort. *Turn left on Colo-162; proceed east* down valley of Chalk Creek.



F1GURE N1 1 —VIEWS OF SOUTHERN SAWATCH AND MOSQUITO RANGES, UPPER ARKANSAS VALLEY REGION, IN THE VICINITY OF STOP **N6,** CHALK CREEK OVERLOOK.

a) View west along the Trout Creek paleovalley and across the upper Arkansas graben to Mt. Princeton in the Sawatch Range. The exhumed north wall of the paleovalley on the right consists of Precambrian rocks overlain by Ordovician to Mississippian limestones and quartzites. The floor of the paleovalley exhumed in the foreground consists of Precambrian rocks plus erosional remnants of the Wall Mountain Tuff (Twn) and boulder alluvium of the Tallahassee Creek Conglomerate, both of early Oligocene age. The high, timbered ridge on the left consists of as much as 1,000 ft (305 m) of the Oligocene Badger Creek Tuff (Tbc) capped by an andesite lava flow. Both the Wall Mountain and Badger Creek Tuffs were erupted from cauldrons in the Sawatch Range and traveled eastward down paleovalleys to spread widely over the late Eocene erosion surface. Important uranium deposits have been found to the southeast in alluvial-filled paleovalleys equivalent to the one viewed here and in underlying arkosic sediments of Eocene age. Stop N5 is at the mouth of Cottonwood Creek, north of Mt. Princeton. The Sawatch Range south of Cottonwood Creek consists mainly of an early Oligocene quartz monzonite batholith that probably represents the plutonic roots of a deeply eroded cauldron complex from which the Wall Mountain and Badger Creek Tuffs were derived.

b) View northeast from the mouth of Chalk Creek towards the Trout Creek paleovalley and the Nathrop volcanics (Tnv). US-285, visible near the left margin, follows the exhumed floor of the Trout Creek paleovalley in ascending Trout Creek Pass. The dark timbered ridge to the right of US-285 consists of as much as 1,000 ft (305 m) of the Oligocene Badger Creek Tuff capped by an andesite lava flow. Note how the Badger Creek Tuff thickens towards the axis of the paleovalley. The water gap where the Oligocene drainage crossed the Mosquito range forms the low point on the skyline directly behind the timbered ridge. Eagle Rock (left center) is an erosional remnant of the early Oligocene Wall Mountain Tuff near the confluence of two forks of the Trout Creek paleovalley. The flat-topped ridge just below the skyline to the right of Eagle Rock is composed of Badger Creek Tuff, which fills the south fork of the paleovalley. Bald Mountain at right center is the vent for late Oligocene (28-29 m.y.) rhyolite flows of the Nathrop volcanics; Sugarloaf Mountain (right middle distance) is a downfaulted remnant of a rhyolite flow. According to Scott (1975), fragments of the rhyolite from Bald Mountain occur in the Wagontongue Formation of South Park at least 13 mi (20 km) to the northeast. This occurrence indicates that the northeast-trending Oligocene drainage was not disrupted by subsidence of the upper Arkansas graben until sometime after 28-29 m.y. ago.

c) View northwest across the upper Arkansas Valley at Mt. Princeton and the cliffs of light-colored, hydrothermally altered quartz monzonite along Chalk Creek. Stop N6 is at the head of the alluvial fan to the right of the Chalk Cliffs. The gently sloping surface in the foreground is a downfaulted, west-tilted remnant of the late Eocene erosion surface carved on Precambrian rocks. The triangular-shaped cliff visible down this surface to the left is part of a large outcrop of the Wall Mountain Tuff (early Oligocene) known as "The Reef." The Wall Mountain Tuff occurs here in a northwest-forking tributary of the large Waugh Mountain paleovalley. The Reef slopes westward to near the level of the Arkansas River in Browns Canyon. The old gold mining camp of Turret is just out of sight beyond the knobs of Precambrian rock in the foreground. The gold veins are probably related to the Whitehorn Granodiorite, a Laramide pluton (70 m.y.) beveled by the late Eocene erosion surface (photos by **G.** R. Osburn).

Road is on first Bull Lake till for a short distance and then passes onto first Pinedale outwash. 4.4

155.9 Junction of Colo-162 and US-285. *Turn right on US-285.* 2.4

158.3 Roadcuts in middle Pleistocene (Kansan?) gravel; white layer of type-O Pearlette ash-600,000 years—near top of cut. Roadcuts just ahead are in lower Pleistocene (Nebraskan?) alluvium overlying Dry Union Formation (Scott and others, 1975). 1.5

159.8 Roadcuts in lower Pleistocene (Nebraskan?) gravel that contains Bishop ash (700,000 years). Next 3 mi (5 km) largely in Dry Union Formation. 2.2

162.0 Hills at left are northwest-trending horst block of Precambrian rocks faulted against Dry Union and the Oligocene volcanic rocks of the paleovalley viewed from last stop. 1.8

163.8 Oligocene volcanic rocks, overlain by Dry Union Formation. 0.7

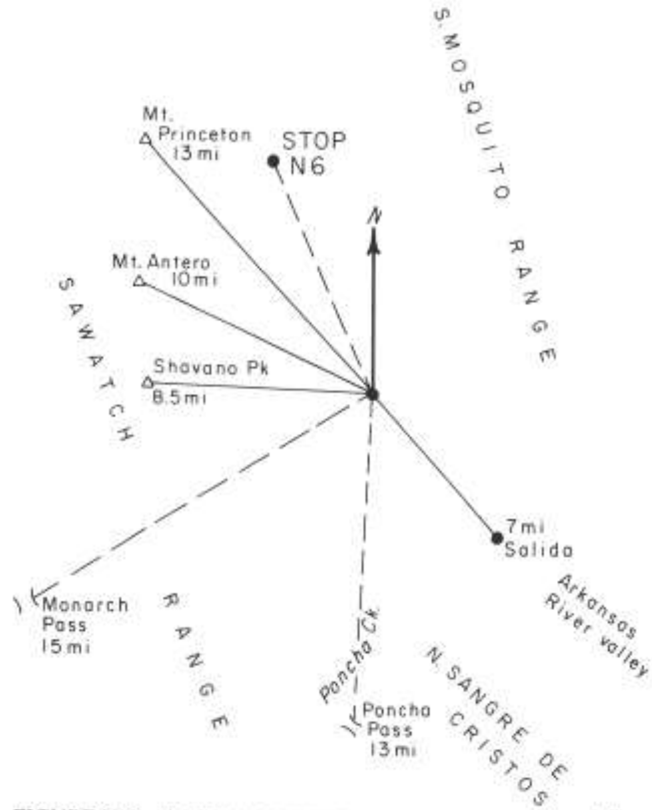


FIGURE N12—PANORAMIC INDEX OF FEATURES SEEN FROM STOP N7 AT HIGHWAY REST AREA ON US-285 WEST OF SALIDA.

164.5 Junction of US-285 and Colo-291. *Continue south on US-285* through area of Dry Union Formation, locally overlain by Quaternary deposits. **1.9**

166.4 **STOP N7, West of Salida.** At highway rest area (figs. N12 and N13). Dissected pediments to west are cut on the Dry Union Formation and are capped in places by middle and lower Pleistocene alluviums (Kansan? and Nebraskan? of Scott and others, 1975). These units are faulted against Precambrian rocks at the heads of the pediments. High mountains to the southeast from this locality are the northern end of the Sangre de Cristo range. This range is cut off abruptly by a west-northwest-trending fault that forms the southerly side of a triangular, deep graben in this vicinity (fig. N4; sheet 1). The Dry Union Formation in front of the fault dips southward or southwestward toward the fault. Post-Dry Union movement on the fault is as young as Pliocene; the age is indicated by the composition of uppermost beds of the Dry Union, which overlie beds containing vertebrate fossils of very late Miocene age. Resistivity and gravity data indicate that the fill in the graben is about 5,000 ft (1,500 m) thick, making a basement relief of 11,500-12,000 ft (3,5003,700 m) between the graben bottom and high peaks of the Sawatch and Sangre de Cristo ranges. From Stop N7, *turn left (north) on US-285; proceed 1.9 mi to Colo-291.* **1.9**

168.3 *Turn right on Colo-291.* **0.5**

168.8 Curve to south. Highway passes onto Pinedale outwash, which is studded in places by large boulders deposited in the floods noted at mile 121.7. **0.6**

169.4 *Cross bridge* over Arkansas River. **5.9**

175.3 *Enter Salida.* **0.9**

176.2 *Turn right on F Street.* **1.1**

177.3 Junction of F Street and US-50. *Stop for night.*

177.3 *Resume route* at F Street and *go west on US-50.* Bluffs of Dry Union Formation at left (south). **4.0**

181.3 Junction of US-50 and US-285 at Poncha Springs, named for hot springs nearby. *Turn left on US-285,* cross South Arkansas River, and start ascent to Poncha Pass. First roadcuts are in terrace gravels underlain by coarse upper facies of Dry Union, dipping southwest toward fault. 1.1

FIGURE N13—UPPER ARKANSAS VALLEY AND SAWATCH RANGE; view north from point 3 mi south of Stop N7. Graben-border faults at base of steep slopes of Sawatch Range. Dry Union Formation in dissected pediments in front of them. Early Pleistocene ash localities are on or near the top of the pediments. High peaks, from left to right, are Mt. Shavano (elevation 14,225 ft), Mt. Antero (elevation 14,269 ft), and Mt. Princeton (elevation 14,197 ft) (photo by Wayne Lambert, October 15, 1977, late afternoon).

182.4 Fault; route ahead is in Precambrian rocks. This is the fault on southern side of the triangular graben of the Salida area. The fault is transverse to and displaces the north-south Arkansas Valley-Poncha Pass-San Luis Valley graben system. 3.0

185.4 Oligocene volcanic rocks, lying on Precambrian rocks and overlain by coarse volcanic-rich Dry Union Formation. From here to Poncha Pass, the highway is back and forth in Precambrian rocks, volcanic rocks, and Dry Union Formation. Main body of Dry Union is west of highway, in graben 2-3 mi (3-5 km) wide, disrupted by many interior faults. 1.0

186.4 Road to Marshall Pass at right; former narrow-gauge railroad route over Sawatch Range. 2.4

188.8 Poncha Pass, elevation 9,010 ft (2,746 m). Entering San Luis Valley and Rio Grande drainage (Upson, 1939). Sangre de Cristo range on left (fig. N4; sheet 1). Mountains at right are Oligocene volcanic rocks of the Bonanza volcanic center, in northeast corner of San Juan volcanic field. Main frontal fault of the Sangre de Cristo range is east of pass, and an echelon fault that continues northward is to west. Pass is in Dry Union Formation, resting on Precambrian rocks. In San Luis Valley, rocks largely equivalent to the Dry Union Formation are called Santa Fe Formation, and in the eastern San Juan Mountains they are called Los Pinos Formation. 4.7

193.5 Alder Creek. Ahead on left, frontal escarpment of Sangre de Cristo range, a modified fault scarp. Note abrupt changes in drainage development and increasing development upslope. Faulted front continues southward into New Mexico. 7.7

201.2 High on fans at left, linear vegetation lines that are probably on faults. **1.9**

203.1 Villa Grove; at left and ahead, low fault scarps in upper Quaternary alluvium. **3.1**

206.2 Outcrops of Santa Fe Formation in sage-covered foothills at right. Slopes beyond are Paleozoic and Precambrian rocks in structurally complex area. **1.3**

207.5 Just before junction of US-285 and Colo-17, *turn left on gravel road;* route ahead crosses northern San Luis Valley. 6.7

214.2 Road fork at base of fault scarp in alluvial fan; *turn right.* 0.3

214.5 **STOP N8, Valley View Hot Springs. Faulted piedmont surface at east edge of San Luis Valley (fig. N14). The frontal fault of the Sangre de Cristo range is at the base of the steep slopes immediately east of this locality (fig. N15). The view westward is across the comparatively narrow northern end of the San Luis Valley. The valley widens to at least five times this width farther south in the Alamosa Basin (fig. N4; sheet 1). The mountains across the valley are Precambrian and Paleozoic rocks. Just beyond their crests are volcanic rocks of the San Juan volcanic field, extending 80 mi (125 km) to the west. The valley is underlain by the Santa Fe Formation, which in turn is probably underlain by Oligocene volcanic and volcaniclastic rocks. The valley fill at this latitude has been estimated on the basis of geophysical data to be 5,000 ft (1,524 m) in maximum thickness but may be considerably thinner (G. V. Keller, personal communication in Pearl and Barrett, 1976).**

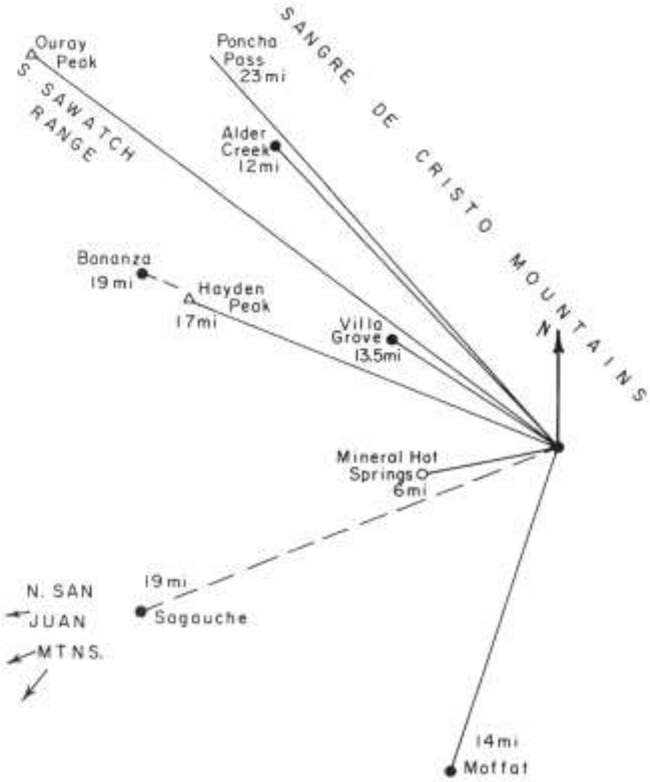


FIGURE N14—Panoramic index of features seen from Stop N8 in northern San Luis Valley near Valley View Hot Springs.

FIGURE N15—Fault in alluvial fan at base of Sangre de Cristo range in San Luis Valley; view east toward Stop N8 (mile 214.5) at fault. Fan is of late Pleistocene Pinedale age. Building to left of fan marks Valley View Hot Springs, near main Sangre de Cristo fault. Mountains consist of Paleozoic rocks (photo by Wayne Lambert, October 15, 1977, mid-day).

The fault scarp here is in an alluvial fan of Pinedale age. The fault is an element of a northwest-trending zone of young faults that extends diagonally across the valley to the vicinity of Villa Grove, 8 mi (13 km) to the northwest. Valley View Hot Springs is in the gulch just north of this locality, in the acute angle between the scarp fault and the Sangre de Cristo frontal fault. Mine dumps on the slopes to the north mark the Orient mine. Limonitic iron ore in Paleozoic limestone was mined there for about 50 years, beginning in 1881. **7.0**

221.5 *Return to US-285* at junction with Colo-17 and *go left on Colo-17.* **1.5**

223.0 Mineral Hot Springs. Route ahead crosses broad, central plain of the Alamosa Basin, as is illustrated by a Landsat image of the San Luis Valley area from here to near Taos, New Mexico (fig. **N16). 11.5**

234.5 Moffat; highway is in a zone of high gravity gradient between a deep low to the east and a high to the west. The high is interpreted as a horst in the bedrock beneath the valley fill. See Stop N9 discussion. **0.7**

235.2 Crestone road at left. Rugged peaks on skyline include Kit Carson and Crestone Peaks. The peaks and upper slopes consist of the Crestone Conglomerate Member (Pennsylvanian or Permian) of the Sangre de Cristo Formation; the lower slopes are Precambrian rocks thrust over the Sangre de Cristo Formation. **10.0**

245.2 **STOP N9, San Luis Valley** (figs. N17 and N18). The San Luis Valley, 50 mi (75 km) wide and 100 mi (160 km) long, is a major basin in the Rio Grande rift zone (fig. N16; sheet **1).** Viewed broadly, the valley is a half graben with a floor that dips eastward to the frontal fault of the Sangre de Cristo range. However, this pattern is disrupted by an inferred horst block trending

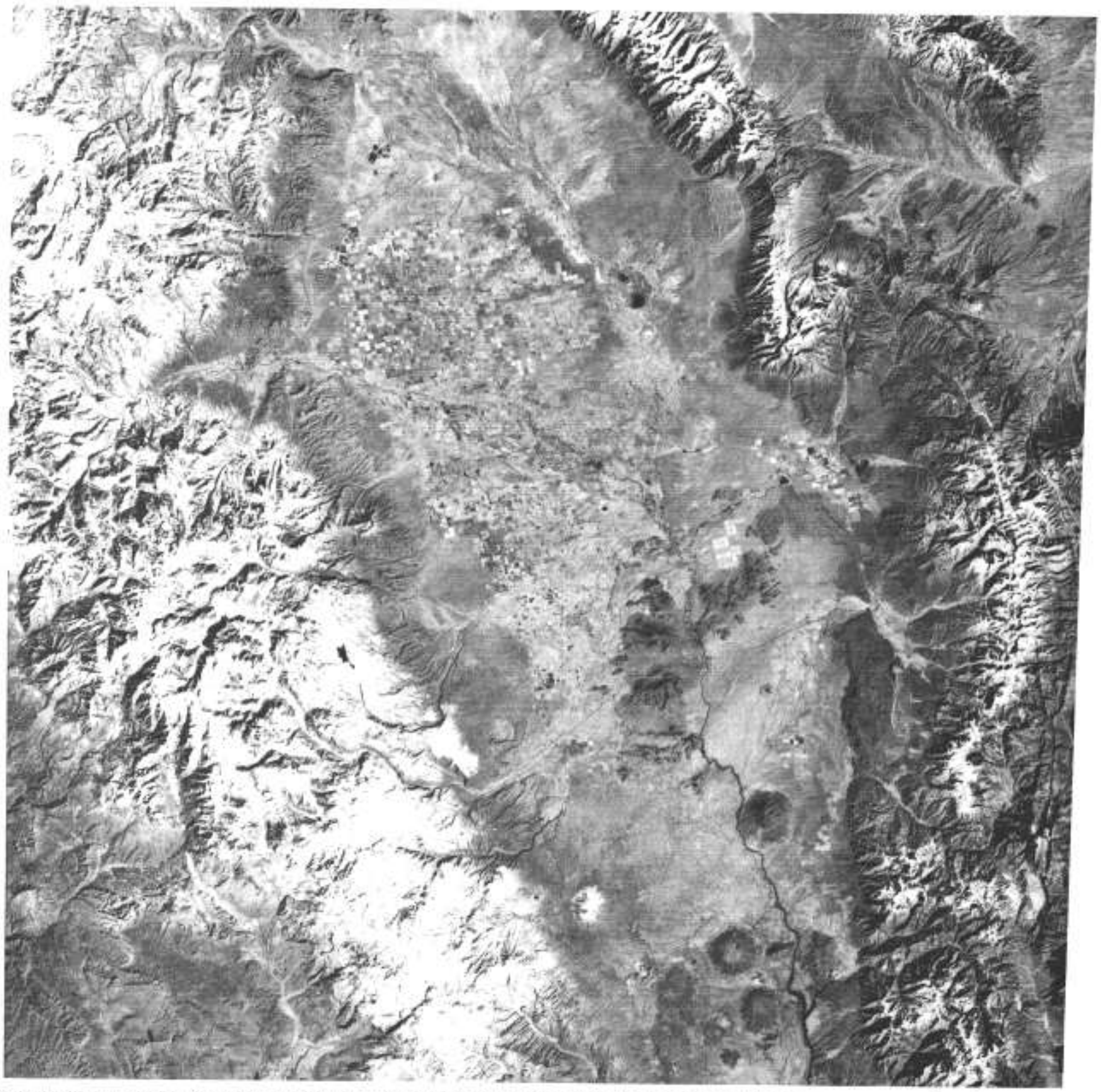


FIGURE N16—LANDSAT IMAGE **(a, above)** AND INDEX MAP **(b, at right)** OF THE SAN LUIS VALLEY SEGMENT OF NORTHERN RIO GRANDE RIFT AND ADJACENT AREAS IN COLORADO AND NEW MEXICO; image scale approximately 1:1,000,000 (image E2276-17013-7 transmitted October 25, 1975; courtesy of Technology Application Center, University of New Mexico).

northerly beneath the center of the valley. Thickness and character of the fill in the valley are known only from a few deep test borings and from gravity interpretations. An oil test on the west side of the valley at this latitude, between the horst block and the foot of the San Juan Mountains, reached basement at a depth of about 10,000 ft (3 km). A boring near Mosca (ahead on Colo-17) reached basement on the horst block at a depth of about 5,500 ft (1,675 m). A geothermal test well, 11 mi (18 km) east-northeast of Mosca, went to a depth of 10,000 ft (3,050 m) without reaching basement. Huntley (1976a, b) reports 6,000 ft (1,830 m) of Quaternary to Oligocene basin fill at this site; however, data on the boring are contradictory and need further study. All of these borings, plus another that went 8,000 ft (2,440 m) without reaching basement, encountered thick volcaniclastic sediments and interbedded lava flows and ash-flow tuffs beneath the Santa Fe Formation. An upper ash-flow tuff correlates in position with the projection of one that dips beneath the valley fill at the foot of the San Juan Mountains, indicating that the volcaniclastic unit is of Oligocene age. The volcaniclastic rocks are underlain by as much as 2,000 ft (600 m) of nonvolcanic arkose

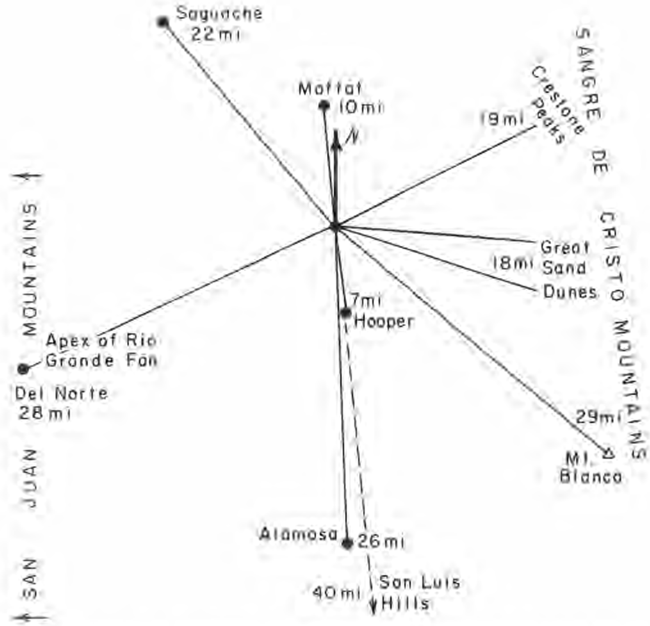
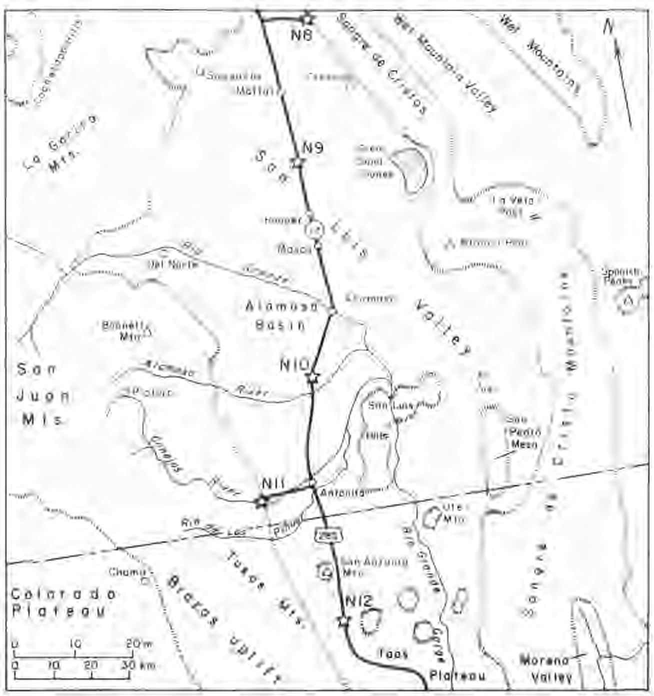


FIGURE N17—PANORAMIC INDEX OF FEATURES SEEN FROM STOP N9 IN NORTH-CENTRAL SAN LUIS BASIN BETWEEN CRESTONE AND MOSCA.



and mudstone similar to a prevolcanic Eocene unit in the region east and northeast of Salida. The arkose lies on the Precambrian basement. A deep gravity low between Colo-17 and the Sangre de Cristo range suggests a much greater thickness of fill in that area. This low was originally interpreted to indicate 30,000 ft (about 9 km) of valley fill (Gaca and Karig, 1966), but this figure has been recently reduced to about 20,000 ft (about 6 km) on the basis of additional gravity work and modeling. See concluding discussion at this stop by Davis and Keller.

The San Luis Valley is a foundered segment of a paleotectonically persistent positive area. In the late Paleozoic, the valley was part of a highland that supplied sediments of the thick Sangre de Cristo Formation to the east. In Laramide time, the highland was re-elevated and supplied arkosic sediments to the Raton Basin to the east. The present Sangre de Cristo range is a remnant of the eastern flank of the Laramide uplift, elevated to its present height in late Cenozoic time. However, the presence of thick Eocene and Oligocene rocks beneath the valley indicates that a valley and a mountain range to the east existed before the late Tertiary rifting episode.

FIGURE N18—BLANCA PEAK MASSIF OF PRECAMBRIAN ROCKS IN SANGRE DE CRISTO RANGE; view southeast across San Luis Valley from Stop N9 (mile 245.2). Great Sand Dunes at base of mountains at left. Culebra Range unit of Sangre de Cristo range in distance at right. Basement-rock surface is displaced a minimum of 5 km along fault at base of this part of the Sangre de Cristos (photo by Wayne Lambert, October 17, 1977, sunset).

Subsurface structure of San Luis Valley

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A major purpose of this stop is discussing the dramatic gravity anomalies in the area and the inferred subsurface structure. A generalized subsurface structure section is shown in fig. N19. This structure is inferred from gravity modeling and is subject to uncertainties, because densities in the subsurface are not well known; however, the general configuration of the basement is satisfactorily shown. Stop N9 is located near the eastern edge of a horst that rises to within approximately a kilometer of the surface. To the east of this horst, the basement is at a depth of about 20,000 ft (about 6 km). Thus, this stop is located over a fault zone whose throw is approximately 16,500 ft (about 5 km). In addition, the Sangre de Cristo fault, which marks the front of the mountains, represents over 23,000 ft (7 km) of structural relief. **7.0**

252.2 Hooper; Colo-112 to right. Great Sand Dunes in distance at left, nestled against mountain front (figs. N16, N18). In far distance at right, volcanic rocks of San Juan Mountains dip eastward beneath the San Luis Valley. **6.0**

258.2 Junction; Colo-150 and Great Sand Dunes National Monument to left. **0.8**

259.0 Mosca; an oil test near here in area of central horst block (Stop N9 discussion) reached Precambrian basement at depth of 5,500 ft (1,675 m).

(COMPILER'S NOTE—This concludes the log from Denver to Alamosa by Ogden Tweto. Comments below adapted from Burroughs and McFadden, 1976a, b.)

The part of the San Luis Valley between Mosca and the San Juan Mountains is a great alluvial fan built by the Rio Grande upon emergence from its valley in the San Juan Mountains at Del Norte. The river earlier flowed eastward to the vicinity of the Great Sand Dunes and then made a sharp bend to the south toward the San Luis Hills (11:30), traversing the hills south of La Sauses. The Rio Grande has since migrated in a southwesterly direction to Alamosa, leaving behind a wide floodplain. Sand that built the Great Sand Dunes was picked up by prevailing southwesterly winds crossing the floodplain and then deposited against the front of the Sangre de Cristo Mountains. **6.5**

265.5 Mt. Blanca, elevation 14,363 ft (4,376 m), at 9:00. The planar piedmont surfaces south of Mt. Blanca are on pediment gravels capping Santa Fe Formation basin fill. Note triangular facets located at break in slope between Mt. Blanca and pediment. Irregular hills on piedmont surface are composed of upper Cenozoic volcanics.

San Luis Hills, at 11:00-12:00, are an intrarift horst of Oligocene volcanics (Conejos Formation) and associated intrusions (see Stop N10 discussion). Eastern San Luis Hills make up irregular topography at 11:00, a reflection of southeastward-tilted fault blocks. Flat-topped western San Luis Hills are seen at 12:00. The Rio Grande flows through the La Sauses Gorge between the two areas and then continues south into New Mexico west of Ute Mountain, the domed stratovolcano seen at 11:30 in the far distance. The main Rio Grande Gorge begins near Old State Bridge, 6.5 mi (10.8 km) north of the state line. The canyon gradually deepens southward for the next 50 mi (83 km), cutting through the Taos Plateau subdivision of the San Luis Valley (Upson, 1939), until its walls become about 1,200 ft (367 m) high near Embudo (Alamosa-Santa Fe log, mile 148.6). **3.0**

268.5 Crossing floodplain of Rio Grande. Trees from 11:00 to 3:00 outline course of river. **2.9**

271.4 Junction of Colo-17 and US-160; *turn right (west) on US-160.* End of Denver-Alamosa road log.

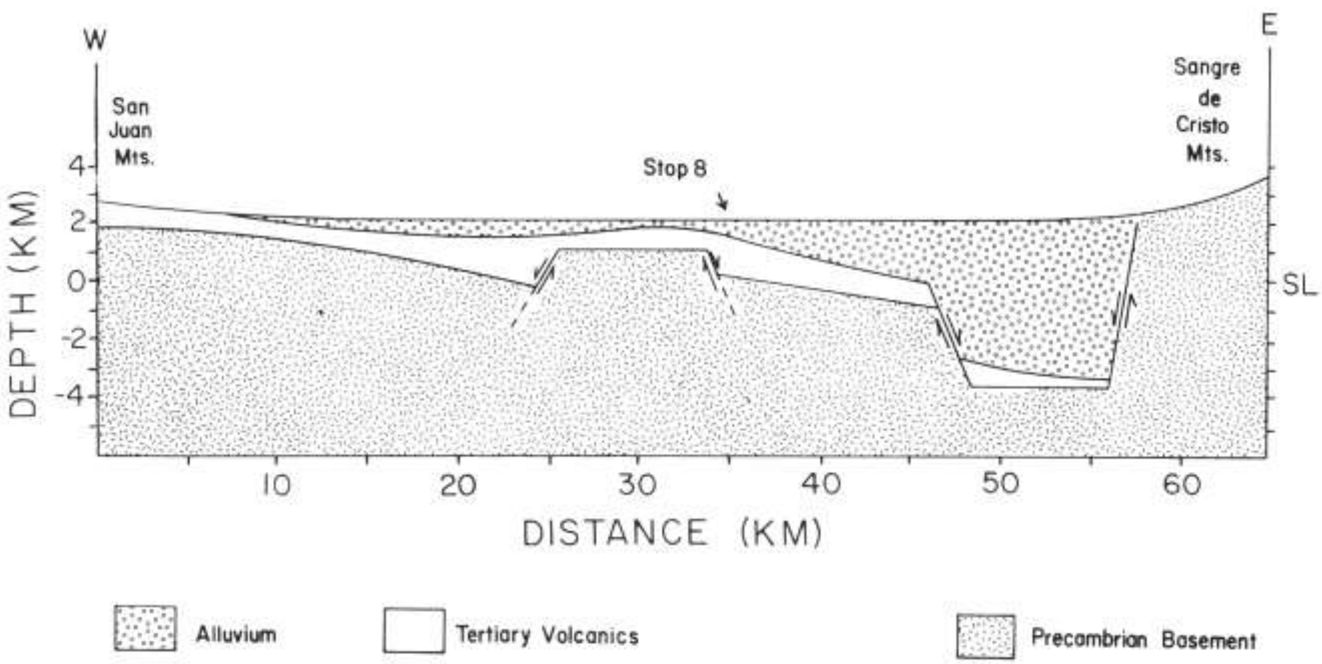

FIGURE N19—GENERALIZED EAST-WEST SUBSURFACE STRUCTURE SECTION in the vicinity of Stop N9, inferred from gravity data.

ALAMOSA TO EISENHOWER TUNNEL, COLORADO

This log is compiled from the more detailed southbound road log by Ogden Tweto. The emphasis is on geologic and geomorphic features seen from a northbound perspective between tour stops N1 and N9 in the rift segment of the route traversed. The eastern slope of the Rocky Mountains (east of Loveland Pass and Eisenhower Tunnel) and individual stops are described in the Denver to Alamosa tour guide.

Mileage

0.0 Junction of Colo-17 and US-160 at east edge of Alamosa. *Take Colo-17 North.* **2.9**

2.9 North edge of Rio Grande floodplain. The west central part of the San Luis Valley between here and the San Juan Mountains is a great alluvial fan built by the Rio Grande upon emergence from its valley in the San Juan Mountains at Del Norte about 30 mi (48 km) to the northwest. The river earlier flowed eastward past Mosca (mile 12.4) to the vicinity of the Great Sand Dunes (2:00-2:30) and then made a sharp bend to the south toward the San Luis Hills, traversing the hills in the gorge south of La Sauses. The Rio Grande has since migrated in a southwesterly direction to Alamosa, leaving behind a wide floodplain. Sand that built the Great Sand Dunes was picked up by prevailing southwesterly winds crossing the floodplain and was then deposited against the front of the Sangre de Cristo Mountains.

Mt. Blanca, elevation 14,363 ft (4,376 m), at 2:00 to 3:00. The planar piedmont surfaces south of Mt. Blanca are on pediment gravels capping Santa Fe Formation basin fill. Note triangular facets located at break in slope between Mt. Blanca and pediments. Irregular hills on piedmont surface are composed of upper Cenozoic volcanics. (Comments above adapted from Burroughs and McFadden, 1976a). **9.5**

12.4 Mosca; an oil test near here, in area of central horst block (Stop N9 discussion), reached Precambrian basement at depth of 5,500 ft (1,675 m). **0.8**

13.2 Junction; Colo-150 to right leads to Great Sand Dunes National Monument. **6.0**

19.2 Hooper; Colo-112 to left. Great Sand Dunes at 3:00 nestled against base of Sangre de Cristos below Mosca Pass. **7.0**

26.2 **STOP N9, San Luis Valley.** Discussion of central San Luis Valley. See mile 245.2 entries in Denver to Alamosa road log by Tweto and others. To the north the frontal escarpment of the Sangre de Cristo range, a modified fault scarp, swings closer to the highway. Note abrupt changes in drainage development and increasing development upslope. Faulted front is a northward continuation of similar features seen in New Mexico. **9.0**

35.2 Highway marker: Crestone Peak, elevation 14,294 ft (4,397 m), to right. Rugged peaks on skyline are the Crestone Needles. The peaks and upper slopes consist of the Crestone Conglomerate Member (Pennsylvanian or Permian) of the Sangre de Cristo Formation; the lower slopes are Precambrian rocks thrust over the Sangre de Cristo Formation. **1.0**

36.2 Crestone road to right. **0.5**

36.7 Moffat; route crosses the 38th parallel. The highway is in a zone of high gravity gradient between a deep low to the east and a high to the west. As discussed at Stop N9 the high is interpreted as a horst in the bedrock beneath the valley fill. **11.6**

48.3 Mineral Hot Springs; buildings of former spa to right. Area of Stop N8 at 3:00 on upper piedmont slope near Valley View Hot Springs. From here north numerous fault scarps offset upper Quaternary basin-fill units. **1.6**

49.9 Junction of Colo-17, US-285, and graded road to Valley View Hot Springs. *Turn right* for excursion to **STOP N8, Valley View Hot Springs,** at piedmont fault scarp near base of Sangre de Cristos. See miles 207.5 to 214.5 in Denver to Alamosa road log. After excursion *proceed north on US-285.* **1.1**

51.0 Outcrops of Santa Fe Formation in sage-covered foothills at left. Slopes beyond are Paleozoic and Precambrian rocks in structurally complex area of the northeastern San Juan Mountains. **2.6**

53.8 South edge of Villa Grove; low fault scarps in upper Quaternary alluvium in valley to right. **0.4**

54.2 Crossing Kerber Creek; Bonanza volcanic center in northeast San Juan Mountains ahead on left. High on fans at right are linear vegetation lines, probably on faults. **9.7**

63.9 Alder Creek; Ouray Peak at 11:00. **4.5**

68.4 Poncha Pass, elevation 9,010 ft (2,746 m). Leaving San Luis Valley and Rio Grande drainage; upper Arkansas Valley ahead; and north part of Sangre de Cristo range on right. Mountains to left are Oligocene volcanic rocks of the Bonanza center in northeast corner of San Juan volcanic field. Main frontal fault of the Sangre de Cristo range is east of pass, and an echelon fault that continues northward is to west. Pass is in Dry Union Formation, resting on Precambrian rocks. The Dry Union is the upper Arkansas Valley equivalent of the Los Pinos and Santa Fe Formations in the San Luis Valley. For next 3.5 mi, highway is back and forth in Precambrian rocks, Tertiary volcanics, and Dry Union Formation. Main body of Dry Union is west of highway, in graben 2-3 mi (3-5 km) wide, disrupted by many interior faults. **2.5**

70.9 Site of Mears Junction on former narrow-gauge railroad route over southern Sawatch Range via Marshall Pass to left. **1.0**

71.9 Oligocene volcanic rocks, lying on Precambrian rocks and overlain by coarse volcanic-rich Dry Union Formation. **3.0**

74.9 Fault; leaving Precambrian rocks. This fault is on the southerly side of the triangular graben of the Salida area. The fault is transverse to and displaces the north-south Arkansas Valley-Poncha Pass-San Luis Valley graben system. Roadcuts ahead are in Dry Union Formation, dipping southwest toward fault and overlying terrace gravels. **0.8**

75.7 Cross South Arkansas River; enter Poncha Springs, named for hot springs nearby. **0.1**

75.8 Junction of US-50 and US-285; *turn right and continue east on US-50* into Salida. Bluffs of Dry Union Formation at right (south). **4.2**

80.0 Junction of F Street and US-50 in Salida. *Stop for night.*

80.0 *Resume route* at F Street. *Continue northeast* through downtown Salida. **1.1**

81.1 Traffic light; intersection of F Street and Colo-291. *Turn left and continue northwest on Colo-291* up Arkansas Valley. **1.2**

82.3 Crossing Arkansas River. **4.5**

87.8 Crossing Pinedale outwash terrace studded in places by large boulders deposited in floods noted at mile 134.6. **1.6**

88.4 Curve to west; *keep left* for junction ahead. **0.6**

89.0 Junction of US-285 and Colo-291. *Turn left onto US-285 and continue south* through area of Dry Union Formation, locally overlain by Quaternary deposits. **1.9**

90.9 **STOP N7, West of Salida.** Rest area west of highway at "Christmas 1806" historic marker commemorating Zebulon Pike's expedition in southern Colorado in winter of 1806-1807. Discussion of features that are in the south end of the upper Arkansas Valley. See mile 166.4 entry in Denver to Alamosa road log. After stop, *continue north on US-285* up Arkansas Valley. **1.9**

92.8 Junction of Colo-291 to right; *continue straight on US-285.* **0.6**

93.4 Oligocene volcanic rocks, overlain by Dry Union Formation. **0.4**

93.8 Hills to right are northwest-trending horst block of Precambrian rocks faulted against Dry Union and Oligocene volcanic rocks of the (late Eocene) paleovalley viewed from Stop N6. Next 3 mi largely in Dry Union Formation. **3.5**

97.3 Roadcuts in lower Pleistocene (Nebraskan?) gravel that contains Bishop ash (700,000 years). **1.5**

98.8 Roadcuts in lower Pleistocene alluvium overlying Dry Union Formation. Cuts just ahead near north end of exposure (mile 99.0) are in middle Pleistocene (Kansan?) gravel; white layer of type-O Pearlette ash (600,000 years) near top of cut on left (Scott and others, 1975). **2.6**

101.4 Junction of US-285 and Colo-162; *turn left on Colo-162 and continue west* up valley of Chalk Creek. Route ahead is mainly on upper Pleistocene, Pinedale outwash (Wisconsinan). **4.2**

105.6 *Cross bridge* over Chalk Creek. Mt. Princeton Hot Springs resort ahead on left. **0.2**

105.8 Junction of Colo-162 and Chaffee County Road 321; *turn right on County Road 321.* Road here is on first Bull Lake till of late Pleistocene (early Wisconsinan?) age. **0.2**

106.0 Starting to ascend steep grade to high-level piedmont surface underlain by a thick section of lower Pleistocene alluvium on Dry Union Formation. **0.4**

106.4 On steep grade, at very small angle to road, contact between old alluvium with angular clasts and coarse glacial gravel with rounded clasts. **0.2**

106.6 STOP N6, Chalk Creek overlook. High surface, extending out from base of Mt. Princeton, which overlooks the Arkansas Valley; Mosquito Range to east and Sawatch Range to west. See mile 150.7 entry in Denver to Alamosa road log. After stop *continue north on County Road 321.* **0.5**

107.1 Private road left to Young Life Campaigns Frontier Ranch. Road ahead to Buena Vista descends for about 2.5 mi on early Pleistocene alluvium and, for the next 2.5 mi, crosses **Bull** Lake outwash. The route then crosses low ridges capped by middle Pleistocene alluvium standing above outwash surfaces. The final 1.7 mi of the route is on second Bull. Lake outwash. **6.7**

113.8 *Enter Buena Vista;* junction ahead with Colo-306. *SLOW!* **0.2**

114.0 *Make sharp left turn onto Colo-306; continue up valley* of Cottonwood Creek on Pinedale and Bull Lake outwash terraces. **3.9**

117.9 **STOP N5, West of Buena Vista.** Cottonwood Creek at canyon entrance, with view of young faults along the Sawatch Range front. See mile 139.4 entry in Denver to Alamosa road log. After stop, *return to Buena Vista.* **4.0**

121.9 West edge of Buena Vista; County Road 321 to right. *Continue straight on Colo-306.* **0.7**

122.6 Junction of Colo-306 and US-24; *turn left and continue north on US-24.* **0.7**

123.3 *Leave Buena Vista.* Crossing Pinedale outwash terrace studded with huge boulders deposited in floods noted at mile 134.6. **1.7**

125.0 Mt. Yale on skyline to left (14,194 ft, about 4,367 m). Route is mainly on lower Pleistocene alluvium (Nebraskan? of Scott, 1975). Outcrops of Precambrian rocks near highway to right; early Pleistocene valley axis was to west. **0.8**

125.8 Highway drops to surface on upper Pleistocene deposits. **3.1**

128.9 Surface above terrace front to left is on middle Pleistocene alluvium (Kansan? of Scott, 1975) overlying Dry Union Formation. The alluvium contains a layer of type-O Pearlette volcanic ash, 600,000 years in age. On lower slopes at right, across river, remnants of pre-Dry Union pediment cut on Precambrian granite. **0.6**

129.5 Mt. Harvard on skyline to left; elevation 14,417 ft (4,394 m). 2.5

132.0 Landslide area to left is underlain by Dry Union Formation at constriction of graben that widens southward in Arkansas Valley. **2.6**

134.6 Terminal moraine of Pinedale glacier of Pine Creek on left. The glacier dammed and impounded the Arkansas River; and at least twice, catastrophic floods were released when the ice dam was breached. The floods transported large boulders now seen studding the Pinedale terraces southward to Salida. **2.0**

136.6 Low Pinedale moraine of Clear Creek between high Bull Lake lateral moraines. Here graben defined by Dry Union and early glacial fill constricts to a few hundred meters in width. **2.6**

139.2 Village of Granite. Here highway and river are in Precambrian rocks, but a graben filled by Dry Union Formation and early glacial deposits is only a short distance to west. **1.8**

141.0 Twin Lakes (Colo-82) junction ahead; *prepare for left turn.* Old gold placer workings at left are in Bull Lake outwash. **0.8**

141.8 Junction of US-24 and Colo-82. *Turn left* for 8.7-mi excursion via Colo-82 to **STOP N4, Twin Lakes** (lunch). See mile 115.4 entry in Denver to Alamosa road log. After excursion *continue north* on US-24. **1.2**

143.0 Approaching head of shallow canyon in Precambrian rocks. A thick prism of Dry Union Formation lies to west of a fault that is only 300-600 ft (100-200 m) west of canyon wall. Bedrock pediments on right are pre-Dry Union, covered in places by scabs of Dry Union, which in turn is pedimented to the same level. 1.0

144.0 Upper end of shallow canyon; ahead is northernmost open segment of Arkansas Valley. Pediments ahead on left, ascending to the Sawatch Range front, are cut on Dry Union Formation and pre-Bull Lake glacial deposits. Landslide terrain on Dry Union at pediment front. 4.7

148.7 Railroad overpass. Pediments ahead on right, ascending to the Mosquito Range front, are cut on Dry Union Formation and, near their heads, on first pre-Bull Lake till. Both units are faulted against bedrock at pediment heads. 0.2

148.9 Crossing Arkansas River. 1.8

150.7 Mt. Elbert on skyline to west, elevation 14,433 ft (4,399 m), is the highest peak in Colorado and the second highest in the conterminous United States. 2.2

152.9 Route makes sharp turn to east at Malta railroad junction. Lowest gravity low (-338 mgals) in the conterminous United States is in valley bottom to west. On the basis of gravity, Tertiary valley fill is estimated to be 3,000-4,000 ft (900-1,200 m) thick, placing the bedrock (Precambrian?) surface at an elevation of about 6,600 ft (2,000 m). 1.8

154.7 Stringtown and, at left, former smelter. Water well at smelter bottomed in Dry Union Formation at depth of 600 ft (183 m). **1.1**

155.8 *Enter Leadville,* elevation 10,152 ft (about 3,125 m). 0.6

156.4 *Make left jog onto south end of Harrison Avenue; immediately turn right onto Monroe Street.*

0.1 156.5 *Continue east* on Monroe Street to Toledo Street. 0.2

156.7 *Turn left onto Toledo Street.* **0.2**

156.9 STOP N3, Leadville. Toledo Street just south of 3rd Street. View westward across upper Arkansas River Valley to the Sawatch Range. See mile 100.4 entry in Denver to Alamosa road log. After stop *continue north* through Leadville via 3rd Street and Harrison Avenue. 0.3

157.2 Intersection of 3rd and Harrison; *turn right; continue north on US-24.* **0.1**

157.3 Lake County Courthouse, Harrison at 5th Street. 0.2

157.5 Intersection, Harrison and 9th; *turn right.* Streets; **0.1**

157.6 Intersection, 9th and -Poplar *turn left; continue north on US-24.* **0.5**

158.1 Pre-Bull Lake moraine in cuts behind Safeway store. 0.5

158.6 Junction of US-24 and Colo-91; *proceed straight (northeast) on Colo-91* beside East Fork of the Arkansas River. Ahead, the highway crosses Bull Lake medial moraine formed at the junction of glaciers from East Fork and from Evans Gulch to the east. Beneath the highway and the medial moraine is a deep channel in the bedrock surface. This channel was the pre-Dry Union course of the East Fork of the Arkansas River. 1.6

160.2 East Fork of Arkansas River here cuts through first Pinedale terminal moraine, remnants of which form low hummocky benches at each side. For about the next 17 mi, bedrock terrane comprises Pennsylvanian rocks that are extensively intruded by porphyry sills, dikes, and stocks. Mountain slopes on left from here to Climax are intricately sliced by north-trending faults that, at Leadville, have been proved to have had major late Tertiary displacement. 4.3

164.5 Second Pinedale terminal moraine of East Fork of Arkansas River, overlain on east side by younger alluvial fan. 2.7

167.2 *Enter San Isabel National Forest.* Huge "cave hole" of Climax mine ahead on mountain slope at upper end of valley. 0.8

168.0 Route crosses third Pinedale moraine (late Wisconsin). 0.4

168.4 Gravel pits are in a filled basin behind the third Pinedale moraine. Peak to left is Chalk Mountain, an Oligocene rhyolite porphyry pluton. En route to the switchback ahead, there are good views of the cirque at the source of the East Fork of the Arkansas River. 0.9

169.3 Storke tunnel level of the Climax mine and coarse-crushing plant. 0.6

169.9 STOP N2, Climax. On Continental Divide at Fremont Pass and Climax, elevation 11,318 ft (3,450 m). See mile 87.4 entry in Denver to Alamosa road log. After stop, *continue north* on Colo-91, descending into valley of Tenmile Creek and across the tailing disposal system for the Climax mine. **0.8**

170.7 Route crosses end of large tailings lake. 3.0

173.7 Major tailings holding structure to left above site of Kokomo town and zinc-lead mining area. The most productive part of the area is now beneath tailings, and the remainder will be buried when all the structures seen en route are filled. 2.0

175.7 Opposite lowest tailings structure for Climax disposal system. **1.8**

177.5 Valley here is in the Mosquito fault zone; the Gore fault joins the Mosquito fault in this vicinity. Relations are obscured by a Laramide stock and extensive glacial cover. The Mosquito fault is a north-trending Laramide or older normal fault, downthrown to the west, that underwent major reactivation in Neogene time. From this vicinity northward, the fault borders the west side of the Tenmile Range. Northward, it extends acutely through the north-northwest-trending tectonic block outlined by the Gore and Blue River faults and ends against the Blue River fault. 3.6

181.1 Junction; Copper Mountain resort to left. The Gore fault crosses the valley at left about 1.5 mi (2.5 km) west of Colo-91. This fault was the border of a late Paleozoic highland; reddish mountains beyond it are Pennsylvanian and Permian rocks. 0.1

181.2 Junction of Colo-91 and 1-70; *proceed north on 1-70.* Descending lower Tenmile Canyon cut in Precambrian gneisses. Note glacial erosional features on canyon walls. Tenmile Range to east and Gore Range to west. 5.6

186.8 Frisco (southwest) exit; crossing Blue River fault, which forms the eastern boundary of the Gore and Tenmile Ranges. **1.6**

188.4 Frisco (northeast) exit; tour stop turnoff ahead. **0.9** 189.3 *Exit* at scenic viewpoint. 0.2

189.5 **STOP N1, Dillon Reservoir viewpoint.** This is the last stop on the northbound tour. See mile 67.9 entry in Denver to Alamosa road log. After stop *continue east on 1-70.* Between here and the Blue River bridge, below Dillon Dam, the route crosses the Bull Lake terminal moraine of the Tenmile Creek glacier. Pre-Bull Lake moraine is visible to the left of the highway about 1 mi (northeast) of this stop. Both moraines contain rock and ores derived from the Climax and Kokomo area, 20 mi to the southwest. 2.0

191.5 US-6 and Colo-9, Dillon-Silverthorne exit at Blue River. High earth-fill dam on right impounds Dillon Reservoir seen at Stop N1. 2.9

194.4 Crossing Williams Range thrust fault, which brings Precambrian rocks over Pierre Shale (Upper Cretaceous). This fault extends north-northwest continuously for 60 mi (nearly 100 km); a closely related echelon fault, the Elkhorn thrust, extends another 25 mi (40 km) south in South Park. The route east ascends the long, steep grade up the valley of Straight Creek. Many faults, transverse to the road, occur in Precambrian gneisses. Fracturing and alteration related to the faults account for the great height of many roadcuts. Faults are in a north-northwest-trending zone of Precambrian origin, but late Tertiary movement is proved 20 mi (30 km) to the north, where the faults border a graben filled with Miocene sediments. 3.6

198.0 Approaching Eisenhower Tunnel. The 1.7-mi (nearly 3-km) long tunnel passes beneath the Continental Divide in saddle area on the skyline north of Loveland Pass. The saddle site provided the shortest tunnel route but is also the site of a wide faulted and crushed zone that greatly increased the difficulty and cost of the tunnel. To stabilize the ground for a second bore, in progress, small tunnels are driven in advance on each side and are filled with reinforced concrete, making large dowels through the mountain. **1.8**

198.8 *Enter Eisenhower Tunnel;* elevation 11,013 ft (3,357 m). **1.7**

201.5 *Exit tunnel* and start down long, steep grade in valley of Clear Creek.

This is the end of the northbound road-log segment. See resume and mile 00.0 to 55.6 entries in the Denver -Alamosa road log for information on the route from here to Denver.

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Northern rift guide 2,
Alamosa, Colorado-Santa Fe, New Mexico

The Alamosa-Santa Fe segment of the northern-rift field trip begins in the southern Alamosa Basin subdivision of the San Luis Valley, between the San Juan Mountains to the west and the San Luis Hills to the east. The surface area traversed by US-285 comprises the coalescent alluvial plains of the Rio Grande, the Alamosa and Conejos Rivers, and La Jara Creek, all heading in the San Juan Mountains. Discussion at Stop N10, near La Jara, mainly deals with the mid-Tertiary volcanic sequence and structural features in the San Luis Hills area.

A short excursion to the southeastern front of the San Juan Mountains is made west of Antonito, near the Colorado-New Mexico State line. The route (Colo-17) passes the basaltic Los Mogotes shield volcano (5 m.y.) and ascends to the edge of Oligocene volcanics of the southern San Juan volcanic field near Aspen Glade campground (lunch stop). The Oligocene volcanic sequence in this area includes pre-caldera rocks (the Conejos Formation) and widespread units derived from the 29-m.y.-old Platoro caldera, including ash-flow tuffs and associated lavas and intrusives.

Back on US-285, south of Antonito, the route enters New Mexico. For the next 70 mi it crosses the Taos Plateau subdivision of the San Luis Valley (Upson, 1939; Lambert, 1966). This region of broad plains is mostly underlain by tholeiitic basalts of the Servilleta Formation (Pliocene). The region is trenched by the gorges of the Rio Grande and its major tributaries, which head mainly in the Sangre de Cristo Mountains. The mountains and hills scattered across the plateau are primarily constructional volcanic features (also Pliocene) ranging from silicic alkalic basalt to rhyolite. Stop N12, in the No Agua perlite district south of the San Antonio stratovolcano (3 m.y.), emphasizes the constructional forms and economic geology of the northwestern plateau as well as the outcrop geology of a Servilleta flow sequence. Discussions at Stop N13, overlooking the Rio Grande Gorge and US-64 bridge, deal both with the 600-ft (180-m) sequence of Servilleta basalts and interbedded sediments exposed in the gorge and with the structural evolution of the southeastern San Luis Basin adjacent to the Taos segment of the Sangre de Cristo range. The final stop (N14) on the Taos Plateau, southwest of Ranchos de Taos, is a walking tour of four roadcuts along NM-68 where the highway drops first into Hondo Canyon and then into the canyon of the Rio Grande at Pilar. Clastic units of the Servilleta Formation and the underlying Santa Fe Group are displaced along a major boundary fault zone that marks the southern edge of the San Luis Basin and the northwestern front of the Picuris range. The fault is also along the northeast extension of an important structural zone crossing the Española Basin segment of the rift.

Stop N15, near Pilar on NM-68, is opposite the mouth of the Taos Plateau segment of the Rio Grande Gorge. The stop is also at the head of the southeast-trending canyon reach that closely follows the fault contact between Miocene basin fill of the Santa Fe Group and Precambrian rocks of the Picuris uplift. Mesas flanking the canyon from Pilar to the point where the river enters the Española Basin at Velarde are capped with the youngest (upper Pliocene) basalt flow of the Servilleta Formation. Discussions at Stop N16 in the northeastern part of the Española Basin (NM-68 at Alcalde) supplement information on Santa Fe Group stratigraphy and Neogene structural deformation and volcanism presented in the guidebook sections covering the Española Basin and Jemez Mountain tours. The final leg of the northern-rift tour crosses the southeastern basin segment between Española and Santa Fe via US-285. Members of the main Santa Fe Group subdivision, the Tesuque Formation, are well exposed along the route.

ALAMOSA TO ANTONITO, COLORADO

by R. L. Burroughs, *Adams State College, Alamosa, Colorado*

Mileage

0.0 Junction of Colo-17 and US-160 at east edge of Alamosa. *Proceed west on Colo-17-US-160.* 0.3

0.3 Crossing Rio Grande. 0.2

0.5 Intersection; *turn right* on Main Street. *Continue west* on US-160. 0.2

0.7 Traffic light; downtown Alamosa. 0.4

1.1 Junction of US-285 and US-160 in southwestern Alamosa. *Turn left; proceed south on US-285Colo-17.* Adams State College is located two blocks west of this intersection on north side of US-160-US-285. 2.9

4.0 Colo-370 to right. *Continue south* on US-285. For a tour guide to the eastern San Juan Mountains via Colo-370, see road log in James (1971).

At 3:00 is Green Ridge, the northeast flank of the eroded Cat Creek stratovolcano (28 m.y.) on the east side of Platoro caldera (Lipman, 1975a). The ridge consists of rhyodacite and andesite lava flows capped by basalt of Hinsdale Formation. Cornwall Mountain, to the left of Green Ridge, is a structurally uplifted resurgent block of densely welded ash-flow tuff within Platoro caldera. Bennett Mountain, elevation 13,189 ft (4,023 m), to the right of Green Ridge consists of post-caldera andesite lavas and quartzlatite welded tuffs, also within the caldera. The western boundary of the San Luis Basin is a dip slope of eastward-tilted volcanic rocks of the San Juan Mountains. This dip slope is cut by numerous, north-trending, antithetic faults, dropped down to the west with small normal displacements. 7.2

11.2 **STOP N10, San Luis Hills and west-central San Luis Valley.** Rest area west of highway. Discussion of San Luis Valley area south of Alamosa (fig. N20). The San Luis Hills from 9:00 to 11:00 (Mesa de la Sauses and Flattop at 9:30, Piñon Hills at 10:00) form a structural divide that trends northeasterly across the central part of San Luis Basin between the northern (Alamosa Basin) and southern (Taos Plateau) parts of the basin. The San Luis Hills are also believed to be a hydrologic barrier between the northern and southern basin subdivisions (Burroughs and McFadden, 1976).

General features

Before development of the San Luis Basin, an Eocene erosion surface of low relief existed throughout southern Colorado and northern New Mexico (Epis and Chapin, 1975).

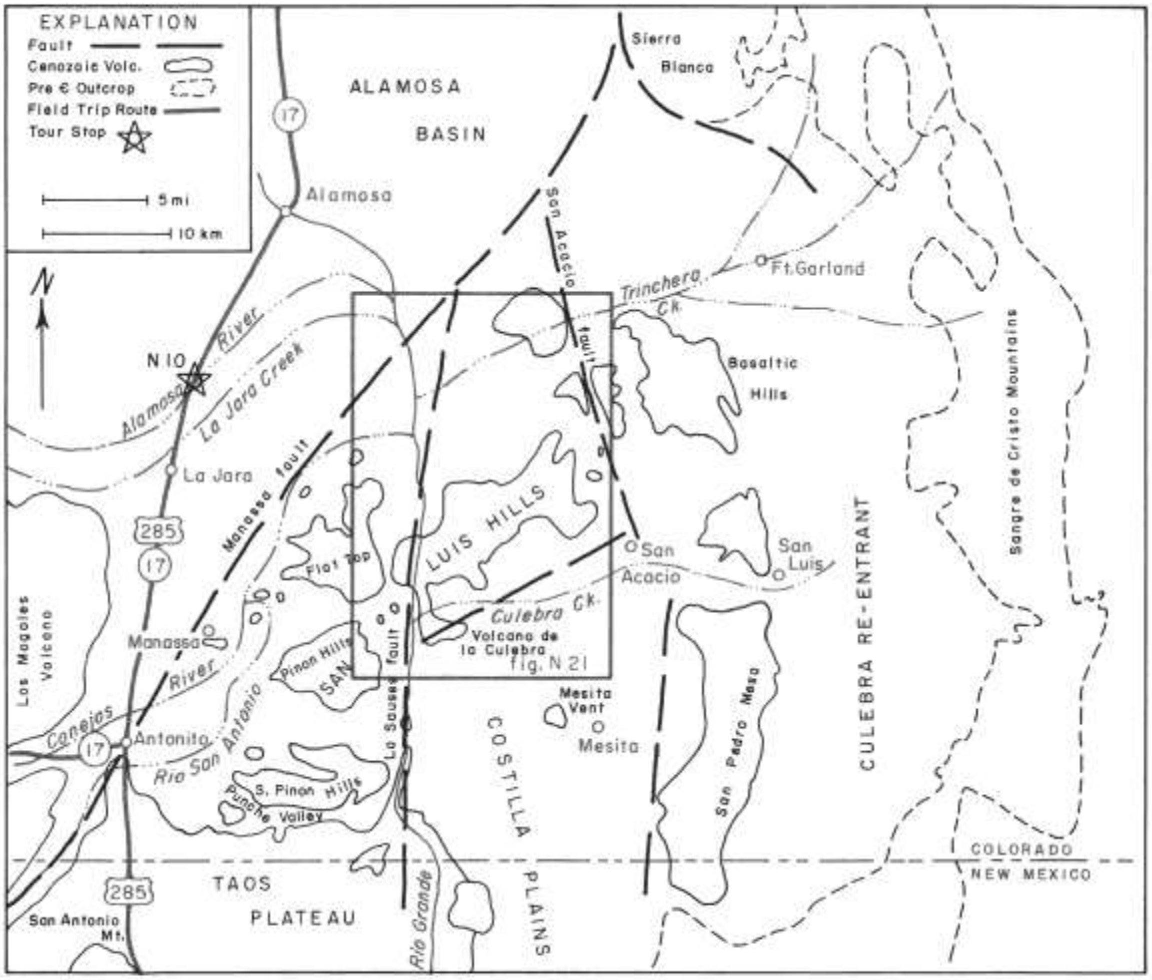


FIGURE N20—INDEX MAP SHOWING LOCATION OF SAN LUIS HILLS AND OTHER MAJOR GEOMORPHIC FEATURES OF THE CENTRAL SAN LUIS VALLEY, COLORADO; outline of fig. N21 is indicated.

This surface truncated rocks deformed during the Laramide orogeny. Beginning about 40 million years ago, an extensive volcanic field, subsequently fragmented by block faulting and related erosion, developed throughout this area (Steven and Epis, 1968). The San Luis Hills, a small erosional remnant of this fragmented—but once extensive—volcanic field, represent a local accumulation equivalent to that of the Conejos Formation (Oligocene) of the San Juan volcanic field. A K-Ar date of 27.6 m.y. (Oligocene) was obtained from a stock that intrudes the uppermost flows of the Conejos Formation in the San Luis Hills. The times of intrusions are believed to be closely related to the volcanic events. Three local members of the Conejos Formation have been recognized. The Conejos volcanics and their associated intrusions are rhyodacites of intermediate composition. The rock suite has a Peacock alkali-lime index of 55.8, falling on the boundary between alkali-calcic and calc-alkalic classes (Burroughs, 1971, 1972). The rock units are quite different texturally, mineralogically, and chemically; the units are composed of flows, flow breccias, crystal tuffs, tuff-breccias, and vitrophyres. After the San Luis Hills were eroded to a mature topography, the Servilleta basalts (3.6-4.5 m.y.) flooded the southern and eastern margins of the hills, which became like islands in a sea of lava (Burroughs, 1974).

Structural features

The San Luis Hills, composed of a series of upthrown blocks, extended over an area of 413 mil (1,070 km^2). They are shown as two north-trending gravity highs arranged en echelon north-northeasterly across the central part of the San Luis Basin (Kleinkopf and others, 1970). To the north, the San Luis Hills are flanked by a pronounced gravity low (Alamosa Basin) in the area discussed at Stop N9. In a north-northeast direction the San Luis Hills appear to be connected to the Mt. Blanca massif by a narrow ridge. This connection is suggested by the presence of a gravity high beneath the northwestern margin of the Costilla Plains southeast of the hills (fig. N20). The west side of this ridge is probably bounded by a northeasterly extension of the Manassa fault, upthrown to the east, which marks the western boundary of the San Luis Hills. This fault and the Sangre de Cristo fault mark the eastern and southern boundaries of the Alamosa Basin. A gravity low is present along the eastern side of the San Luis Hills. A fault (or faults) upthrown to the west marks the boundary between this gravity low and the San Luis Hills. Thus the San Luis Hills are an intrarift horst within the San Luis Basin.

The La Sauses fault divides the San Luis Hills into eastern and western components; although not controlled by this fault zone, the Rio Grande follows it through the hills and separates them physiographically. The western hills are upthrown along the Manassa fault; and the eastern hills, although topographically lower, are upthrown in respect to the western hills, forming a series of fault blocks tilted 10-15 degrees to the southeast. The western hills are essentially horizontal.

The San Luis Hills have at least seven major fracture sets, and all have controlled emplacement of dikes in one locality or another. Although a detailed study of the joint system has not been made, the dikes, which are more easily mapped, are reflective of the joint patterns. The dikes are concentrated in the area of the La Sauses gorge and the adjacent eastern San Luis Hills. Relative ages of the dikes are not known, because no crosscutting relationships have been observed with different types of dikes. The eastern hills have a more extensive fracture system than do those to the west. The fracture system is summarized in fig. N21.

The Pliocene olivine-tholeiites of the Servilleta Formation are present along the southern and eastern margins of the San Luis Hills. In several areas tributary streams are hooked near their mouth so that their flow is north into the main drainage system. These anomalous drainage patterns are thought to be controlled by faults in the Servilleta. Two vents, the Mesita and Volcano de la Culebra, younger than the Servilleta, have

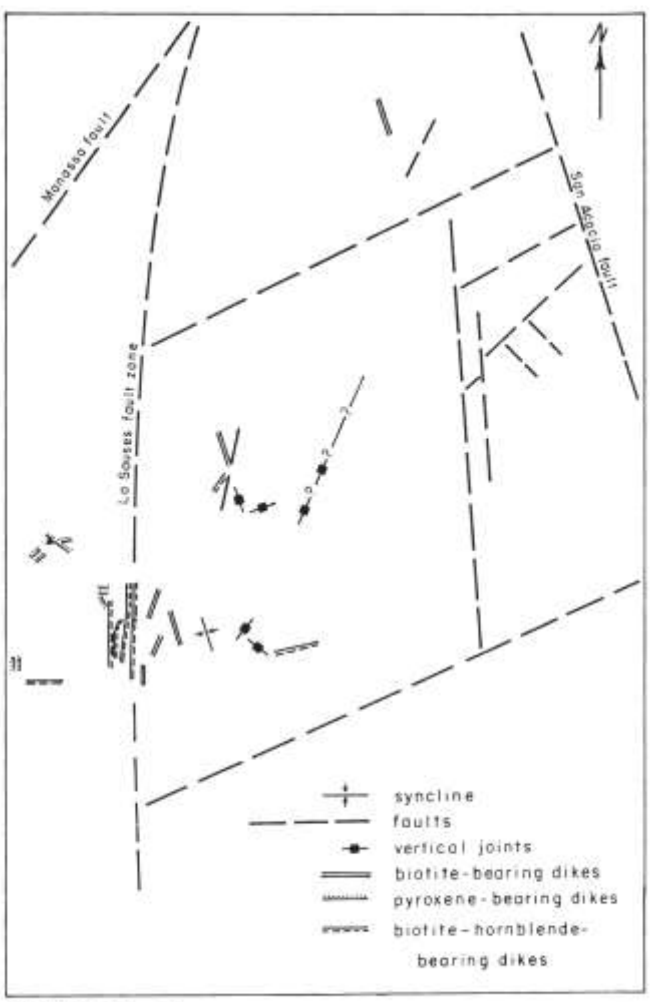


FIGURE N21—GENERALIZED LOCATION AND ORIENTATION MAP FOR THE FRACTURE SYSTEM OF THE SAN LUIS HILLS.

been noted by Burroughs (1971, 1974). Recent drilling on opposite sides of a north-south striking fault, which cuts the Mesita vent, has indicated an offset of 50-100 ft (15-30 m) in the Servilleta. Along the Colorado-New Mexico State line, the Servilleta is offset by about 2,000 ft (600 m) along another fault in the area of Costilla, New Mexico. This fault dies out northward in the vicinity of San Luis, Colorado. **1.8**

13.0 Alamosa Creek. See comments on stream drainage patterns at mile 27.4. **1.8**

14.8 Junction with Colo-15 at north edge of La Jara. *Continue south* on US-285. **1.0**

15.8 Junction (left) with road to Pike Stockade State Historical Monument. The stockade was established by Zebulon Pike early in 1807 in Spanish Territory on the north bank of the Conejos River near its confluence with the Rio Grande. He was captured there by Spanish military authorities from Santa Fe and taken to Mexico. 3.0

18.8 Bountiful, Colorado. At 9:00 jagged outcrops halfway up south slope of Mesa de la Sauses are formed on east-striking Manassa dike. Most dikes in San Luis Hills have a northerly trend. At the southwest edge of the mesa, upper flows lap up against a buried hill of crystal tuff exposed along the cliff edge. At 9:30 a quartz-monzonite-granodiorite stock is exposed at valley head along north slope of Piñon Hills. **3.7**

22.5 Junction with Colo-142 at Romeo. At 2:00 is Los Mogotes shield volcano of Hinsdale Formation basalt (see mile 30.1). The town of Manassa, 3 mi east, is the birthplace of Jack Dempsey, the "Manassa Mauler," former world heavyweight boxing champion. **0.1**

22.6 At 9:30 andesitic laharic breccia makes up the western end of a small hill with an "M" on its north slope. **1.9**

24.5 South Piñon Hills at 9:30; stock located along east side of irregular topography at north end of hills has been K-Ar dated at 27.0 ± 0.6 to 27.4 ± 0.6 m.y. **2.9**

27.4 Crossing Conejos River bridges for next 0.3 mi. The Conejos River has built a long alluvial fan extending eastward from the 5-m.y.-old Los Mogotes shield volcano to the San Luis Hills. The present river swings northward, opposite the south-flowing Rio Grande. The Alamosa River, after flowing due east from the San Juan Mountains, makes a sudden turn to the northeast about 10 mi (16.6 km) from the Rio Grande; and only after having flowed for some distance in that direction does it join the Rio Grande. La Jara Creek shows a similar pattern. Surface flow of the Alamosa River generally terminates about 3 mi west of the Rio Grande. The deflection of Alamosa River and La Jara Creek to the north is puzzling because there are no "San Luis Hills" to block their path to the Rio Grande, as there are for the Conejos River. However, Kleinkopf and others (1970) showed that the gravity high of the western San Luis Hills extends about 6 mi (10 km) north of the hills. The flow direction of Alamosa River and La Jara Creek has probably been influenced by the subsurface high.

Siebenthal (1910) pointed out that the fan of the Conejos River partly extended south of the San Luis Hills and into New Mexico. He suggested that the

Conejos River, or at least its distributaries, must have discharged in that direction at one time. Endlich (1877) suggested that the Conejos had to abandon its flow to the southeast because of confining volcanic rocks (Servilleta). The Rio San Antonio flows nearly parallel to the Conejos, but it makes a wide swing toward the San Luis Hills before joining the Conejos near Manassa. At one time Rio San Antonio continued to flow eastward to the Rio Grande by way of Punche Valley near the state line. The Conejos River may also have made its way to the Rio Grande by the same route (summary adapted from Burroughs and McFadden, 1976b, p. 548). 1.1

28.5 Conejos (oldest church in Colorado) 1 mi to west. **0.5**

29.0 Antonito, elevation 7,888 ft (2,406 m); *SLOW!* 25-mph speed limit strictly enforced. **0.8**

29.8 *Leave Antonito;* Cumbres and Toltec Scenic Railroad yard (narrow gauge) to left. The train travels during summer months from Antonito to Chama, New Mexico, via Cumbres Pass. See geologic rail log by James (1974). 0.3

30.1 Junction of US-285 and Colo-17; *continue west on Colo-17.* End of Alamosa-Antonito road log.

ANTONITO, COLORADO, TO RIO GRANDE GORGE, NEW MEXICO

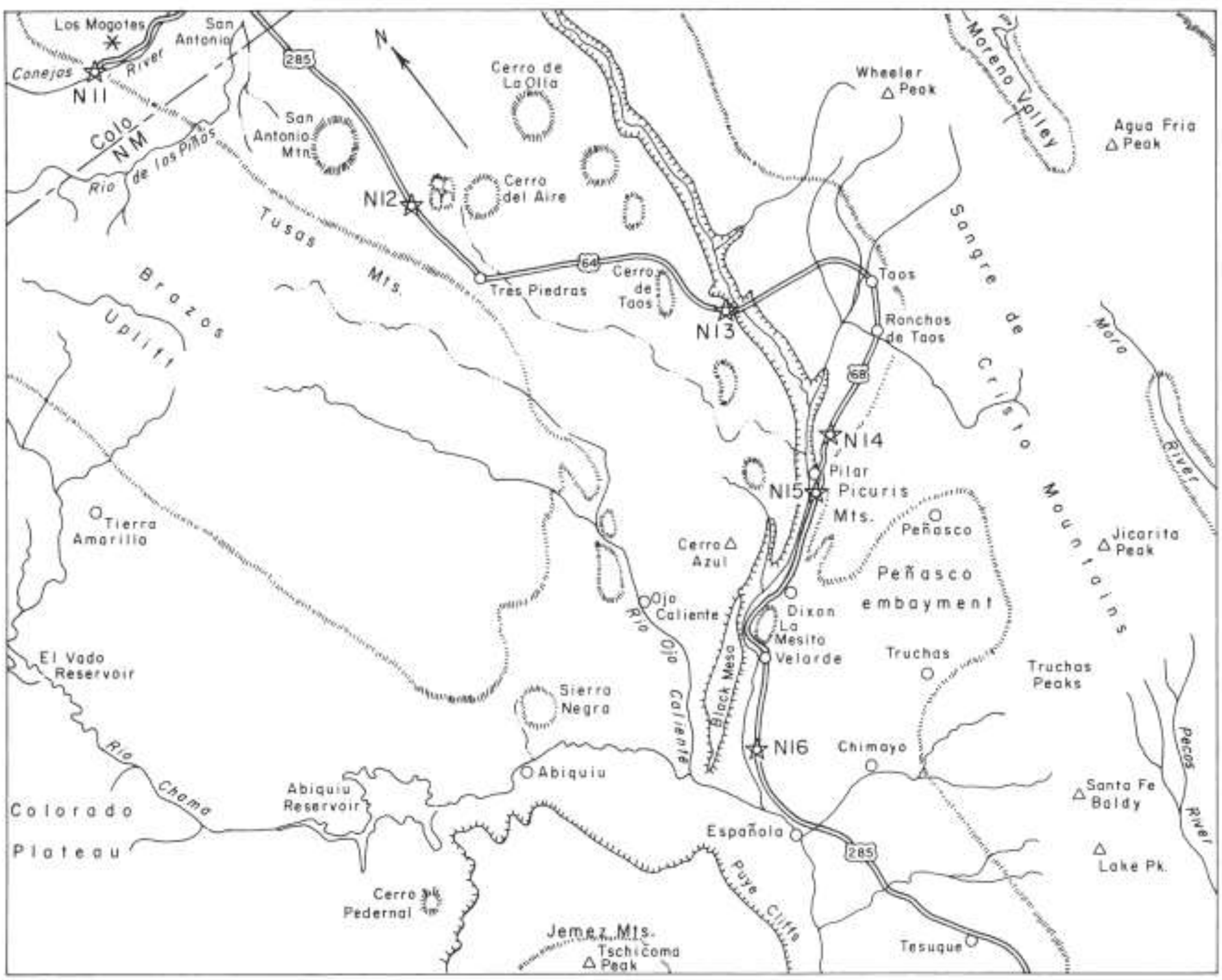
by Peter W. Lipman, *U.S. Geological Survey, Denver, Colorado*

30.1 Junction of US-285-Colo-17. *Continue west* on Colo-17 for side trip to Aspen Glade campground (lunch stop). The area for this segment of the field trip is covered by a recently published geologic map (Lipman, 1975b). Fig. N22 is a Skylab 2 photo and index map of the region traversed from here to Santa Fe. After junction, at 2:00 there is a good view of Los Mogotes (the mounds), a small 5-m.y.-old shield volcano of silicic alkalic basalt (50-54 percent SiO_2). The three points on the volcano are eroded remnants of the cone and a central diabasic intrusion. The Conejos River has cut a canyon through the south flank of this volcano. **4.0**

34.1 *Enter* small Hispanic village of Mogote. **0.7**

34.8 Crossing Conejos River. **2.8**

37.6 On cliffs at right for the next 0.5 mi are exposed as many as 11 silicic alkalic basalt flows from Los Mogotes volcano (Hinsdale Formation). These flows, which contain sparse phenocrysts of olivine, tend to become more mafic upward and may reflect draining



of a differentiated magma chamber. Across the river to the south are good exposures of the Los Pinos Formation, a complex volcaniclastic sequence interbedded with and underlying the basalt. Two thin light-colored layers are local nonwelded ash-flow tuffs; most of the Los Pinos Formation is composed of alluvial-fan deposits derived from Oligocene volcanics of the San Juan field to the west. These rocks were deposited in the evolving Rio Grande rift valley between 25 and 5 m.y. ago, as indicated by K-Ar dates on interlayered basalt flows in southern Colorado (Lipman and Mehnert, 1975). 3.2

40.8 Across road from turnout are roadcut exposures of volcaniclastic rocks of the Los Pinos Formation, overlain by basalts from the Los Mogotes volcano. All these rocks are part of a large coherent block slump. 2.2

43.0 Campground. To north, the Los Pinos Formation is poorly exposed in slopes below the basalts of the Los Mogotes volcano; the ledges ahead are densely welded central parts of several major ash-flow sheets of the San Juan volcanic field, including the Treasure Mountain and Masonic Park Tuffs. **0.8**

43.8 Above road sign for Rio Grande National Forest are exposed thin distal facies of most of the major ash-flow units of the quartz latitic Treasure Mountain Tuff, erupted between about 30 and 29 m.y. ago from the Platoro caldera complex, 25 mi (40 km) to the

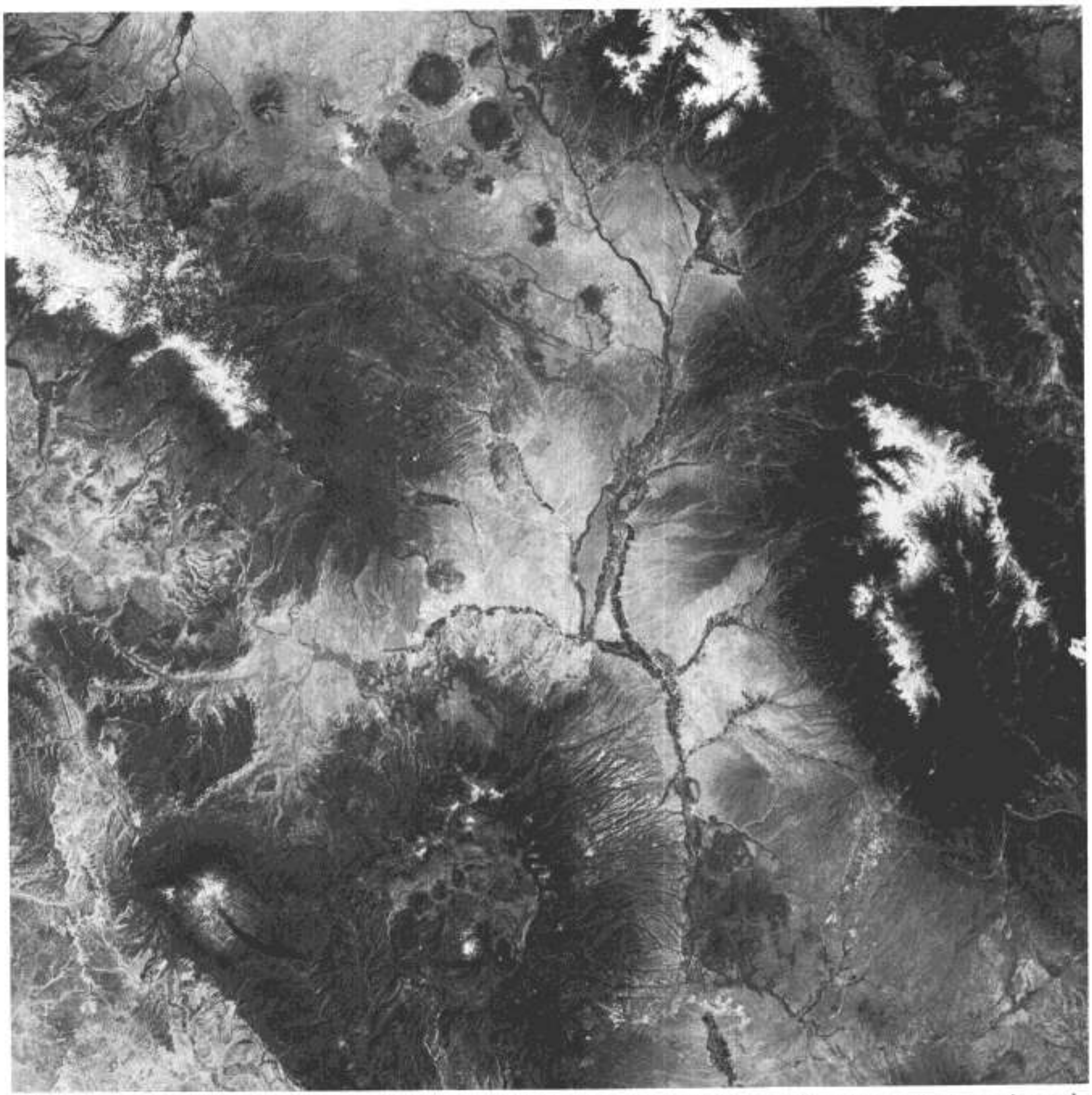


FIGURE N22—SKYLAB 2 PHOTO **(a, above)** AND INDEX MAP **(b, at left)** OF TAOS PLATEAU AND NORTHERN ESPAÑOLA VALLEY REGION, north-central New Mexico; (photo SL2-10-020 courtesy of Technology Application Center, University of New Mexico; scale approximately 1:500,000).

northwest (Lipman, 1975b). In ascending order, the exposed ash-flow sheets of the Treasure Mountain Tuff include 1) several discontinuous, local, generally phenocryst-poor ash-flow sheets of the lower member; 2) thin, weakly welded marginal facies of the La Jara Canyon Member-a large, regional, phenocryst-rich, quartz latitic ash-flow sheet erupted during the main caldera collapse at Platoro; 3) poorly exposed, weakly welded, ash-flow and ash-fall tuffs of the middle member; 4) densely welded, thin ash-flow tuff of the Ojito Creek Member, which is unique among the main Treasure Mountain ash-flow deposits in being characterized by normal magnetic polarity; and 5) the Ra Jadero member, the uppermost widespread unit of the Treasure Mountain Tuff. The capping welded ash-flow unit in the section is the 28.2-m.y.-old Masonic Park Tuff, a phenocryst-rich (plagioclase-biotiteaugite) quartz-latitic tuff erupted from the Mount Hope caldera in the central San Juan Mountains, 44 mi (70 km) to the northwest (Steven and Lipman, 1976). 0.6

44.4 Landslide debris for next 0.7 mi, consisting mostly of ash-flow tuff. 0.9

45.3 Poor exposures of pyroxene-andesite flow breccia of the Conejos Formation, underlying the ash-flow sequence of the Treasure Mountain Tuff. The Conejos Formation is a complex assemblage of intermediate-composition lavas, breccias, and volcaniclastic sedimentary rocks erupted from central volcanoes in the southeastern San Juan Mountains between about 35 and 30 m.y. ago (Lipman and others, 1970). **0.7**

46.0 **STOP N11, Aspen Glade campground.** Lunch. Most of the volcanic units described above can be examined in the large blocks used to mark the edges of the campground roads. Along river at west end of the campground, 1.45-b.y.-old Precambrian granitic rocks are exposed below the Oligocene volcanics. After lunch *retrace route to US-285-Colo-17 junction at south edge of Antonito.* **15.9**

61.9 *Turn right (south) onto US-285,* heading south from Antonito. **0.1**

62.0 Narrow Gauge Railway Cafe and Inn on left (east). **0.4**

62.4 Crossing Rio San Antonio, a shallow, generally dry, stream valley cut on basalts of the Servilleta Formation (Butler, 1971; Montgomery, 1953). The Servilleta Formation (2.0-4.5 m.y.) is a widespread sequence of distinctive diktytaxitic vuggy flows of olivine tholeiite that underlies most of the southern San Luis Valley, forms the Taos Plateau, and surrounds most of the central volcanoes of the Taos Plateau volcanic field. These basalts may be examined at the next two stops. **2.8**

65.2 Junction; road to village of San Antonio to right. Hills beyond are eastern edge of the Tusas (or southern San Juan) Mountains, underlain by east-dipping silicic alkalic basalt flows of late Cenozoic age interlayered with volcaniclastic sedimentary rocks of the Los Pinos Formation. **2.0**

67.2 Colorado-New Mexico State line. Fig. N23 comprises gravity and elevation profiles along the 37th parallel, crossed here by the tour route. Cross-state profiles of New Mexico, taken from Cordell (1978), are included

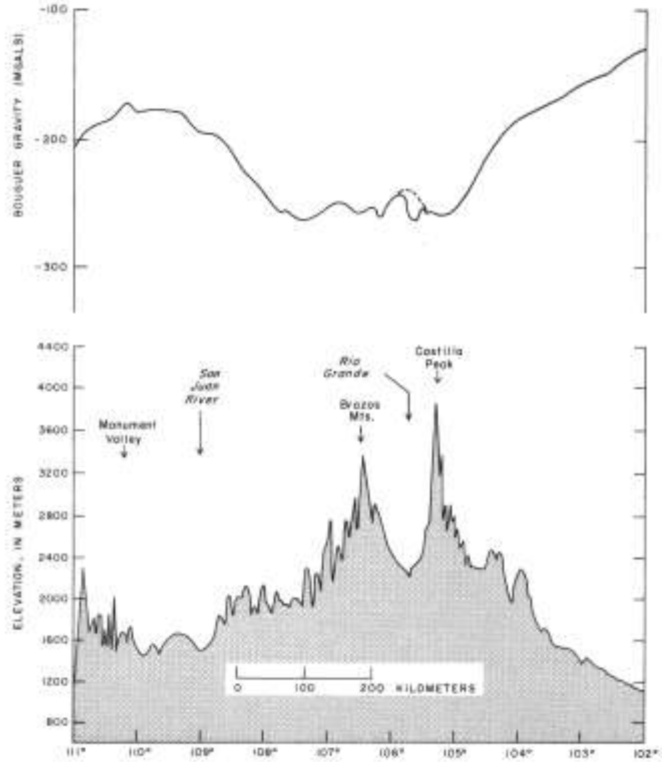


FIGURE N23—GRAVITY AND ELEVATION PROFILES ALONG 37° N. LATITUDE, NEW MEXICO-COLORADO STATE LINE (source: Cordell, 1978; with permission from the Geological Society of America).

in the guidebook near points where the tour route crosses each degree of latitude. **1.0**

68.2 *Enter San Antonio Mountain Wildlife Area;* common animals include deer, antelope, and coyote. San Antonio Mountain is a large stratovolcano consisting of homogeneous, phenocryst-poor rhyodacite (60-61 percent SiO_2). A single whole-rock K-Ar date indicates an age of 3.0 m.y. Another large isolated volcano of similar rhyodacite-Ute Mountain-can be seen 16 mi (25 km) to the east across the San Luis Valley. **4.8**

73.0 Road on right to cinder cone and quarry. This cone is source of a distinctive xenocrystic (resorbed quartz and plagioclase) basaltic andesite that forms an obscurely defined flow extending across US-285 for about 3 mi (5 km) to the northeast. This is one of the youngest volcanic rocks exposed along the road during this segment of the field trip, having yielded a whole-rock K-Ar age of 2.2 m.y. Similar rock on an eroded cinder cone (Pinabetoso Peaks) about 2.5 mi (4 km) to the southeast has been dated at 1.8 m.y. **5.0**

78.0 Road to San Antonio Mountain on the right. **3.0** 81.0 Crest of rise. Perlite mines in rhyolite of No Agua are visible at 11:00; Sangre de Cristo Mountains on east side of rift valley at 10:00. **1.2**

82.2 Picnic area on right (west). Fig. N24 is a photo of San Antonio Mountain taken from near this point. **0.9**

83.1 STOP N12, No Agua. Roadcut through basalt flows of Servilleta Formation and interlayered sedimentary rocks. *Participants will get off bus at top of hill (north end of outcrop) and will be picked up at south end. Watch out for high-speed traffic.*

FIGURE N24—LOOKING NORTHWEST AT SAN ANTONIO MOUNTAIN, NORTH FROM STOP N12 NEAR NO AGUA (photo by Wayne Lambert, October 14, 1977, sunset).

From the top of the outcrop, there is a fine panorama of many key features in this sector of the Rio Grande rift (fig. N25). Most of the hills scattered across the southern San Luis Valley are primary-construction volcanic features, ranging in composition from silicic alkalic basalt to rhyolite. The alluviated flats in between are mostly underlain by the tholeiitic basalts of the Servilleta Formation. In the distance to the east is the high mountain crest of the Sangre de Cristo range, which forms the east boundary of the rift. In this sector the gross structure of the rift is an asymmetrical graben, with the main bounding fault along the west foot of the Sangre de Cristo range. No similar major bounding fault exists on the west side of the rift valley in this area, which is a structurally simple dip slope. Late Cenozoic basaltic lavas and interlayered volcaniclastic sedimentary rocks can be seen to dip 5-10° eastward off the Tusas Mountains into the rift structure.

To the southeast are perlite mines in the rhyolite of No Agua, a semicircular cluster of four coalescing domes of phenocryst-poor silicic alkalic rhyolite erupted about 3.8 m.y. ago, as indicated by K-Ar and fission-track dating. The interiors of the domes consist of devitrified flow-laminated rhyolite, while the glassy margins contain abundant obsidian "apache tears" (nonhydrated glass with 0.2-0.3 percent water). Perlite on the upper parts of the domes, mined by the Johns Manville Company, is expanded and used for

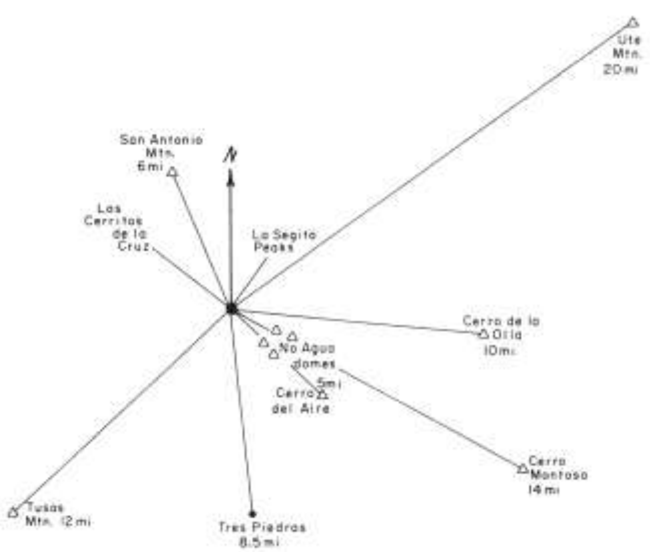


FIGURE N25—PANORAMIC INDEX OF FEATURES SEEN FROM STOP N12, NEAR NO AGUA, NEW MEXICO.

manufacturing wallboard and insulation and for other construction purposes.

The large isolated volcanic cones to the northeast and to the north-northwest are Ute Mountain and San Antonio Mountain, both compositionally similar rhyodacites (SiO_2 content 60-61 percent). The lower hills to the north-northeast between the two rhyodacite cones are La Segita (Buffalo) Peaks, a composite volcanic-vent structure in which tholeiitic Servilleta basalt was erupted from within an earlier cone complex of xenocrystic basaltic andesite. In this same general direction two cinder cones of younger eruptions of xenocrystic basaltic andesite are visible; these cones postdate all local basalt flows of the Servilleta. One of these young cones is obscurely visible (depending on sun angle) on the south flank of the La Segita Peaks; the other is more readily discernible on the north flank of the rhyolite of No Agua, due east of the viewpoint.

Looking northwest, three additional basaltic cinder cones occur along a northwest-trending zone just southwest of San Antonio Mountain. These are Los Cerritos de la Cruz (in Spanish, "little hills of the cross"); the middle cone is xenocrystic basaltic andesite, and the other two are silicic alkalic basalt. The small light-colored hills in the distance, due south at Tres Piedras, are windows of Precambrian granite, probably 1.45 b.y. old.

Turning to the roadcut geology at hand, two basalt flows of the Servilleta Formation can be seen interlayered with valley-fill sediments. These sediments were derived partly from rhyolite of No Agua, and fragments of black obsidian are conspicuous; thus, the local Servilleta flows are younger than the rhyolite (K-Ar age: 3.8 m.y.). The upper Servilleta unit, though only a few meters thick, consists of two separate pahoehoe flows; the lower unit is a single thicker flow. 0.7

83.8 Road to Johns Manville perlite mines on left (east). 0.9

84.7 Road to Grefco perlite mill on left. 0.3

85.0 Basalt flow in roadcut to right (west) is silicic alkalic basalt from the most southerly of the three vents in Los Cerritos de la Cruz. This flow is also younger than the rhyolite of No Agua, as demonstrated by rhyolite fragments in the sediments below the basalt flow. From here south almost to Tres Piedras, the road is on poorly exposed volcaniclastic sedimentary rocks of the Los Pinos Formation. Scattered basalt outcrops of the Servilleta Formation can be seen in the arroyo to the east. The large, low volcanic shield farther east is Cerro del Aire, composed of uniform olivine andesite (57 percent SiO_2) having a K-Ar age of 3.4 m.y. 6.2

91.2 New Mexico Port of Entry at Tres Piedras; many exposures of tan Precambrian granite that underlie much of the Tertiary volcanic sequence in the Tusas Mountains to the west. 0.7

91.9 Junction of US-285-US-64 in Tres Piedras; *turn left on US-64.* **0.8**

92.7 Crossing narrow bridge over Arroyo Aguaje de la Petaca. Good roadcut exposures of basalt of the Servilleta Formation. Roadcuts west of the bridge have good examples of segregations, veins, and pipe vesicles. The uppermost exposures show an obscure but interesting irregular contact between two pahoehoe flows; the top of the lower flow is characterized by tumuli (pressure ridges), with local relief of 1-2 m. 3.0

95.7 Dip; Taos area at about 12:30, at base of Sangre de Cristo range. North of road the olivine andesite shield volcano of Cerro del Aire is conspicuous, with a small spatter cone on its left (east) side. Obscurely silhouetted against the base of Cerro del Aire are low timbered slopes that define two very low angle basaltic shield volcanoes: the largest exposed sources of Servilleta basalts. **1.0**

96.7 Low roadcuts in basalt of the Servilleta Formation. Low mesa to northeast consists of gently dipping olivine andesite similar to that on Cerro del Aire; but the primary volcano morphology is more obscure, and these andesites may be older. 5.6

102.3 Curve to right (south) at Arroyo Hondo road junction. Irregularly shaped hills to north are eroded, structurally complex, early-rift volcanics, ranging in composition from andesite to rhyolite (K-Ar ages of 22-25 m.y.). These rocks are preserved in a horst that is structurally continuous with the San Luis Hills in southern Colorado (Stop N10); the structurally deepest part of the rift valley is confined to a relatively narrow zone (10-15 km wide) between this horst and the Sangre de Cristo range to the east. The symmetrical hill farther to the north is Cerro Montoso, a shield volcano of olivine andesite similar to Cerro del Aire. The spoils dump of the Questa molybdenum mine owned by the Molybdenum Corporation of America (Gustafson and others, 1966; Clark, 1968) is visible to the east as a conspicuous scar in a saddle, high in the Sangre de Cristo range above the mouth of the Red River. Molybdenite mineralization is associated with granitic intrusions emplaced in a sequence of mid-Tertiary andesitic to rhyolitic volcanics (Pillmore and others, 1973). K-Ar ages of intrusive rock are in the 22.3 to 23.5 m.y. range (Laughlin and others, 1969). 0.3

102.6 Roadcuts in basalt of the Servilleta Formation. 3.2

105.8 Cerros de Taos on right (west). These hills are composed of two overlapping shield volcanoes of olivine andesite similar to that of Cerro del Aire and Cerro Montoso. 4.5

110.3 Highway curves east (left); roadcuts in basalt of the Servilleta Formation. 0.6

110.9 Rest area entrance; *turn right (south).* 0.3

111.2 STOP N13, Rio Grande Gorge bridge. Parking area; view from west rim of Rio Grande Gorge (figs. N26 and N27). The gorge here is about 1,200 ft (366 m) wide, and the river is entrenched about 600 ft (185 m) below the Taos Plateau. The gorge is cut in tholeiitic flows of the Servilleta Formation and interlayered sediments. K-Ar ages of flows in this area range from 4.5 to 3.6 m.y. (Ozima and others, 1967). Two main sedimentary units, comprising fluvial sand and gravel, are present in the gorge section, but they are largely covered by basaltic talus. Typical basalt of the Servilleta Formation can be examined at the bridge abutment. The basalt is relatively coarse grained, is diktytaxitic (vuggy), and contains nearly equigranular plagioclase, olivine, augite, and a few percent interstitial glass. This basalt was erupted as highly fluid

FIGURE N26—SOUTHEASTERN TAOS PLATEAU, RIO GRANDE GORGE, AND SANGRE DE CRISTO RANGE. Oblique air view to the southeast from over Tres Piedras area. The canyon of Rio Lucero lies between snow-capped Wheeler Peak at upper left edge and Pueblo Peak to the south. Moreno valley is the light-colored patch beyond these peaks. Taos is in right center at base of the range. The canyon of lower Arroyo Hondo enters the Rio Grande Gorge below left center. Rio Grande Gorge bridge (Stop N13) is at lower right.

FIGURE N27—RIO GRANDE GORGE FROM STOP N13; a (at top) view of bridge is northeast across southeastern San Luis Basin toward Sangre de Cristo Mountains. Mouth of Red River Canyon at Questa on far upper left. High peaks of Vallecito Mountain and Wheeler Peak area on upper right seen above arch of bridge. Rio Hondo Canyon to left of peaks and Rio Lucero Canyon to right (photo by H. L. James); b (at left) view of 600-ft gorge is to the south toward the Picuris Mountains and area of Stop N14. The gorge is cut in basalt of the Servilleta Formation (Pliocene). Interflow sedimentary units underlie basal parts of slopes mantled with basalt talus (photo by G. R. Osburn).

pahoehoe flows that traveled many kilometers yet were only a few meters thick.

(COMPILER'S NOTE: This concludes the log from Antonito to Rio Grande Gorge by P. W. Lipman. The following comments are by W. R. Muehlberger.)

Taos is in a topographic reentrant at the base of the Sangre de Cristo Mountains (figs. N22, N26, and N28). The topographic low results from the absence of constructional volcanic forms—such as the late Cenozoic volcanic area of Cerro Negro, north of Arroyo Hondo—combined with continuing downdropping of the Taos Plateau against the foot of the Sangre de Cristo Mountains.

At Taos the Sangre de Cristo Mountains can be divided into two segments, each with its characteristic skyline. To the north, the Taos range has high, irregular peaks formed of Precambrian igneous and metamorphic rocks. To the south, the lower, smooth, tilted surfaces are formed of Pennsylvanian sedimentary rocks.

Precambrian granite is exposed on the north-trending ridges separating the Sangre de Cristo Mountains on the east from the Picuris Mountains on the west. The west-trending ridges of the Picuris Mountains are held up mainly by quartzite units of the Precambrian metasedimentary rocks of the range. The north-trending Picuris-Pecos fault (Montgomery, 1953), east of Picuris Peak, separates east-west Precambrian structures of the Picuris block from north-south-trending Laramide structures of the area to the east transitional to the Sangre de Cristo Mountains. Right-lateral slip (probably Precambrian) caused major horizontal displacement of beds (Miller and others, 1963). Lambert (1966) pointed out trends of Quaternary faults on the southeastern San Juan Basin (Taos Plateau) that are on strike with the Picuris-Pecos fault.

The Taos reentrant shows many drainage anomalies that are the result of warping and faulting younger than the Servilleta basalts (3.6 to 4.5 m.y., Ozima and others, 1967) of the Rio Grande Gorge. Lambert (1966) first pointed out the asymmetry of the valleys of the reentrant. He also mapped a group of small faults, downthrown to the west, north of Rio

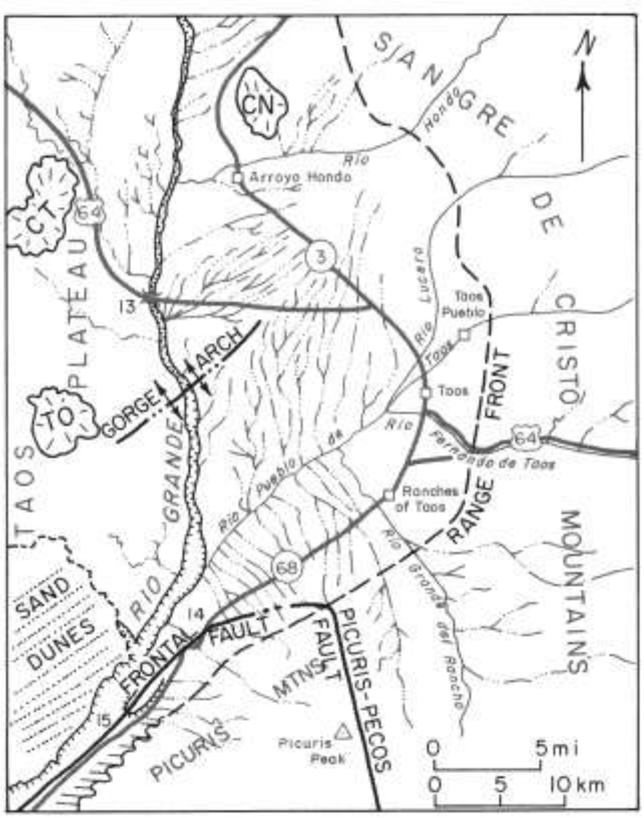


FIGURE N28—MAP OF TAOS AND VICINITY, the area of Stops N13-N15. Drainage pattern shows divergence of drainage away from Rio Grande Gorge arch. Asymmetry of stream valleys shows homoclinal shifting away from the arch. South of Rio Pueblo de Taos all side streams show homoclinal shifting to the east. Trellis patterns of streams north of US-64 bridge over the Rio Grande (Stop N13) are caused by faults downthrown to the east. Similar pattern on streams east of the Gorge arch and north of Rio Pueblo de Taos are caused by faults downthrown to the west. The parallelism of the Gorge arch, of the Rio Pueblo de Taos, and of the Picuris frontal fault (see fig. N31 for map of Stop N14 geology) and its continuation down the Rio Grande (Montgomery, 1953) to the Velarde graben of Manley (1978a, b) suggests a common origin for these features. Symbols: CT—Cerros de los Taoses; CN—Cerro Negro; TO—Tres Orejas; AH—Arroyo Hondo; T—Taos; P—Pueblo de Taos; R—Ranchos de Taos. Heavy dashed line marks boundary between mountain and plateau.

Pueblo de Taos and US-64 that are in line with the northward extension of the major Picuris-Pecos fault.

The consistent asymmetrics of the stream valleys, a broad anticline (Gorge arch) that developed in the Servilleta basalts across the gorge east of Tres Orejas, reverse faults in the frontal fault zone of the Picuris Mountains (see Stop N14), and scarps cutting late Quaternary surfaces along the base of the Sangre de Cristo Mountains all indicate continuing deformation of the reentrant. In effect, Taos is subsiding relative to the rest of the reentrant. As a result, all drainage from the high mountains is deflected eastward toward Taos. The Rio Taos lies along a structural low that aligns with the northeastern extension of the frontal fault zone of the Picuris Mountains in the Rio Grande Canyon. Parallel to the Rio Pueblo de Taos is the anticlinal Gorge arch that causes the stream-valley asymmetry to change sides. The Taos Municipal Airport is on the topographic divide marking this zone of change.

Return to US-64. 0.2

RIO GRANDE GORGE TO RIO EMBUDO, NEW MEXICO

by W. R. Muehlberger
University of Texas at Austin, Austin, Texas
and
J. W. Hawley
New Mexico Bureau of Mines and Mineral Resources, Socorro, New Mexico

111.4 *Rejoin US-64; continue east* across Rio Grande Gorge bridge. 0.4

111.8 East bridge abutment. "Rio Grande Gorge bridge" historic marker ahead on left. 0.4

112.2 Upper sandy-gravel facies of Servilleta Formation (Lambert, 1966) in roadcut. Steep west-facing scarp in asymmetrical valley ahead. From here to valley of Arroyo Seco (mile 118.7), the roadcuts are in upper Servilleta sandy gravel capped with brown sandy alluvium or deposits of arroyo-terrace gravel. Soils with prominent horizons of clay and carbonate accumulation are commonly developed in the sandy alluvium that caps the piedmont slopes (Clark and others, 1966, miles 3.8 to 7.5). 0.5

COMPILER'S NOTE-Servilleta terminology used from here to Taos is from Lambert (1966; Lambert and others, 1966). Sedimentary units interbedded with and overlapping basalts of the Servilleta Formation in the Taos area have not been studied in detail, and stratigraphic terminology for such units is in a state of flux.

112.7 Roadcut in yellowish Servilleta sandy gravel facies overlain by sandy alluvium with well-developed soil profile. Steep east-facing scarp in asymmetrical valley ahead. 1.5

114.2 East-facing scarp in broad asymmetrical valley. 1.4

115.6 Side road to Taos Municipal Airport. Airport is on west flank of broad divide where asymmetry of stream valleys changes sides.

At 2:30 is Picuris Peak, elevation 10,801 ft (about 3,325 m), bald side toward us, which is held up by Precambrian quartzite. Right-lateral-slip PicurisPecos fault (Montgomery, 1953; Miller and others, 1963) lies along the north-trending valley to the left (east) of Picuris Peak. Jicarita Peak, elevation 12,750 ft (3,886 m), at 2:00 is on distant skyline (usually has snow patches all year). Jicarita Peak is underlain by gently dipping Pennsylvanian rocks of the southern continuation of the Sangre de Cristo Mountains.

Road ahead points to valley of Rio Fernando de Taos through which US-64 passes; the valley marks the prominent division of the Sangre de Cristo Mountains described at Stop N13. 0.5

116.1 Divide where asymmetry of valleys changes sides. 0.4

116.5 Steep west-facing scarp in asymmetrical valley. 0.2

116.7 Roadcut in alluvium of upper Servilleta Formation. Note strong soil development. 0.2

116.9 Asymmetrical valley. 0.8

117.7 Large asymmetrical valley. Long roadcut in Servilleta sandy-gravel facies overlain by brown sandy alluvium (Clark and others, 1966). 1.0

118.7 Crossing valley of Arroyo Seco. 0.5

119.2 Roadcut in upper Servilleta sandy-gravel facies. The sandy-gravel facies here consist of pebbles and cobbles of Precambrian igneous and metamorphic rocks and Tertiary volcanic rocks derived from the Taos Range. (Clark and others, 1966).

CAUTION! Junction ahead. 0.2

119.4 Junction; *turn right. Continue southeast* on US-64. 0.3

119.7 Dropping onto upper end of broad valley of Rio Lucero. Wet meadows reflect convergence of drainage sources into this valley. To east along base of mountains are scarps that cut upper Quaternary units. 2.7

122.4 *Enter Taos,* elevation 6,950 ft (2,120 m). The European community, southwest of Taos Pueblo, was not settled until 1617 when Fray Pedro de Miranda built a mission as an outpost of Spanish life. The site was abandoned during the 1680-1692 Pueblo Rebellion and was then resettled. French traders came to the Taos fairs in the 18th century, and Anglo-American trappers and traders appeared here after 1820. About 1890 Taos became known to artists, who were followed by writers (including D. H. Lawrence); and many made Taos their permanent home (Pearce, 1965, p. 162). **0.6**

123.0 Junction with Taos Pueblo road.

The pueblo, located 3 mi to the northeast, has a population of 1,516 (1972) and a reservation area of 95,333 acres. According to the U.S. Department of Commerce (1974):

> The Spanish under Hernando de Alvarado discovered Taos Pueblo in 1540 much as it is today, with two large communal houses facing each other across Taos Creek. Colonists from Don Juan De Onate's community soon settled nearby. A series of Indian revolts against the settlers culminated in the successful Pueblo Revolt of 1680 spearheaded from Taos and led by Pope, a San Juan Indian. The Spanish were driven from New Mexico, not to return for 13 years. The Spanish returned in 1693, and, in 1696, with the order by de Vargas that all pueblo governors be shot, effective resistance ceased. After the conquest of New Mexico by the United States in 1847, Taos again revolted against the occupation troops and murdered the American governor, Charles Bent, among others. The revolt was crushed and the leaders were hanged.
>
> The Indians of Taos have an ancient and rich cultural past, much of which continues to survive. They live in large communal houses, the upper stories of which are reached by ladders. Round outdoor baking ovens and strings of chili drying in the sun are typical. The underground kivas serve as meeting places for the men, with women admitted only on certain occasions. The Deer, Turtle, and Sun-Down Dances are unique and noted for their beauty and precision. The latter, given on September 30 yearly, is the most important ceremony and expresses thanksgiving for the harvest. Most of the Taos people are farmers, many are artists, and others find employment in the nearby town of Taos. The Taos are the least typical of the Pueblo Indians, for they share many characteristics with the Plains Indians, particularly the Kiowa with whom they have a linguistic relationship.

0.5

123.5 Traffic light. *Continue straight ahead.* Taos plaza on right. **0.2**

123.7 Crossing valley of Rio Fernando de Taos for next 0.7 mi. **1.9**

125.6 Junction ahead. US-64 turns left to ascend valley of Rio Fernando de Taos. *Proceed straight ahead on NM-68.* At 9:00 are late Quaternary piedmont fault scarps cutting fans to right (south) of green water tank. At 11:00 up the valley of Rio Grande del Rancho is Jicarita Peak on the skyline. This valley was the main route of travel between Taos and Santa Fe prior to the construction of the highway down the Rio Grande Canyon ahead.

To the left of the valley are the gentle dip slopes of Pennsylvanian rocks of the southern Sangre de Cristo Mountains. To the right of the valley is a ridge held up by Precambrian granite (pink) with steeply dipping Mississippian-Pennsylvanian rock along the left border (Laramide upthrust). The broad valley is underlain by Tertiary Picuris tuff; its eastern wall is Precambrian granite against Picuris-Pecos fault. Picuris Peak on skyline beyond. **1.5**

127.1 Junction with NM-3 on left. *Continue straight ahead on NM-68. Enter Ranchos de Taos.* **0.3**

127.4 Church of Ranchos de Taos ahead on left in plaza, described by the state historic marker entry: "This church, the most beautiful example of Spanish mission architecture in the Southwest, was built in 1772, about 150 years after the first great church building era in New Mexico. It is contemporary with the missions in California." 0.2

127.6 Crossing valley of Rio Grande del Rancho. **0.3**

127.9 Llano Quemado. Ascend to fan surface of postServilleta terrace gravels. **1.0**

128.9 Crossing piedmont alluvial slope at north base of Picuris Mountains. Surface is cut by asymmetrical valleys, all having west-facing scarps. **0.2**

129.1 Road (right) to Rio Grande Gorge State Park. **0.9**

130.0 Mile check marker 0. At 9:30, view up valley of Picuris-Pecos fault. Roadcuts ahead are in upper Servilleta Formation(?). **2.4**

132.4 Large asymmetrical valley. **0.6**

133.0 Mile check marker 3. **0.2**

133.2 View to right up Rio Grande Gorge. Gorge arch (anticline) visible where it crosses the canyon. **2.1**

135.3 **STOP N14, Hondo Canyon overlook.** Picnic area north of Hondo Canyon at foot of Picuris range (fig. N29). This stop at the southern edge of the

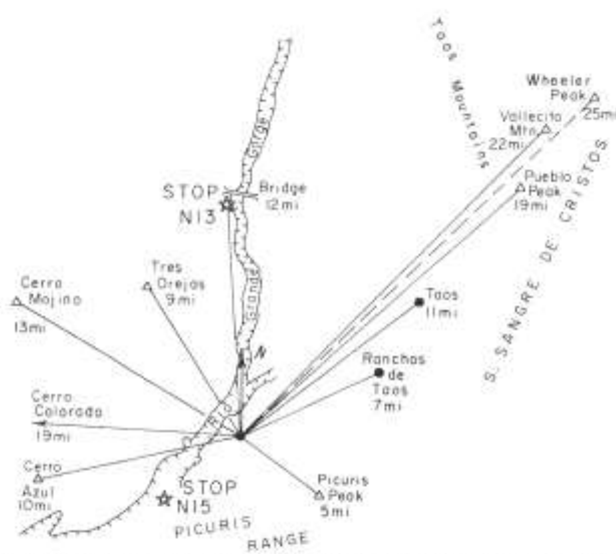


FIGURE N29—PANORAMIC INDEX OF FEATURES SEEN FROM STOP N14, HONDO CANYON OVERLOOK, SOUTHWEST OF RANCHOS DE TAOS, NEW MEXICO.

FIGURE N30—TAOS PLATEAU AND RIO GRANDE GORGE FROM STOP N14; view is to north from Hondo Canyon rest area (photo by G. R. Osburn).

Taos Plateau overlooks the Rio Grande Gorge (fig. N30) and offers a good vantage point for reviewing features of the southern San Luis Basin discussed at Stops N12 and N13 (fig. N22). This stop also includes a walking tour through roadcuts in Hondo Canyon that illustrate a segment of the northern Picuris frontal fault (figs. N31 and N32). *Watch traffic!*

FRONTAL FAULT ZONE OF NORTHERN PICURIS RANGE

by W. R. Muehiberger

The northwest and north boundary of the Picuris Mountains is a major fault zone shown by Miller and others (1963; Montgomery, 1953) as extending from La Mesita, east of Velarde, northeast and east to the frontal faults of the Sangre de Cristo Mountains southeast of Taos. Lambert (1966) recognized that this frontal fault was part of a "major northeast-trending (Jemez) lineament which extends 250 miles from Zuni Salt Lake, New Mexico, to the Moreno Valley east of Taos." This lineament includes Mt. Taylor and the Valles (Jemez) caldera. The lineament can be extended northeastward to the Raton volcanic field and southwestward to the extensive volcanic field near Springerville, Arizona, for a total length of 400 mi (Clark, 1968; Chapin and others, 1978). This alignment of late Cenozoic volcanic centers accounts for most Quaternary volcanism in this region other than the prominent belt associated with the Rio Grande rift.

The frontal fault zone (fig. N31) acts as a transform fault between the Taos and Española Basin segments of the Rio Grande rift. Because of the bend in the mountain front near Arroyo Hondo, this segment of the fault would act as a restraining bend and would cause the northward thrusting so well displayed in roadcuts 1 and 2 (fig. N32). If it is acting as a transform fault, then it should show evidence of left slip. The nearly vertical dips in roadcuts 3 and 4 (fig. N32) and the linearity of the fault zone to the Velarde Mesa permit a strike-slip fault interpretation.

The eastward-tilting of the Taos Plateau is shown by the asymmetrical valleys, the deflection of major drainages

FIGURE N31—MAP OF ARROYO HONDO SEGMENT OF FRONTAL FAULT OF PICURIS MOUNTAINS SEEN FROM STOP N14. Base adapted from U.S. Geological Survey Taos Southwest quadrangle. Trace of main fault marked by topographic step across all geologic units, high side on upthrown block. Roadcuts shown in fig. N32 are numbered squares. Map units A-D are keyed to units described in fig. N32.

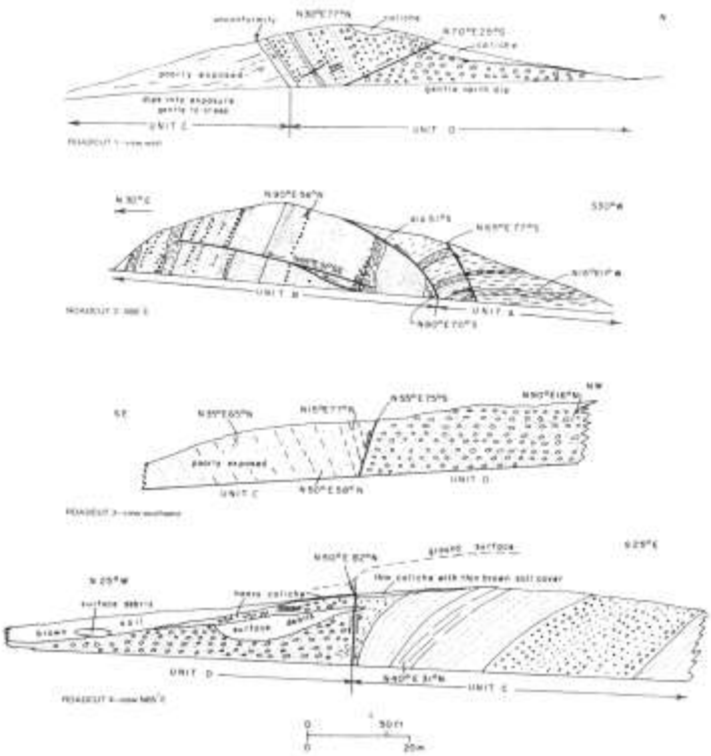


FIGURE N32—FIELD SKETCHES OF ROADCUTS LOCATED ON FIG. N31. UNIT D—Upper Servilleta Formation. Cobble-boulder gravel is composed of large subangular clasts of quartzite, smaller platy clasts of black phyllite, and an unsorted matrix of schist, phyllite, and quartzite fragments, with abundant biotite and garnet grains. These materials are derived from the Picuris Mountains to the south and are mainly debris-flow deposits on an alluvial fan. Hanging wall block (Roadcut 1) shows a general coarsening-upward sequence above a basal zone of mainly reworked Santa Fe Group materials across an angular unconformity in which the beds make an angle of nearly 90°. These beds are younger than the basalts of the Servilleta Formation exposed to the north at the rim of the Rio Grande Gorge. UNIT C—Upper Santa Fe Group, younger than or possibly equivalent to Ojo Caliente Sandstone (Tesuque Formation) of Galusha and Blick (1971). Well exposed in bluffs southwest of Roadcut 4, where it is seen to consist of alternating bands (lenses?) —each 40-50 ft thick—of buff sand (mainly sand-dune facies), gray, pebbly gravel (alluvial fan debris from Picuris Mountains), and brownish silt and sandstone (lacustrine facies). Probably highly faulted in Roadcuts 1 and 3, poor exposures prevent detailed study. UNIT B—Lower(?) Santa Fe Group, Chama-El Rito Member(?) of Galusha and Blick (1971). Consists of fining-upward sequences of conglomerate, volcanic arenite, and mudstone. The subrounded clasts are mainly intermediate and silicic volcanic types, with lesser amounts of amphibolite, quartzite, olive-drab sandstone, rare basalt, and dark-gray limestone. The volcanic arenite is subangular to subrounded, poorly sorted and submature. The red-brown mudstone may be overbank or playa deposits. The coarser units show a general north-to-south transport direction of a braided stream deposit. Roadcut 2 becomes coarser upward on a larger scale than do the smaller fining-upward sequences. UNIT A—(Santa Fe Group?; Chama-El Rito Member? of Galusha and Blick, 1971). Much finer grained; stratigraphically, probably a lower part of Unit B. Clast and sand types are the same as Unit B and are composed of alternating units of gray pebbly sandstone and yellowish-weathering siltstone; probably meandering to braided stream deposits.

parallel to the mountain into Taos, and the presence of fault scarps interrupting late Quaternary surfaces. The tilting shows that this region is still tectonically active. **0.1**

135.4 Roadcut **1** (Stop N14, fig. N32). **0.1**

135.5 Roadcut 2 (Stop N14, fig. N32). 0.5

136.0 Roadcut 3. *Cross* steep reverse fault (Stop N14, fig. N32). To right, down Hondo Canyon, can be seen the southward termination of the Rio Grande Gorge basalts of the Servilleta Formation. 0.6

136.6 Crest of grade. Picnic table; route ahead descends into Rio Grande Gorge. 0.2

136.8 Roadcut 4 (Stop N14, fig. N32). Fault dips steeply northwest. Downhill end of roadcut exposes alternating bands (40-50 ft thick) of eolian sandstone, fluvial gravel (Picuris Mountain source) and dark red-brown mud (lacustrine) of the Santa Fe Group, which may be equivalent Ojo Caliente Sandstone (Tesuque Formation) or possibly younger (see Española Basin log, Manley, this guidebook). 0.5

137.3 Roadcut in Santa Fe Group eolian sand ahead on right has many small faults. Attitudes measured in surrounding stratigraphic units are about N. 60° E., 38° NW. Terrace cap dips gently northwest. Reverse faults in sand dip near 45° S. to W. and strike between north and west. Strike-slip faults (left slip) dip steeply and strike near N. 15 ° E. 0.2

137.5 Coarse alluvial gravel facies on eolian sand facies of Santa Fe Group. Picuris Range ahead and to left. **0.1**

137.6 At 3:00, a Servilleta basalt flow caps mesa. Ahead the flow is missing for a short distance and then is continuous along the mesa edge to Pilar. On the opposite side of the mesa, along the Rio Grande Gorge less than one-half mile to the north, four or more basalt flows cap the mesa. Apparently they terminate against the fault zone, and only the top flow extends across to the outcrops on the mesa above this point. The basalt and underlying rounded stream gravel (non-Picuris source) rest with a strong angular unconformity on the Santa Fe Group. Gravel cap on mesa is derived from Picuris Mountains to south. On left, low hills of embayment into Picuris Mountains are underlain by tilted and faulted Santa Fe Group and capped by terrace deposits. **1.1**

138.7 Arroyo on left is deeply incised into Holocene alluvium. South of arroyo prominent terrace gravel unconformably rests on eolian sand and buff silt of Santa Fe Group. 0.7

139.4 Crossing bridge; Rito Piedra Lumbre. 0.2

139.6 Turnout on right. On right (north) tilted buff sand and gray gravel of Santa Fe Group is overlain, in ascending order, by nearly horizontal gravel, about 40 ft (12 m) thick (northerly source); a single basalt flow; and gravelly alluvium derived from Picuris Mountains to the south. Roadcut to south in coarse upper Pleistocene gravel derived from Picuris Mountains. **0.5**

140.1 Pilar. Junction with NM-96 on right to Rio Grande Gorge State Park (fig. N33). **0.2**

140.3 STOP N15, Rio Grande Gorge at Pilar. Turnout on right. Looking northeast up Rio Grande to Pilar (note decreasing number of basalt flows from north to south). Cleared scar (gas pipeline to Taos) is in fault zone exposed in roadcuts at Stop N14.

Downstream for the next 25 mi are enormous landslide blocks that flank the basalt-capped Santa Fe Group, Black Mesa (north), and La Mesita (south) along the Rio Grande Canyon. Manley (1976b) reports a 2.8-m.y. K-Ar age determination on the Servilleta basalt flow capping Black Mesa near Alcalde (Stop N16).

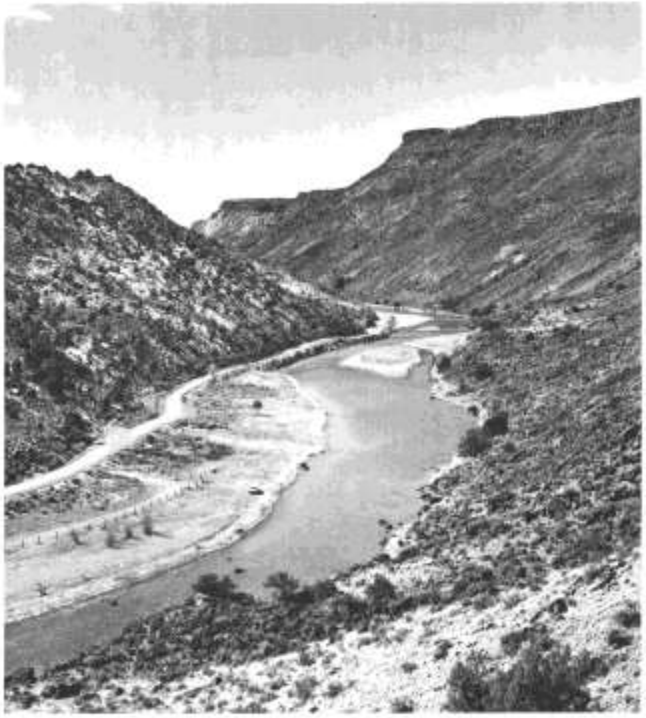


FIGURE N33—View looking southwest down Rio Grande Gorge from junction of Rio Taos and Rio Grande, approximately 5 mi upstream from Pilar (Stop N15), New Mexico; river is Rio Grande (photo by Wayne Lambert, February 19, 1978, mid-day).

The highway skirts the base of cliffs over 1,000 ft (330 m) high held up by the Precambrian metasedimentary rocks of the Picuris Mountains. The Rio Grande parallels the fault zone that bounds the Picuris Mountains on the northwest (studied at Stop N14 and seen downstream in the Velarde graben. See Manley, this guidebook).

Across from turnout are nearly vertical beds mapped as Tesuque Formation (Santa Fe Group) by Miller and others (1963). The beds contain abundant volcanic fragments and probably are, correlative with the Chama-E1 Rito Member of the Tesuque Formation of Galusha and Blick (1971). 0.1

140.4 Steeply south-dipping Precambrian Lower Quartzite member of the Ortega Formation (Miller and others, 1963) in roadcut. Montgomery (1953) measured about 2,500 ft (760 m) of this unit before it passes upward into alternating schist and quartzite units of the Rinconada Schist Member. This sequence forms the cliffs along this canyon for the next 6 mi. 1.2

141.6 Precambrian at river level on right. Usually the river forms the boundary between the Precambrian units and the toe of the landslides. Apparently some major slides blocked and diverted the river so that later downcutting superposed it on the Precambrian rocks. The Precambrian along the river is always highly fractured, probably because of its proximity to the bounding fault that is mostly buried under the landslide debris across the river. **0.8**

142.4 Turnout. Across the river are extensive spring-fed marshy areas in the landslide terrain. **0.4**

142.8 Suspension bridge. Buses not allowed! 0.2

143.0 Sheared Precambrian across river. 2.1

145.1 Roadcut of Pleistocene debris-flow deposit opposite west tip of Picuris salient. This flow moved northward. Road climbs onto upper surface of the deposit. **0.4**

145.5 Roadcut in southwestern edge of debris flow deposit. 0.2

145.7 Roadcut in coarse bouldery gravel over Tesuque Formation of Miller and others (1963). The Tesuque contains abundant volcanic clasts and may be correlative with the Chama-E1 Rito Member of Galusha and Blick (1971). Small fault near south end of cut. 0.2

145.9 Village of Rinconada in valley ahead. Basalt-capped La Mesita at 12:00. Bluffs on left are Tesuque Formation of Miller and others (1963). Upward gradation from volcanic-rich gravel to buff sands is well displayed. **1.1**

147.0 Roadcut in crossbedded sand of the upper Santa Fe Group. The sand unit, which overlies the Chama-E1 Rito(?) facies, has been mapped as Ojo Caliente Sandstone (upper Tesuque) by Galusha and Blick (1971). However, Manley (this guidebook) suggests that the sand unit is a post-Tesuque fill of possible Pliocene age. **0.6**

147.6 Stepped sequence of basalt slide blocks forms southeast shoulder of Black Mesa on skyline north of gorge. 0.5

148.1 Basalt-capped mesa ahead on right. **0.4**

148.5 Roadcut on right; more crossbedded upper Santa Fe(?) sand. 0.1

148.6 Crossing Rio Embudo bridge. Junction with NM-75 to Dixon on left. Basalt cap of mesa to right has tilted block at west end-probably part of fault zone along which we have been driving.

End of Rio Grande Gorge-Rio Embudo log.

RIO EMBUDO TO SANTA FE, NEW MEXICO

by J. W. Hawley

148.6 Bridge over Rio Embudo just above its confluence with the Rio Grande. NM-75 to left provides access to the Harding (pegmatite) mine, Picuris Pueblo, and other points of interest in the Peñasco embayment, an eastern extension of the Española Basin between the Picuris and Sangre de Cristo ranges. The Española Basin road log by Kim Manley covers features of the Peñasco embayment as well as most of the route ahead, via NM-68 and US-285, to Santa Fe. The following general entries supplement more detailed information on mid- to late Cenozoic stratigraphy and structure in Manley's log. 0.5

149.1 The route enters the Embudo-Velarde segment of Rio Grande Canyon, which is flanked by basalt-capped La Mesita (south) and Black Mesa (north). The basin-fill sequence from here to the canyon mouth near Velarde (mile 155.8) has a fairly continuous mantle of bouldery colluvium with basalt clasts. Masses of slump blocks form complex landslide terrain on many slopes, particularly north of the river. Miller and others (1963) and Galusha and Blick (1971) mapped the bulk of the fill as Tesuque Formation. However, recent work by Manley (1978a, b) indicates that significant structural depression and basin filling have occurred in this (Velarde graben) segment of the Española Basin in post-Tesuque time, particularly during the Pliocene. Except where removed by the river, thick upper Santa Fe (Chamita Formation of Galusha and Blick) and probably younger basin-fill deposits should be expected in the zone of maximum structural depression that extends northeast toward the Pilar-Hondo Canyon area at the south end of the San Luis Basin (Stops N14 and N15). 0.4

149.5 Tip of Black Mesa at 2:00. "Francisco Barrionuevo and Hernando de Alvarado, captains in the army of Francisco Vasquez de Coronado, passed this way enroute to Taos Pueblo in 1541, while exploring from Tiguex, Coronado' s headquarters near Bernalillo. . . ." (historic marker entry). **1.8**

151.3 Old Embudo bridge to right. 0.2

151.5 National historic civil engineering landmark (American Society of Civil Engineers) to right commemorates 1889 establishment of first river gaging station by the U.S. Geological Survey. 2.3

153.8 Rio Grande Canyon historic marker to right; leaving upper canyon section of the Rio Grande. From here to Espanola (mile 172.7), route is on the Holocene floor or low Pleistocene terraces of broad inner valley unit of the Espanola Basin. 0.2

154.0 Velarde frontage road to right. **1.0**

155.0 West edge of Velarde. Road ascends from valley floor onto mesa footslope. **0.7**

155.5 Fluvial gravel unit in upper Tesuque Formation forms cliff on skyline at 11:00. This is the Cejita Member of Manley (1976c, 1977). **2.4**

157.9 On skyline to right, 2.8-m.y. basalt of the Servilleta Formation caps Black Mesa (Manley, 1976b). This unit, which is underlain in part by ancestral river gravels, overlies the Chamita Formation (upper Santa Fe) of Galusha and Blick (1971). **3.9**

161.8 **STOP N16, Española Basin at Alcalde.** Junction of NM-68 with NM-389 opposite Alcalde; optional stop to discuss features of the Española Basin (figs. N22 and N34). See entries in Espanola Basin and Jemez Mountain tour guides (Stops E3-E8, E1 1 -E14, and

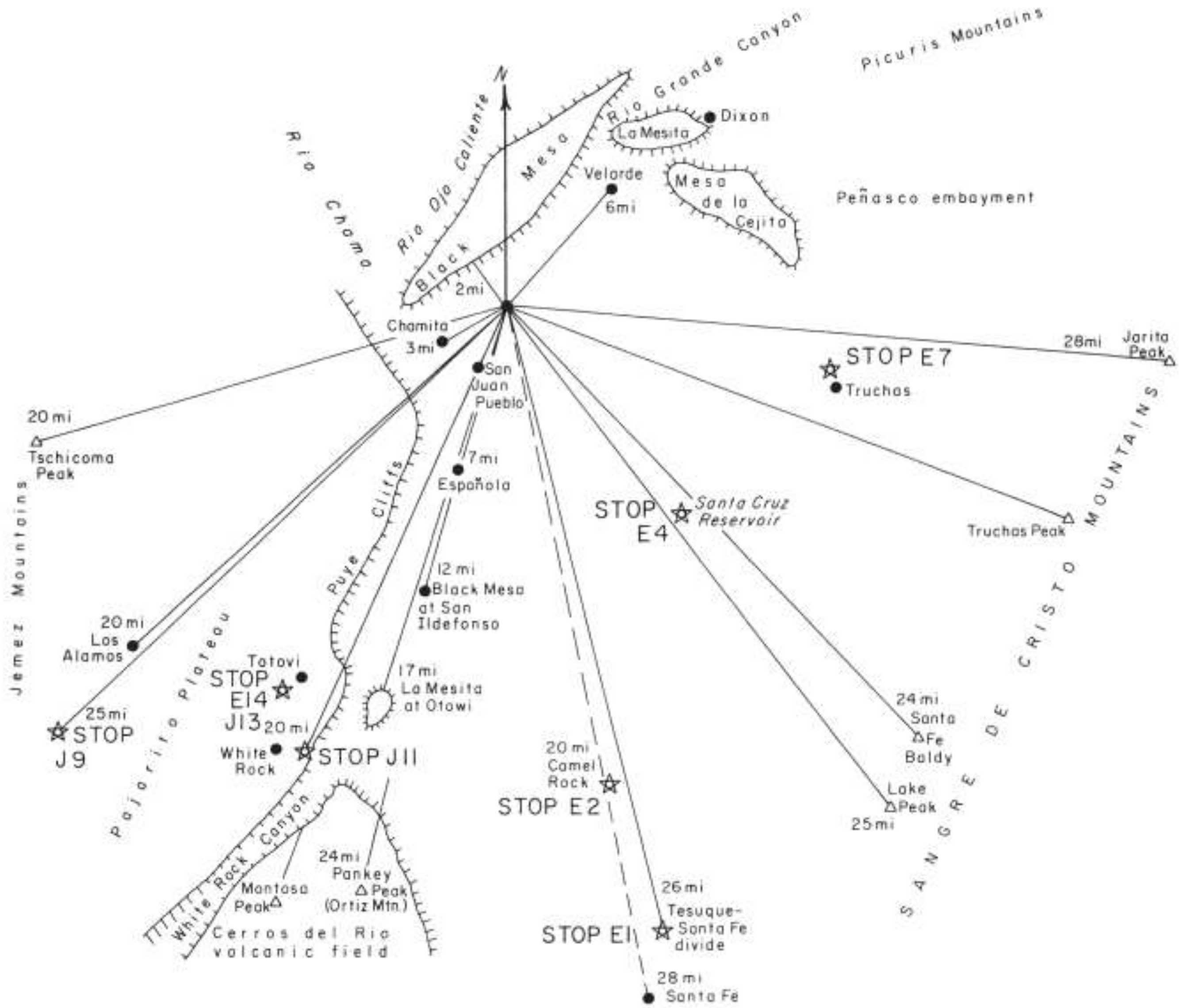


FIGURE N34—PANORAMIC INDEX OF FEATURES SEEN FROM STOP N16, ESPAÑOLA BASIN AT ALCALDE.

J9-J13 and connecting road logs by Manley and by Bailey and Smith, this guidebook). Fig. N35, from Cordell (1978), shows gravity and elevation profiles across the state at 36° north latitude. The route crosses the 36th parallel about 6 mi (10 km) south of this point. 2.2

164.0 Start of four-lane highway. San Gabriel historic marker (turnout to right) states that "The first Spanish Capital in the western United States was established by colonizer Oñate, as San Gabriel del Yunque in 1598. The historic site lies just across the river from the present San Juan Pueblo. It remained the Capital of this vast territory for ten years." **1.4**

165.4 Junction; San Juan Pueblo to right via NM-74 (Española Basin tour route). *Continue south* on NM-68. The pueblo (1972 population: 1,428; reservation area: 12,234 acres) from 1598 to 1610 was near the site of the first Spanish capital (see mile 166.0). "The Spanish serf system was imposed upon the Indians in the area, a way of life which was so restrictive that the pueblos, led by Pope, a native of San Juan, united and drove the Spanish out in 1680. Independence was maintained for 12 years. The Spanish reentered Santa Fe in 1692, and, within 4 years regained control of the area" (U.S. Department of Commerce, 1974, p. 381). **2.4**

167.8 Traffic light (Fairview); north US-84-US-285 bypass route to right. *Continue south* on NM-68. **0.7**

168.5 Traffic light; Chimayo to left via NM-76 (alternate Española Basin tour route). *Stay in left southbound lane of NM-68; prepare to merge* with US-84-US-285 south. **0.5**

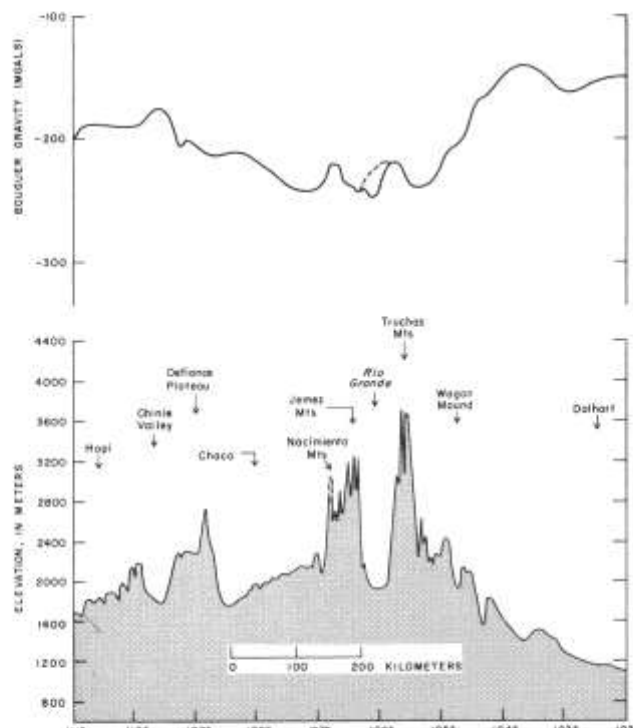


FIGURE N35—GRAVITY AND ELEVATION PROFILES ALONG 36° NORTH LATITUDE (Jemez Mountains-Española Basin). Dashed segment of gravity profile shows, schematically, residual broad positive anomaly upon which the more prominent gravity low associated with graben fill is superimposed.

169.0 Traffic lights; *stay in left lane and proceed south on US-84-US-285* toward Santa Fe. **1.7**

170.7 Junction; NM-106 to left. Badlands cut on Pojoaque Member of Tesuque Formation ahead (Galusha and Blick, 1971). **1.3**

mation ahead (Galusha and Blick, 1971). **1.3**

172.0 Crossing valley of Arroyo Seco. For about the next 5 mi the route is on the upper part of the Skull Ridge Member (medial Miocene) of the Tesuque Formation near its contact with the overlying Pojoaque Member (Galusha and Blick, 1971). Note prominent white beds of volcanic ash in the Tesuque basin-fill sequence. **3.0**

175.0 Crossing divide between Arroyo Seco and Pojoaque River. Panoramic view of southern Española Basin, flanked on the east by the Sangre de Cristo range (fig. N36) and on the west by the Jemez Mountains. See tour stop entries in guidebook sections on Española Basin (Stop E3, Manley) and Jemez Mountains (Stop J11, Bailey and Smith). **1.8**

176.8 Junction; Nambe Pueblo and Santa Cruz Reservoir to left via NM-4. This is the main route of the Española Basin tour (Manley, this guidebook). *Continue south* on US-84-US-285-NM-4 across Pojoaque River. Early 18th-century church of Pojoaque Pueblo (1972 population: 104; reservation area: 11,599 acres) is located on the bluff south of the river and east of US-285 (Pearce, 1965; U.S. Department of Commerce, 1974, p. 369). **0.4**

177.2 Junction; San Ildefonso Pueblo and Los Alamos to right via NM-4. This is the exit route for Española Basin and Jemez Mountain tours. *Continue* on US-285 south. **0.9**

178.1 Pueblo Plaza shopping center to left. **0.2**

178.3 Nambe Mills and bronze metalware center to left. Route ahead ascends valley of Rio Tesuque across outcrop belt of the Skull Ridge Member of the Tesuque Formation (Galusha and Blick, 1971). Note general westward dip of Tesuque beds in exposures ahead. **4.2**

182.5 Camel Rock picnic area to right. This is Española Basin tour Stop E2 (Manley, this guidebook). Camel Rock is an erosional form carved by nature in the Skull Ridge Member (Galusha and Blick, 1971). Rio Tesuque is marked by scattered cottonwoods to the west. **1.4**

183.9 Tesuque Pueblo on the right (1972 population: 252; reservation area: 16,813 acres) was established around 1250 A.D. (U.S. Department of Commerce, 1974, p. 392). 2.2

186.1 Crossing bridge across Rio Tesuque. Lower Tesuque Formation, Nambe Member of Galusha and Blick (1971), exposed in ridges between here and Sangre de Cristo range. **1.0**

187.1 Santa Fe Opera to right. The type area of Tesuque Formation of Spiegel and Baldwin (1963) crosses slopes ahead. An arbitrary type section extends about 9 mi west from the Bishops Lodge area of the upper Rio Tesuque valley. Estimated thickness of the arkosic sandstone, siltstone, and minor conglomerate making up the formation is several thousand feet. **3.3**

190.4 Divide between Rio Tesuque and Santa Fe River drainage at north edge of Santa Fe. This is Española

FIGURE N36—SANGRE DE CRISTO MOUNTAINS, looking southeast from US-85, 1.5 mi north of Pojoaque, New Mexico (1.5 mi north of intersection of US-85 and NM-4 East). Photograph taken several hundred yards east of US-85 and this view is not visible from highway proper. Arroyos in foreground are cut in Quaternary alluvium. Ridges and small mesas in middle ground are underlain by Santa Fe Group (photo by Wayne Lambert, February 19, 1978, afternoon).

Basin Stop E1 (Manley, this guidebook). Santa Fe (Spanish for "holy faith"), elevation 7,000 ft (about 2,123 m), is the capital of New Mexico and the oldest European community in the United States west of the Mississippi River. Santa Fe was founded as a villa by Don Pedro de Peralta in 1610, after the first Spanish governor and colonizer, Oñate, moved his headquarters here. Peralta was instructed to establish a capital for "The Kingdom of New Mexico," and he did so at the edge of the Sangre de Cristos where a Tano Indian village had been abandoned. Santa Fe was the only Spanish incorporated town north of Chihuahua until 1680. The capital was evacuated on August 21, 1680, when the Pueblo Revolt (see mile 165.4) forced Governor Otermin and the colonists down the Rio Grande to Guadalupe Mission at Paso del Norte, present Ciudad Juarez. In 1692 and 1693, many of the colonists returned with the new governor, Don Diego de Vargas, who was able to enter the city without warfare. On August 18, 1846, American forces under General S. W. Kearny also occupied the city without firing a shot. Santa Fe is a cultural center with museums, research institutions, historical monuments of Indian, Spanish, and pioneer American interest (adapted from Pearce, 1965, p. 149). **1.3**

191.7 Descending into valley of Santa Fe River. Panoramic view ahead of northern Albuquerque Basin and the Santo Domingo subbasin, area of Stops S15-S21. The Sandia Mountains on the southwestern skyline overlook Albuquerque. **1.0**

192.2 Business US-84-US-85-US-285 (Rosario Street) exit to right; *continue straight* on US-84-US-285 truck bypass, St. Francis Drive. **0.3**

192.5 Traffic light; intersection of Alamo and St. Francis Drives. *Continue south* on US-84-US-285 truck bypass. **0.4**

192.9 Traffic light; access to city center via Paseo de Peralta loop to left. **0.1**

193.0 Traffic light; intersection of St. Francis Drive and the Alameda at north edge of Santa Fe River. South end of Alamosa to Santa Fe segment of northern rift tour.

SANTA FE TO ALAMOSA

This log is compiled from the more detailed road logs covering the southbound route by Burroughs, Lipman, Muehlberger, and Hawley. The emphasis is on geomorphic and geologic features seen from a northbound perspective between the formal tour stops. Discussions at Stops N16-N10, other long technical entries, and historical notes are not included. Such items are noted at appropriate places in the road log, and they are cross referenced to corresponding mile points in the southbound tour guide.

Mileage

0.0 Traffic light; intersection of St. Francis Drive and the Alameda at north edge of Santa Fe River. *Go north on US-84- US-285 truck bypass.* **0.2**

0.2 Traffic light; Paseo de Peralta loop to right. **0.4**

0.6 Traffic light; intersection of Alamo and St. Francis Drives. *Continue north* on truck bypass. **0.2**

0.8 Underpass. **0.2**

1.0 *Merge* with US-84-US-285 north. Start of Santa Fe to Alamosa segment of northern-rift tour. The Española Basin road log in this guidebook by Kim Manley covers most of the route ahead via US-84- US-285 and NM-68 from Santa Fe to the Embudo-Dixon area (mile 44.3). The following general entries supplement more detailed information on mid- to late-Cenozoic stratigraphy and structure in Manley's log. **1.7**

2.7 Divide between Rio Tesuque and Santa Fe River drainage at north edge of Santa Fe. This is Española Basin tour Stop E1 (Manley, this guidebook). The type area of Tesuque Formation of Spiegel and Baldwin (1963) crosses slopes ahead. An arbitrary type section extends about 9 mi west from the Bishops Lodge area of the upper Rio Tesuque valley. Estimated thickness of the arkosic sandstone, siltstone, and minor conglomerate making up the formation is several thousand feet. **1.4**

4.1 Junction; *continue* straight ahead on US-84-US-285. **1.8**

5.9 Road to left to Santa Fe Opera. **1.0**

6.9 Crossing Rio Tesuque. Lower Tesuque Formation, Nambe Member of Galusha and Blick (1971), exposed in ridges between here and Sangre de Cristo range. 2.2

9.1 Road to left to Tesuque Pueblo. Route ahead crosses outcrop belt of Skull Ridge Member, Tesuque Formation, of Galusha and Blick (1971). **1.4**

10.5 Camel Rock picnic area to right. This is Española Basin tour Stop E2 (Manley, this guidebook). Camel Rock is an erosional form carved in the Skull Ridge Member. Note prominent white beds of volcanic ash in the Tesuque basin-fill sequence and general westward dip of beds. **4.0**

14.5 *Enter Pojoaque.* **0.5**

15.0 Pueblo Plaza shopping center to right. Major intersection ahead; *stay in right lane.* **0.6**

15.6 Junction; *keep to right* on US-84-US-285. San Ildefonso Pueblo and Los Alamos to left via NM-4. This is the exit route for Española Basin and Jemez Mountain tours. **0.3**

15.9 Pojoaque Pueblo to right. View ahead to cliffs of Tesuque Formation, Pojoaque Member (Galusha and Blick, 1971). For about next 5 mi, route is on upper part of Skull Ridge Member near its contact with overlying Pojoaque beds. **0.2**

16.1 Crossing Pojoaque River. **0.1**

16.2 Junction; Nambe Pueblo and Santa Cruz Reservoir to right, via NM-4, on the main route of the Española Basin tour (Manley, this guidebook). *Continue north* on US-84-US-285. **1.8**

18.0 Crossing divide between Arroyo Seco and Rio Pojoaque. Panoramic view of central Española Basin, flanked on the east by the Sangre de Cristo range, on the west by the Jemez Mountains, and on the north by Black Mesa. See tour stop entries in guidebook sections on Española Basin (Stop E3, Manley), and Jemez Mountains (Stop J11, Bailey and Smith). **2.7**

20.7 Crossing valley of Arroyo Seco. Badlands cut on Pojoaque Member of Tesuque Formation ahead (Galusha and Blick, 1971). **1.5**

22.2 Junction; NM-106 to right. Route descends to inner, river-valley segment of Española Basin. From here to Rio Grande Canyon near Velarde (mile 39.7), route is on the Holocene floor or low Pleistocene terraces of broad inner valley of the Rio Grande. **1.6**

23.8 Traffic lights ahead, US-85-US-285 to left; *stay in right lane* and *continue north on NM-68* toward Taos. **0.7**

24.5 Traffic light; Chimayo to right via NM-76 (alternate Española Basin tour route). *Continue north* on NM-68. **0.7**

25.2 Traffic light (Fairview); bypass route to left to US-85-US-285. *Continue north* on NM-68. **1.6**

26.8 North edge of Española; route continues on Rio Grande Valley floor. **0.9**

27.7 Junction; San Juan Pueblo to left via NM-74 (Española Basin tour route). *Continue* up Rio Grande Valley on NM-68. **1.4**

29.1 End of four-lane highway. **2.0**

31.1 **STOP N16, Española Basin at Alcalde,** an optional stop to discuss features of the Española Basin. Junction of NM-68 with NM-389 opposite Alcalde. See entries in Española Basin tour guide by Manley (Stops E3-8, E11-14, and connecting road logs).

On skyline to left 2.8-m.y. basalt of the Servilleta Formation caps Black Mesa (Manley, 1976b). This unit, underlain in part by ancestral river gravels, overlies the Chamita Formation (upper Santa Fe) of Galusha and Blick (1971). **5.5**

36.6 Valley of Rio de Truchas to right. Exposed in cliff at west end of mesa at 1:00 is upper Tesuque fluvial gravel, the Cejita Member of Manley (1977). **1.4**

38.0 Route descends to valley floor from mesa footslope. **0.2**

38.2 *Enter Velarde.* **1.0**

39.2 "Rio Grande Canyon" historic marker to left. The route enters the Velarde-Embudo segment of the Rio Grande Canyon, which is flanked by basalt-capped La Mesita (south) and Black Mesa (north). The basin-fill sequence from here to Rio Embudo (mile 44.4) has a fairly continuous mantle of bouldery colluvium with basalt clasts. Masses of slump blocks form complex landslide terrain on many slopes, particularly north of the river. Miller and others (1963) and Galusha and Blick (1971) mapped the bulk of the fill as Tesuque Formation. However, recent work by Manley (1978a, b) indicates that significant structural depression and basin filling occurred in this (Velarde graben) segment of the Española Basin in post-Tesuque time, particularly during the Pliocene. Except where removed by the river, thick upper Santa Fe (Chamita Formation of Galusha and Blick) and probably younger basin-fill deposits should be expected in the zone of maximum structural depression that extends northeast toward the Pilar-Hondo Canyon area at the south end of San Luis Basin (Stops N14, N15). 2.3

41.5 National Historic Civil Engineering Landmark (American Society of Civil Engineers) to left commemorates 1889 establishment of first river gaging station by the U.S. Geological Survey. **0.2**

41.7 Old Embudo bridge to left. **2.6**

44.3 NM-75 to left provides access to the Harding (pegmatite) mine, Picuris Pueblo, and other points of interest in the Peñasco embayment, an eastern extension of Española Basin between the Picuris and Sangre de Cristo ranges. A loop of the Española Basin tour (Manley, this guidebook, Stops E7-E11) covers much of the Peñasco embayment area. **0.1**

44.4 Crossing Rio Embudo just above its confluence with the Rio Grande. Start of road log section by Muehlberger and Hawley. Basalt cap of small mesa to left has tilted block at west end-probably in major fault zone that forms the north boundary of Picuris range ahead and the eastern margin of the Velarde graben of Manley (1978a, b). **0.1**

44.5 Roadcut to left in crossbedded sand of upper Santa Fe(?) Group. This unit has been mapped as Ojo Caliente Sandstone (upper Tesuque Formation) by Galusha and Blick (1971), and it overlies a facies with abundant volcanic clasts correlated with their Chama-E1 Rito Member. However, Manley (this guidebook) suggests that the sand units may be a post-Tesuque fill of possible Pliocene age. **1.4**

45.9 Roadcut in crossbedded, upper Santa Fe(?) sand. **0.1**

46.0 Village of Rinconada ahead. Bluffs to right are Tesuque Formation of Miller and others (1963). Upward gradation from volcanic-rich gravel to buff sands is well displayed. **1.0**

47.0 Roadcut to right in coarse bouldery gravel on Tesuque Formation of Miller and others (1963). The Tesuque contains abundant volcanic clasts and may be correlative with the Chama-El Rito Member of Galusha and Blick (1971). Small fault near southwest end of cut. 0.3

47.3 Entering roadcut of Pleistocene debris flow deposit. This flow moved northward. Road climbs onto upper surfaces of the deposit. **0.5**

47.8 Roadcut in northeastern edge of debris-flow deposit adjacent to western Picuris range block. Upstream from this point the Rio Grande closely parallels the fault zone that bounds the Picuris range on the northwest and is a northeast continuation of the eastern border zone of Velarde graben (Manley, this guidebook). The Precambrian sequence forming cliffs south of the river for the next 6 mi is part of the Ortega Formation, here including the Lower Quartzite member and alternating schist and quartzite units of the Rinconada Schist Member (Montgomery, 1953; Miller and others, 1963).

The Picuris range forms a salient or prong extending westward toward the Precambrian terrane at the southern end of the Brazos uplift near Ojo Caliente, about 12 mi west-northwest. An intervening mass of Precambrian quartzite, Cerro Azul, rises about the southern Taos Plateau about 5 mi northwest of here. The Embudo constriction along the Picuris-Cerro Azul-Ojo Caliente trend defines the boundary between the San Luis and Española structural basins (Kelley, 1952, 1956). **1.9**

49.7 Sheared Precambrian across river. **0.5**

50.2 Glen Woody suspension bridge to left. Buses not allowed! 0.3

50.5 Turnout to left. Across the river are extensive springfed marshy areas in the landslide terrain. **0.5**

51.0 Precambrian at river level to left. Usually the river forms the boundary between the Precambrian units and the toe of the landslides. Apparently some major slides blocked the river and diverted it so that later downcutting superposed it on the Precambrian rocks. The Precambrian along the river is always highly fractured, probably because of its proximity to the bounding fault that is mostly buried under the landslide debris across the river. **1.4**

52.4 Steeply south-dipping Precambrian Lower Quartzite member of the Ortega Formation (Miller and others, 1963) in roadcut. Montgomery (1953) measured about 2,500 ft (760 m) of this unit before it passes upward into the Rinconada Schist member. **0.2**

52.6 **STOP N15, Rio Grande Gorge at Pilar.** *Turn out to left.* View northeast up Rio Grande to Pilar. (See mile 140.3 entry in Alamosa to Santa Fe tour guide.) **0.3**

52.9 Pilar; junction with NM-96; road left leads to Rio Grande Gorge State Park. **0.5**

53.4 Turnout on left. Roadcut to south is in coarse upper Pleistocene gravel derived from Picuris Mountains. **In** cliff to north, tilted buff sand and gray gravel of Santa Fe Group is overlain, in ascending order, by nearly horizontal fluvial gravel, about 40 ft (12 m) thick (northerly source); a single basalt flow; and gravelly alluvium derived from Picuris Mountains to the south. Along the Rio Grande Gorge (less than one-half mile to the north), four or more basalt flows cap the mesa. Apparently they terminate against the Picuris frontal fault zone, and only the top flow extends across to the outcrops on the mesa above this point. The basalt and rounded fluvial gravel (non-Picuris source) under it lie with a strong angular unconformity on coarse alluvial gravel and eolian sand facies of Santa Fe Group. **0.2**

53.6 Crossing bridge; Rito Piedra Lumbre. Channel upstream on right is deeply incised into Holocene alluvium. Gravel of prominent terrace south of arroyo unconformabley rests on eolian sand and buff silt of the Santa Fe Group. **2.1**

55.7 Roadcut in eolian sand unit that has many small faults. Attitudes measured in surrounding stratigraphic units are about N. 60° E. 38° NW. Terrace cap dips 8° NW. Reverse faults in sand dip near 45° S. to W. and strike between north and west. Strike-slip faults (left slip) dip steeply and strike near N. 15 ° E. **0.4**

56.1 Roadcut 4 described at Stop N14. Fault of Picuris frontal zone dips steeply northwest. Downhill end of roadcut exposes alternating bands (40-50 ft thick) of eolian sandstone, fluvial gravel (Picuris Mountain source), and dark red-brown mud (lacustrine) of the Santa Fe Group, which may be equivalent Ojo Caliente Sandstone (Tesuque Formation) or possibly younger. **0.3**

56.4 Crest of grade. Picnic table; route ahead crosses ridge and descends into Hondo Canyon. **0.6**

57.0 Roadcut 3 described at Stop **N14.** Crossing steep reverse fault of Picuris frontal zone. To left, down Hondo Canyon, can be seen the southward termination of the Rio Grande Gorge basalts (Servilleta Formation) in a piedmont gravel facies derived from the Picuris range. **0.5**

57.5 Roadcut 2-Stop N14. **0.1**

57.6 Roadcut 1-Stop N14. **0.1**

57.7 **STOP N14, Hondo Canyon overlook.** Picnic area north of Hondo Canyon at foot of Picuris range.

This stop at the southern edge of the Taos Plateau overlooks the Rio Grande Gorge and offers a good vantage point for reviewing southern San Luis Basin features discussed at Stops N12 and N13. The stop also includes a walking tour through roadcuts in Hondo Canyon that illustrate a segment of the northern Picuris frontal fault zone.

Watch traffic! See entry by W. R. Muehlberger at mile 135.3 in Alamosa to Santa Fe tour guide. **2.3** 60.0 Mile check marker 3 to left. Crossing piedmont alluvial slope, at base of Picuris range, which is underlain by lower(?) Pleistocene fan deposits as well as by local pediment and terrace veneers of Quaternary age. Surface is cut by asymmetrical valleys, all having west-facing scarps. 0.5

60.5 Crossing large asymmetrical valley. 2.5

63.0 Mile check marker 0 to left. At 3:30, view up valley of Picuris-Pecos fault (Montgomery, 1953). See mile 65.9 entry. 0.9

63.9 Road (left) to Rio Grande Gorge State Park. **1.1** 65.0 Descending into valley of Rio Grande del Rancho from a Pleistocene alluvial terrace. **0.1**

65.1 Llano Quemado to right. 0.3

65.4 Crossing Rio Grande del Rancho; *enter Ranchos de Taos.* St. Francis of Assisi Church ahead on right. See mile 127.4 entry in Alamosa to Santa Fe tour guide. **0.5**

65.9 Junction with NM-3, which passes southward through valley of Rio Grande del Rancho. This valley was the main route of travel between Taos and Santa Fe prior to the construction of the Rio Grande Canyon highway. East of the Rio Grande del Rancho Valley are gentle dip slopes of Pennsylvanian rocks of the southern Sangre de Cristo Mountains. West of the valley is a ridge held up by Precambrian granite (pink) with steeply dipping Mississippian-Pennsylvanian rock along the left border (Laramide upthrust). The broad valley beyond the ridge is underlain by Tertiary Picuris tuff; its western wall is Precambrian granite against Picuris-Pecos fault. **1.4**

67.3 Junction of US-64 and NM-68. *Continue straight* on US-64. To the east (2:00) US-64 ascends valley of Rio Fernando de Taos. At 3:00, late Quaternary, piedmont fault scarps cut fans to south of green water tank. **1.3**

68.6 Valley of Rio Fernando de Taos ahead; *enter Taos,* elevation 6,950 ft (2,120 m). See historical entries on Taos and Taos Pueblo at miles 122.4 and 123.0 in Alamosa to Santa Fe tour guide. 0.9

69.5 Traffic light; Taos plaza on left; *continue straight* on US-64 and NM-3. Road log for next 11 mi adapted in part from New Mexico Geological Society, 17th field conference log by Clark and others (1966, p. 11-13). **0.5**

70.0 Junction with Taos Pueblo road; *bear left on US-64 and NM-3.* **0.2**

70.2 Road descends to low terrace flanking broad valley floor of Rios Pueblo de Taos and Lucero. Wet meadows ahead reflect convergence of major drainageways into this valley. **0.3**

70.5 Crossing Rio Pueblo de Taos. 0.2

70.7 From 1:00 to 3:00, an alluvial-fan apron borders the base of the Taos segment of the Sangre de Cristo range. Upper Quaternary units are cut by fault scarps. **0.2**

70.9 Crossing Rio Lucero. **0.7**

71.6 On skyline from 1:00 to 3:00, Lobo Peak consists of Precambrian rocks, mainly granite and gneiss; Cuchillo del Medio is underlain on its south side by Tertiary granite; and Pueblo Peak is formed on Precambrian gneiss. **1.1**

72.7 Higher piedmont surface across meadows to the left is formed on sandy gravel facies of upper Servilleta Formation of late(?) Pliocene to early(?) Pleistocene age (Lambert, 1966).

COMPILER'S NOTE—Servilleta terminology used from here to the Rio Grande Gorge is from Lambert (1966) and Clark and others (1966). Sedimentary units interbedded with and overlapping basalts of the Servilleta Formation in the Taos area have not been studied in detail, and stratigraphic terminology for such units is in a state of flux. **0.6**

73.3 Ascending to piedmont surface on Servilleta Formation. *CAUTION!* Junction ahead; *prepare for left turn.* **0.2**

73.5 Junction of US-64, NM-3, and NM-150. *Turn left and continue west on US-64.* **0.1**

73.6 Roadcut in upper Servilleta sandy gravel facies. This unit consists here of pebbles and cobbles of Precambrian igneous and metamorphic rocks and Tertiary volcanics derived from the Taos range. 0.2

73.8 Crossing dry tributary valley of Arroyo Seco. Picuris range from 9:00 to 10:30 on skyline. At 11:00 is Cerro Azul, an isolated mass of Precambrian quartzite at the southern edge of the Taos Plateau. At 11:30 in the southern San Luis Basin is Tres Orejas, a Pliocene basaltic volcano. The Tusas Mountains, from 11:30 to 1:00, form the west border of the basin and consist mainly of Precambrian rocks. **0.1**

73.9 Main valley of Arroyo Seco ahead and to left. Roadcuts on valley flanks are in thin terrace gravels capped with brown sandy alluvium. These deposits overlie poorly exposed Servilleta sandy gravel facies. **1.1**

75.0 Entering long roadcut. From here to Rio Grande Gorge, the roadcuts are in upper Servilleta sandy gravel capped with brown sandy alluvium or deposits of arroyo-terrace gravel. Soils with prominent horizons of clay and carbonate accumulation are commonly developed in the sandy alluvium that caps the piedmont slopes. 0.2

75.2 Crossing asymmetrical valley with steep, west-facing scarp. **0.7**

75.9 Another asymmetrical valley. **0.1**

76.0 Roadcut in upper Servilleta Formation. 0.5

76.5 Steep west-facing scarp in asymmetrical valley. **0.5**

77.0 Divide where valley asymmetry changes sides. **0.4**

77.4 Taos Municipal Airport to left. On the southern skyline at 8:30 is Picuris Peak, elevation 10,801 ft (about 3,325 m), bald side toward north, that is held up by Precambrian quartzite. Right-lateral slip Picuris-Pecos fault (Montgomery, 1953; Miller and others, 1963) lies along the north-trending valley to the left (east) of Picuris Peak. Jicarita Peak, elevation 12,750 ft (about 3,923 m), at 2:00 is on distant skyline (generally has snow patches all year). The peak is formed on gently-dipping Pennsylvanian rocks of the southern continuation of the Sangre de Cristo Mountains.

Several volcanic centers of the Taos Plateau can be seen from this point. Some of these will be discussed in more detail at stops N13 and N12 and in log entries between the Rio Grande Gorge Bridge and Antonito (miles 81.4 to 131.4). Close at hand are Tres Orejas at 11:00, Cerros de Taos from 12:30 to 1:00, and Cerro Negro at 3:00. The high domes on the distant skyline at 1:30 and 2:45 are San Antonio Mountain (near Stop N12) and Ute Mountain, respectively. 1.4

78.8 East-facing scarp in broad asymmetrical valley. 1.2

80.0 Another asymmetrical valley with east-facing scarp. 0.2

80.2 Roadcut in yellowish Servilleta sandy gravel overlain by sand alluvium with well-developed soil profile. 0.2

80.4 Descending west-facing valley scarp. 0.3

80.7 Roadcut in sandy gravel facies of upper Servilleta Formation. 0.4

81.1 Rio Grande Gorge bridge historic marker on right. **0.1**

81.2 East bridge abutment. 0.4

81.6 Rest area entrance; *turn left.* 0.3

81.9 **STOP N13, Rio Grande Gorge bridge.** View from west rim of gorge. See mile 111.2 entries in Antonito to Rio Grande Gorge road log by Lipman and Muehlberger. **0.2**

82.1 *Rejoin US-64.* Log from here to Antonito, Colorado, is adapted from P. W. Lipman (this guidebook). *Continue north and west* across Taos Plateau. Roadcuts are ahead in basalt of Servilleta Formation. The basalts (2.0-4.5 m.y. old) in the Servilleta form a widespread sequence of distinctive diktytaxitic vuggy flows of olivine tholeiite that underlies most of the southern San Luis Valley, forms the Taos Plateau, and surrounds most of the central volcanoes of the Taos Plateau volcanic field. **0.9**

83.0 Cerros de Taos on left (west). These hills are composed of two overlapping shield volcanoes of olivine andesite similar to that of the Cerro del Aire (Pliocene) shield volcano described at mile 97.2. **4.0**

87.0 Irregularly shaped hills to north (1:00) are eroded, structurally complex, early rift volcanics, ranging in composition from andesite to rhyolite (K-Ar ages of 22-25 m.y.). These rocks are preserved in a horst that is structurally continuous with the San Luis Hills in southern Colorado (Stop N10); the structurally deepest part of the rift valley is confined to a relatively narrow zone (10-15 km wide) between this horst and the Sangre de Cristo range to the east. The symmetrical hill farther to the north is Cerro Montoso, a shield volcano of olivine andesite similar to Cerro del Aire (mile 97.2) and Cerros de Taos. 3.0

90.0 Roadcuts in basalt of Servilleta Formation. To the northeast (2:30 to 3:00) the spoils dump of the Questa molybdenum mine, owned by the Molybdenum Corporation of America (Gustafson and others, 1966; Clark, 1968), is visible as a conspicuous scar in a saddle, high in the Sangre de Cristo range above the mouth of the Red River. Molybdenite mineralization is associated with granitic intrusions emplaced in a sequence of mid-Tertiary andesitic to rhyolitic volcanics (Pillmore and others, 1973). K-Ar ages of intrusive rock range from 22.3 to 23.5 m.y. (Laughlin and others, 1969). **0.4**

90.4 Road curves to the left (northwest). 0.3

90.7 Junction; Arroyo Hondo road (NM-111) to right. 2.3

93.0 Low mesa to north consists of gently dipping olivine andesite similar to that on Cerro del Aire (mile 97.2); but the primary volcano morphology is more obscure, and these andesites may be older. **4.2**

97.2 North of the highway, at 2:00, the large, low shield volcano of Cerro del Aire is conspicuous, with a small spatter cone on its east side. The volcano is composed of uniform olivine andesite (57 percent SiO_2) having a K-Ar age of 3.4 m.y. Obscurely silhouetted against the base of Cerro del Aire are low, timbered slopes that define two, very low angle, basaltic shield volcanoes; these are the largest exposed sources of Servilleta basalts. 3.0

100.2 Crossing narrow bridge over Arroyo Aguaje de la Petaca. Good roadcut exposures of basalt of the Servilleta Formation. Roadcuts west of bridge have good examples of segregations, veins, and pipe vesicles. The uppermost exposures show an obscure but interesting irregular contact between two pahoehoe flows; the top of the lower flow is characterized by tumuli (pressure ridges), with local relief of 3-6 ft (1-2 m). **0.9**

101.1 Junction US-285 and US-64 in Tres Piedras; *turn right (north) on US-285.* There are many exposures of tan Precambrian granite that underlie much of the Tertiary volcanic sequence in the Tusas Mountains to the west. For a tour guide to the Tusas Mountains and Petaca pegmatite district, see New Mexico Geological Society, 25th field conference road log by Burroughs and Woodward (1974). **0.7**

101.8 New Mexico Port of Entry at north edge of Tres Piedras. From near here to No Agua (about 6 mi) the road is mainly on poorly exposed volcaniclastic sedimentary rocks of the Los Pinos Formation (Butler, 1971); a complex volcaniclastic sequence interbedded with and underlying the basalt of the Hinsdale Formation. Two thin light-colored layers are local non-welded ash-flow tuffs. Most of the rest of the Los Pinos Formation is composed of alluvial-fan deposits derived from Oligocene volcanics of the San Juan field to the west. These rocks were deposited in the evolving Rio Grande rift valley between about 25 and 5 m.y. ago, as indicated by K-Ar dates on interlayered basalt flows in southern Colorado (Lipman and Mehnert, 1975). **2.0**

103.8 Milepost 387; San Antonio Mountain, a rhyodacite stratovolcano, at 12:00 to 12:30; and perlite mines in rhyolite domes of No Agua district at 1:00. **4.1**

107.9 Basalt flow in roadcut to left is silicic alkalic basalt from the most southerly of the three vents in Los Cerritos de la Cruz located just southwest of San Antonio Mountain. This flow is also younger than the rhyolite of No Agua (3.8 m.y. old), as demonstrated by rhyolite fragments in the sediments below the basalt flow. Scattered basalt outcrops of the Servilleta Formation can be seen in the arroyo to the east. 0.3

108.2 Road to Grefco perlite mill to right. **1.0**

109.2 Road to Johns Manville perlite mines on right. **0.6**

109.8 Milepost 393; we are approaching Stop N12 at the lower end of roadcut through basalt flows of Servilleta Formation and interbedded sediments. *North-*

bound participants will get off bus here and will be picked up at top of hill at north end of outcrop. **0.2**

110.0 **STOP N12, No Agua.** Discussion of upper Cenozoic volcanics and structural features of west-central Taos Plateau. See mile 83.1 entry in Alamosa to Rio Grande Gorge road log. **0.8**

110.8 Milepost 394; picnic area on left. San Antonio Mountain (11:00) is a large stratovolcano consisting of homogeneous, phenocryst-poor rhyodacite (60-61 percent SiO_2). A single whole-rock K-Ar date indicates an age of 3.0 m.y. Another large isolated volcano of similar rhyodacite, Ute Mountain, can be seen 20 mi (32 km) to the east across the San Luis Valley. **4.2**

115.0 Road to San Antonio Mountain on left. Panorama of Alamosa Basin subdivision of San Luis Valley (Upson, 1939) ahead. The basin is flanked on the northeast from 12:00 to 1:00 by the northern Sangre de Cristo range, with Mt. Blanca (1:00) at the south end of the range. San Luis Hills (Stop N10) in the middle ground at 12:30 form the southern border of Alamosa Basin. **4.0**

119.0 Road on right to cinder cone and quarry on left. This cone is the source of a distinctive xenocrystic (resorbed quartz and plagioclase) basaltic andesite that forms an obscurely defined flow extending across US-285 for about 3 mi (5 km) to the northeast. This is one of the youngest volcanic rocks exposed along the road during this segment of the field trip, having yielded a whole-rock K-Ar age of 2.2 m.y. Similar rock on an eroded cinder cone (Pinabetoso Peaks) about 2.5 mi (4 km) to the southeast has been dated at 1.8 m.y. **5.8**

124.8 Milepost 408; Platoro caldera complex (Lipman, 1975a) in the eastern San Juan Mountains at 10:00 to 11:00. **1.0**

125.8 New Mexico-Colorado State line. Los Mogotes shield volcano of Hinsdale Formation basalt at 10:30 north of canyon mouth of Conejos River. Stop N11 is located west of Los Mogotes at eastern edge of the San Juans. Hills in the state-line area to the west form eastern edge of the Tusas (or southern San Juan) Mountains and are underlain by east-dipping silicic basalt flows of late Cenozoic age interlayered with volcaniclastic sedimentary rocks of the Los Pinos Formation. **2.0**

127.8 Junction; village of San Antonio to left. **2.8**

130.6 Crossing Rio San Antonio, a shallow, generally dry, stream whose valley is cut in basalts of the Servilleta Formation. **0.4**

131.0 Cumbres and Toltec Scenic Railroad center (narrow gauge) to right. The train travels during summer months from Antonito, Colorado, to Chama, New Mexico, via Cumbres Pass. See geologic rail log by James (1974). **0.1**

131.1 Junction of US-285 and Colo-17. *Turn left* for excursion to **STOP N11** and lunch in **Aspen Glade campground** at edge of San Juan Mountains (Lipman, 1975b). See miles 30.1 to 46.0 in Antonito to Rio Grande Gorge road log.

After Aspen Glade lunch stop, *return to this point and continue north on US-285-Colo-17.* Log from here to Alamosa is adapted from southbound guidebook contribution by R. L. Burroughs. **0.3**

131.4 *Enter Antonito,* elevation 7,888 ft (2,406 m); *SLOW!* 25-mph speed limit strictly enforced. **1.3**

132.7 Conejos is 1 mi to west. San Luis Hills, from 1:30-3:30, are an intrarift horst of Oligocene volcanics (Conejos Formation) and associated intrusions (see Stop N1O discussion). Stock located along east side of irregular topography at north end of South Piñon Hills (3:00) has been K-Ar dated at 27.0 ± 0.6 to 27.4 ± 0.6 m.y. **0.8**

133.5 Crossing Conejos River bridges for next 0.3 mi. See Alamosa to Antonito road log entry at mi 27.5 for discussion of patterns of drainage in the Alamosa Basin area between the San Juan Mountains and San Luis Hills. **4.2**

137.7 Andesitic laharic breccia makes up western end of small hill to the east ("M" on north slope). The town of Manassa, north of the hill, is the birthplace of Jack Dempsey, the "Manassa Mauler," former world heavyweight boxing champion. **1.0**

138.7 Junction with Colo-142 at Romeo. Mt. Blanca on skyline at 1:00; Platoro-Summitville area of San Juan Mountains at 10:00. **0.7**

139.4 At 3:00 north slope of Piñon Hills with exposure of quartz monzonite-granodiorite stock. **2.0**

141.4 At 3:00 jagged outcrops halfway up south slope of Mesa de la Sauses are formed on east-striking Manassa Dike. Most dikes in the San Luis Hills have a northerly trend. At southwest edge of the mesa, upper flows lap up against a buried hill of crystal tuff exposed along the cliff edge. **4.0**

145.4 Junction (left) with road to Pike Stockade State Historical Monument (mile 15.8, Alamosa to Antonito log). **2.8**

148.2 Alamosa Creek. **0.8**

149.0 Highway curves to right. Great Sand Dunes at 12:30 at base of Sangre de Cristo range. **1.0**

150.0 **STOP N10, San Luis Hills and west-central San Luis Valley.** Rest area west of highway. Discussion of San Luis Hills and adjacent basin areas in San Luis Valley, Colorado. See mile 11.2 entry in Alamosa to Antonito log by R. L. Burroughs.

Peaks of the Platoro caldera (Lipman, 1975a) to west in the eastern San Juan Mountains from 8:00 to 10:00. At 9:00 is Green Ridge, the northeast flank of the eroded Cat Creek stratovolcano (28 m.y.) on the east side of Platoro caldera. The ridge consists of rhyodacite and andesite lava flows capped by basalt of Hinsdale Formation. Cornwall Mountain, to the left of Green Ridge, is a structurally uplifted resurgent block of densely welded ash-flow tuff within Platoro caldera. Bennett Mountain, elevation 13,189 ft (4,023 m), to the right of Green Ridge consists of post-caldera andesite lavas and quartz-latite welded tuffs, also within the caldera. The western boundary of the San Luis Basin is a dip slope of eastward-tilted volcanic rocks of the San Juan Mountains. This dip slope is cut by numerous, north-trending, antithetic faults, dropped down to the west with small normal displacements. **9.7**

159.7 *Enter Alamosa.* **0.4**

160.1 Junction US-285 and US-160 in southwest Alamosa. *Turn right and continue east* on US-160-Colo-17. Adams State College is located two blocks west of this intersection on north side of US-160-US-285. **0.4**

160.5 Traffic light; downtown Alamosa. 0.2

160.7 Intersection; *turn left.* 0.2 160.9

Crossing Rio Grande. 0.3

161.2 Junction of Colo-17 and US-160 at east edge of Alamosa. End of Santa Fe to Alamosa segment of northbound road logs.

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Southern rift guide 1,
El Paso, Texas-Socorro, New Mexico

The southern segment of the Rio Grande rift tour (Stops S1 - S22) emphasizes stratigraphic units and structural features of late Cenozoic age. Sedimentary fills and associated volcanics of intermontane basins along the Rio Grande Valley are observed, and tour discussions include reviews of geophysical as well as of geological studies. Structures and erosional-depositional features associated with Laramide tectonism and middle Tertiary cauldron formation as related to Neogene rifting are also discussed. Most tour stops, near Highways 1-10 and 1-25, are in areas of rift-related field research. A large body of published information is available to supplement guidebook entries.

Thick sections of Precambrian and Paleozoic rocks are exposed in the Franklin, San Andres, Caballo, and Fra Cristobal Mountains seen en route between E1 Paso and Socorro (Stops S1-S9). Laramide deformational features are evident in many parts of these ranges. Mountains dominated by middle Tertiary volcanic and clastic sequences associated with large cauldron structures include the Organ, Doña Ana, Uvas, San Mateo, and Magdalena uplifts.

Guidebook entries at the Assembly Point and Stop S1 discuss the Franklin Mountains and adjacent basins and ranges in the E1 Paso-Juarez area. The first part of the tour provides a close look at the margins and interior features of the southern Franklins, including piedmont fault scarps of Pleistocene age, Laramide precursors to rift structures, and a thick sequence of Precambrian and Paleozoic strata. Regional geophysical studies at the south end of the Rio Grande rift, basin-and-valley-fill stratigraphy, Pleistocene basaltic volcanism, and the local tectonic setting are reviewed at Stop S1 b.

The tour route north of Stop S1 enters New Mexico and continues up the Mesilla Valley of the Rio Grande to the mouth of Selden Canyon at Radium Springs. From Las Cruces north the route follows 1-25 except for short excursions to stops. Stop S2 examines middle Tertiary evolution of the Organ Mountain cauldron near Tortugas Mountain on the edge of the Mesilla Valley. Stop S3 at Leasburg State Park overlooks Leasburg Dam and Radium Springs resort. The park is a good place to review recent work on geothermal resources and to discuss middle Tertiary to Quaternary evolution of the uplifts (Doña Ana, Robledo, Cedar Hills, and Selden Hills) that flank the northern Mesilla Valley and Selden Canyon.

Between miles 86.4 and 89.1 the route (via 1-25) leaves the river valley and ascends to the broad central plain of the southern Jornada del Muerto Basin. This high-level surface is a remnant of the middle Pleistocene floodplain of the ancestral Rio Grande. The Jornada del Muerto is a major intrarift basin that extends more than **100** mi between the Organ-San Andres-Oscura range on the east and a discontinuous western chain of uplifts, including the Doña Ana Mountains, Tonuco uplift, Rincon Hills, and Caballo and Fra Cristobal Mountains. Stop S4 is on the Jornada basin floor at the rim of the Rio Grande Valley near Rincon. Tour-stop discussions emphasize stratigraphy and deformation of basin fill in the Rincon Hills-southern Caballo area. Stop S5 is in the valley southeast of Rincon at the base of San Diego Mountain **(Tonuco uplift). A thick section (more than 5,000 ft) of** Santa Fe beds (Miocene to Pleistocene) is exposed between the summit of the mountain and the east valley rim. The relations between modern rift structures, their early Miocene precursors, and late Miocene to early Pliocene magmatism is stressed at this stop.

The route returns to 1-25 at Rincon, continues northwest up the Rio Grande Valley, and enters the Palomas Basin near Hatch. This basin is flanked on the east by the intrarift Caballo block and on the west by the Animas-Hillsboro foothill belt of the Black Range, which forms the rift's western boundary in this area. Basin fill exposed from here to Socorro is mainly upper Santa Fe piedmont alluvium of Pliocene and Pleistocene age. After crossing the Rio Grande below Caballo Dam (mile 148.3), the route skirts the west edge of the Caballo Reservoir (Elephant Butte Irrigation Project) to the north end of the basin near Truth or Consequences. Stop S6, on a high surface overlooking Caballo Reservoir, offers an excellent view of the western escarpment of the east-tilted Caballo block and the piedmont fault scarps along the base of the range. Discussions center on 1) relationships between Laramide and younger tectonic features in the Caballos and 2) the influence of middle Tertiary structures of the Emory Cauldron-Black Range area on the western boundary of the rift.

Northwest of Truth or Consequences the route crosses the **Mud Springs uplift that separates the Palomas and Engle** (Cuchillo) Basins. Engle Basin is bounded on the east by the Fra Cristobal Range and northern Caballo Mountains and on the northwest by the San Mateo Mountains. Stop S7, at the southern end of the basin, is in two parts, with discussions at points overlooking Elephant Butte Reservoir and Dam. Between Stops 7a and 7b, the route crosses the Hot Springs fault zone, an intrarift belt of Miocene to Pleistocene offsets, that separates the Engle Basin from the Caballo and Fra Cristobal blocks. Basalt flows and cones of Pliocene and early Pleistocene(?) age occur along and east of the fault zone. Stop S8 on the Cuchillo plain in central Engle Basin offers a good vantage point for discussions of Cenozoic structural evolution of the Fra Cristobal Mountains and the middle Tertiary cauldron structures in the Black and San Mateo ranges.

Between Stop S8 and the Chupadera uplift (mile 224.0), the route skirts a foothill salient of the San Mateo Mountains and crosses an area of dissected piedmont surfaces grading eastward from the mountains to the Rio Grande Valley. The San Marcial intrarift basin lies north of a constricted valley segment between the San Mateos and the north end of the Fra Cristobal Mountains. This basin is flanked on the north by the Magdalena and Chupadera uplifts, and the basin opens eastward into the northern Jornada del Muerto Basin on the opposite side of the river valley. Predominantly volcanic and volcaniclastic rocks of the ranges are flanked by thick alluvial deposits of the upper Santa Fe Group. Discussion at Stop S9, in central San Marcial Basin, emphasizes the western margin of the rift and the controls exerted by cauldron precursors centered in the San Mateo and Magdalena ranges. Northeast of Stop S9 the San Marcial Basin is transitional to the southern Socorro Basin located between the Chupadera Mountains (west) and the Loma de las Canas-Cerro Colorado uplift (east). The final leg of the trip to Socorro skirts the southern Chupadera block and crosses a belt of deformed Lower Santa Fe deposits southwest of San Antonio.

EL PASO TO NEW MEXICO-TEXAS STATE LINE

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Assembly Point—Holiday Inn-Downtown E1 Paso, on North E1 Paso Street between Missouri and Wyoming Avenues. Assemble in top-floor observation area for introductory remarks and discussion of geomorphic and tectonic features seen from this point. After discussion, board vehicles; *proceed north on El Paso Street* to Wyoming Avenue; *turn right on Wyoming* at traffic light and *travel east two blocks (parallel to 1-10) to Mesa Street* (0.0 mile **point).**

Review of regional Cenozoic geomorphic and tectonic elements

Welcome to the sister cities of E1 Paso, Texas (1970 population 322,261), and Ciudad Juarez, Chihuahua (1970 population 407,370). This area is a major center for international trade and tourism, transportation, textile manufacture, military and civilian aerospace programs, copper and custom-metal refining, oil refining, and natural-gas pipeline operations. The University of Texas at E1 Paso is an important division of the state university system and an outgrowth of the Texas College of Mines established here in 1913.

First European contact with local Indians was in 1535-1536 when the Alvar Nuñez Cabeza de Vaca party wandered through this area. In 1598 the river valley between the Franklin and Juarez Mountains was named E1 Paso del Norte (the pass of the north) by Juan de Oñate, leader of the New Mexico colonists. In 1659 Franciscan fathers founded the Mission of Nuestra Senora de Guadalupe on the south side of the river. The mission formed the center of the original Paso del Norte community that served as the northern outpost of Spanish colonial government during the 1680-1692 Pueblo revolt. In 1889 the city was renamed Ciudad Juarez after President Benito Juarez, who was headquartered there in 1865-1866 during the struggle against the Imperial French occupation of Mexico. The north-bank community, established in the 1820's, became United States territory in 1848 and was formally platted as the town of E1 Paso, Texas, in 1858. Shifts of the Rio Grande between 1853 and 1865 resulted in the Chamizal international-boundary dispute, which was finally settled in 1963 with subsequent exchanges of territory and rectification of the river channel (Horgan, 1954; Sonnichsen, 1968; Mueller, 1975).

Many of the major geomorphic features of the E1 Paso region can be seen from the Assembly Point. These include the Hueco, Franklin, and Juarez Mountains, Cerro de Cristo Rey, Hueco and Mesilla Bolsons, and the Lower (E1 Paso) Valley of the Rio Grande (figs. S1 and S2).

The Hueco Mountains on the eastern skyline (mainly flat, upper Paleozoic carbonate strata) form the west edge of the Diablo Plateau. Hueco Bolson, a 25-km-wide structural basin, lies between the Hueco and Franklin Mountains (northeast foreground). The Lower Valley of the Rio Grande (E1 Paso or Juarez Valley), southeast of the Paso del Norte constriction, is entrenched about 300 ft (100 m) below the bolson floor. The broad floodplain is underlain by about 80 ft (25 m) of upper Quaternary alluvium, which rests on thick bolson deposits.

The northern part of Hueco Bolson is structurally asymmetrical with upper Cenozoic fill estimated to be about 9,000 ft (2,750 m) thick, along a western belt of greatest structural depression at the foot of the Franklin Mountains (Mattick, 1967). The basin fill overlies gently west-dipping Paleozoic strata (Mattick, 1967), probably Permian Hueco Limestone (Cliett, 1969), at 5,000 ft (1,525 m) below sea level.

The bulk of the fill of Hueco Bolson, excluding upper Quaternary (piedmont-slope, playa, and eolian) deposits, has been correlated with the Santa Fe Group of Miocene to middle Pleistocene age (Hawley and others, 1969, 1976; Strain, 1969a). Vertebrate faunas collected from the upper 400 ft (122 m) of the fill in the E1 Paso Valley area are of Blancan (Pliocene and early Pleistocene) and Irvingtonian (early and **middle** Pleistocene) provincial ages (Strain, 1966, 1969a, b). Bolson fill exposed in valley areas above and below E1 Paso has been subdivided by Strain into two formations of the upper Santa Fe Group: 1) the Fort Hancock Formation of Blancan and possibly greater age comprising central bolson (playa) and peripheral piedmont (alluvial) facies, and 2) the Camp Rice Formation (Blancan and Irvingtonian) comprising axial fluvial beds (ancestral Rio Grande) and flanking piedmont deposits. Hawley considers the basal Camp Rice river beds to be transitional southeastward (downstream) with upper Fort Hancock playa-lake deposits. Preliminary studies of volcanic ash lenses in the Camp Rice Formation indicate that they are air-fall deposits derived from caldera-forming eruptions at Yellowstone, Wyoming, and Long Valley, California (Hawley, 1975a). Yellowstone-derived Pearlette **"B" and "0"** ashes (2.0 and 0.6 million years in age, Naeser and others, 1973) and the Long Valley-derived Bishop ash (0.7 m.y., Bailey and others, 1976) have been tentatively identified (see Stops S1 and S4).

Thick Blancan-age river deposits along the eastern base of the Franklin Mountains provide good evidence of tectonic depression of the west side of Hueco Bolson, relative to the Franklin uplift in early Pleistocene and latest Tertiary time. Recognition of deformational features in upper Blancan and younger strata along the western edge of the bolson have allowed at least general assessment of amounts and rates of Quaternary tectonic activity along the East Boundary fault zone discussed below.

The Franklin Mountains are a west-tilted (average 35 °) fault block with about 8,200 ft (2,500 m) of Paleozoic carbonate rocks on 4,900 ft (1,500 m) of Precambrian metasedimentary and metavolcanic rocks and an unknown thickness of granite (Harbour, 1972; Richardson, 1909). **North Franklin Mountain, elevation 7,192 ft (2,191 m), capped by Precambrian rhyolite, is the highest** structural point in Texas (Adams, 1944). According to Lovejoy (1975b), 17 major landslides and complex gravity glides have aided in range denudation (fig. S2b). The Eastern Boundary fault zone of the Franklin Mountains is about 1 km wide at the surface and is marked by nearly continuous piedmont scarps (Harbour, 1972; Richardson, 1909; Sayre and Livingston, 1945). The dip of the fault zone has been variously interpreted as 90 ° W. (Richardson, 1909), 60° E. (Harbour, 1972), 25° E. (Mat-tick, 1967), and 60-80° W. (Lovejoy, 1975a, b). Lovejoy estimates Cenozoic throw to be about 30,000 ft (9,000 m), and

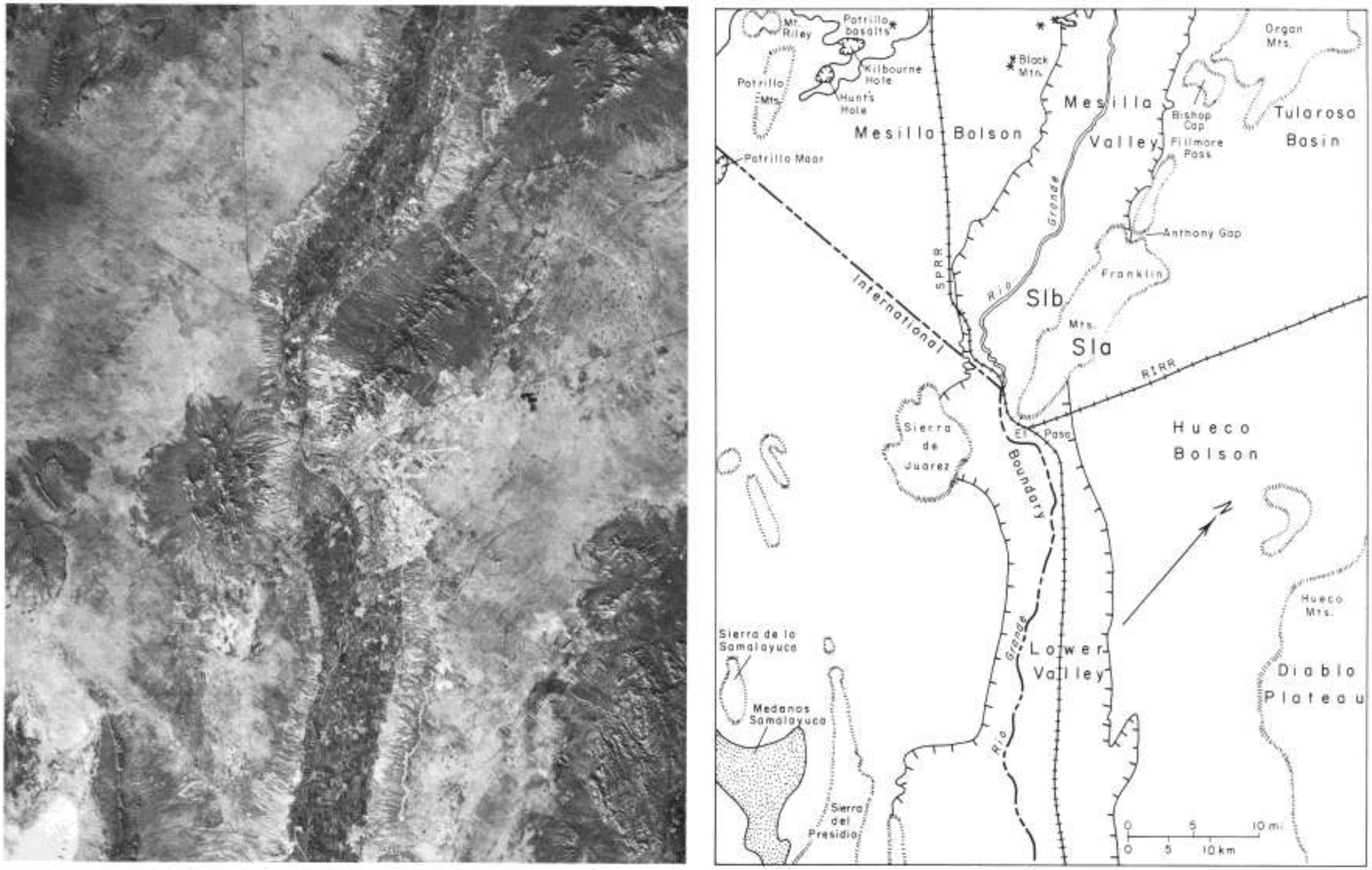


FIGURE S1—SKYLAB-4 PHOTO (a) AND INDEX MAP (b) OF THE INTERNATIONAL BOUNDARY REGION NEAR EL PASO, TEXAS (photo SL4-92-024 courtesy of Technology Application Center, University of New Mexico; photo scale approximately same as map scale).

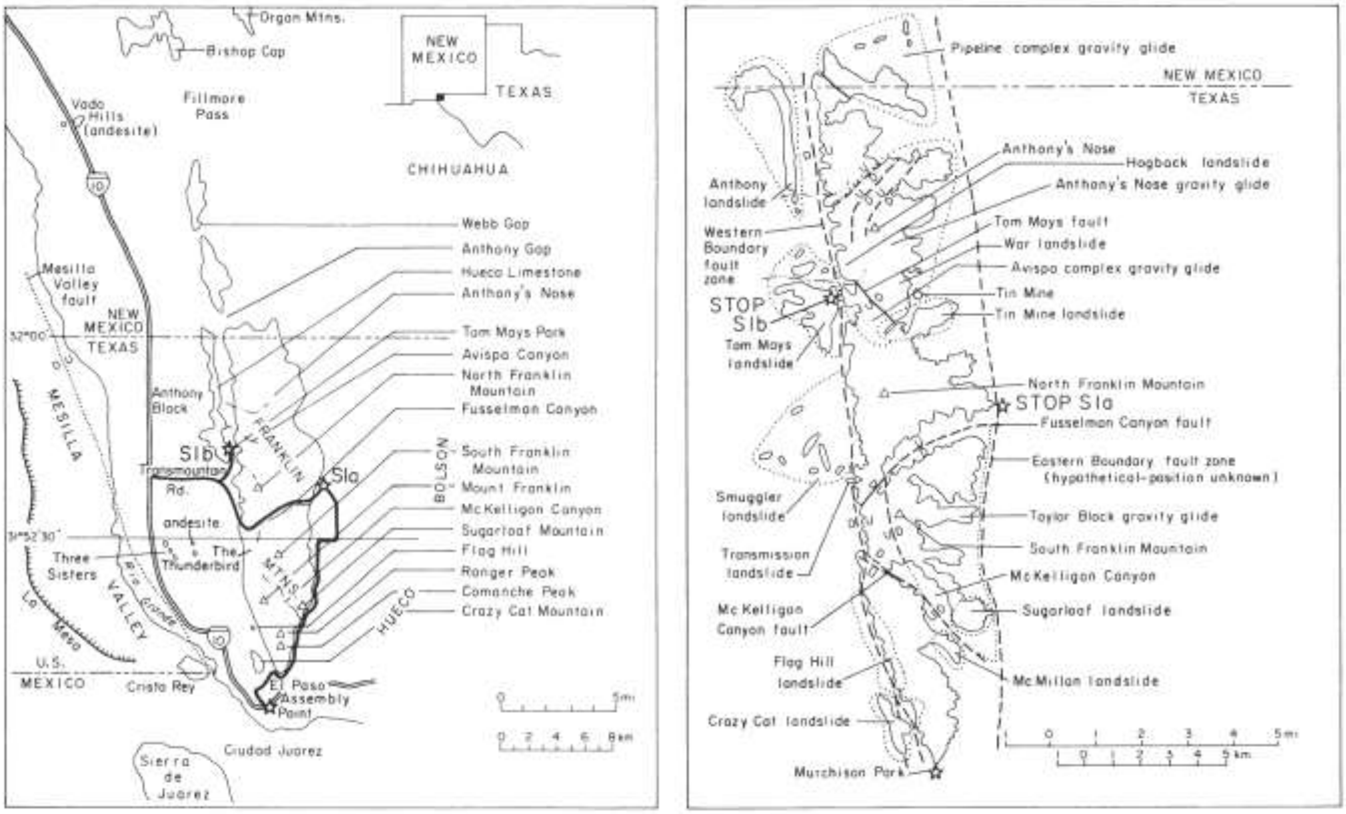


FIGURE S2—MAPS OF FRANKLIN MOUNTAIN AREA, TEXAS AND NEW MEXICO. At left, index map; at right, map showing locations of gravity glide and landslide masses. Dotted lines indicate approximate boundaries of masses; solid lines show outcrop pattern; dashed lines show faults. Note that the part of Fusselman Canyon fault that bounds the Taylor block is downthrown on the south side, but the part that cuts the main mountain block is downthrown on the north (from Lovejoy, 1975b, figs. 1 and 2).

he interprets the fault zone as being active throughout Cenozoic time, but mostly during the Paleogene.

The Western Boundary fault zone of the Franklins is locally well exposed, separating lower Paleozoic and upper Precambrian rocks in the mountain block from Cretaceous or Permian rocks in the downthrown block (Harbour, 1972; Lovejoy, 1973; Richardson, 1909); stratigraphic separation is about 8,200 ft (2,500 m), according to Harbour. The exposed fault zone contains vertical faults (Richardson, 1909), normal west-dipping faults (Harbour, 1972), and reverse east-dipping faults (Lovejoy, 1975c), all with major throw. According to Lovejoy (1975c, 1976b, c), unfaulted (Blancan age) deposits of the Fort Hancock Formation and two late Neogene, pre-Fort Hancock landslides cover the fault zone locally. Reverse and normal faults of small throw cut the older (Neogene) Flag Hill landslide, and minor faults cut the younger (pre-Blancan) Crazy Cat slide, which is visible at the south end of the range.

At the south end of the Franklin Mountains (northeast foreground from Assembly Point), the northeast-striking Gold Hill fault zone, downthrown to the southeast, offsets upper Santa Fe strata about 100 m (pre-Blancan throw unknown). According to Lovejoy the zone probably is continuous with the Eastern Boundary fault zone to the northeast. It also continues southwest beneath Rio Grande valley fill, and gravity data indicate that the zone extends southward into Mexico.

Sierra de Juarez to the southwest is part of the Mexican Chihuahua tectonic belt. The range consists of 1,500 m of Albion-Aptian carbonate rocks deposited in the northeast flank of the Sonoran geosyncline (Cordoba, 1969). The strata are folded and thrusted (Campuzano, 1973; Wacker, 1972) and translated perhaps 20 km northeast (Nodeland, 1977). The northeast part of the range has been most intensively deformed (Wacker, 1972; Campuzano, 1973; Nodeland, 1977), and the complex structure there has been interpreted by Lovejoy as indicating a mid-Eocene "collision" with the already forming Franklin Mountains. The sudden termination of the Franklin Mountains, the change of tectonic style between them and the Sierra de Juarez, and the regional structure have all been interpreted as evidence of the (here) N. 60° W.-trending Texas lineament. This feature has been considered to be Precambrian or pre-Pennsylvanian by Wiley and Muehlberger (1971) with some deformation, possibly Cenozoic. Drewes (1978, fig. 1) infers that the trend from Las Vegas, Nevada, to E1 Paso marks the northern border continuation of the Cordilleran orogenic belt. The belt is a zone of compressive deformation of Late Cretaceous and early Tertiary age.

Mesilla Bolson, the broad intermontane basin west of the Franklin-Organ ranges, is similar to the Hueco Bolson in many respects. Santa Fe Group deposits may locally exceed 3,300 ft (1,000 m) in thickness; the upper several-hundred meters of fill comprise the upper Santa Fe, Camp Rice-Fort Hancock sequence; and the 5-mi (8-km) wide Mesilla Valley of the Rio Grande is cut about 300 ft (90 m) below the bolson floor. Extensive plains in both bolsons are interpreted as remnants of a fluvial-fan-delta complex constructed by the upper Rio Grande in late Pliocene to middle Pleistocene (Blancan-Irvingtonian) time prior to formation of a through-flowing system. Strain (1966, 1971) shows that the ancestral upper river terminated in a huge lake and playa complex, which he designates Lake Cabeza de Vaca. Quaternary basaltic volcanics and structural features of the Mesilla Bolson will be discussed at Stop S1 b.

The Mesilla Valley is straight between Las Cruces and E1 Paso. Lovejoy (1976a) interprets the valley to follow a fault (zone), which he designates the Mesilla Valley fault, that has been upthrown to the east about 360 ft (110 m) since Fort Hancock deposition. Associated with the fault is a pronounced gravity inflection that continues as far north as Las Cruces (Ramberg and others, 1978). There is general agreement (Hawley, 1975b; Lovejoy, 1975b) that the Rio Grande has been structurally guided into the Paso del Norte constriction during late-stage (middle Pleistocene) deposition of the Camp Rice Formation. The narrow Paso del Norte segment connecting the Mesilla and Lower Valleys is a superimposed feature cut through a Camp Rice-Fort Hancock cover into Cretaceous strata between two mid-Eocene andesitic plutons-Campus and Cristo Rey (Hoffer, 1970; Lovejoy, 1976d). Mechanisms of integration of the upper and lower Rio Grande systems and onset of valley incision in the El Paso region have been discussed by a number of investigators, including Kottlowski (1958), Strain (1971), Hawley (1975b), and Lovejoy (1975b). Integration by north-to-south bolson overflow and headward erosion of lower Rio Grande tributaries are possible mechanisms that also may have occurred in combination. Depression of the Mesilla and Hueco Bolson blocks relative to the Franklin uplift certainly played a major role in the local evolution of the Rio Grande Valley.

According to Lovejoy (1976a), the Gold Hill fault probably intersects the Mesilla Valley fault in western downtown E1 Paso near the Assembly Point. If so, the north-trending Franklin Mountains and the triangular block between them and the northwest-trending Mesilla Valley fault represent a tectonic union that has been raised in Pleistocene time. Lovejoy interprets this younger (Mesilla Valley) faulting to be Rio Grande rifting, which cuts diagonally across earlier Basin and Range (Franklin Mountains) structure. According to Lovejoy development of this earlier structure commenced in Paleogene time.

Mileage

0.0 Traffic light; intersection of Mesa Street (US-85) and Wyoming on south side of I-10. *Travel north* on Mesa Street. For next 0.7 mi, route ascends stepped sequence of Quaternary geomorphic surfaces (erosional and constructional) that border the floodplain of the Rio Grande. 0.6

0.6 Traffic light ahead at Mesa and Schuster Avenues; *prepare to turn right* 1 block north of Schuster at Rim Road. University of Texas at E1 Paso campus 0.5 mi northwest of this intersection. 0.1

0.7 *Turn right onto Rim Road (Scenic Drive); continue east* on an intermediate valley-border surface of mid- to late Pleistocene age-the Kern Place "Terrace" (Kottlowski, 1958). This partly erosional, partly constructional surface grades from the foot of the Franklin Mountains to a former floodplain base level 115-150 ft (34-45 m) above the present valley floor. 0.2

0.9 Route follows Rim Road along edge of Kern Place surface and above prominent erosional scarp bordering lower (E1 Paso-Juarez) valley of the Rio Grande. 0.2

1.1 Scenic view turnout to right at Tom Lea Park (optional stop). The southern Franklin Mountains in northeast foreground are formed of carbonate rocks of the E1 Paso and Montoya Groups (both Ordovician) about 1,500 ft (460 m) thick, dipping 30-40° W. Television towers are on basal Montoya (Upham Formation), and radio towers, on Comanche Peak, are on an isolated mass of Upham Formation on the ridge crest. The rest of the Montoya Group and overlying Fusselman Dolomite (Silurian) slid downslope to form Crazy Cat Mountain (microwave tower and roadcuts; fig. S2b), which is a landslide mass of Montoya-Fusselman breccia 8,000 ft (2,500 m) long (north-south), 5,000 ft (1,500 m) wide, and about 330 ft (100 m) thick (Lovejoy, 1976b). The breccia lies across the Western Boundary fault zone of the Franklins and is faulted less than 16 ft (5 m), probably less than 6 ft (2 m). The age of the slide is not known, but it is older than bolson-floor deposits of the upper Santa Fe Group on the mountain footslopes. Lovejoy correlates these Santa Fe strata, which have not been obviously displaced, with the Blancan-age Fort Hancock Formation of Strain (1966, 1969b). 0.4

1.5 Intersection with Brown Street; *continue straight* on Rim Road. Narrow divide ahead on Kern Place surface is between upper Arroyo Park drainage (left) and Rio Grande (right). Stream capture here is geologically imminent. Abstraction of drainage around the south end of the Franklin Mountains has proceeded this way since the river began to flow through E1 Paso del Norte in middle Pleistocene time. 0.2

1.7 Kern Place surface here overlies the western fault of the Western Boundary zone; there is no evidence that the surface gravels, which are about 30 ft (10 m) thick, have been offset. Beneath the gravels, upper Santa Fe bolson-floor deposits extend across the fault zone without offset and rest directly on Ordovician bedrock. 0.3

2.0 Kern Place surface here overlies the eastern fault of the Western Boundary zone; the surface has not been displaced. At 9:00-11:00 note irregular folding (rumpling) of E1 Paso and lower Montoya Group beds. This deformation is associated with Crazy Cat landsliding of the post-E1 Paso, Montoya-Fusselman sequence. 0.2

2.2 Sharp curve; cherty mid-Montoya Group beds on left. A minor fault of the Western Boundary zone is in roadcut; note breccia and vertical chert beds adjacent to fault zone. Minor rumpling in E1 Paso Group beds ahead. 0.2

2.4 Lower Montoya Group in cuts on left. 0.1

2.5 Sharp curve to left ahead; *slow* for scenic view turnout. Contact of gray Montoya Group and buff E1 Paso Group on curve. 0.1

2.6 Scenic view turnout to right, Murchison Park (optional stop). Panorama of E1 Paso-Juarez Valley and Hueco Bolson (figs. S1, S2a). Mountains to far south in Mexico are formed of Cretaceous rocks with some Jurassic rocks. Sierra de Juarez to southwest on opposite side of valley. To the east are the Hueco Mountains capped by Permian carbonate rocks (see mile 13.1). This is the southern end of the combined Oscura-San Andres-Organ-Franklin range that extends almost 150 mi (240 km) between the Jornada del

Muerto-Mesilla (west) and Tularosa-Hueco (east) bolson complexes. Ranges dominated by thick Paleozoic sections are not found south of here in Mexico for a distance of over 100 mi (160 km). The Texas lineament (Wiley and Muehlberger, 1971) extends N. 60° W. between this front and Sierra de Juarez. The Cerro de Cristo Rey andesitic pluton (Lovejoy, 1976d) to the northwest is on this alignment.

Upper Santa Fe bolson-floor deposits on mountain footslopes to the south are offset by the Gold Hill fault. This fault extends southwesterly from the Eastern Boundary fault zone to the vicinity of the Holiday Inn, where it probably joins the Mesilla Valley fault zone.

There is some disagreement on correlation of upper Santa Fe formations in the southern Franklin piedmont area. Lovejoy designates sand and clay deposits of the bolson-floor facies as Fort Hancock, while Hawley correlates these beds with the lower part of the Camp Rice Formation fluvial facies. Both consider the exposed bolson-floor strata to be no older than Blancan provincial (Pliocene to early Pleistocene) age, and they concur (see miles 7.9 and 13.1) that about 400 ft (120 m) of range uplift has taken place along the Eastern Boundary fault zone in post-Blancan time (approximately the past 1.5 m.y.).

The route from here to Stop S1a (mile 13.1) traverses the piedmont slope of Hueco Bolson. It closely follows the Eastern Boundary zone of the Franklin block and crosses individual fault scarps in several places. The geomorphology of piedmont slopes on both sides of the range is complex (Lovejoy, 1971; Metcalf, 1969). Upper Quaternary arroyo (channel, terrace, and fan) deposits and erosion-surface veneers form a discontinuous mantle of alluvium on piedmont-slope and basin-floor facies of the upper Santa Fe Group. Episodes of slope instability and resultant erosion-sedimentation have been triggered not only by faulting but also by climatically controlled processes. Rates of late Quaternary faulting cannot be estimated until details of younger bolson-fill stratigraphy have been worked out. 0.6

3.2 E1 Paso Police Academy to left; cuts in lower E1 Paso Group dolomites. 0.1

3.3 Dark-red sandstone at 12:00 is the Bliss Sandstone (Cambrian-Ordovician); note high- level pediment gravels lying on the Bliss at 1:00. Lower E1 Paso Group dolomites on left are capped with upper Santa Fe bolson-floor facies and piedmont gravels. 0.2

3.5 Bliss Sandstone in canyon at 9:00; cuts ahead in upper Santa Fe and younger basin fills. 0.3

3.8 *Prepare for left turn* ahead at traffic light (Alabama Street). Gold Hill fault cuts upper Santa Fe beds about 0.2 mi south of here; dissection of the fault scarp produced the erosional features to the right. 0.2

4.0 Traffic light; *turn left onto Alabama Street* from Scenic Drive. 0.1

4.1 Whitewashed "A" on mountain at 9:00 is on contact of Red Bluff granite (Precambrian; 980 m.y.) and overlying Bliss Sandstone (about 500 m.y.). KTSM-TV tower at 10:30 is on ridge-forming beds in upper E1 Paso Group; ridge to north of tower is formed on Montoya Group. High-level, upfaulted piedmont gravels (upper Santa Fe) at 8:30 are on hill to south of "A." Part of Eastern Boundary fault zone lies along mountain front at 9:00, but another-perhaps major-part lies about 0.75 mi to the east (see mile 5.0). 0.6

4.7 Traffic light, Fort Street. At 9:00 Red Bluff granite and Bliss Sandstone, with overlying E1 Paso Group carbonates. Note fault scarp at base of hill. McMillan quarry and landslide block at 11:00; Sugar Loaf Mountain and landslide at 12:00 (fig. S2b; Lovejoy, 1975a, b). 0.3

5.0 Traffic light, McKinley Street entrance to KTSM-TV aerial tramway on left. Northern television tower is above range reentrant from which the McMillan quarry landslide block slipped. The block consists of brecciated E1 Paso and Montoya Groups in normal stratigraphic position. McKelligon Canyon from 11:00 to 12:00 west of Sugar Loaf. Surface of large alluvial fan that spreads out from canyon mouth at 12:00 to 3:00 is offset by minor fault scarps about 0.75 mi to the east along Copia Street. 0.8

5.8 Traffic light. McKelligon Canyon Road; route curves to right (east). Highly fractured E1 Paso and Montoya Group rocks form Sugar Loaf Mountain landslide at 9:00-11:00. 0.6

6.4 Intersection ahead with Fred Wilson Road; *bear left* (north) on Alabama Street. To southeast a fault scarp passes along west side of Beaumont Hospital ball park. Route runs west of the Eastern Boundary fault zone; poorly displayed fault scarp 0.1 mi ahead. 0.7

7.1 Route continues on fault scarp; the east side of Eastern Boundary fault zone is about 0.6 mi to the east along the Gateway Freeway. 0.5

7.6 In roadcut, piedmont gravels (carbonate clasts) interfinger with bolson-floor facies of upper Santa Fe; note that beds are flat. Here fault scarp is on east side of hill. 0.3

7.9 At 12:00 water tank on fault scarp; below tank east-dipping upper Santa Fe beds dip into the Eastern Boundary fault zone. These ancient bolson-floor deposits are about 400 ft (120 m) above the present floor of Hueco Bolson. Street name changes ahead, Alabama to Magnetic. 0.4

8.3 Apartments at 9:00 on fault scarp and downthrown block; houses on upthrown block are 40 ft (12 m) higher. 0.4

8.7 Traffic light, Hercules Avenue. Fault scarp to west of Magnetic Street in this area is indicated by steeper slopes in east-west streets. 0.2

8.9 Fault scarp at 9:00. At 12:00 on skyline is an uplifted pediment cut on Lanoria quartzite (Precambrian) intruded by Red Bluff granite (see Stop S1a). West-dipping Precambrian strata are parallel with overlying Paleozoic strata and all beds are essentially planar; thus, these west-dipping beds are not part of a fold, and the Franklin Mountains are definitely a tilted fault-block range. 0.8

9.7 *Turn right (east) onto Hondo Pass Road;* descending toward bolson floor. Low sun angles in the late afternoon highlight piedmont fault scarps to the north. 0.7

10.4 Traffic light, Gateway South; *prepare for left turn ahead.* 0.1

10.5 Traffic light, *turn left onto Gateway North.* The eastern fault of the Eastern Boundary zone probably lies nearly beneath route. The large alluvial fan de-

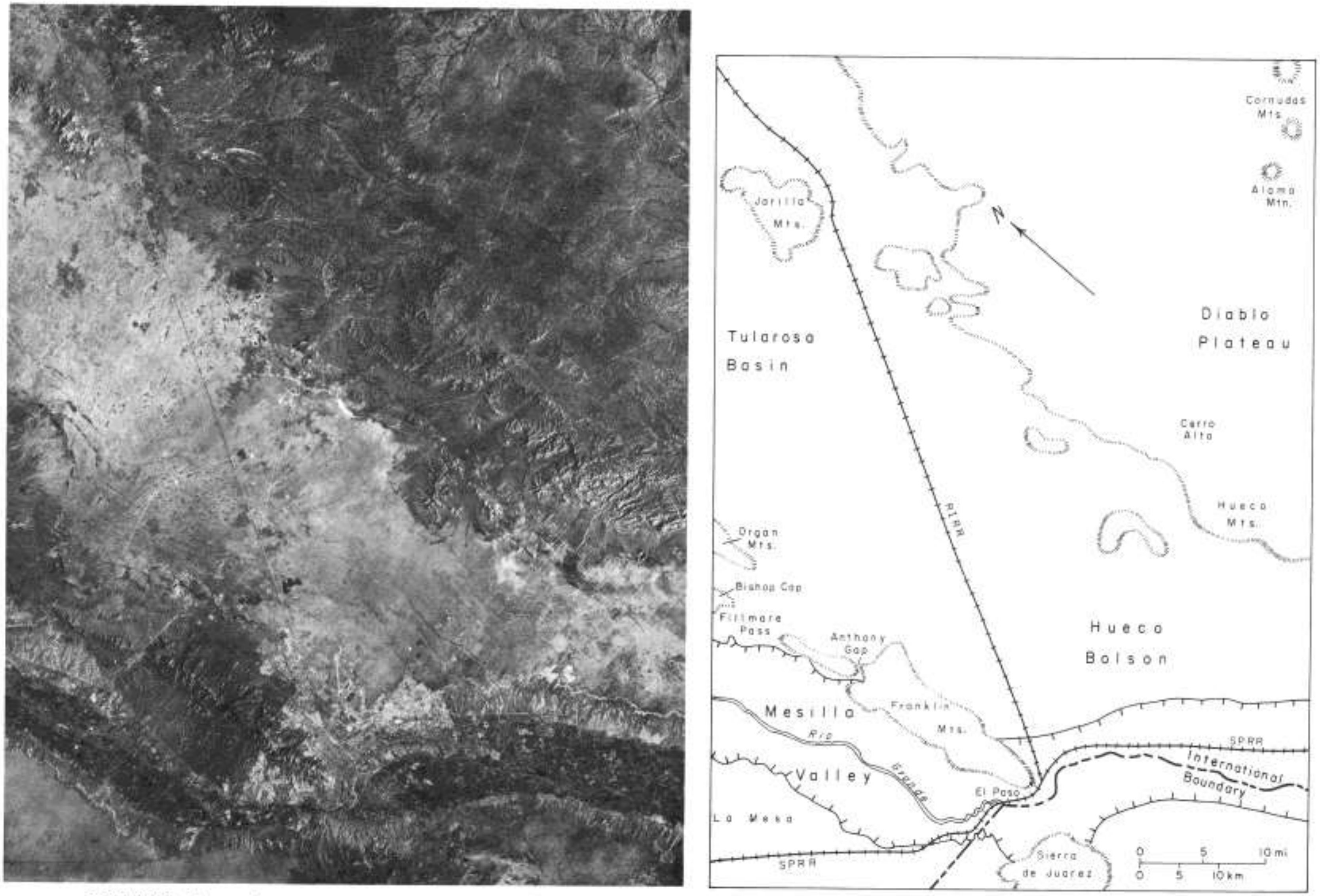


FIGURE S3—SKYLAB-4 PHOTO (a) AND INDEX MAP (b) OF THE FRANKLIN MOUNTAIN-HUECO BOLSON-HUECO MOUNTAIN REGION (photo SL4-92-025 courtesy of Technology Application Center, University of New Mexico; photo scale approximately same as map scale).

bouching from Fusselman Canyon at 9:00 interfingers with and overlies the Camp Rice fluvial facies that was deposited when the ancestral Rio Grande flowed east of the Franklins. **2.0**

12.5 *Turn left (west) onto Trans-Mountain Highway. CAUTION! Dangerous intersection ahead.* **0.1**

12.6 *Cross Gateway South. WATCH FOR TRAFFIC!* **0.3**

12.9 Wilderness Park Museum and Stop S1a ahead on right. Piedmont fault scarps at 2:00; top of ridge at 10:00 is uplifted pediment remnant on Red Bluff granite. **0.2**

13.1 STOP Sla (optional), Wilderness Park Museum. Parking area to right; orientation point for Fusselman Canyon area of Franklin Mountains, Eastern Boundary fault zone, and Hueco Bolson (figs. S3-S4).

To the east across bolson are the Hueco Mountains, which form a highland belt capped by Permian carbonate rocks (Hueco Formation) along the western margin of the Diablo Plateau. The high peak in the northern Huecos is Cerro Alto, a middle Tertiary syenite intrusion. Similar syenite intrusions in the Diablo Plateau about 25 mi (40 km) east of Cerro Alto have K-Ar ages in the 32-35 m.y. range (Barker and others, 1977). The Sacramento Mountains far to the northeast form the eastern edge of the Basin and Range structural province (Mexican Highlands section of Basin and Range physiographic province). South of the Sacramentos the edge of the structural province shifts eastward about 60 mi (100 km) to the east side of the Salt Flats graben between the Hueco-Diablo Plateau and Guadalupe-Delaware uplifts.

The crest of the Franklins on the northwest skyline, near Anthony's Nose, is formed on Fusselman Dolomite (Silurian). To the west, North Franklin Mountain, also called Cabeza de Vaca Peak, elevation 7,192 ft (2,192 m), and capped with Precambrian rhyolite, forms the high point of the range as well as the highest structural point in Texas (Adams, 1944; Harbour, 1972).

The Fusselman Canyon area, extending southwest of this point, contains "the most complete and least metamorphosed section of Precambrian rocks in west Texas and southern New Mexico" (McAnulty, Jr., 1968, p. 59). The sequence of Precambrian rocks is more than 4,500 ft (1,370 m) thick. It includes, from oldest to youngest: the Castner (Marble) Limestone, 1,300 ft (400 m) thick; the Mundy (basalt) Breccia, 200 ft (60 m) thick; the Lanoria Quartzite, 2,000 ft (600 **m)** thick; and an unnamed (Thunderbird) rhyolite porphyry unit, 1,000 ft (300 m) thick. Two Precambrian silicic intrusions—porphyritic microgranitic and granite—and numerous diabase dikes and sills intrude the sedimentary and extrusive igneous rocks (McAnulty, Jr., 1968, p. 59). According to Denison and Hetherington (1969), the intrusive Red Bluff granite and the rhyolite porphyry were emplaced essentially contemporaneously. K-Ar and Rb-Sr ages determined for these units are in the 950-1,000 m.y. range. Refer to McAnulty, Jr. (1968), Denison and Hetherington (1969), and Harbour (1972) for a more detailed guide to Precambrian rocks of the North Franklin Mountain-Fusselman Canyon area.

North and south of this point are piedmont scarps that mark offsets in upper Santa Fe Group and younger alluvium along the Eastern Boundary fault zone. Intertonguing of Camp Rice piedmont and fluvial facies occurs in upthrown blocks 5-10 mi (8-16 km) north of here near the state line. Hawley estimates that fluvial-facies offset is about 330 ft (100 m) in the state-line area. The floor of Hueco Bolson, extending eastward from a point about 2 mi east of here, is a broad alluvial plain constructed by the ancestral Rio Grande prior to its shift to the southern Mesilla Bolson in early Pleistocene time. The surface is locally modified by elongate (north-south) swales and depressions of combined structural subsidence and erosional (water and wind) origin. Numerous shallow excavations in the western bolson floor expose gravelly sands of the Camp Rice fluvial facies beneath a surface veneer of caliche and dune sand. The surficial gravelly zone grades downward and eastward first into sand and then into interbedded clay and sand (Cliett, 1969). The gravelly sand-to-sand sequence is as much as 1,500 ft (450 m) thick in this (western) part of the bolson and is the major aquifer in the area. The basal sand zone is greater than 1,000 ft (300 m) thick. This zone and transitional sand-and-clay beds to the southeast are interpreted by Hawley as being the distal part of a fluvial-fan to delta sequence built into a subsiding basin by the ancestral Rio Grande, primarily in Pliocene time. This unit is correlated with the Fort Hancock Formation of Strain (1966, 1971).

Interpretations by Mattick (1967) and Cliett (1969) indicate that near the west edge of the bolson the Hueco Limestone lies beneath about 9,000 ft (2,750 m) of bolson fill in the belt of thick (upper Santa Fe) fluvial-deltaic deposits. The lower 7,500 ft (2,300 m) is tentatively correlated with the lower Santa Fe Group (Miocene). This correlation puts the base of the fill in this part of the bolson at approximately 5,000 ft (1,525 m) below sea level. If the Hueco Limestone were replaced on the Franklin block, the projected elevation would be about 25,000 ft (7,625 m). Thus, total throw on the East Boundary fault zone is estimated to be about 30,000 ft (9,150 m). If the Camp Rice Formation—with an estimated age range (here) of 0.9-2.5 m.y.—is offset 400 ft (120 m), a constant-rate displacement of 30,000 ft (9,150 m) would have taken from 67-287 m.y. However, Lovejoy (Stop S 1 b discussion) suggests 50 m.y. as the probable date of inception of Eastern Boundary fault displacement. Following this line of speculation, the throw rate during the past million years is less than the Cenozoic rate.

Continue west up Trans-Mountain Highway. Road log in part from McAnulty, Sr. (1968). **0.5**

13.6 Red bluff granite in roadcuts and slopes ahead. **0.4**

14.0 Major roadcut. Vertical, greenish Castner Marble is intruded by granite, which in turn is intruded by diabase, aplite, and pegmatite dikes. **0.4**

14.4 High-level terrace gravels (Camp Rice? valley fill) in roadcut to right. **0.3**

14.7 Roadcut in Red Bluff granite on right. High terrace gravels ahead on left. Almost all of the Fusselman Canyon Precambrian sequence is exposed on mountain slopes west of this point. Lower bedded unit is Castner Marble, with Mundy (basaltic) Breccia form-

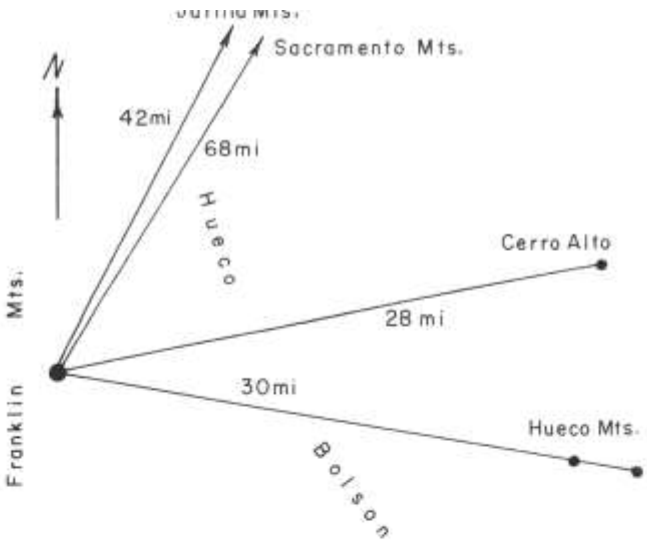


FIGURE S4—Panoramic index of features seen from Stop S1a, Wilderness Park Museum, at east foot of Franklin Mountains and west edge of Hueco Bolson.

ing the slope above the Castner. The massive cliff-forming unit is the Lanoria Quartzite. Thunderbird rhyolite caps North Franklin Mountain on skyline. **0.3**

15.0 Castner Marble in major roadcut on right exhibits many algal mounds and soft-sediment deformation structures. Fluidized breccia dike in Castner includes clasts of rock types not exposed in the range. **0.1**

15.1 Contact of Castner Marble and Mundy (basalt) Breccia on right at upper end of roadcut. High Lanoria Quartzite cliffs to west. **0.2**

15.3 Roadcut in dark-gray, porphyritic microgranite sill that cuts Lanoria Quartzite. **0.2**

15.5 Diabase dike cuts microgranite at southwest end of cut. High-level terrace gravels ahead on right. **0.2**

15.7 Lanoria Quartzite intruded by granite in roadcut on right. To the south (9:00) is Fusselman Canyon, eroded on the Fusselman Canyon fault (fig. S2b); stratigraphic separation is equivalent to the thickness of the Lanoria Quartzite, about 1,500 ft (460 m) down on the south. The downthrown block is the Taylor block, bounded on the east by the Eastern Boundary zone, on the northwest by the Fusselman Canyon fault, and on the southwest by the McKelligon Canyon fault (fig. S2b). Richardson (1909) and Harbour (1972) considered the McKelligon Canyon-Fusselman Canyon fault to be a continuous, open-U-shaped fault. As interpreted by Lovejoy, the McKelligon Canyon fault continues through the range to the Western Boundary zone but with very small throws; the Fusselman Canyon extension is downthrown on the northwest. According to Lovejoy (1975b), the Taylor block may be the largest landslide block in the range. This block was originally outlined by small-throw, oblique, normal dip-slip faults, which provided loci of slip during range uplift. **0.2**

15.9 Across the canyon at 9:00 is base of the Thunderbird rhyolite. Roadcut on right in Lanoria Quartzite. High-level terrace gravels on quartzite ahead on right. **0.4**

16.3 Roadcut on right in high terrace gravels. Across valley at 9:00, note Paleozoic (Bliss Sandstone) contact on Precambrian rock. **0.5**

16.8 Upper end of high-level terrace gravels (Camp Rice? valley fill) to right and left. Canyon to south, through "gunsight" pass, is on the south-trending part of the Fusselman Canyon fault, downthrown to the east about 1,500 ft (460 m); terrace gravels at left cover the fault. At 12:00 is the Smuggler's Gap roadcut in Thunderbird rhyolite. Lanoria Quartzite-Thunderbird contact in slope at 4:00 across arroyo. **0.4**

17.2 Smuggler's Gap pass, elevation 5,250 ft (1,600 m); high roadcuts in Thunderbird rhyolite. *Slow* for scenic view turnout to left. **0.2**

17.4 Scenic view turnout west of Smuggler's Gap (figs. S1-S3). Mesilla Valley of the Rio Grande, in middle distance to west, is cut about 330 ft (100 m) below the broad floor of Mesilla Bolson (La Mesa geomorphic surface). This surface extends about 20 mi (32 km) farther west to the Potrillo Mountains. To the south are the Sierra de Juarez and Cerro de Cristo Rey (fig. S2a). The small hills in the southwest foreground, east of the Mesilla Valley, are the Three Sisters, andesite intrusions of mid-Eocene(?) age aligned about N. 20° W. The low hills in the closer foreground are remnants of Hueco Limestone considered by Harbour (1972) to be in place, but by Lovejoy (1975b) to be landslide block remnants. Structural features of the Franklin west slope will be discussed at Stop S1b in Tom Mays Park about 3 mi north of this point. **0.6**

18.0 End of Thunderbird rhyolite outcrop to right. Lower E1 Paso Group carbonates crop out ahead; cream-colored rock is a lower to middle Tertiary felsite sill. **0.3**

18.3 End of roadcut exposures of bedrock. Caliche-cemented piedmont gravels of the Camp Rice Formation, primarily derived from Thunderbird rhyolite, crop out in most of cuts downslope. **0.1**

18.4 Route is probably on buried trace of Western Boundary fault zone. No evidence of scarp is found in gravels here, but about 2 mi north of here an old alluvial fan contains a piedmont fault scarp several meters high. **0.5**

18.9 Yellow shale and white limestone in small outcrop beneath gravels is probably Del Norte Formation (lower Cretaceous). **0.4**

19.3 End of roadcuts in rhyolite-derived piedmont gravels. Sweeping curve to left ahead. Anticlinally folded beds to north (1:00) are in Permian Hueco Limestone west of Western Boundary fault zone. The fold axis trends northwesterly, and the axial plane has a steep north-easterly dip. Triangular, light-gray outcrop on range front to east (4:00) is an infaulted block of lower E1 Paso Group carbonates with Thunderbird rhyolite around it. **0.3**

19.6 *Caution!* Prepare for sharp right turn ahead. **0.2** 19.8 Junction; *make sharp, 180° turn to right* into Tom Mays Memorial Park. **0.5**

20.3 An exposure of Western Boundary fault zone to right, not visible from road, shows Thunderbird rhyolite against breccia of Paleozoic rocks. Major fault plane dips 45° E. in an exposure 50 ft (15 m) high. **0.3**

20.6 Hueco Limestone outcrops to left and right in arroyo. **0.1**

20.7 Vertical dips of Hueco Limestone beds at 9:00 to 10:00 change to gentle dips on ridge summit at 10:30. Movement of this rock mass thus appears to have been from northeast to southwest. Structure is interpreted by Harbour (1972) as Laramide overturned folding and is interpreted by Lovejoy (1975b) as the result of landsliding. **0.3**

21.0 Route on high-level alluvium that covers trace of Western Boundary fault zone; Hueco Limestone to left; lower E1 Paso Group carbonates on range front at 3:00. **0.8**

21.8 **STOP S1b, Tom Mays Memorial Park.** Shelterhouse parking area at north end. *Walk south from shelter to crest of Hueco Limestone ridge,* elevation 5,150 ft (1,570 m). Discussions at this stop emphasize structural features in the southern Mesilla Bolson and western slope of the Franklin Mountains (figs. S1, S2, S5, and S6). Detailed tour guides to the Mesilla Bolson area are included in Hoffer (1973) and Seager, Clemons, and Callender (1975). Concluding discussions at this stop by Lovejoy and Seager, and by Keller, Graham, and Roy summarize results of recent geologic and geophysical investigations in the region.

Anthony Gap, located about 6 mi (10 km) north of this stop, is at the New Mexico-Texas State line (latitude 32° N.). The gap separates the main southern Franklin mass from the low mountain ridge extending into New Mexico (fig. S2a). The high peak of the Franklins on the northeast skyline is Anthony's Nose, elevation 6,927 ft, (2,100 m), capped with Fusselman (Silurian) dolomite. North Franklin Mountain, elevation 7,192 ft (2,192 m), capped with Precambrian rhyolite, is the high point on the southeast skyline.

Rounded twin peaks to the west on the far side of Mesilla Bolson are Mts. Cox (south) and Riley (north), hypabyssal andesite to rhyodacite intrusions of mid-Eocene(?) age (Hoffer, 1976). The long ridge to the left of these peaks is formed by the East Potrillo Mountains, a west-tilted fault block of lower Cretaceous and Permian carbonate rocks (figs. S5, S6). Numerous small hills north of Mt. Riley are some of about 160 north-south aligned cinder cones of the West Potrillo Basalt field of Quaternary age (Hoffer, 1976). Younger basalts of the Potrillo field, the Afton and Aden Basalts (upper Pleistocene) of Hoffer, spread out over a large area of bolson floor northeast of Mt. Riley. The Afton flows are cut by large craters of two maar volcanoes, Kilbourne and Hunts Holes. Two K-Ar whole-rock age determinations of a sample from the oldest Afton flow at Kilbourne Hole give dates of 0.141 (± 0.075) and 0.103 (±0.084) m.y. **(R.** E. Denison, Mobil Field Research Laboratory, FPL #1318). The younger Aden Basalts associated with a shield cone, Aden Crater, are dated as older than 11,000 years B.P. on the basis of carbon-14 dating of ground-sloth *(Nothrotherium shastense)* remains recovered from a fumarole in the crater (Simons and Alexander, 1964). In this guidebook, Renault presents an overview of basalts in the rift. The following discussion from Hoffer (1976) reviews important features of the Potrillo Basalts and compares them with the Santo Tomas-Black Mountain basalts (Hoffer, 1971) that locally spill into the Mesilla Valley about 20 mi (32 km) northwest of this stop.

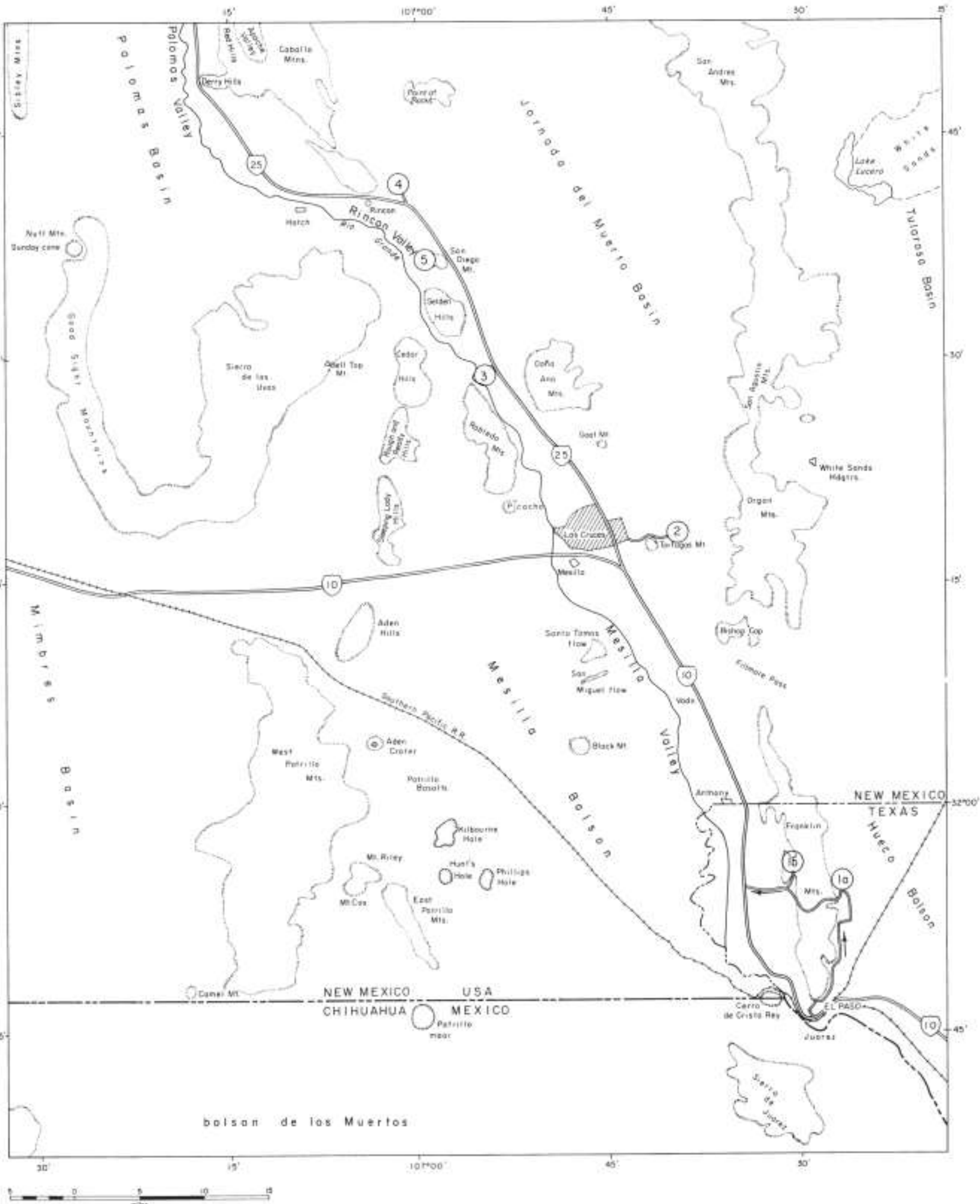
> The Potrillo Basalt is alkali olivine, typical of the type that occurs on the flanks of the Rio Grande rift to the north. Preliminary analyses of the lavas indicate that chemical and mineralogical variations correlate with tectonic setting across the field.
>
> Renault (1970) reported that the Potrillo Basalt is undifferentiated and the differences in TiO_2 correlate with structural setting; basalts on structurally higher rocks possess higher mean titanium concentrations than those on structurally lower rocks. This suggests that upthrown blocks have deep penetrating fractures, are under low compressive stress, and based upon the experimental system, MgO-SiO_2-TiO_2 would therefore allow higher concentrations of titanium in the associated basalts than in those associated with adjacent downthrown blocks (Renault, 1970). In addition to variations in titanium, the basalts show differences in sodium, potassium and phosphorous. . . .
>
> In the Potrillo Basalt, the West Potrillo Basalt and Santo Tomas-Black Mountains basalts are associated with upthrown blocks whereas the Aden-Afton Basalts lie in a graben. The basalts erupted in the depression are lower in total alkalies and P2O, than those on the outside of the graben. TiO2 concentration correlates from the west side into the rift, but not across the east side. The reason for these variations from the typical sequence appears to be due to differentiation of the Santo Tomas-Black Mountain basalts. The Solidification Index of each group of lavas indicates that the West Potrillo Basalt and Aden-Afton Basalts are undifferentiated. The mineralogy of these two basalts is similar, and differences in chemistry correlate with structural setting across the rift. However, the much lower Solidification Index and much higher total alkalies of the Black Mountain-Santo Tomas basalts indicate some differentiation before eruption at the surface.
>
> Regardless of these inconsistencies, it appears that variations in chemistry of the Potrillo Basalt correlates moderately well with tectonic environment and are typical of other rift valleys (Hoffer, 1976, p. 25).

The Mesilla Bolson west of this stop has two major geomorphic subdivisions: 1) Mesilla Valley of the Rio Grande in the foreground and 2) the broad bolsonfloor remnant lying about 330 ft (100 m) above the valley floor and extending west to the Potrillo Mountains. The river valley is a middle to late Quaternary erosional feature cut during several major episodes of Rio Grande entrenchment. Times of widespread valley incision seem to correlate with Pleistocene glaciations in the southern Rocky Mountain headwaters area. Kottlowski's (1958) Kern Place, Gold Hill, and low-terrace sequence of valley-border surfaces in the E1 Paso area correlates with Ruhe's (1964) Tortugas, Picacho, and Fort Selden sequence near Las Cruces. These surfaces are graded to temporary base levels formed during interglacial intervals (like the Holocene) of floodplain stability or slow aggradation.

The Tortugas-Kern Place and Picacho-Gold Hill base levels are estimated to have been about 115-150 ft (34-45 m) and 70-90 ft (21-27 m) respectively above present floodplain level (Hawley, 1965; Hawley and Kottlowski, 1969). The bulk of terrace and arroyo-fan deposits associated with the Tortugas-Kern Place and Picacho-Gold Hill surfaces probably dates from pre-Wisconsinan late-Pleistocene time. The Picacho-Gold Hill surfaces stabilized in early Wisconsinan time (Hawley, 1975b). Correlation of Quaternary units in the Rio Grande rift region is shown in Hawley, Correlation Chart 1 (p. 238).

The Mesilla Bolson floor, La Mesa geomorphic surface of Ruhe (1964), was constructed by the ancestral Rio Grande during final depositional stages of the

FIGURE S5—APOLLO-6 PHOTO (a) AND INDEX MAP (b; AT RIGHT) OF THE SOUTH-CENTRAL NEW MEXICO REGION IN AND AROUND DOÑA ANA COUNTY (photo scale approximately same as map scale; adapted from Seager, Clemons, and Callender, 1975).


Palomas Valley
Palomas Basin
Caballo Mtns.
Derry Hills
Point of Rocks
Jornada del Muerto Basin
San Andres Mts.
Lake Lucero
White Sands
Tularosa Basin
Hatch
Rincon
Rincon Valley
Rio Grande
San Diego Mt.
Selden Hills
Nutt Mts.
Sunday cone
Good Sight Mountains
Sierra de las Uvas
Cedar Hills
Doña Ana Mts.
Robledo Mts.
Goat Mt
White Sands Hdqtrs.
Organ Mts.
Picacho
Las Cruces
Tortugas Mt
Mesilla
Aden Hills
Santo Tomas flow
San Miguel flow
Mesilla Valley
Mesilla Bolson
Bishop Cap
Fillmore Pass
Vado
Southern Pacific R.R.
Aden Crater
West Potrillo Mts.
Potrillo Basalt
Black Mt
Anthony
Mimbres Basin
NEW MEXICO
TEXAS
Hueco Bolson
Franklin Mts.
Kilbourne Hole
Mt. Riley
Hunt's Hole
Phillips Hole
Mt. Cox
East Potrillo Mts.
Camel Mt.
NEW MEXICO USA
CHIHUAHUA MEXICO
Potrillo maar
Cerro de Cristo Rey
EL PASO
Juarez
Sierra de Juarez
bolson de los Muertos
25
4
5
3
2
10
1a
1b
107°00'
45'
30'
15'
32°00'
miles

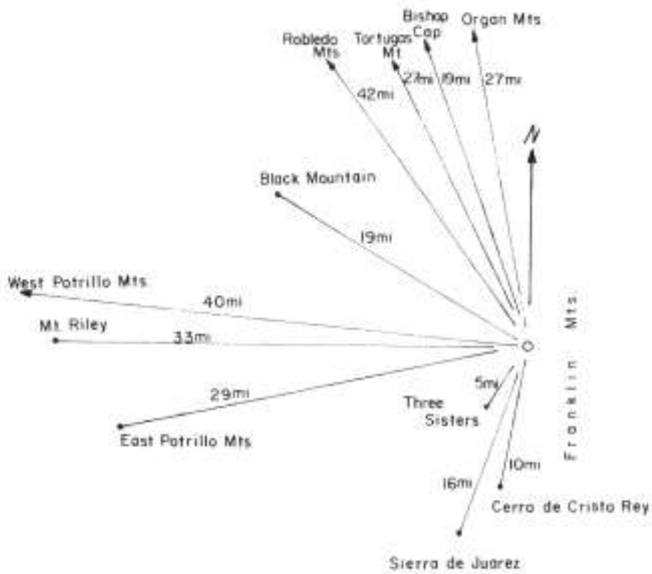


FIGURE S6—PANORAMIC INDEX OF FEATURES SEEN FROM STOP S1b, TOM MAYS PARK, in western foothill belt of Franklin Mountains overlooking the Mesilla Bolson.

Camp Rice Formation in early to middle Pleistocene time. Piedmont slopes graded to the La Mesa surface have been designated the Jornada geomorphic surface by Ruhe (1964) and the La Mesa pediment by Kottlowski (1958). High-level piedmont gravels at Anthony Gap, which are associated with the Jornada-La Mesa complex, overlap bolson fill with lenses of volcanic ash. Preliminary work by Izett and Naeser (1976) on samples from this air-fall deposit indicates that it is derived from the eruption of Long Valley caldera (Mono County, California) that produced the Bishop tuff (Bailey and others, 1976). This event is dated at about 0.7 m.y. ago (Izett and Naeser, 1976). Olivine basalts of the Santo Tomas-Black Mountain field, about 20 mi (32 km) to the northwest on the opposite side of the valley (figs. S5 and S6), cap an older surface of the valley-border sequence possibly correlative with the Kern Place surface at E1 Paso (miles 0.7-2.0). These basalts, as well as the olivine basalts of the Afton (central Potrillo) field, have K-Ar ages in the 0.226-0.026 m.y. range (Hoffer, 1971, 1973, 1976). Thus, the time of initial trenching of the lower Mesilla Valley is bracketed between the 0.7-m.y. ash fall and the earliest extrusion of valley basalt 0.2 to 0.25 m.y. ago. Previously mentioned studies of vertebrate faunas (Strain, 1966, 1969a; Hawley and others, 1969, 1976) indicate that youngest Camp Rice deposits are of early and middle Pleistocene (Irvingtonian provincial) age.

Logs and cuttings from deep water wells and oil-test wells in the southeastern Mesilla Bolson (Cliett, 1969; King and others, 1971; Thompson and Bieberman, 1975; Uphoff, 1978) show an upper Santa Fe fill sequence similar to that described in the northwestern Hueco Bolson at Stop S1a. The Camp Rice-Fort Hancock fluvial-deltaic sequence in the Texas part of the Mesilla Valley is as much as 1,500 ft (450 m) thick and comprises a major aquifer system utilized by E1 Paso (Cliett, 1969). However, in possible contrast with the Hueco Bolson, maximum thickness of Santa Fe beds in the Mesilla Bolson probably does not greatly exceed 3,300 ft (1,000 m) (King and others, 1971). Furthermore, the Santa Fe is demonstrably underlain by a very thick sequence of middle Tertiary volcanic and volcaniclastic rocks and lower Tertiary sediments. According to Uphoff (1978), a deep oil test (Grimm et al. No. 1 Mobil 32; sheet 2, hole b) in the central bolson area about 25 mi (40 km) northwest of here penetrated the following Cenozoic sequence, which was 12,800 ft (3,900 m) thick: 1,920 ft (586 m) of Santa Fe "valley fill"; 3,850 ft (1,174 m) of rhyolitic to andesitic volcanics and volcaniclastic rocks; and 7,030 ft (2,144 m) of lower Tertiary sediments, including red beds with a basal 700-ft (213-m) zone of gray sands and shales with coal stringers above Cretaceous rocks. At the total depth of 21,759 ft (6,632 m) the well was in the lower Montoya Group, only about 150 ft (46 m) above the top of the El Paso (Thompson and Bieber-man, 1975, p. 173). Estimated depth to Precambrian basement is 22,380 ft (6,821 m) or an elevation of 18,160 ft (5,535 m) below sea level (Foster, this guidebook, hole b). Subsurface data from both bolsons flanking the Franklins (Stop. Sla) illustrate the great relative (as well as absolute) structural relief of the area.

DISCUSSION OF STRUCTURAL GEOLOGY OF FRANKLIN MOUNTAINS

by E. M. P. Lovejoy, *University of Texas at El Paso, El Paso, Texas*
and
W. R. Seager, *New Mexico State University, Las Cruces, New Mexico*

The Franklin Mountains (fig. S4) have long been considered a classic example of a late Tertiary fault block (Richardson, 1909; Dunham, 1935; King, 1935; Harbour, 1972). Recently Lovejoy (1972, 1974, 1975a, b) suggested that uplift of the Franklins was largely accomplished in the Paleogene and continues with diminishing effect to the present. This interpretation is based partly on the following reasoning. The rate of throw on the Eastern Boundary fault is estimated to have been 120 m per million years in Pleistocene time. Because the total throw on the fault is about 30,000 ft (9,000 m), inception of faulting (assuming linear throw rate) is calculated to be about 75 m.y. However, Lovejoy suggests 50 m.y. as the probable inception date because throw rate was not linear and deformation did not begin until Cenozoic. Also, Lovejoy (1976d) shows that north-trending reverse faults and folds were deflected by the emplacement of the 47m.y.-old Cristo Rey andesite pluton, and he considered the northeasterly translated Sierra de Juarez multiple allochthons to have impacted against a nascent Franklin Mountains block.

Using these observations, Lovejoy (1975b) was the first to hypothesize an evolution of the Franklin Mountains. He suggested that the Franklin Mountains block was squeezed up, mostly in the Paleogene, between inward-dipping, high-angle, range-bounding reverse faults by regional (plate-tectonics-induced?) crustal compression. Later Lovejoy (1977a, b, 1978) modified this view and considered the western boundary fault to be an upthrust, the eastern to be reverse, and both to be penetrating the crust into the mantle. The base of the crust thus displaced formed a sub-range crust-mantle reentrant in which rising mantle magma globules accumulated during crust-mantle relative shear. The range rose as the result of this magma-induced, buoyant, isostatic pressure and because of continued crustal compression. Heat-induced and pressure-produced plasticity and penetrative micro-shearing in the range block infrastructure was accompanied by both horizontal constriction and vertical expansion, producing supra-crustal uplift and "trapdoor" tilting; the range was squeezed and buoyed up and out plastically at depth and at the surface. Therefore, according to Lovejoy, the Franklins were mostly uplifted in the Paleogene, are totally unrelated to the Rio Grande rift (which transects their structure), and have both history and structure representative of all the ranges of the Basin and Range province (Lovejoy, 1977a, b; 1978).

Other workers in New Mexico and west Texas disagree with the view that the fault-block mountains in this region date from the Laramide. These reservations are based on three kinds of data: 1) Unequivocal Laramide structures (angularly unconformable beneath middle Tertiary rocks) often trend obliquely to and are truncated at the present range fronts. These structures generally are of a completely different tectonic style from the late Tertiary fault blocks; in some cases they have been eroded to moderate or low relief by late Eocene time and segmented by block faulting 15-30 m.y. later. 2) Late Eocene and Oligocene volcanic centers apparently reflect no regional stress field until later than 30 m.y. ago (Chapin, 1974, 1975), and ash-flow tuff sheets as young as 30 m.y. failed to encounter any significant topography other than volcanic edifices over thousands of square kilometers. These sheets remained undeformed until early Miocene time or later (Chapin and Seager, 1975). 3) Bolson fanglomerates, associated with large normal faults and extensive basaltic lava flows and their vents, appear in the stratigraphic record relatively suddenly, between 20 and 28 m.y. ago. These are interpreted by many to mark the beginnings of the extensional regime responsible for the present fault-block topography. Further discussions of these points will compose important parts of the next several stops.

All evidence for Laramide deformation in the Franklin Mountains is ambiguous. "Thrust" relations (Permian over Cretaceous), typical of Laramide deformation in the Chihuahua tectonic belt, are reported in a drill hole northwest of this stop, but are interpreted by Lovejoy (1975a, b) to result from large-scale gravity sliding off the west slope of the range. Harbour (1972) regarded several low-angle "thrusts" and associated folds as evidence of an "early compressional phase" of tectonism in the Franklins. Lovejoy (1975a) convincingly showed that these thrusts and folds could be more easily understood as gravity-driven low-angle normal faults and drag folds that moved rocks down the western dip slope of the range. The Western Boundary fault and its associated flexures certainly resemble Laramide upthrusts geometrically, but they have not been more precisely dated than post-Lower Cretaceous, pre-late Pliocene. However, similar faults and folds in the Organ range are older than 32 m.y. Such high-angle reverse faults have been noted in many of the ranges of central New Mexico and generally have been interpreted as borders to Laramide block uplifts (Reiche, 1949; Woodward and others, 1972; Seager, 1975b; Kelley, 1977). These Laramide uplifts, however, are regarded as ancestral to—but not genetically related to—the present fault blocks by most workers. Chapin (1971) and Chapin and Seager (1975) point out, however, that the Laramide and older structural grain greatly influenced the location and trends of late Tertiary uplifts and basins in the Rio Grande rift. If the Franklin Mountains had a Laramide ancestor, which seems likely but has not been proven, part of the structural height of the Franklins clearly would be relict from that time.

While many geologists have no trouble accepting the Franklin range as late Tertiary in age, there is general disagreement about whether the Franklins are part of the Rio Grande rift; that is, the statement "the Rio Grande rift extends into southern New Mexico, west Texas, and Chihuahua" is as steadfastly supported by some as it is loudly rejected by others. Some of the geophysical and geological evidence bearing on this controversy is summarized in the next section and at succeeding stops.

REGIONAL GEOPHYSICS OF THE SOUTHERN RIO GRANDE RIFT by G. R. Keller, R. G. Graham, and R. F. Roy,

University of Texas at El Paso, El Paso, Texas

From central New Mexico northward into southern Colorado, the Rio Grande rift is a well-defined feature both geologically and geophysically. However, extension of the rift southward into the E1 Paso-Las Cruces area (Chapin and Seager, 1975) is less clear geologically; at least in part, this is because the rift merges with the Basin and Range province in this region. Although additional data are needed (seismic data are particularly sparse), available geophysical data provide a good case for the extension of the rift at least as far south as the E1 Paso-Las Cruces area. Heat-flow data (Decker and Smithson, 1975; Reiter and others, 1975, 1978, this guidebook) clearly show that high heat-flow values associated with the rift to the north extend into the E1 Paso-Las Cruces area. A zone of anomalously high conductivity at depth (upper mantle and/or lower crust) has been found to extend all along the rift from southern Colorado to the E1 Paso-Las Cruces area (Schmucker, 1964, 1970; Swift and Madden, 1967; Porath, 1971; Gough, 1974; Towle and Fitterman, 1975; Pedersen and Hermance, 1976). A generalized heat-flow profile is shown on fig. S7. The boundaries of the zone of high conductivity are not well defined, but this zone generally coincides with the area of high heat flow. Gravity data (Mattick, 1967; Decker and Smithson, 1975; Ramberg and Smithson, 1975; Decker and others, 1975; Barrie, 1976; Keller and Covert, 1977; Bath and others, 1977; Ramberg and others, 1978) have been very useful in determining the general configuration of basins in the southern New Mexico-west Texas region. The general basin geometry, as derived by Ramberg and others (1978) from a profile along 32° north latitude (the Texas-New Mexico border), is shown in fig. S7.

The deeper crustal structure in the southern Rio Grande rift is poorly known. A preliminary unreversed profile across the area by McCullar and Smithson (1977) indicates the crust is 27 km thick in the Las Cruces area. Surface-wave data (Keller and others, 1976) show the crust to be approximately 30 km thick in southern New Mexico, but these data cannot resolve any difference between Basin and Range and Rio Grande rift crust. Modeling of regional gravity anomalies (Decker and Smithson, 1975; Ramberg and others, 1978) suggests that the crust thins under the southern rift. A profile from Ramberg and others (1978) is shown in fig. S7.

Retrace route to Trans-Mountain Highway. **2.0**

23.8 *Rejoin Trans-Mountain Highway; continue west* toward Mesilla Valley. Route crosses remnant of high alluvial-fan surface graded to ancestral-river base

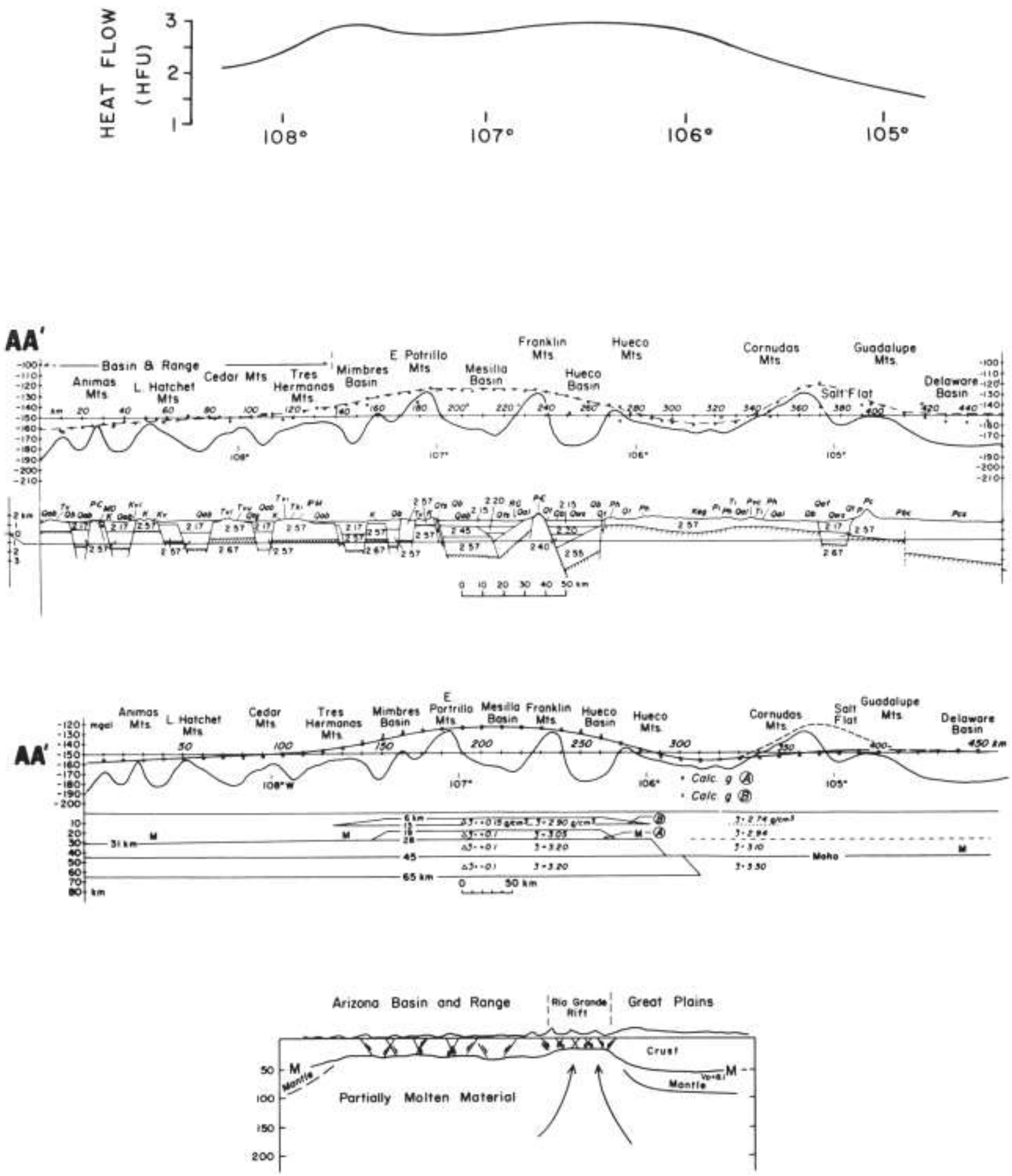


FIGURE S7—GENERALIZED HEAT-FLOW PROFILE, GRAVITY PROFILES SHOWING BOTH SHALLOW AND DEEP STRUCTURE INFERRED FROM COMPUTER MODELING, AND INTERPRETATIONAL MODEL OF THE CRUST AND UPPER MANTLE along 32° north latitude, the Texas-New Mexico border (gravity profiles and interpretational model modified from Ramberg and others, 1978, with permission).

level at least 330 ft (100 m) above the present valley floor. This piedmont slope is correlated with La Mesa pediment of Kottlowski (1958) in the E1 Paso area and with the Jornada I geomorphic surface in the Las Cruces area (Stop S2). These late mid-Pleistocene piedmont surfaces appear to be graded to younger parts of the La Mesa bolson-floor complex. Constructional phases of the Jornada I surface are associated with alluvial-fan and pediment-veneer deposits of the upper Camp Rice piedmont facies. 1.1

24.9 Route descends stepped sequence of middle to late Quaternary valley-border surfaces that are associated with at least three major intervals of river entrenchment and subsequent local base-level stability. Metcalf (1969) correlates surfaces in this area with the Kern Place-Tortugas, Gold Hill-Picacho and low-terrace-Fort Selden sequences discussed at Stop S1b. 0.8

25.7 Pipeline road; outcrops of Camp Rice Formation along pipeline to north show intertonguing of axial-river and piedmont-slope facies. 1.3

27.0 *Turn right onto I-10 approach ramp; continue north* on 1-10. 2.8

29.8 Anthony's Nose at 3:00; well-bedded units at base of Franklins are Mississippian and Pennsylvanian carbonate rocks. 0.7

30.5 Underpass; Vinton interchange. 0.5

31.0 Border Steel rolling mill on left. Organ Mountains on skyline at 12:00. 1.1

32.1 La Tuna Federal Correctional Institution at 9:00. Well-bedded carbonate rocks in foothills at 2:30 are Hueco Limestone (Permian) forming west limb of south-plunging syncline discussed at Stop S1b. This is the Anthony "landslide" block of Lovejoy (1975b). 0.6

32.7 Texas Tourist Information Bureau on west side of highway. 0.3

33.0 Anthony exit. Camp Rice fluvial facies, with thin eolian and colluvial veneer, forms low hills on right and crops out in roadcuts ahead. 0.5

33.5 New Mexico-Texas State line. End of road log for Texas leg of tour.

NEW MEXICO-TEXAS STATE LINE TO ELEPHANT BUTTE RESERVOIR

by J. W. Hawley and W. R. Seager

This log is compiled in part from logs in Seager, Clemons, and Callender (1975, p. 30-68). Fig. S8 shows major structural features of the area traversed. Fig. S9 shows gravity and elevation profiles along the 32nd parallel, crossed by the tour route at the start of this log. Cross-state profiles of New Mexico, taken from Cordell (1978), are included in the guidebook at or near points where the tour route crosses each degree of latitude.

33.5 New Mexico-Texas State line; *continue north on 1-10.* 0.3

33.8 New Mexico Tourist Information Center and rest area to right. Anthony Gap at 3:00. Trenches cut for natural gas pipeline just northwest of gap expose high-level Camp Rice piedmont deposits with interbedded volcanic ash. As mentioned at Stop S1b this rhyolitic ash may have been derived from the eruption 0.7 m.y. ago of the Long Valley caldera near Bishop, California. Towards the basin, the piedmont deposits overlap and intertongue with Camp Rice fluvial beds. This facies change can be seen in the valley-rim bluffs about 2.5 mi east of 1-10. From here to Las Cruces (next 22 mi) the route is mainly on valley-border surfaces of Holocene age. Dune sand, arroyo channel fill, and Fort Selden alluvial-colluvial deposits form a thin cover on sandy Camp Rice (fluvial) strata. Remnants of gravelly arroyo-fan and river deposits associated with the Picacho surface (late Pleistocene) are locally present. 2.0

35.8 Milepost 162. Crossing E1 Paso Natural Gas pipeline. Northern Franklin range from 1:30 to 4:00, Webb Gap at 2:00. The apparent contorted bedding pattern on steep western dip slope of the range is an erosional pattern in well-stratified Pennsylvanian rocks and was not caused by folding (Kottlowski, 1960; Harbour, 1972). 1.6

37.4 Underpass, north Anthony interchange. 1.4

38.8 Milepost 159, opposite New Mexico Port of Entry stations. Fillmore Pass from 2:00 to 3:00, between Franklin and Organ Mountains, underlain by thick fill of late Pliocene-early Pleistocene Rio Grande (lower Camp Rice Formation), which once flowed through the gap into Hueco Bolson. 1.2

40.0 Road crosses culvert; north tip of Franklin Mountains at 3:00. Bishop Cap at 1:00 forms group of low peaks at southwest base of Organ Mountains, 1:00 to 2:00 on skyline. 2.8

42.8 Underpass, Vado interchange. Vado Hills ahead on right are the northernmost of a series of Eocene andesitic intrusions in the southern Mesilla Valley; these intrusions also include Cerro de Cristo Rey and Three Sisters (Assembly Point; Stop S1b; Garcia, 1970). The hills are the tip of a rock mass that projects through thick upper Santa Fe basin fill. 0.7

43.5 Quarry on right in andesite of Vado Hill. Small hills of andesite project through more than 330 ft (100 m) of basin fill in feedlot area ahead on left. 1.6

45.1 Feedlot on left. Bishop Cap, at 2:30, is the highest peak of a series of fault-block ridges of Paleozoic rocks that range in age from Ordovician to Pennsylvanian (Seager, 1973). The rocks form part of the southern rim of the Organ caldera discussed at Stop S2. 1.5

46.6 Underpass, Mesquite interchange. Low ridges ahead on right are remnants of a late Pleistocene (Picacho) alluvial fan spreading out from an arroyo valley cut in Camp Rice fluvial deposits. 1.5

48.1 Culverts at arroyo crossing on apex of large alluvial fan of Holocene age. Tilted mass of light-colored ash-flow tuff at 3:00 forms part of the Organ caldera fill. 0.9

49.0 Milepost 149. On west side of Mesilla Valley at 9:00, upper Pleistocene (about 180,000 years) basalt flows from the Santo Tomas center cap an older valley-border surface (Hoffer, 1971). The Santo Tomas cinder cone has nearly been obliterated by cinder-quarry operations. 1.0

50.0 Milepost 148. Fort Fillmore (1851-1862) ruins 1 mi to west near edge of floodplain. Route ahead through Las Cruces is on complex of upper Quaternary arroyo-fan deposits associated with the Picacho and Fort Selden geomorphic surfaces. Carbon-14 dates on charcoal recovered from deposits of tributary arroyo systems indicate that the river base level has been essentially stable for the past 7,500 (carbon-14) years, with expansion of arroyo-mouth fans taking place at the expense of river floodplain width (Hawley, 1975b). 2.4

52.4 Crossing Fillmore Arroyo. 1-25 entrance ahead. *KEEP RIGHT.* 0.6

53.0 *Bear right onto 1-25 northbound lane.* Soledad Canyon area of Organ Mountains at 3:00 on skyline. Tortugas Mountain at 2:00 is a segment of the west rim of Organ caldera, located about 1.5 mi west of Stop S2. 1.1

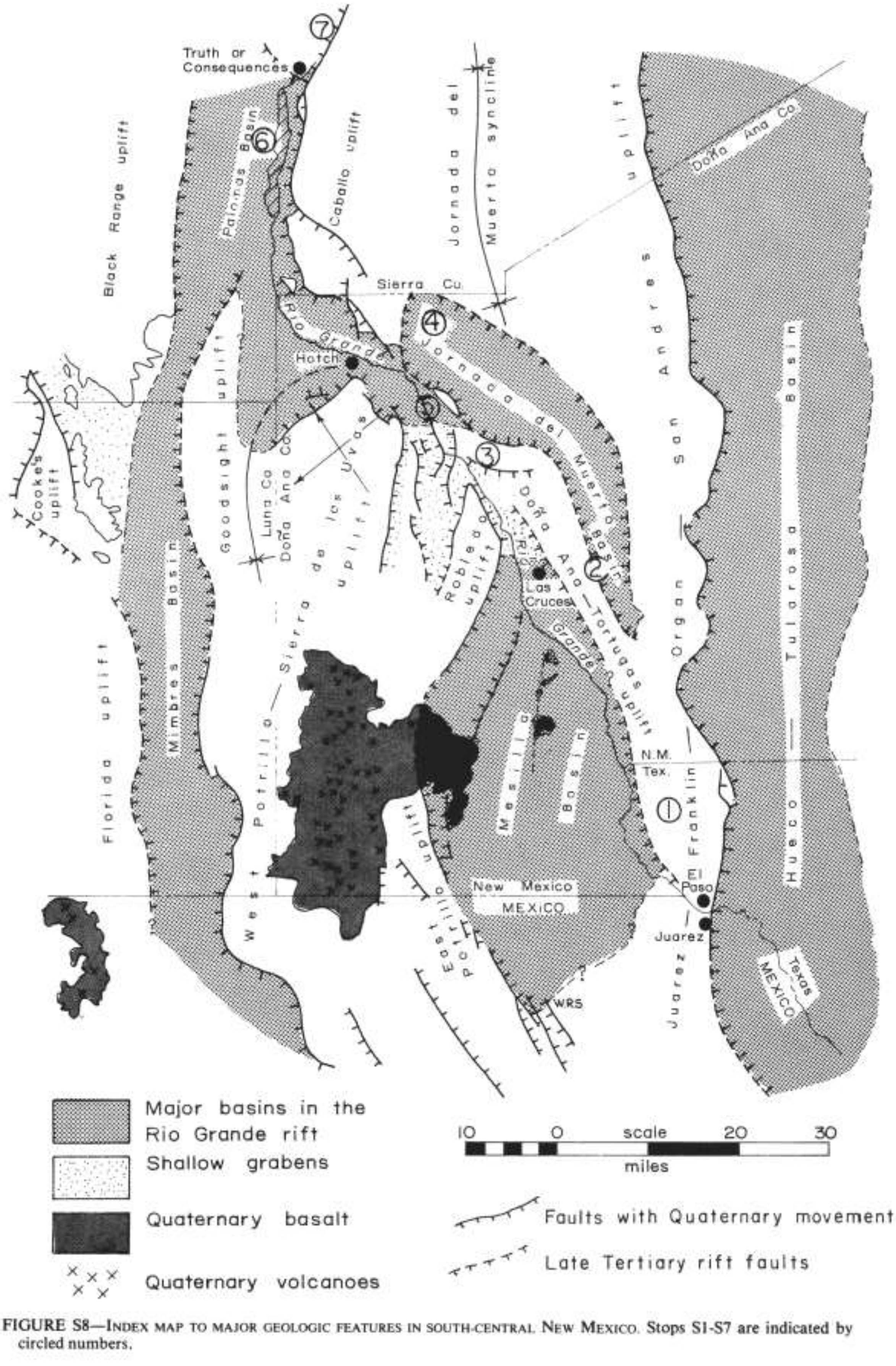


FIGURE S8—INDEX MAP TO MAJOR GEOLOGIC FEATURES IN SOUTH-CENTRAL NEW MEXICO. Stops S1-S7 are indicated by circled numbers.

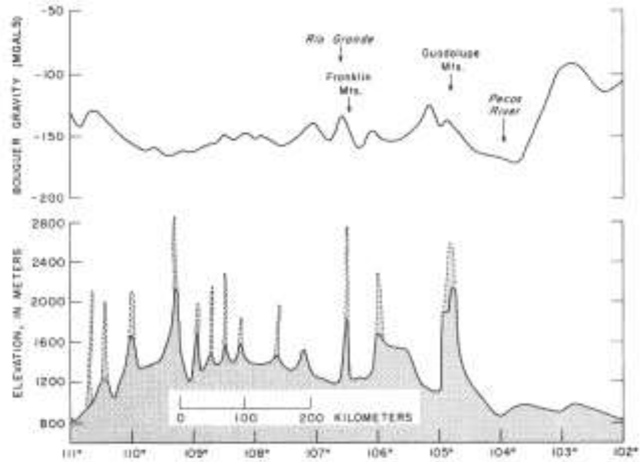


FIGURE S9—GRAVITY AND ELEVATION PROFILES ACROSS NEW MEXICO ALONG 32° NORTH LATITUDE, Texas-New Mexico border (source: Cordell, 1978, with permission).

54.1 Milepost 0 (1-25). Las Alturas subdivision on right. New Mexico State University campus ahead. A reasonably large area of hot water (200° C) at depth in this area has been outlined using geochemical and geophysical techniques (Swanberg, 1975). Geothermal resources of the area will be discussed at Stop S3. **0.9**

55.0 Crossing Tortugas Arroyo; solar energy research house on right adjacent to golf course. *Prepare to take next exit.* **0.2**

55.2 *Take Exit 1* to University Avenue (NM-101). **0.3**

55.5 Stop sign; *turn right (east) onto University Avenue.* **0.4**

55.9 End of pavement; *continue east* on graded Dripping Springs Road toward Tortugas ("A") Mountain. Route is on Picacho geomorphic surface, here a remnant of an alluvial fan at the mouth of Tortugas Arroyo Valley. This late Pleistocene surface grades up-valley to arroyo terraces that are inset below ridge remnants of Camp Rice fluvial gravel and sand facies. **0.5**

56.4 Route skirts north abutment of a Soil Conservation Service flood-and-sediment-control structure. **0.3**

56.7 Dip; Tortugas Arroyo channel. **0.4**

57.1 Ascend to Picacho alluvial terrace. Monzonite spires form high peaks of the Organs at 12:00. The ridge extending west from Tortugas Mountain, from 2:00 to 3:00, is capped with channel gravel and sand of the Camp Rice fluvial facies. The ancestral Rio Grande impinged high on the west slope of the mountain but did not swing east of it. **0.5**

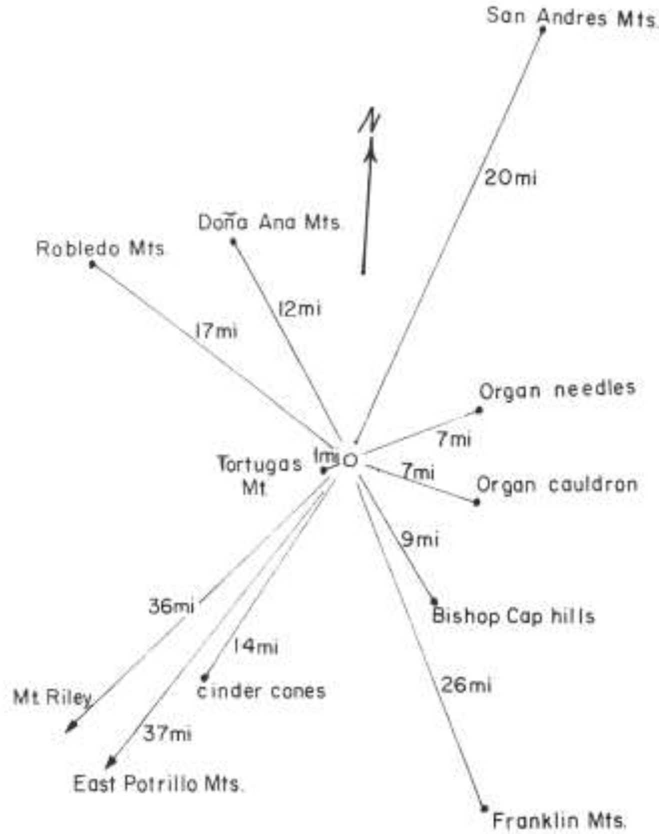


FIGURE S10—PANORAMIC INDEX OF FEATURES SEEN FROM STOP S2, EAST OF TORTUGAS MOUNTAIN AND AT WEST EDGE OF ORGAN CALDERA.

57.6 Road to Physical Science Lab research facility and Tortugas Mountain Observatory on right. *CAUTION! Blind curve ahead!* **0.4**

58.0 Sharp curve around north base of Tortugas Mountain. Outcrops on right of lower Permian or upper Pennsylvanian limestone, dipping west 20°. Route east of mountain continues on Picacho alluvial terrace. **1.5**

59.5 Cattle guard. Route ahead ascends from Picacho alluvial terrace to remnant of a high-level piedmont surface. **0.5**

60.0 **STOP S2, Tortugas Mountain and Organ caldera.** Dripping Springs Road at power-line crossing (figs. S5, S8, S10, and S11). Discussion of Organ caldera and adjacent parts of the Jornada structural basin by W. R. Seager and J. W. Hawley.

This area is the site of classic early studies by K. C. Dunham (1935). Detailed studies of Cenozoic stratigraphy and structure are currently in progress by

FIGURE S11—ORGAN MOUNTAINS VIEWED ACROSS SOUTHERN END OF JORNADA DEL MUERTO BASIN FROM TOP OF TORTUGAS MOUNTAIN. Stop S2 by power line in lower center. On left, Organ needles, elevation 9,012 ft (2,773 m), are carved on monzonite porphyry phase of the Organ batholith (32 m.y.). Peaks in center and at right are eroded on thick ash-flow-tuff deposits (32 m.y.) that accumulated in the Organ caldera (photo by L. F. Brown).

Seager, Hawley, and others. Tortugas Mountain and the Organ Mountains flank the southern tip of the Jornada del Muerto Basin. This complex structural basin extends northward more than 120 mi (190 km) between the Organ-San Andres-Oscura range on the east and several isolated uplifts on the west, including the Doña Ana, Caballo, and Fra Cristobal ranges.

Organ Needle, elevation 9,012 ft (2,747 m), on the northeastern skyline is the southernmost and highest of the series of spires cut on a quartz-monzonite porphyry (border) phase of the Organ batholith. The batholith extends north from and along the eastern edge of Organ caldera (Seager and Brown, 1978). Rocks deposited in the caldera form the southern part of the range between Organ Needle and Bishop Cap. The caldera, about 10 mi (16 km) in diameter, is a trap-door-style structure, hinged on the north and east, faulted at the south and west. About 9,000 ft (2,740 m) of ash-flow tuffs fill the caldera. These are exposed in the southern part of the range, where they dip about 35-45 degrees west. Seven sheets have been mapped. The lower five, which comprise the Cueva Tuff (32 m.y.) and the tuff of Cox Ranch, appear to be relatively widespread and only about 2,000 ft (600 m) thick; they are interpreted to be pre-caldera flows. The upper two sheets (tuffs of Achenbach Park and Squaw Mountain) are at least 7,000 ft (2,100 m) thick and probably are restricted to the caldera. Postcaldera basaltic andesite flows overlie the youngest tuffs within the caldera but were deposited on basal units of the sequence outside of the caldera along the eastern slopes of the range.

The Organ batholith (also 32 m.y. old) forms a very thick semi-concordant mass between the volcanics and Paleozoic or Precambrian rocks along the eastern side of the range. The similar age and compositions of the batholith and caldera fill suggest that the batholith represents the source of the volcanics; perhaps the batholith is an exposure of the magma chamber into which the tuff sequence foundered. Actually the batholith is somewhat more intermediate in composition (61-69 percent SiO_2) compared with the volcanics (73 percent SiO_2). Eruption of a silica-rich differentiate from the top of the magma chamber may explain the difference; but strontium isotope, geochemical, and petrographic studies are needed to evaluate the hypothesis.

The southern end of the Jornada del Muerto graben system is superimposed on the Organ caldera in this area. The graben is very shallow here, as indicated by gravity and drilling. A water well located about 1 mi (1.6 km) ahead bottomed in undetermined igneous rock at a depth of only 285 ft (84 m) (King and others, 1971). This stop is on a remnant of the Jornada geomorphic surface (Ruhe, 1964) that was once part of a broad piedmont plain graded from the Organ Mountain front to adjacent floors of the Mesilla and Jornada del Muerto Basins. This part of the Jornada surface predates entrenchment of the Mesilla Valley and is designated Jornada I (Gile and Hawley, 1968) because of its relatively great age, estimated to be more than 250,000 years (Hawley, 1975b; see Stop S1 discussion). Surfaces this old are characterized by very well developed soils, which in this region commonly have strong zones of carbonate accumulation within a few feet (1-2 m) of the ground surface. Rhyolite-derived fan gravels exposed in a shallow trench at this site are well cemented with secondary carbonate to form an indurated soil caliche or petrocalcic horizon.

Soil-geomorphic relationships have been intensively studied in the southern Jornada del Muerto area as part of the Soil Conservation Service Desert Project. The project involved studies by a soil-scientistgeologist team from 1957 to 1972 (Ruhe, 1967; Hawley, 1972, 1975a). The most notable contribution has been the pioneering research by soil scientist Leland H. Gile and associates on genesis and classification of horizons of carbonate and clay accumulation in soils of arid and semiarid lands. (Gile, 1961, 1975, 1977; Gile and Grossman, 1968; Gile and others, 1965, 1966). A field guide to Desert Project soil-geomorphic studies is in preparation as a New Mexico Bureau of Mines and Mineral Resources memoir.

Retrace route to University Avenue. **4.1**

64.1 Start of pavement. *Continue west on University Avenue* to 1-25 interchange; stop sign ahead at Tel-shore Blvd. 0.2

64.3 *Take 1-25 northbound access ramp.* 0.3

64.6 *Merge with 1-25 North.* The route for the next 4 mi is on sandy Camp Rice fluvial beds that are thinly mantled with upper Quaternary (Fort Selden-Picacho) valley fill including some eolian sand. 1.7

66.3 Underpass, Lohman Avenue interchange. Picacho fan remnant ahead on left with water tank. Mural on tank depicts Spanish colonization of New Mexico in 1598. Las Cruces Flood-Control Project structure (U.S. Army Corps of Engineers) on right for next 2.5 mi. 2.4

68.7 Crossing Alameda Arroyo, outlet channel for flood-control structure. 0.3

69.0 Underpass, US-70 interchange. Roadcuts here expose a veneer of Picacho fan gravel over sandy Camp Rice fluvial deposits. Logs of water wells and gravel-pit exposures 2 mi east of this interchange show the following Santa Fe section: upper, caliche-capped rounded gravel of mixed siliceous composition and sand, about 60 ft (18 m) thick; pebbly sand, partly calcite-cemented, with silt and clay beds, as much as 200 ft (66 m) thick; and basal, partly gravelly clay, loam, and sand, as much as 400 ft (130 m) thick, over andesitic volcanic rock. An early to middle Pleistocene vertebrate fauna *(Mammuthus, Equus,* and *Cuvieronius)* of Irvingtonian provincial age has been collected from the upper gravel-and-sand unit 1 mi to the east. At least the upper 260 ft (80 m) are Camp Rice Formation fluvial facies (Hawley and others, 1969; King and others, 1971). **0.8**

69.8 Route ahead is on thin, sandy alluvial and eolian deposits primarily associated with Holocene components of the Fort Selden valley-border surface. These sediments rest on a broadly undulating erosion surface cut in sandy Camp Rice deposits. **1.2**

71.0 Milepost 8. Picacho Mountain across valley at 9:00 is the exhumed root of a flow-banded rhyolite dome intruded through andesite-latite laharic breccia and other volcaniclastics of the Palm Park Formation (Eocene). Goat Mountain at 3:00 on the Jornada del

Muerto Basin rim is a mid-Tertiary microsyenite plug. **1.7**

72.7 Overpass, Doña Ana interchange. Picacho (upper Pleistocene) fan alluvium forms low ridges on right. Dona Ana Mountains on skyline at 1:00 to 2:00. The village of Doña Ana to the left is the oldest community in the Mesilla Valley. Dona Ana was permanently settled in 1843 as the administrative center for an 1839 Mexican land grant. 1.3

74.0 Milepost 11. The southern Robledo Mountains from 9:00 to 10:00 are a south-tilted horst capped by Lower Permian limestone and intertonguing red beds (Hueco-Abo units) that dip beneath a sequence of lower Tertiary sediments and Eocene volcaniclastic rocks near Picacho Mountain. The prominent piedmont platform extending along the base of the Picacho-Robledo block comprises Picacho and Tortugas members of the valley-border sequence, here graded to former base levels of about 70-90 ft (24-30 m) and 120-130 ft (37-43 m), respectively, above the present floodplain (Hawley and Kottlowski, 1969; Metcalf, 1967). For next 6.5 mi roadcuts are mainly in Picacho alluvium that exhibits complex intertonguing of arroyo-fan and river facies. Picacho and Tortugas deposits in the northern Mesilla Valley have been warped and faulted, most noticeably along the eastern fault-zone boundary of the Robledo-Picacho block, with offsets in the range of 10-100 ft (3-30 m). Major features of valley-filling units from here to mile 80.0 are shown in fig. S12. **2.5**

76.5 Overpass. At 3:00 western foothills of Dona Ana Mountains are composed of intrusive flow-banded rhyolite and a thick, massive, welded ash-flow tuff that fills the Doña Ana cauldron (about 35 m.y.). The dissected pediment at the foot of the mountains is cut mainly on ash-flow tuff. This erosion surface has been exhumed from beneath a Camp Rice Formation cover. The Doña Ana Mountains have been mapped by Seager and others (1976). **0.7**

77.2 Arroyo crossing; good view of central Doña Ana Mountains at 3:00. The northern and central parts of the mountains are largely underlain by a stock or sheet of upper Eocene andesite, with andesitic flows, laharic breccias, and other volcaniclastics dipping off its western flank. The stock may be the source of part of the Palm Park Formation, a major (upper Eocene) volcaniclastic and epiclastic unit in the Las Cruces-Caballo region. The southern, highest part of the range is carved on a partly exposed Oligocene cauldron complex about 6-8 mi (10-13 km) in diameter. An ash-flow tuff 2,500 ft (762 m) thick below Doña Ana Peak is associated with the eruption that initiated the cauldron cycle. Younger cauldron fill includes rhyolite flows and domes, bedded tuff and breccia, and ash-flow tuffs. The northwest edge of the cauldron, exposed east of here near the center of the range, consists of swarms of rhyolite, monzonite, and ignimbrite dikes that separate pre-cauldron (upper Eocene) rocks of the cauldron wall from ash-flow tuffs and associated rocks of its interior. **2.8**

80.0 Milepost 17. Mt. Summerford, the northern peak of the Doña Ana Mountains on east skyline, is the exposed part of a monzonitic to syenitic laccolith dated at 35 m.y. (Seager and others, 1976). 1.0

81.0 Milepost 18. *Prepare to exit to right ahead.* In arroyo to right, with dam, Picacho alluvium overlaps basal Camp Rice sandstone and conglomerate that is angularly unconformable on Palm Park laharic breccias and mudstones. A small fault block of Hueco Limestone (Permian) is located just east of dam. **0.7**

81.7 *Take Exit* 18, Fort Selden-Radium Springs interchange. **0.3**

82.0 Stop sign. *Turn left (west); cross 1-25 overpass* and descend to surface of late Pleistocene river terrace. **0.7**

82.7 Atchison, Topeka, and Santa Fe (ATSF) Railroad crossing. **0.2**

82.9 *Turn right at Leasburg State Park entrance; continue north on park road, taking right-hand forks.* **0.7**

83.6 Pit in upper Pleistocene river-terrace gravel to right. **0.2**

83.8 **STOP S3, Leasburg Dam-Radium Springs overlook** (figs. S5, S8, S13, S14, S15). Leasburg Dam is an irrigation diversion structure for the Elephant Butte Irrigation Project (see Stop S7b).

COMPILER'S NOTE-The following discussion is by W. R. Seager and Paul Morgan, *New Mexico State University, Las Cruces, New Mexico.*

At this stop and at San Diego Mountain the emphasis is on the structural evolution of the Rio Grande rift in this area. Details of local geology can be found in Seager (1975a) and Seager and others (1976). Most of

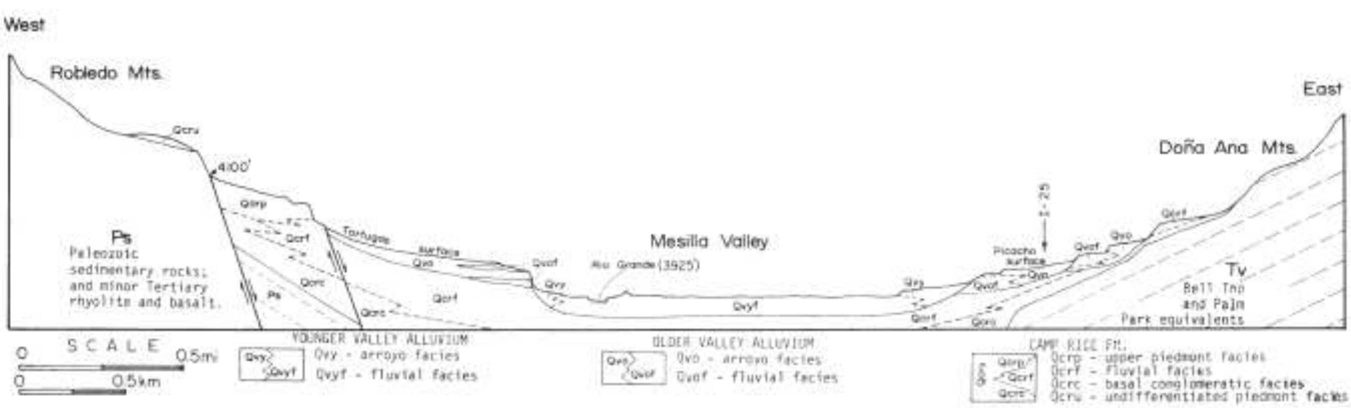


FIGURE S12—DIAGRAMMATIC CROSS SECTION OF NORTHERN MESILLA VALLEY, south of Stop S3, showing relationships of Quaternary (and upper Pliocene) stratigraphic and geomorphic units between the Robledo and Doña Ana Mountains.

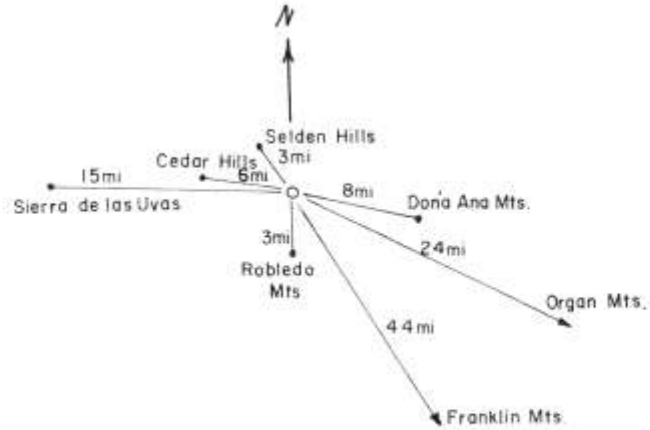


FIGURE S13—PANORAMIC INDEX OF FEATURES SEEN FROM STOP S3, LEASBURG DAM-RADIUM SPRINGS.

FIGURE S14—VIEW SOUTH FROM NEAR STOP S3, LEASBURG DAM OVERLOOK; ruins of Fort Selden (1865-1879, 1881-1892) are in middle ground, Robledo Mountains in background. Lookout Peak, the high point on skyline, is part of a 35-m.y.-old rhyolite sill intruded into gently dipping Paleozoic rocks that compose the rest of the mountains visible from here. The light-colored spurs extending to the left (east) from the mountain front are intertonguing fan gravels and ancestral-river deposits (Pliocene-Pleistocene) in fault contact with Paleozoic rocks (photo by J. W. Hawley).

this evolution is interpreted from Miocene-Pliocene rift deposits, largely fanglomerates and playa facies with interbedded basalt flows, that were uplifted and exposed late in the history of the rift. Overprinting of the rift on north-trending Laramide uplifts can also be demonstrated and supports the contention by many investigators that the rift trends are inherited from an old zone of structural weakness.

For example, in the Robledo Mountains across the Rio Grande from this stop, about 3,000 ft (1,000 m) of Paleozoic strata are truncated downward south to north along the length of the range by a pre-late Eocene erosion surface. Ten miles (16 km) to the northwest at San Diego Mountain, the erosion surface has cut into the Precambrian core of the presumed Laramide uplift. Reconstruction of the uplift suggests that its geometry was similar to that of the Colorado Plateau or to some of the smaller Laramide block uplifts of the Southern Rockies. Similar north-trending Laramide uplifts have been identified by unconformities and distinctive Laramide structural features elsewhere in southern New Mexico. In fact, the Fra Cristobal, Caballo, southern San Andres, Organ, and Franklin ranges all have north-trending Laramide ancestors.

Calc-alkalic volcanism dominated the area of the southern rift in middle Tertiary time. Late Eocene andesitic volcanism was followed by rhyolitic ash-flow tuff eruptions during the Oligocene. Cauldrons or volcano-tectonic depressions associated with the tuffs were uplifted and eroded by the rifting process later in the Tertiary. The Dona Ana cauldron, 33-37 m.y., with more than 3,000 ft (1,000 m) of rhyolitic volcanic fill forms part of the southern Doña Ana Mountains; the Organ cauldron, 32 m.y., with about 9,000 ft (2,740 m) of ash-flow tuff forms part of the Organ Mountains; and the Good Sight-Cedar Hills depression, 39-33 m.y., with about 2,130 ft (650 m) of volcanic fill forms part of the Sierra de las UvasCedar Hills area. The more widespread ash-flow tuff sheets fail to reflect in their distribution any of the early or modern basins of the Rio Grande rift; the rift apparently had not yet begun to form by 33 m.y. ago.

About 26 m.y. ago the volcanism changed to calc-alkalic basaltic andesite. Some flows issued from a cinder cone constructed on one of the through-going rift faults in the Cedar Hills, about 6 mi (10 km) west of this stop. The flows interfinger with fanglomerate derived from the uplifted footwall block of the fault. These relations are interpreted to mean that rifting was in progress in southern New Mexico by 26 m.y. ago. The basaltic andesite volcanism may indicate that the deep regional rift faults were able to trigger partial melting of the upper mantle or lower crust in areas where isotherms already were high—in the regions of Oligocene calc-alkalic magmatism. The idea has support because in south-central and southwest New Mexico extensive basaltic andesite volcanism is restricted to the areas of Oligocene calc-alkalic magmatism (Chapin and Seager, 1975).

Evolution of the rift during the Miocene is recorded in thick bolson deposits exposed in fault blocks between the Robledo and Caballo Mountains. The bolson deposits, which comprise most of the Santa Fe Group in this area, formed in a broad deep basin that connected the present Jornada del Muerto Basin to the east of this stop with the Palomas Basin to the west of the Caballo Mountains. Oldest deposits interfinger downward with Uvas basaltic andesite (26 m.y.), and youngest deposits contain the Selden Basalt (9 m.y.). Compositional facies indicate that many of the modern fault blocks in the area were not sources of the ancient basin fill, while a few modern ranges (Sierra de las Uvas) appear to have been part of the rift landscape from the beginning. Still others (Caballo Mountains) become a source part way through the Miocene.

Most of the fault blocks in the Radium Springs-Caballo area, however, are comparative newcomers to the rift; they were pushed up through or formed by segmentation of the old basin deposits after emplacement of the Selden Basalt. For example, deformed fanglomerate with interbedded Selden Basalt crops out next to the Robledo Mountains but contains no detritus from that range; the Robledos must have been uplifted within the last 9 m.y. Similar relations exist at San Diego Mountain, and this evidence plus observations that the 9-m.y.-old bolson deposits are offset thousands of feet by movement along nearly all the range boundary faults in the region has prompted the interpretation that faulting in the rift culminated or accelerated between 9 and 2 or 3 m.y. ago. The latter date is the age of nearly undeformed deposits of

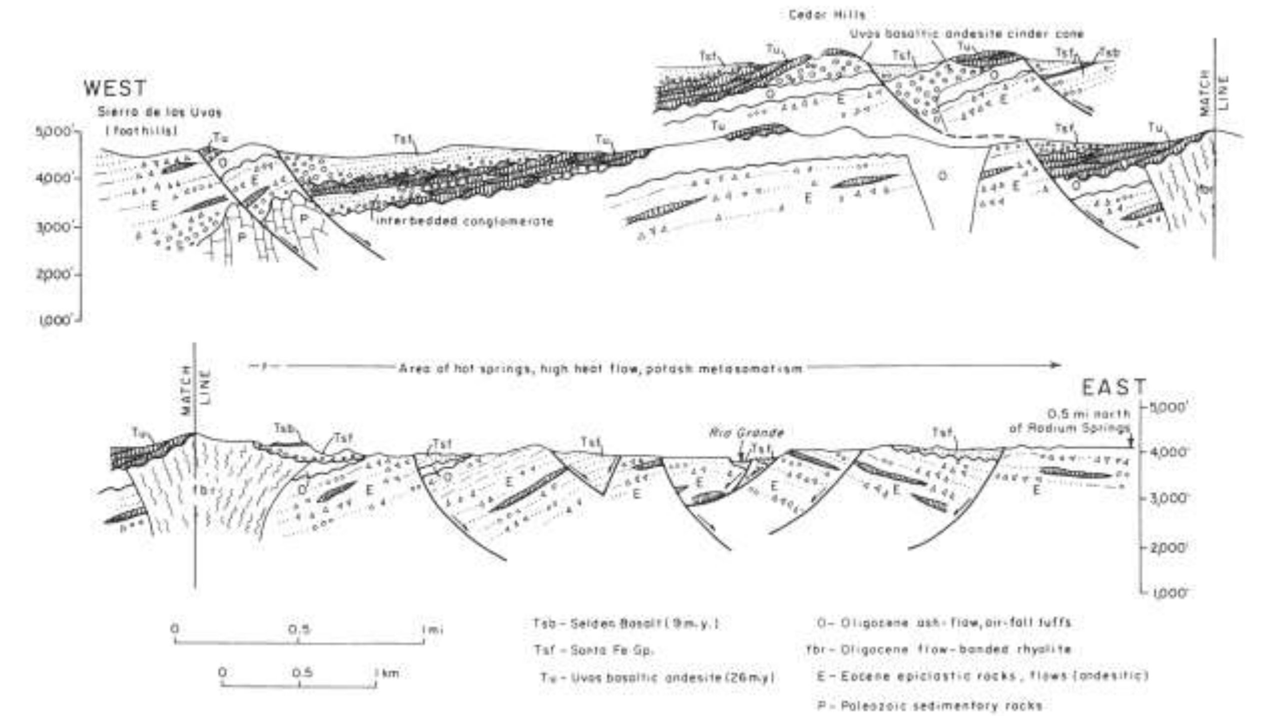


FIGURE S15—Diagrammatic structure section between Sierra de las Uvas and Radium Springs near Stop S3 (with inset section of Cedar Hills).

Camp Rice Formation (upper Pliocene-lower Pleistocene) that overlap the erosion surfaces at the edges of south-central New Mexico ranges.

Most of the early basins along the Rio Grande rift were not segmented during their evolution and persist today as the well-known linked system of large basins. In only two areas were early basins broken up, one in the Socorro area (Popotosa basin) and the other described above. Deformation of both basins involved thin-skinned distension over an area where a major thermal anomaly persists to the present. The significance of this observation will be considered further in discussions at San Diego Mountain. Fig. S15 shows an east-west cross section that passes just north of this stop and illustrates the thin-skinned style of faulting.

The middle Miocene and younger basalts in the rift in southern New Mexico are alkali olivine basalts, chemically and lithologically distinct from the earlier basaltic andesites (Hoffer, 1976; Kudo and others, 1971; Aoki and Kudo, 1976; Renault, 1970). Chapin and Seager (1975) suggest that by 13 m.y. ago the rift had sufficiently necked to allow intrusion of hot mantle material into the crust. The alkali olivine basalts and the accelerated faulting and uplift during the late Miocene and Pliocene may be a product of that new thermal regime.

Quaternary movement on range boundary faults is rather commonplace in the southern part of the rift (figs. S12, S14, S15), as well as in the northern part. In fact, the abundance of youthful scarps and their distribution, together with latest Pliocene and Quaternary volcanic activity and high heat flow, may be used to help define the rift here. The scarps indicate that the rift may be tectonically more active and thermally anomalous relative to immediately adjacent parts of the Basin and Range province. These adjacent areas appear to lack the concentration of youthful faults and volcanoes, and high heat-flow values.

Piedmont scarps along the eastern side of the Franklin Mountains have already been seen; equally spectacular ones will be viewed along the Caballo and Fra Cristobal ranges and in the Socorro area. The eastern boundary fault of the Robledo horst also has important late Quaternary movement. Fans correlative with or slightly older than the river terrace gravels at this stop have been displaced 10-100 ft (3-30 m) by movement along the Robledo fault zone. Fan and terrace deposits range in age between 10,000 and several hundred thousand years (Hawley and others, 1976). We believe the faulting (and associated warping) involves fans as young as 25,000 years. Camp Rice deposits (2.5-0.5 m.y.) are offset about 330 ft (100m).

Several earthquakes (M = 3.0-3.5) have been reported in the general vicinity of this stop since 1962 (Sanford, 1965; Sanford and Cash, 1969). Three are grouped in the Faulkner Canyon area 2 or 3 mi west of this stop (depth estimated to be 10 km). The most recent recorded earthquake (M = 3.0) was in January 1976 and was located near Doña Ana (mile 72.7) (G. R. Keller, personal communication, 1976). A very high rate of microearthquake activity, 40 to 70 events per day, has been reported for the area in the immediate vicinity of Radium Springs (Quillin and Combs, 1976). Subsequently, much lower rates of activity have been recorded in this region, typically four to six clearly identified events per month (P. Morgan, unpublished data), and this lower rate of activity is thought to be more representative of the southern rift zone. Most of the small microearthquakes cannot be located with any precision. Activity has been indicated, however, on the Robledo fault west of the Rio Grande.

Radium Springs takes its name from the hot springs at this stop; the water, at 86° C, is a manifestation of the high heat flow in the rift (Reiter and others, 1975, this guidebook; Decker and Smithson, 1975) and this location has been classified as a Known Geothermal Resource Area (KGRA). Heat-flow values of 104 ± 10 and 135 ± 28 mWm^{-2} (2.48 ± 0.23 and 3.24 ± 0.68 HFU) have been measured in deep boreholes (greater than 800 m) approximately 18 mi (30 km) east of here, north of the town of Organ (Reiter and others, 1978). Geothermal-gradient measurements in water wells indicate ubiquitous high heat flow in the Rio Grande valley south of Radium Springs, locally augmented by hydrothermal systems (P. Morgan and C. A. Swanberg, unpublished data). Water-geochemistry data also indicate that hydrothermal circulation systems in the valley have some structural control, because many of the geochemically high temperature samples are concentrated close to the valley fault, which approximately follows the line of interstate highways 1-25 and I-10 between Radium Springs and E1 Paso (Swanberg, 1975).

Geothermal waters at Las Alturas Estates, near mile 54.1 southeast of Las Cruces, are currently being studied for possible use in space heating on the New Mexico State University campus. Gradients in excess of 300° C km^{-1} have been measured at Las Alturas (P. Morgan and C. A. Swanberg, unpublished data), and electrical resistivity measurements show a low resistivity layer (hot water?) at a depth of 650-985 ft (200-300 m) extending over about 10 mil at this site (C. T. Young, personal communication, 1977). Application of the silica and sodium-potassium-calcium geothermometers to ground waters from Las Alturas indicate base-reservoir temperatures in excess of 170° C (C. A. Swanberg, personal communication, 1978). Electrical resistivity measurements indicate that the hot water at Radium Springs originates from a similar hydrothermal system, which is partly contained in an aquifer 165 ft (50 m) thick at a depth of 395 ft (120 m) (C. Smith, personal communication, 1977), and which has a geochemical base-reservoir temperature in excess of 180° C (C. A. Swanberg, personal communication, 1978).

Continue north to riverside camp ground, past park headquarters and across canal. **0.1**

83.9 *Turn left (south) on paved river road* (Radium Springs to Fort Selden). Ruins of Fort Selden on terrace ahead to left. 0.9

84.8 Stop sign; *turn left (east) onto 1-25 access highway.* US-85 to right follows alternate tour route up Selden Canyon to San Diego Mountain and Rincon (Stops S4 and S5). Refer to detailed road log in Seager, Clemons, and Callender (1975, p. 39-53). 0.2

85.0 Fort Selden Ruins State Monument and Museum on left. This frontier post, named after Col. Henry R. Selden (1820-1865), was garrisoned from 1865 to 1879 and 1882 to 1892 (Milton, 1971). The fort was served by a heliograph station on the north peak of the Robledos (fig. S14), one of a series of installations on peaks between E1 Paso (Fort Bliss) and Cooke's Peak (Fort Cummings). E1 Camino Real, the route established in 1598 by Spanish colonists under Onate's leadership, ascended from the valley floor to the Jornada del Muerto Basin near this point (Moorhead, 1958). The tour route between here and Stop S4 closely follows E1 Camino Real. 0.7

85.7 ATSF Railroad. 0.7

86.4 *Cross overpass; turn left onto northbound approach ramp.* 0.3

86.7 *Merge with 1-25.* Route ascends long (2.7 mi) grade out of the Mesilla Valley. Slopes ahead have thin cover of upper Quaternary alluvial and eolian deposits on Camp Rice fluvial facies. Selden Hills at 11:00 form east wall of Selden Canyon. Basaltic andesitecapped mesas of Sierra de las Uvas from 9:00 to 10:00. 1.2

87.9 Roadcut in Camp Rice fluvial sand. **1.2**

89.1 On drainage divide between Rio Grande watershed and a bolson segment of the Jornada del Muerto. The basin floor ahead is part of the La Mesa geomorphic surface. A buried Tertiary bedrock high connecting the Doña Ana and Selden Hills uplifts passes beneath this point. Caliche-capped Camp Rice fluvial sand (exposed in rock cuts) and the basin floor have been upwarped in this immediate area. This Pleistocene deformation, with about 330-ft (100-m) displacement, is related to movement along the Jornada fault zone that forms the northeastern boundary of the Selden Hills and Doña Ana blocks (Seager, 1975a). **1.0**

90.1 *Take exit to rest area (optional stop).* The San Andres Mountains on the skyline about 25 mi (40 km) to the east separate the Jornada del Muerto and Tularosa Basins. This west-tilted structural block is the northern continuation of the Franklin-Organ chain, and it is primarily formed on a thick sequence of Paleozoic rocks (mostly Ordovician to Permian carbonates) over Precambrian rocks.

The water supply here is developed from tongues of gravel and sand in generally fine-grained bolson fill of the lower Santa Fe Group (see Stop 5). Static water level is 295 ft (88 m) below the surface. The Camp Rice Formation comprises the upper 60 ft (18 m) of the fill and may be as much as 250 ft (75 m) thick (King and others, 1971). Numerous small depressions mark the basin floor in this area. Most are aligned with major structural features such as the Jornada fault (and flexure) zone. Temporary flooding of these depressions after rainstorms provided the sole source of water for E1 Camino Real travelers prior to the late 19th century. In 1844 the Santa Fe-Chihuahua Trail trader Josiah Gregg (1954, p. 271) stated:

> There is a tradition among the arrieros (muleteers) from which it would appear that the only road known in ancient time about the region of the *Jornada,* wound its circuitous course on the western side of the river. To save distance, an intrepid traveler undertook to traverse this desolate tract of land in one day, but having perished in the attempt, it has ever after borne the name of *La Jornada del Muerto,* "the Dead Man's Journey," or more strictly, "the Day's Journey of the Dead Man." 2.0

92.1 Opposite microwave tower. Flat-topped San Diego Mountain at 11:00 overlooks area of Stop S5 about 3 mi west of this point. 2.9

95.0 Scenic view area on right *(optional turnout).* Southern Caballo Mountains on skyline at 11:00 and Point of

Rocks hills at 1:30 will be discussed at Stop S4. San Diego Mountain, the peak of the small Tonuco uplift just west of 1-25, is capped by a thick section of conglomerates to mudstones of the Hayner Ranch Formation of the lower Santa Fe Group (see Stop S5). The Precambrian granitic core of the Tonuco uplift forms the group of hills just east of the mountain. Outcrops of Bliss Sandstone (Cambrian-Ordovician), overlain by several hundred feet of E1 Paso Group limestone (Ordovician), form the dark band on the east side of the uplift. A thick section of lower Tertiary sedimentary and volcanic rocks that include the Palm Park Formation is unconformable on the E1 Paso and Precambrian. **1.5**

96.5 Milepost 29. Sierra de las Uvas at 9:00; Rincon Hills (microwave tower) at 11:00. **2.5**

99.0 Upham exit 1 mi; *prepare to leave 1-25.* **1.1**

100.1 *Take Upham exit to right.* **0.2**

100.3 Stop sign; *turn right on graded road. Continue north* across basin floor. **1.0**

101.3 Road fork, *bear left.* **0.2**

101.5 **STOP S4, Rincon overlook.** The following discussion of southern Caballo Mountain-Rincon Hills area (figs. S5, S8, S16, and S17) is by W. R. Seager and Paul Morgan, *New Mexico State University, Las Cruces, New Mexico* and J. W. Hawley, *New Mexico Bureau of Mines and Mineral Resources, Socorro New Mexico.*

The Rincon Hills, west of this stop, form the southern foothills of the Caballo Mountains. Details of the local geology can be found in Seager and Hawley (1973). The hills comprise Oligocene and Eocene volcanic rocks overlain by Uvas basaltic andesite and by more than 4,920 ft (1,500 m) of rift basin deposits.

Most of the basin deposits are part of the Santa Fe Group, subdivided into several formations. The thick succession of Santa Fe strata (mostly piedmont-slope, alluvial-flat, and playa deposits) record semi-continuous deposition in the early rift basin, which dates back to the Uvas basaltic andesite (26 m.y.). The basin is inferred to have connected the Jornada Basin east of this stop with the Palomas Basin west of the Caballo Mountains. The basin began to be split into the two modern basins by the rise of the Caballo Paleozoic-Precambrian sequence prior to 9 m.y. ago (the age of the Selden Basalt). The precursor basin was totally segmented between 9 and 2 or 3 m.y. ago by uplift of the Rincon Hills-San Diego Mountain horst. This evolution is read largely from stratigraphic studies of the basin fill, which have distinctive compositional facies reflecting source areas, and intraformational unconformities that document local uplift and erosion.

The microwave tower across the valley, near the southern end of the hills, is on lower Santa Fe fanglomerate of the Hayner Ranch Formation (fig. S17). To the north, the fanglomerate is in fault contact with Uvas basaltic andesite, which forms the dark hills. Beyond the effects of the faulting, the fanglomerate interfingers downward into basin-center elastics, which intertongue with the Uvas. Oligocene ash-flow tuffs and volcaniclastics rise from beneath the Uvas farther north. South of the microwave tower the Santa Fe fanglomerates contain barite, fluorite, and psilomelane mineralization; and younger beds of the lower Santa Fe Group (Rincon Valley Formation, correlative with the section containing Selden Basalt) angularly overlap the mineralized basal Santa Fe strata. The mineralization is thus constrained between 9 and 26 m.y.

Two ash-flow tuff units of Oligocene age (middle part of Bell Top Formation) are exposed at the northern end of the Rincon Hills and in Point of Rocks farther northeast. The tuff units, dated at 35-36 m.y. (Clemons, 1976), probably originated in the general Sierra de las Uvas area; from there the units spread out in all directions to cover about 1,430 mil (3,700 km^2) of south-central New Mexico. The older of the two tuffs ranges in thickness from about 300 ft (90 m) to a feather edge, thinning uniformly away from the Sierra de las Uvas area. The younger tuff averages

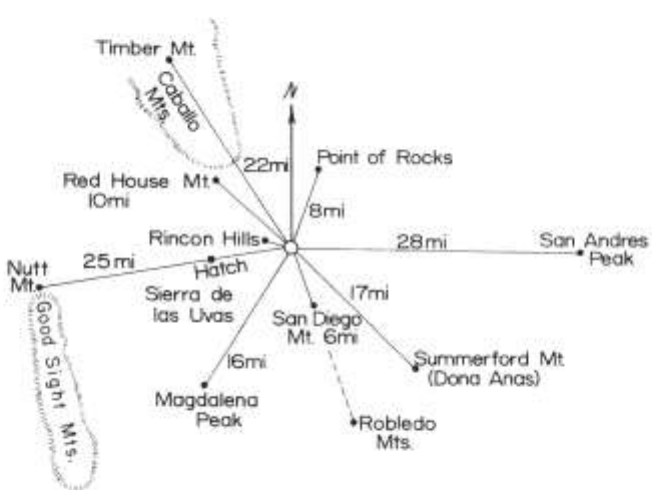


FIGURE S16—PANORAMIC INDEX OF FEATURES SEEN FROM STOP S4, RINCON OVERLOOK.

FIGURE S17—VIEW SOUTH FROM CREST OF RINCON HILLS WEST OF STOP S4. Looking down Rio Grande Valley; Robledo Mountains on center skyline, Cedar Hills on right skyline, San Diego Mountain (Stop S5) in left middle distance, and Rincon Hills in foreground. Lower to middle Miocene conglomeratic sandstones and conglomerates deposited in an early rift basin are exposed in the Rincon Hills. Light-colored slopes on middle left foreground are ancestral river deposits of Pliocene-Pleistocene age. These deposits form the floor of the Jornada del Muerto Basin east of San Diego Mountain and Stop S4 (photo by J. W. Hawley).

about 100 ft (30 m) thick over virtually all of its known extent. Clearly the ash flows did not encounter any of the present rift topography, or even incipient rift topography, 35 m.y. ago. The landscape was plateau-like and featureless over large areas.

Uvas basaltic andesite flows, which issued in part from a shield-like cluster of volcanoes in the Sierra de las Uvas, also flowed into the southern Caballo region, across the present Hatch-Rincon graben area, without having flow thickness affected by any sort of structural or topographic relief. The flows thin gradually northward and pinch out in the central part of the Caballos. By 26 m.y. ago (the age of the Uvas), there still was no early rift basin north of the Sierra de las Uvas. But through-going faulting, interpreted to be early rifting, was developing east of the Sierra de las Uvas (Stop S3 discussion). The thick section of clastics that interfinger with and overlie the Uvas in the Rincon Hills (upper part of the Thurman Formation of Kelley and Silver, 1952) argues strongly for the development of the earliest rift basin in the CaballoHatch Valley area shortly after 26 m.y. ago.

An east-west Bouguer gravity anomaly profile across the rift at approximately the latitude of this stop is shown in fig. S18 (after Ramberg and others, 1978). Also shown is the modeling of the gravity data by Ramberg and others with respect to the crustal structure across the rift at this latitude. Ramberg and others prefer to interpret this structure as an upwarp of the upper mantle; this interpretation is consistent with other geological and geophysical data from the southern portion of the rift (see Stop Sib).

Late Pliocene to Pleistocene Camp Rice Formation overlaps all older units with angular unconformity (fig. S19). Camp Rice piedmont deposits interfinger basinward with up to 300 ft (90 m) of fluvial sandstone and conglomerate and associated floodplain claystone or siltstone. These facies, especially the fluvial facies, are well displayed in the badlands along Rincon Arroyo north of this stop (fig. S19). Conglomeratic piedmont facies crop out west of the arroyo in a narrow band along the east front of the hills. Two opalized beds, with well-preserved plant fossils ("w" layer in fig. S19), are present in the middle part of the section about 130 ft (40 m) below the level of the Jornada plain. LeMone and Johnson (1969) infer that the fossil flora grew in a marshy, cienega-type environment. The opal beds, upper Pliocene or lower Pleistocene, have been displaced as much as 175 ft (53 m) by the east Rincon Hills fault. The lowermost conglomeratic unit of the Camp Rice river deposits underlies the opalized material in the central part of the arroyo valley. Uppermost Camp Rice fluvial sand and gravel crop out in the immediate area of this stop. An early to middle Pleistocene deposit of rhyolitic volcanic ash, probably from the 0.7-m.y. Bishop tuff eruption (see Stop S1b), caps the Camp Rice section at Grama Siding about 4 mi north of this stop (Seager and Hawley, 1973, p. 17).

The area of the Jornada del Muerto east and southeast of this point is a vast constructional plain that originally graded to the Mesilla and Hueco Bolson floors south of Las Cruces. The surface of this plain (La Mesa geomorphic surface of Ruhe, 1964) marks the upper limit of Camp Rice deposition by ancestral river distributaries that fanned out from relatively narrow basins north of Rincon and Hatch (see mile 131.3). The main upstream course of the

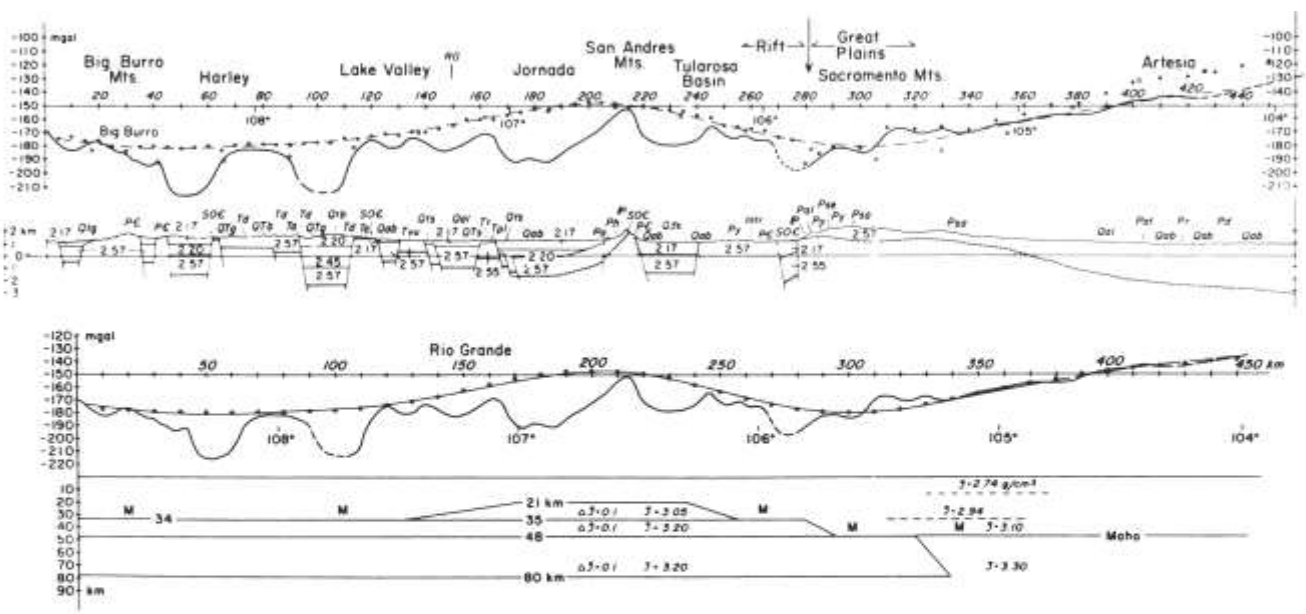


FIGURE S18—West-to-east gravity profile and models across the Rio Grande rift approximately at the latitude of Stop S4 at Rincon overlook. The upper curve shows the measured Bouguer gravity anomaly in mgals (solid curve), with the regional anomaly (dots) calculated by removing the effects of the sedimentary basins shown below the curve (densities given in g/cm³). The inferred regional anomaly fitted to the calculated anomaly is shown by the dashed line. The lower curves show the measured Bouguer gravity anomaly in mgals (irregular solid curve) with the inferred regional anomaly (smooth solid curve) and the fit to the regional anomaly data (dots) by the gravity model shown below the curves. Densities (g) are given on the gravity model in g/cm³ and Δg indicates the density contrast. Horizontal scales are in km (figure reproduced from Ramberg and others, 1978, with permission).

river was in the Palomas-Cuchillo-Engle chain of basins west of the Caballo-Fra Cristobal Mountains. However, recent field work in the Jornada Basin east of the Fra Cristobals indicates that a short-lived distributary flowed down the basin at least as far as Engle. This channel presumably extended into the southern segment of the Jornada through gaps east and/or west of Point of Rocks.

Caliche caprock, which typically occurs within several feet of the La Mesa and Jornada **I** surfaces in this region, is well exposed at this stop. Carbonate impregnated zones in the uppermost Camp Rice beds are as much as 10 ft (3 m) thick and commonly include indurated layers of laminar carbonate in their upper parts. Much of the surficial caliche formed in this arid region is pedogenic (Gile and others, 1966, 1970). The present water-table position (King and others, 1971) and past configurations, reconstructed on the basis of information on basin-fill hydrologic properties and river-valley evolution, indicate that ground-water and capillary-fringe processes have not played a significant role in genesis of soil-caliche in this area. However, much of the carbonate-cemented alluvium exposed in valleys of the region, which has been loosely designated caliche, has carbonate cements that were not emplaced by near-surface pedogenic processes. Rather, cementation has resulted from processes related to deeper circulation of subsurface water in vadose and upper phreatic (ground-water) zones (Seager, Clemons, and Hawley, 1975, p. 20).

Return to 1-25 at Upham exit. **1.2**

102.7 Cattle guard; *turn right onto 1-25 approach ramp*. **0.6**

103.3 Begin descent into Rincon Valley. About 250 ft (75 m) of Camp Rice fluvial deposits are exposed in slopes and roadcuts ahead. This facies consists mainly of pebbly channel sand, with coarse gravel near the top and thin loamy layers at intervals throughout the section. The latter probably represent overbank deposits. Paleosols present in a number of the loamy units indicate periods of nondeposition and surface stability. **0.8**

104.1 Roadcut in Camp Rice Channel and floodplain deposits. **1.1**

105.2 *Cross bridge* over Rincon Arroyo; *prepare to take next exit.* Spurs of the Rincon Hills in foreground at 1:00 are capped with well-indurated sandstones (iron oxide and silica cements) of the Camp Rice and Rincon Valley Formations. **0.3**

105.5 *Take Exit 35* to Rincon; road loops to right through cuts exposing eastern boundary fault of the Rincon Hills block. Reddish, gypsiferous sediments of the Rincon Valley Formation (middle to late Miocene) in the upthrown block are faulted against light-gray sand and sandstone of the Camp Rice Formation. **0.3**

105.8 *Bear right through underpass onto NM-140.* **0.3**

106.1 Cattle guard; entering Rincon. Here the valley makes a sharp bend *(el rincon* is Spanish for interior corner) from an east to a south trend. This village has been an important junction on the Santa Fe Railroad since tracks were first laid in 1881. **0.7**

106.8 Roadcuts ahead in reddish, gypsiferous, basin-floor facies of the Rincon Valley Formation with cap of upper Pleistocene river-terrace deposits. **0.4**

107.2 Railroad crossing. *Continue straight ahead* on NM-140; Hatch fork of highway to right. **0.5**

107.7 *Cross canal and turn left on paved road.* Continue south on Rio Grande floodplain. The Rincon Valley floor is about 1.5 mi (2 km) wide. As in the Mesilla Valley, climate, soil, and irrigation water are ideal for production of chili, cotton, lettuce, and pecans. **2.2**

109.9 Curve to right. San Diego Mountain, Stop S5 area, at 12:00. **2.1**

112.0 Sharp curve to right. Sierra de las Uvas and Mesa Azul, elevation 6,600 ft (1,980 m), at 12:00 on skyline. **0.4**

112.4 *Turn left onto Rio Grande levee road;* entering Hayner Ranch and Farm. **0.6**

113.0 Intersection; *turn left* on road to farm headquarters. Rio Grande bridge and US-85 to right. **0.4**

113.4 Hayner Farm headquarters. *Check here or at Hayner residence* (mile 115.9, west of river) *for permission to proceed further.* **0.8**

114.2 Curve to right, around fence and canal. **0.3**

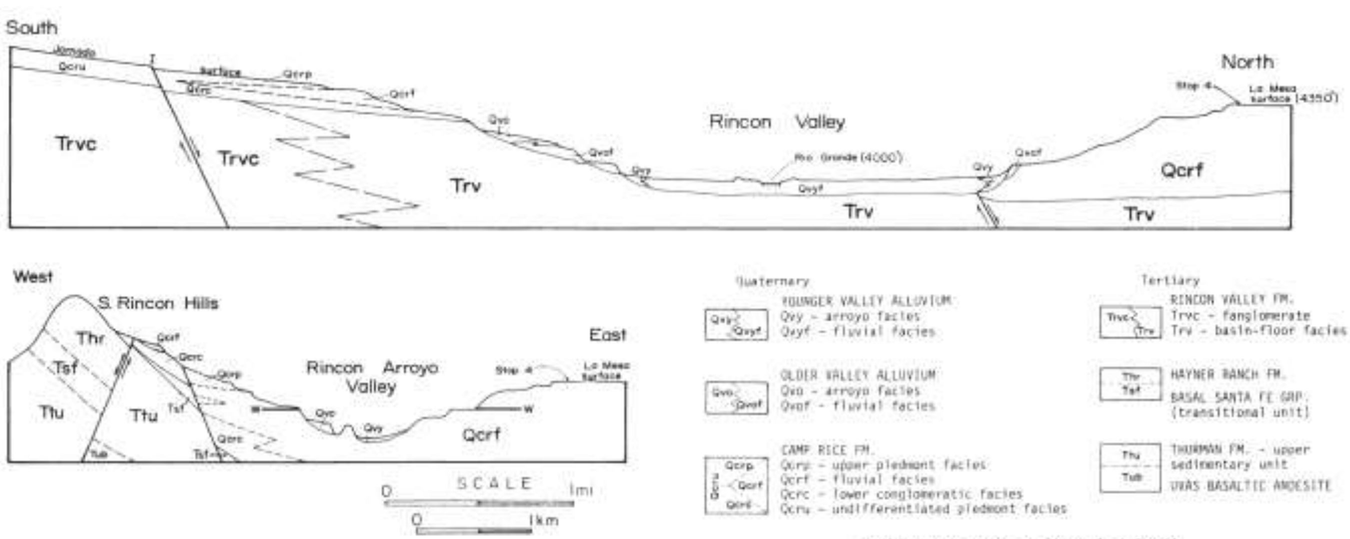


FIGURE S19—DIAGRAMMATIC CROSS SECTIONS OF RINCON VALLEY AND OF THE RIO GRANDE-RINCON ARROYO VALLEY near Stop S4, showing relationships of upper Cenozoic stratigraphic and geomorphic units.

114.5 *Take left road fork.* **0.1**

114.6 Railroad crossing; locked gate ahead; *bear right* after crossing tracks; continue southeast along base of San Diego Mountain. **1.1**

115.7 **STOP S5, San Diego Mountain.** East edge of Rio Grande floodplain at southern base of mountain (figs. S5 and S8). Discussion by W. R. Seager and Paul Morgan.

The San Diego Mountain block (Tonuco uplift) is a comparatively narrow horst exposing Precambrian, lower Paleozoic, and Tertiary rocks (Seager and others, 1971; Seager, 1975a; fig. S20). The uplift is connected to the Rincon Hills and to the Radium Springs area by a narrow zone of faulting along the western edge of the deep Jornada del Muerto Basin. It was movement along this zone of faulting, together with displacement on the boundary faults of the Caballo uplift, that broke the large early rift basin described at Stops S3 and S4 into the two modern basins, Palomas and Jornada.

Precambrian granitic rocks form the core of the Tonuco uplift, and these are overlain by steeply dipping lower Paleozoic rocks along the east side. Eocene volcanics with a basal fanglomerate overlap the Paleozoic and Precambrian rocks. The unconformity is interpreted to indicate Laramide uplift in the San Diego Mountain area followed by erosion of 6,500-9,800 ft (2,000-3,000 m) of Mesozoic and Paleozoic rocks before late Eocene time. This area probably was the core of the Laramide uplift whose southern flank is inferred to extend to the Robledo Mountains as noted at Stop S3. Trends of bedding and structural features suggest that the uplift trended north, parallel to the rift in this area.

More than 1 mi (1,600 m) of clastic rocks of the lower Santa Fe Group overlie the Eocene at San Diego Mountain, exposed mostly in downfaulted blocks around the central horst (fig. S20). These are all younger than or contemporaneous with Uvas basaltic andesite and clearly correlate with the Santa Fe beds of the Rincon Hills. In fact, the same formations (Hayner Ranch and Rincon Valley) are recognized in both areas. The lower Santa Fe strata grade from piedmont slope and alluvial flat deposits upward into playa deposits, and they represent the fill of the large early rift basin described at Stops S3 and S4. The upper part of the sequence contains the Selden Basalt, 9 m.y. old.

None of the clasts in the lower Santa Fe section exposed here were derived from the Tonuco uplift, except perhaps those in the upper 150 to 200 ft (up to 65 m). The Tonuco uplift was clearly not a source until after 9 m.y., when the horst—and the Rincon Hills block—were pushed up through the center of the paleobasin. Judging from compositional facies, however, the Sierra de las Uvas was a positive feature from the inception of rifting, and various Oligocene volcano-tectonic structures persisted as sources of clastics far into the Miocene.

Rifting in this area culminated between 9 and 2 m.y. ago. At this time fault blocks like the Tonuco uplift, Rincon Hills, and Robledo Mountains, as well as numerous smaller blocks, were raised through older basin deposits. The uplift of older blocks like the Sierra de las Uvas and Caballos culminated during the same time. Upper Pliocene and Pleistocene strata—the Camp Rice Formation, uppermost beds of the Santa Fe Group—unconformably overlap the edges of all the fault blocks in the region.

The large fault blocks in the southern rift are all horsts, grabens, or tilted blocks that probably resulted from deep-seated extension (Stewart, 1971). In the San Diego Mountain-Radium Springs area, however, the Miocene-Pliocene basin deposits have been moderately rotated on low- to moderate-angle faults that probably flatten downward and suggest thin-skinned distension in this region (fig. S15). The deformation is similar to that described by Anderson (1971) in southern Nevada and attributed by him to distension above shallow spreading plutons. The San Diego Mountain-Radium Springs area is the most geothermally active area in the region with hot springs and young travertine mounds. The highest conductive heat-flow values in the state have been measured in boreholes at San Diego Mountain (670 ± 75 and 640 ± 125 mWm^{-2}; 16.1 ± 1.8 and 15.3 ± 3.0 HFU: Reiter and others, 1978; this guidebook), and a ground-water base reservoir temperature of near 200° C here has been estimated from geochemical data (Swanberg, 1975, and personal communication, 1978). At least some Oligocene felsic volcanic rocks have a high K_2O content (greater than 7.0 percent) and

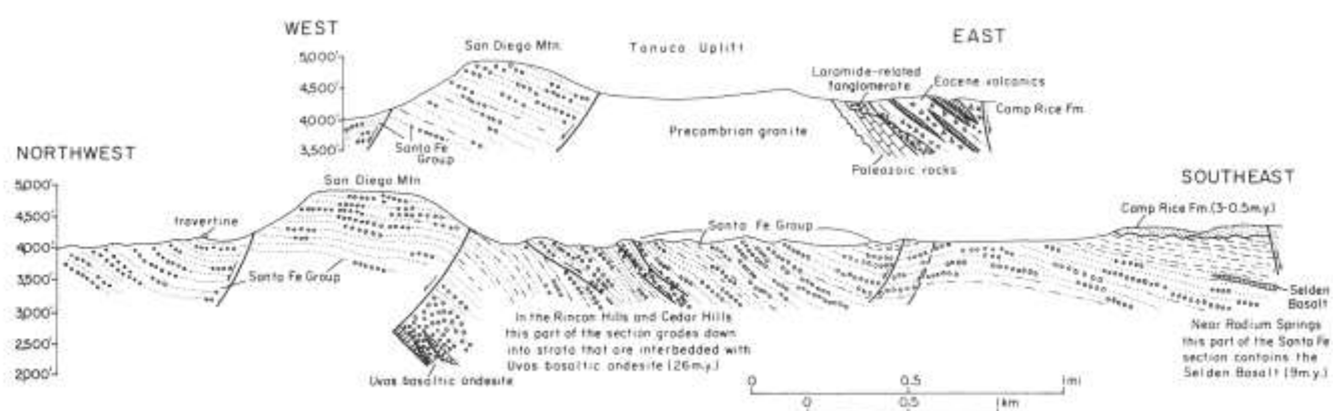


FIGURE S20—Diagrammatic structure sections across the Tonuco uplift east and southeast of San Diego Mountain, near Stop S5.

a low Na content (less than 1.0 percent) in this area; these percentages suggest cation exchange by hot water (Baptey, 1955; Orville, 1963). The thermal anomaly, as well as the structural style, suggest the emplacement of a shallow pluton in the area within the past few million years. In terms of the tectonic disruption of an early rift basin, the structural style, and the geochemical and thermal anomalies, this part of the rift-like the Socorro area-is anomalous, relative to the rest of the rift in the south-central New Mexico region.

Return to Rio Grande levee road. **2.6**

118.3 Rio Grande levee road. Light vehicles continue straight across Tonuco Bridge to US-85. Buses and other heavy vehicles retrace inbound route to 1-25 at Rincon. 0.3

118.6 Stop sign; *bear right (north) on US-85.* **0.6**

119.2 Hayner residence on right. Leaving Sierra Alta 7 1/2-minute quadrangle (Seager, Clemons, and Hawley, 1975); entering Rincon quadrangle (Seager and Hawley, 1973). Roadcuts ahead in complexly inter-tonguing arroyo-fan and river deposits of upper Pleistocene age. **1.4**

120.6 Northern Sierra de las Uvas at 10:00 to 11:00. The highest piedmont slope east of the mountains is the Jornada I surface, here comprising terraces, pedi-ments, and fans graded to the Jornada del Muerto plain (La Mesa surface) near Stop S4. Fig. S19 shows relationships between basin-and-valley fills in this area. **1.9**

122.5 *SLOW; prepare for sharp right turn.* 0.2

122.7 *Turn right onto NM-140, Rincon Road.* **0.1**

122.8 *SLOW!* Narrow bridge ahead. Southern Caballo Mountains on skyline at 11:00. Light-gray hills be-tween the Rincon Valley and the Caballos are formed on Oligocene ash-flow tuffs of the Thurman Forma-tion of Kelley and Silver (1952). Highest Rincon Hills (relay tower) at 12:30 are formed on Santa Fe group (lower to middle Miocene) beds (see Stop S4 discussion of Hayner Ranch Formation). At the base of the hills, reddish, gypsiferous mudstone to sandstone of the Rincon Valley Formation (middle to upper Miocene), with a cap of light-gray Camp Rice sandstone, has been eroded into badlands. Both formations are broadly folded and cut by high-angle faults. 0.3

123.1 Crossing Rio Grande. **0.4**

123.5 Crossing irrigation canal; *join alternate route* from Hayner Farm (Stop S5). *Return to Rincon via NM-140.* **1.6**

125.1 Cattle guard; *continue straight ahead.* 0.3

125.4 Underpass. *Prepare for left turn.* **0.1**

125.5 *Turn left onto 1-25 approach ramp.* 0.3

125.8 *Merge with 1-25;* cut on right in deformed Camp Rice beds. 0.6

126.4 Cuts ahead in gypsiferous, reddish mudstone to sandstone (basin-floor facies) of the Rincon Valley Formation (middle to upper Miocene). Both this unit and the unconformably overlying Camp Rice Forma-tion in bluffs to right are tilted and offset by faults. **0.4**

126.8 Mileage sign-Hatch 5, Socorro 114, Albuquerque 191. **0.7**

127.5 Cross arroyo. Roadcuts for next 5 mi in complexly intertonguing arroyo-fan and river deposits (upper Pleistocene) that cap erosion surfaces cut in Rincon Valley Formation red beds. **1.5**

129.0 Cross valley of Johnson Spring Arroyo. Road up arroyo leads to type areas of Palm Park (Eocene) and Thurman Formations (Oligocene-early Miocene) about 2.5 mi north of highway. High bench at 3:00 on skyline is the Rincon geomorphic surface with the very strong caprock caliche described at Stop 4. This surface may be as old as 1-2 m.y. 2.3

131.3 Underpass, Hatch interchange. Mesa from 11:00 to 12:00 on the far side of the valley is underlain by about 300 ft (90 m) of Camp Rice fluvial deposits over Rincon Valley red beds. A Blancan vertebrate fauna has been collected from the basal Camp Rice. This area is at the apex of the large fluvial-fan-delta complex (Pliocene to middle Pleistocene) that extends into Texas and Chihuahua and makes up the bulk of Camp Rice and Fort Hancock deposits. From here north, the zone of ancestral river deposits in the upper Santa Fe Group narrows to a belt 2.5-5 mi (4-8 km) in width, and the Pliocene to middle Pleistocene basin-fill sec-tion is dominated by piedmont-slope facies rather than by fluvial facies. In most areas from here nearly to Socorro, the lower Santa Fe Group (Miocene) is buried by younger basin-and-valley-fill units, and formational subdivisions of the Santa Fe have yet to be defined. However, upper Santa Fe Group correlatives of the Camp Rice fluvial facies are readily recognized in axial basin areas along the Rio Grande from here to Santo Domingo, near Stop S20. **1.2**

132.5 Crossing Thurman Arroyo. Leaving Rincon Valley and entering the Palomas Valley of the Rio Grande. The river valley is located near the east edge of the Palomas structural basin, adjacent to short, steep piedmont slopes ascending to the western escarpment of the Caballo uplift. The basin is bounded on the west by the Animas-Hillsboro blocks that form the foothill belt flanking the high Mimbres-Black Range chain at 10:00 to 12:00 on the western skyline (Kelley, 1952, 1955). Fig. S21 is a Skylab-2 view of the area crossed from here to near Stop S8 (mile 192.7). **1.2**

133.7 Cuts on right for next mile are in upper Pleistocene river-terrace deposits. Older valley-fill units equiv-alent to deposits of Picacho-Kern Place surfaces have been identified by Metcalf (1967) on the basis of molluscan fauna correlation. 0.5

134.2 Cooke's Peak, at 9:00 on skyline, rises behind Nutt Mountain (Sunday Cone), a rhyolite intrusive body at the north end of the Good Sight Mountains. Cooke Range forms the west boundary of the Rio Grande rift in this area, according to Chapin (1971) and Chapin and Seager (1975). **0.8**

135.0 Milepost 45. Round and Nakeye Mountains at 12:30. Timber Mountain, elevation 7,330 ft (2,234 m), high point of the Caballos at 1:00; Red House Mountain at the southern end of the range from 2:00 to 3:00. The thick Paleozoic sequence forming these mountains has been described by Kelley and Silver (1952). **1.0**

136.0 Milepost 46. For the next 5 mi the route crosses a complex of older valley-border surfaces that are partly constructional and partly erosional. Valley fill caps surfaces cut on upper Santa Fe fluvial and piedmont facies. A few of the deeper arroyo valleys may cut

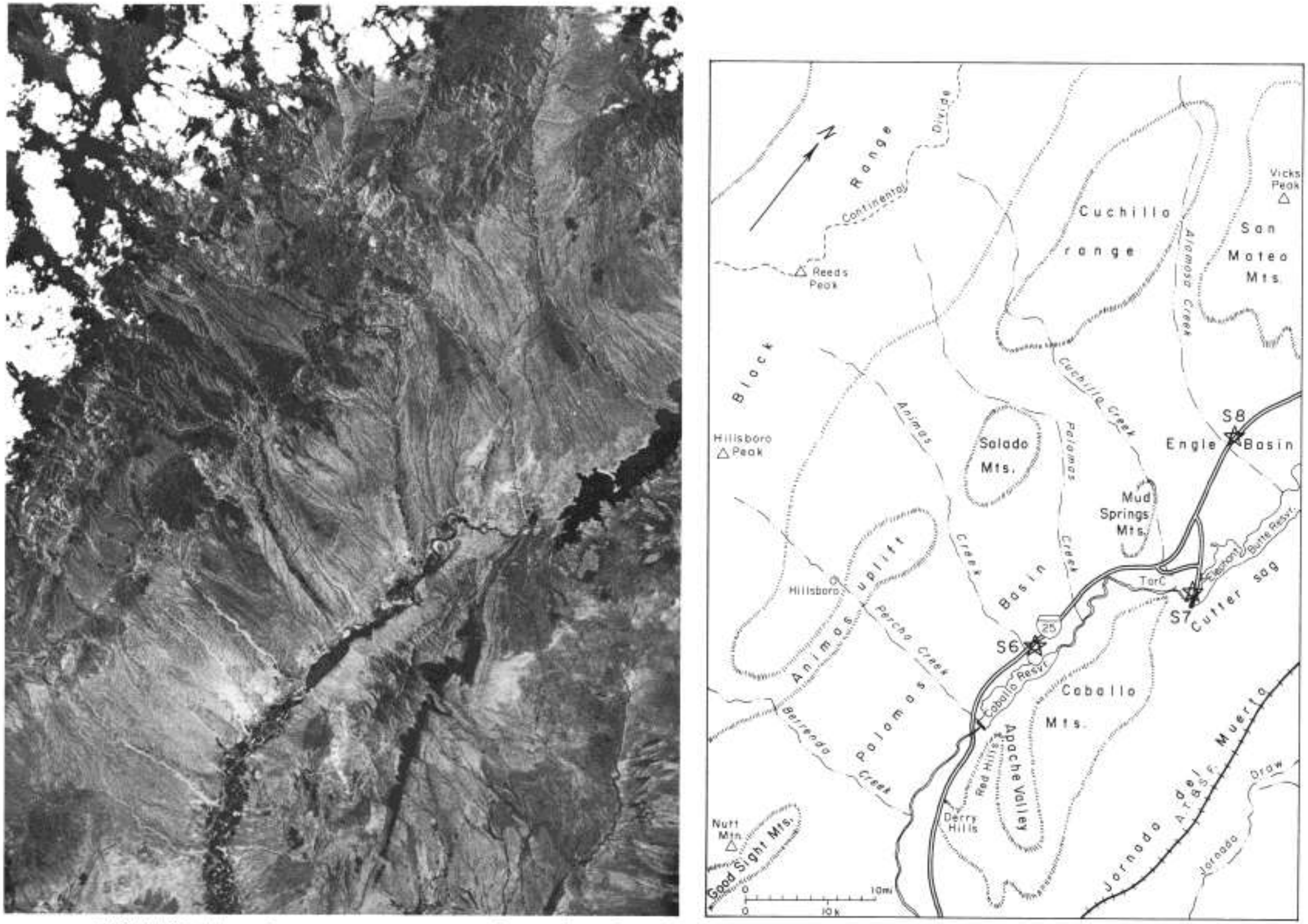


FIGURE S21—SKYLAB-2 PHOTO (a) AND INDEX MAP (b) OF PALOMAS BASIN, ENGLE BASIN, AND MONTICELLO TROUGH SEGMENTS OF THE RIO GRANDE RIFT, EAST OF BLACK RANGE (photo SL2-86-58 courtesy of Technology Application Center, University of New Mexico; photo scale approximately same as map scale).

through the upper Santa Fe into the Rincon Valley Formation. **3.1**

139.1 Faulted and folded Paleozoic rocks of the outlying Round-Nakeye Mountain block of the southwestern Caballo uplift can be seen up the arroyo to the right. **1.6**

140.7 Doña Ana-Sierra County line. **0.5**

141.2 Underpass, Garfield-Derry interchange. Derry Hills, ahead on right, are a complex fault block with overturned structures in the eastern part. The exposed section includes Percha Shale (Devonian), Pennsylvanian limestone of the type Derry Series (King, 1973), and Permian red beds of the Abo Formation. **1.0**

142.2 Percha Shale in roadcut to right is unconformably overlain by Pennsylvanian limestone. Derry Hot (warm) Springs to west of highway along Derry Hills fault zone. **0.3**

142.5 Reddish Abo sandstone on right downthrown in Derry Hills fault zone. **0.7**

143.2 Pennsylvanian limestone to left, Abo red beds to right. **0.5**

143.7 North edge of Derry Hills block. Cuts for next 4.5 mi are in upper Santa Fe fluvial and piedmont facies locally capped with upper Quaternary deposits of the valley-border sequence. **2.3**

146.0 Curve left. Red Hills to right are a northwestern continuation of the Round-Nakeye mountain blocks. Red Precambrian granite is overlain by faulted lower Paleozoics, with both units being overlapped by Eocene fanglomerates (basal Palm Park Formation). Farther east, early Tertiary fanglomerates were deposited on successively younger units up to the Cretaceous. **1.0**

147.0 Fluorspar mine in Red Hills at 2:00. **1.3**

148.3 Crossing Rio Grande. Bluffs to right are tilted basal, upper Santa Fe conglomerates capped with fluvial sandstones. Main fault block of the Caballo Mountains to the northeast exposes Precambrian to Pennsylvanian rocks in the steep western escarpment. **0.8**

149.1 Caballo Dam of the Elephant Butte Irrigation Project to right. **0.5**

149.6 Underpass, old US-85. **0.4**

150.0 Percha Creek to left is main drainage line from the central Black Range. From this point north thick sections of upper Santa Fe piedmont gravel are exposed in walls of deeply incised valleys of streams heading in the Black Range and adjacent parts of the Animas-Hillsboro uplift. In deep highway cuts ahead, gravels of the piedmont facies intertongue with fine-grained basin-floor deposits that have been interpreted as both river floodplain and as playa deposits (Davie and Spiegel, 1967). The exposed basin fill in this area is correlated with the Camp Rice Formation. **1.1**

151.1 Milepost 61. Caballo Reservoir and Caballo Mountains to right. Just east of the lake, placer gold deposits have been developed in upper Santa Fe fan deposits derived from Precambrian granite that forms the lower slopes of the Caballo escarpment. Low sun-angle illumination highlights a prominent piedmont scarp that extends along the foot of the range just below apex areas of high-level fans and pediments. **2.0**

153.1 Milepost 63. Roadcuts ahead in late Pleistocene arroyo-terrace deposits (Picacho-Tortugas equivalents; Hawley, 1965). **0.6**

153.7 Pass exit 63; NM-90 to Hillsboro and the Black Range; *continue north* on 1-25. **0.4**

154.1 Milepost 64. High roadcut in gravelly fan alluvium of the upper Santa Fe Group. The carapace and some limb bones of a giant tortoise were collected from near the base of this cut during highway construction. **0.4**

154.5 Crossing Animas Arroyo valley. Cuts ahead in piedmont alluvium that intertongues with basin-floor sand to clay. **1.6**

156.1 Crossing valley of Arroyo Seco. Ascend stepped sequence of Pleistocene arroyo terraces to summit of high-level valley-border surface. *Prepare to exit* at rest area ahead. **1.0**

157.1 *Take rest area exit at milepost 67.* **0.2**

157.3 **STOP S6, Caballo Reservoir.** Rest area at 33° north latitude overlooking Caballo Reservoir at base of Caballo Mountains (figs. S22 and S23). Details of local geology have been described by Kelley and Silver (1952). The following discussion is by Seager and Morgan.

At first glance the Caballo range to the east of this stop appears to be a magnificent example of a simple

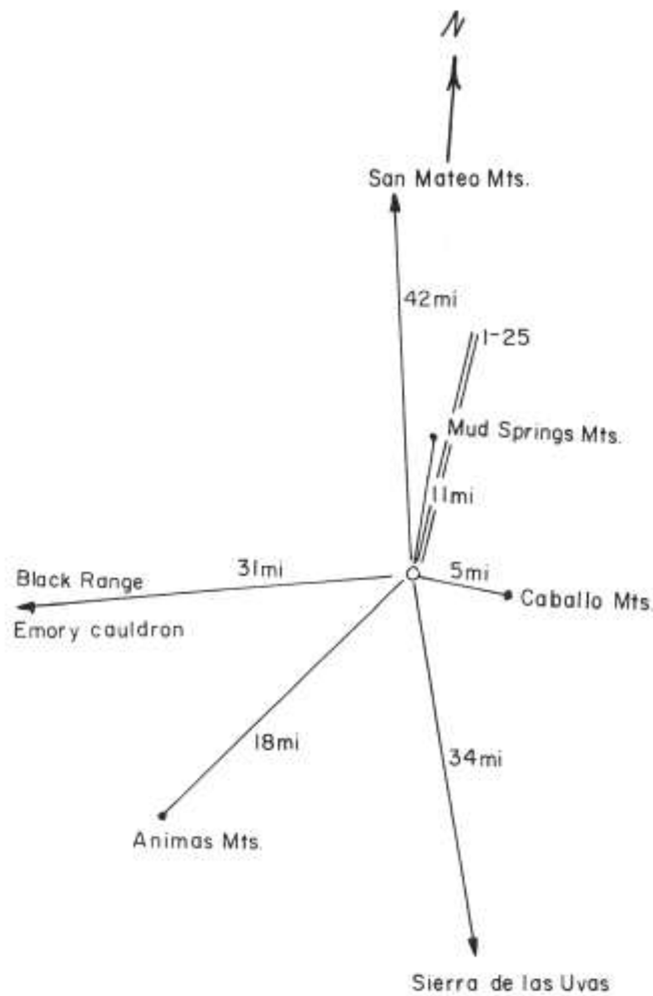


FIGURE S22—PANORAMIC INDEX OF FEATURES SEEN FROM STOP S6 AT CABALLO RESERVOIR REST AREA in east-central Palomas Basin, overlooking Caballo Reservoir at base of Caballo Mountain.

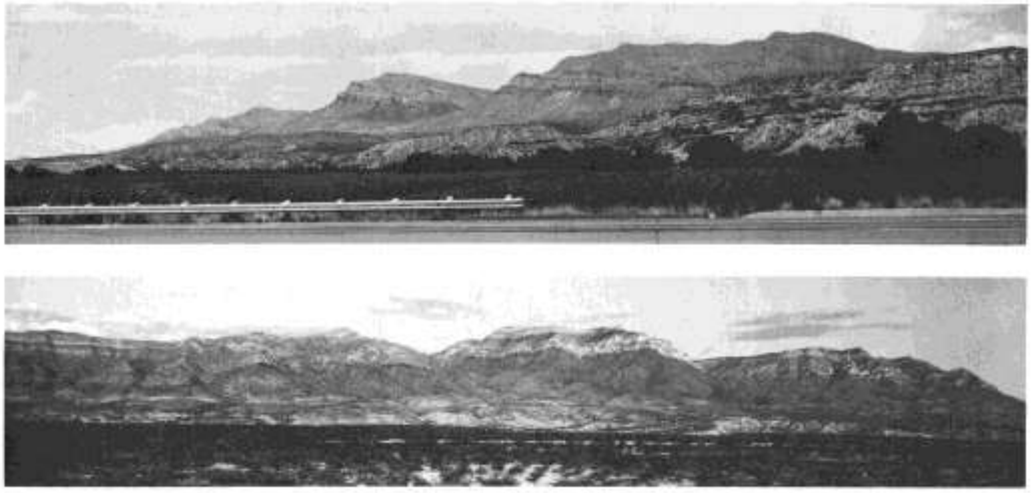


FIGURE S23—CABALLO MOUNTAINS AND CABALLO RESERVOIR AREA OF EASTERN PALOMAS BASIN. **Upper view** is from near the Rio Grande bridge (mile 148.3) below Caballo Dam northward along the mountain front; note prominent east tilt of the Caballo block. The northern peaks are opposite Stop S6. Concave slopes below the main escarpment of Paleozoic rocks are formed on Precambrian granitic rocks, overlain by Cambrian-Ordovician Bliss Formation (dark band). The first two cliff-forming units are lower Paleozoic carbonate rocks of the El Paso and Montoya Groups (Ordovician), with a thin cap of Fusselman Dolomite (Silurian). Devonian shale forms the slope above the Fusselman bench, and the crest of the range is formed by Pennsylvanian limestones. The piedmont benches east of the Rio Grande floodplain are mainly erosion remnants of upper Santa Fe Group basin fill. Tilted fanglomerate exposed in bluff at right center is capped by sandy channel deposits of the ancestral river. **Lower view** is from I-25 rest area north of Seco Creek (Stop S6) to the east-southeast across Caballo Reservoir to the main Caballo Mountain escarpment. Burbank Point of Timber Mountain forms the central part of the range and is flanked by South Ridge across Granite Wash (canyon) to the north and Jornada Point of Timber Mountain to the south. The exposed Paleozoic over Precambrian section is the same as is noted above, with Precambrian rocks forming dark rounded ridges of the lower escarpment. Complex, partly overturned, compressional structures of Laramide age are particularly well exposed in the South Ridge-Granite Wash area. The high piedmont slopes adjacent to the range front are cut by at least one major fault scarp of Pleistocene (post-Santa Fe) age.

late Tertiary fault block, tilted moderately to the east. But there is compelling evidence within the range that 50 percent or more of the structural relief is relict from the Laramide. From Santa Fe southward, no uplift more conclusively demonstrates the idea that at least some of the uplifts along the rift had important Laramide ancestors and that much of the present observable tilt is Laramide and not entirely because of late Tertiary uplift and rotation. Kelley and McCleary (1960), Eardley (1962), Kelley and Northrop (1975), and Kelley (1977) also recognized this relationship for the Fra Cristobal, Sandia and Manzano-Los Pinos ranges.

The most important evidence for major Laramide uplift in the Caballo area is the nature of the basal Tertiary unconformity. Along the eastern side of the range, far down on the dip slope, andesitic rocks of the Palm Park Formation (Eocene) overlie sedimentary rocks of the McRae Formation or the Mesaverde Group (Cretaceous-Paleocene). Just west of the main escarpment of the Caballos, which marks a prominent late Cenozoic fault, Eocene strata were deposited on Pennsylvanian and Permian rocks. A little farther west, in the Red Hills just south of Caballo Dam, the same Eocene beds are found on Precambrian and lowest Paleozoic strata. About 6,900 ft (2,100 m) of Paleozoic and Mesozoic rocks were stripped from the flanks and core of this Laramide uplift prior to late Eocene time. A major part of the tilt and structural relief that we see today must have been a product of the Laramide uplift. No doubt substantial topographic relief was still present by Eocene time, and in the Robledo Mountains (Stop S3) an escarpment of Pennsylvanian-Permian rocks nearly 1,000 ft (300 m) high can be shown to have existed during the Eocene.

Structures of Laramide style were recognized by Kelley and Silver (1952) in the Caballos. These include overturned synclines, tight to open anticlines, chevron folds and small thrusts. Overturning and thrusting is consistently east, away from the core of the uplift, so it may be presumed that these features accommodated the lateral spread of the uplift. The numerous small open-to-tight, nearly symmetrical folds in the Caballos suggest that the uplift was more in the nature of an anticlinorium than a simple "broad-backed" dome. The uplift is interpreted to be similar in geometry and origin to those of the southernmost Rockies or to some of those on the Colorado Plateau.

The Emory cauldron (Elston and others, 1975) makes up almost all of the southern part of the Black Range west of this stop. The cauldron, about 34 by 16 mi (55 by 25 km), is elongated northerly, parallel to the Black Range and to the Rio Grande rift. The resurgent dome nearly fills the cauldron and forms the summit of the range. The cauldron is the source of the Kneeling Nun Tuff, 33.4 ± 1.0 m.y. old, (McDowell, 1971). Thickness of tuff within the cauldron (cauldron facies) is generally at least 3,300 ft (1,000 m), while an outflow sheet, which spread at least 19 mi (30 km) beyond the cauldron margins, is generally less than about 330 ft (100 m) thick. The distal edge of the Kneeling Nun outflow sheet is exposed above Eocene rock in the Caballo Mountain foothills just southeast of Caballo Reservoir; it is about 50 ft (15 m) thick there. Peripheral ring fractures invaded by rhyolite domes mark the margin of the Emory Cauldron. The domes are associated with thick pumiceous "moat deposits"; within the cauldron, these deposits accumulated to be hundreds of meters thick above the cauldron facies of the Kneeling Nun Tuff.

Resurgence of the cauldron floor, as well as late Tertiary faulting, raised the cauldron fill to more than 10,000 ft (3,000 m) above sea level along the summit of the range. Resulting erosion has been deep, and pre-cauldron rocks (Precambrian, Paleozoic, Cretaceous, and Eocene) have been exposed over wide areas. Of special interest are Cretaceous andesites near Hillsboro that have been intruded by a 73.4-m.y. (Hedlund, 1974) stock containing a porphyry copper system.

Fig. S24, from Cordell (1978), shows gravity and elevation profiles across the state at this latitude. The only direct geophysical evidence for the crustal structure in the southern portion of the Rio Grande rift comes from an unreversed west-to-east seismic refraction profile also located near the latitude of this stop (McCullar and Smithson, 1977). The refraction interpretation gives a two-layered crustal model with thinning of the crust from 35 km near Santa Rita to the west to 27 km under the center of the rift. Beneath the rift the mantle P wave velocity is anomalously low (7.4 km s^{-1}) and has been interpreted as a "pillow" of hot mantle material (McCullar and Smithson, 1977). 0.2

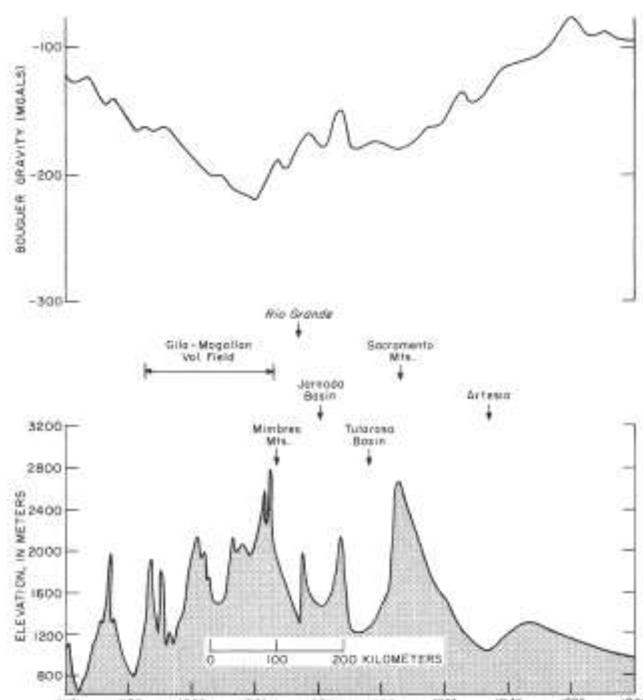


FIGURE S24—GRAVITY AND ELEVATION PROFILES ACROSS NEW MEXICO ALONG 33° NORTH LATITUDE (from Cordell, 1978, with permission).

157.5 Descending long grade; cuts ahead in distal piedmont-alluvial facies of upper Santa Fe, which overlaps and interfingers with fluvial beds to north and east. **1.0**

158.5 Maroon clay and gray sand of fluvial(?) facies in cuts ahead. 1.6

160.1 Crossing arroyo valley; cuts in upper Pleistocene terrace alluvium. 0.7

160.8 Palomas Gap through northern Caballo range at 3:00. Route crosses badlands carved in distal piedmont facies of upper Santa Fe. 0.8

161.6 Underpass; crossing valley of Palomas Creek. A test well near here (B. Iorio No. 1 Fee) "was drilled to 2,100 ft (640 m) and plugged back to 1,550 ft (472 m) for a flow of 30 gallons a minute of water having a temperature of 32 ° C (90° F). In this well the Santa Fe Formation had a thickness of 1,165 ft (355 m)" (Kelley and Silver, 1952, p. 189). The hole bottomed in the Thurman Formation. 0.5

162.1 Cuts ahead in upper Santa Fe basin fill with a thin cap of upper Pleistocene terrace gravel of Palomas Creek. 0.7

162.8 At 12:00 Mud Springs Mountains, a northeast-tilted block of Precambrian to Pennsylvanian rocks. 0.5

163.3 Thick section of upper Santa Fe alluvium exposed in bluffs to left. These distal piedmont-slope deposits were derived mainly from two large tributary stream systems (ancestral Palomas and Cuchillo creeks) that headed in the Black and Cuchillo ranges. **1.8**

165.1 Williamsburg underpass; milepost 75. 0.5

165.6 Tilted upper Santa Fe beds in roadcut to left; deformation is related to offset of the Palomas basin block along the Mud Springs fault zone. The valley of Williamsburg (Mud Springs) Arroyo follows this northwest-southeast-trending zone. Precambrian rocks that form the core of the Mud Springs uplift are exposed along the Rio Grande about 2 mi east of this point as well as in the mountains to the north (Kelley and Silver, 1952). 0.5

166.1 Milepost 76. Cuts ahead in (basal upper?) Santa Fe conglomeratic mudstone to sandstone. 1.5

167.6 Nearly vertical beds of Pennsylvanian limestone in roadcuts to left and right mark the southeast extension of the Mud Springs uplift. Upper Santa Fe basin fill exposed from here to Elephant Butte Reservoir (mile 174.3) comprises sandy fluvial deposits of the ancestral Rio Grande (Pliocene-Pleistocene) with local tongues of conglomeratic piedmont alluvium.

The city of Truth or Consequences was formerly known as Hot Springs. Springs in the center of town issue warm mineralized waters (temperatures from 98-114 ° F) from fissures at the base of a Pennsylvanian (Magdalena Group) limestone hill that also lies along the southeast extension of the Mud Springs uplift. In 1950 the city voted to adopt the name of the then popular radio show "Truth or Consequences." In return, the show's master of ceremonies, Ralph Edwards, agreed to bring his program to the annual fiesta held in the city. The community is often simply designated by the initials T or C (Jahns, 1955a; Pearce, 1965). 0.7

168.3 *Keep right; prepare for exit ahead.* Roadcuts in fluvial sand facies. 0.7

169.0 *Turn right at exit 79-Truth* or Consequences. 0.3

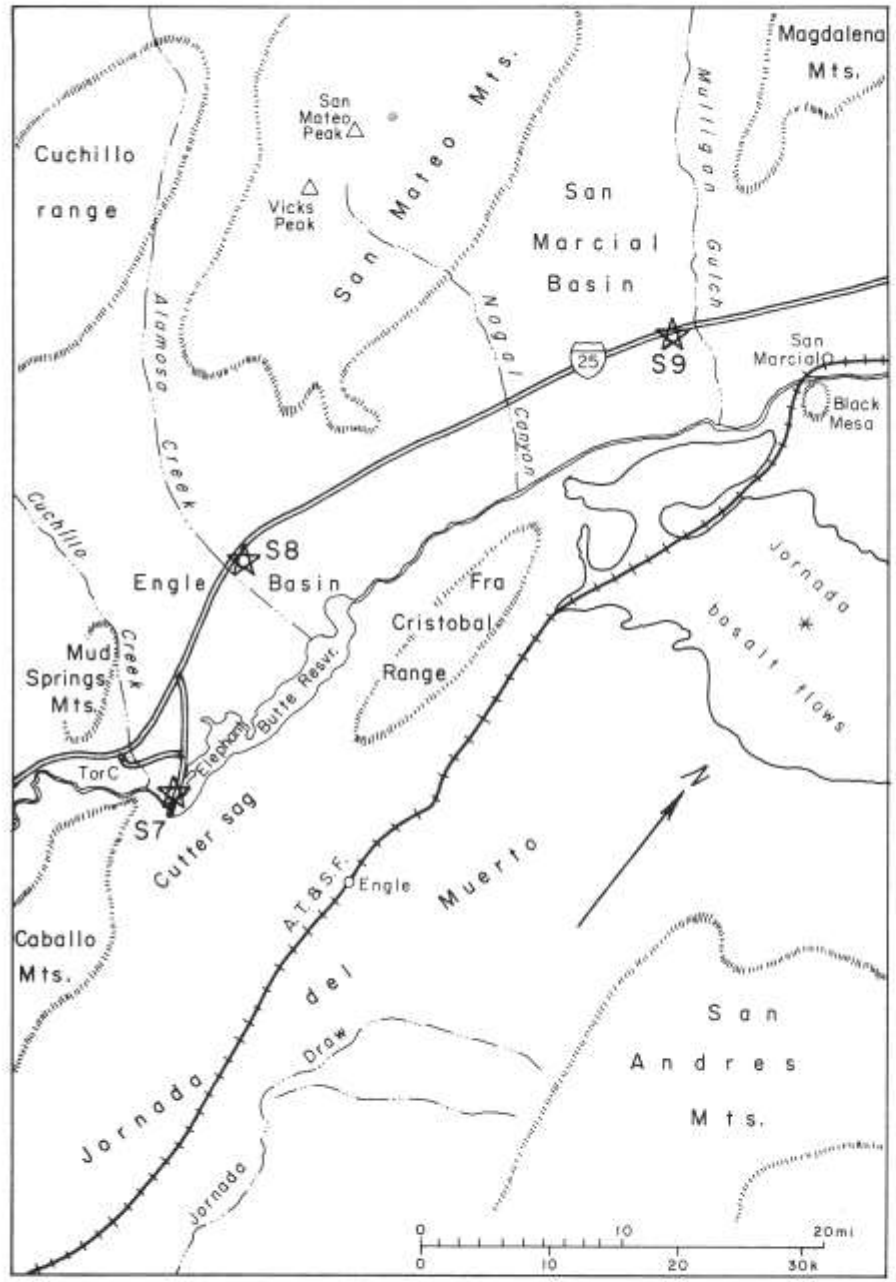


FIGURE S26—Skylab-2 photo (a) and index map (b) of the Engle-San Marcial-Northern Jornada del Muerto Basin area (photo SL2-86-56 courtesy of Technology Application Center, University of New Mexico; photo scale approximately same as map scale).

169.3 *Keep left* for Elephant Butte turnoff ahead. **0.4**
169.7 *Turn left onto US-85 northbound.* **0.2**
169.9 Descending into valley of Cuchillo Creek; cuts ahead in Santa Fe fluvial deposits capped with upper Pleistocene terrace gravel. **0.3**
170.2 Bridge over Cuchillo Creek. In bluffs downstream (to right) basal, upper Santa Fe conglomerate underlies sandy fluvial facies. **0.3**
170.5 Roadcuts ahead in fluvial sand and conglomeratic sandstone capped with upper Pleistocene terrace gravels of Cuchillo Creek. **0.5**
171.0 Ascending to terrace surface. *Prepare for right turn ahead.* **0.2**
171.2 *Bear right on NM-Spur 52* to Elephant Butte State Park. **0.6**
171.8 Ascend hill; roadcuts in upper Santa Fe fluvial facies. **1.0**
172.8 *Turn right (south) onto NM-52;* crossing broad ridge cut in sandy fluvial deposits. **0.3**
173.1 Entering Elephant Butte State Park; reservoir to left. **0.4**
173.5 Lions Beach recreation area to left. **0.3**
173.8 NM-135 (truck and trailer bypass) to right. *Continue straight* on NM-52; one-way eastbound across Elephant Butte Dam. **0.2**
174.0 **STOP S7a, Elephant Butte Reservoir.** Discussion of northern Caballo-Fra Cristobal area (fig. S25; fig. S26 Skylab photo; fig. S27a).

The broad area of basalt-capped tablelands between the Fra Cristobal and Caballo uplifts has been designated the Cutter sag (Kelley, 1952, 1955). This complexly faulted structural trough contains a thick section of Upper Cretaceous to Paleocene(?) clastic rocks (Mesaverde Group and McRae Formation; Bushnell, 1955). The basalt flows rest on a broad erosion surface cut in these rocks, and Santa Fe Group deposits are thin or absent. Basalt from a cone on the Jornada Basin rim about 6 mi (10 km) east-southeast of this stop has a K-Ar age of 2.1 ± 0.4 m.y. (Bachman and Mehnert, 1978, no. 29). This age indicates that at least part of the high-level erosion surface predates formation of the Palomas, Jornada, and La

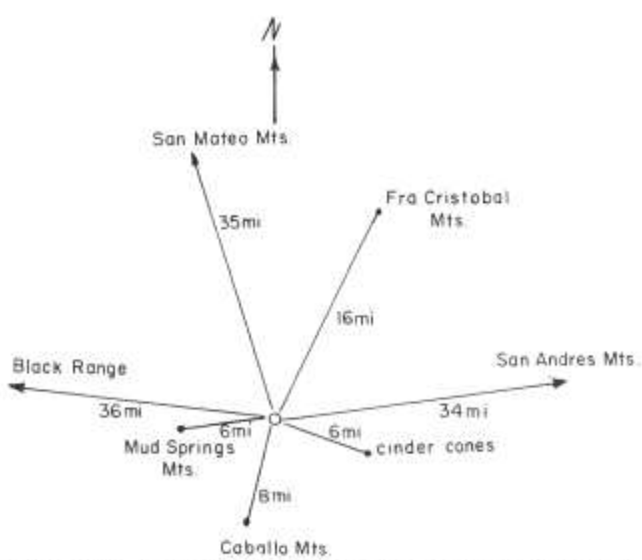


FIGURE S25—PANORAMIC INDEX OF FEATURES SEEN FROM STOP S7a AT SOUTHWESTERN END OF ELEPHANT BUTTE RESERVOIR, SOUTHERN ENGLE BASIN.

Mesa surfaces seen at previous stops. The northeastern flank of the Caballo Mountains to the south is formed on a thick section of Permian and Cretaceous (carbonate and clastic) rocks that dip into the Cutter sag.

The Fra Cristobal-Cutter sag-northern Caballo trend forms a structural high that is separated from the Engle Basin to the west by the Hot Springs fault zone. This zone is located in the reservoir to the north and east of this stop (fig. S27a) and extends southward through the Truth or Consequences area, where southeast-trending structures of the Mud Springs uplift encounter the Caballo block, and merges with the central Caballo fault zone seen at Stop S6.

Upper Santa Fe beds in this part of the Engle Basin, primarily the fluvial facies, are downfaulted along the Hot Springs zone. A typical section of these beds is exposed between here and the lake. Near Mitchell Point, about 13 mi (21 km) north of this stop, a basalt tongue in the lower part of the fluvial facies has a K-Ar age of 2.9 ± 0.3 m.y. (Bachman and Mehnert, 1978, no. 28). These ancestral Rio Grande deposits appear to correlate with the lower part of the Camp Rice section near Rincon (Stop S4) as well as with much of the Sierra Ladrones Formation of the Socorro-San Acacia area (Stops S10-12).

This stop is followed by a brief tour of the Elephant Butte area with an optional stop (S7b) at a point overlooking the dam. A detailed road log and discussion of local geology has been prepared by Bushnell and others (1955). **0.3**

174.3 Crossing reservoir wing dam. The east end of the dam is over a concealed segment of the Hot Springs fault zone, with upper Santa Fe beds downthrown against the Upper Cretaceous Mesaverde Formation. **0.3**
174.6 Mesaverde sandstones, mudstones, and shales exposed in roadcuts ahead. **0.9**
175.5 *Cross Elephant Butte Dam; load limit 10 tons.* **0.3** 175.8 *Slow* for sharp left turn at east abutment of dam. Cuts ahead in Mesaverde beds. **0.1**
175.9 Elephant Butte island (peninsula) to left. **0.1**
176.0 Junction. *Turn sharp right* on switchback. **0.1**
176.1 STOP S7b, Elephant Butte Dam. This stop overlooks Elephant Butte gorge (fig. S27b), here cut into the Mesaverde Formation. Rio Grande diversion from a former course west of the Hot Springs fault zone and superposition in its present location was first recognized by W. T. Lee (1907). The foothills south of this point are formed on Mesaverde beds and on the lower (Jose Creek) member of the McRae Formation (Bushnell and others, 1955). The river valley in this part of the reservoir is cut mainly in the upper (Hall Lake) member of the McRae. This unit comprises a thick section of purple-to-buff shale and sandstone beds. Fossil fragments of *Triceratops* and plant remains recovered from the Hall Lake Member indicate that the bulk of the unit is late Cretaceous in age; however, the youngest beds may extend into the early Tertiary (Bushnell, 1955). Andesitic laharic breccia forms much of the lower member south of this stop. The basalt plug that forms Elephant Butte intrudes the upper McRae Member and is probably related to the Pliocene-Pleistocene extrusive sequence capping mesas east of the reservoir.

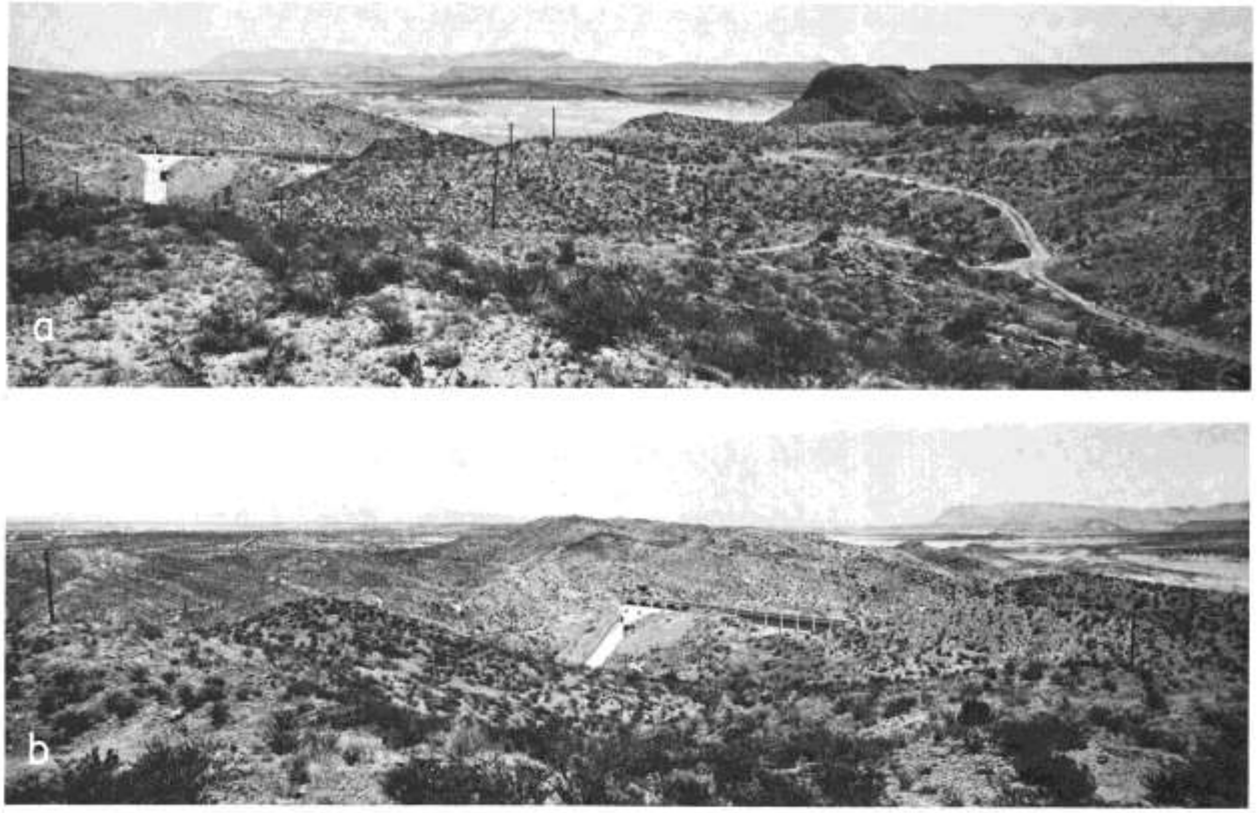


FIGURE S27—ELEPHANT BUTTE DAM AND RESERVOIR, AREA OF SOUTHERN ENGLE BASIN. The upper view **(a)** is north up the reservoir toward the Fra Cristobal Range. Elephant Butte, a basalt plug intruded in the McRae Formation (Upper Cretaceous-Paleocene?), is beyond trees and building to right of center. Elephant Butte Dam and spillway is left of center. Dam abutments are anchored in Mesaverde sandstones and mudstones (Upper Cretaceous). The lower reservoir area is eroded in shales and sandstones of the McRae. Upper Pliocene basalt caps the high-level erosion surface east of the reservoir in the area of Cutter sag between the Caballo Mountains (just south of photo point) and the Fra Cristobals. The lower view **(b)** is north-northwest across Long Ridge, west of dam, toward the San Mateo Mountains (west of center) and the Fra Cristobal Range (right of center). Hot Springs fault forms the western boundary of the Long Ridge block of Mesaverde rocks, with upper Santa Fe basin fill forming the downthrown block in the area of Stop S7a. The fault continues across and up the east side of the reservoir to merge with the (western) frontal of the Fra Cristobal Range (see Stop S8 discussion). The upper reservoir area is eroded in upper Santa Fe Group basin fill and associated basaltic volcanics.

ELEPHANT BUTTE DAM AND RESERVOIR

by Jerry Mueller
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Extensive development of irrigation in the San Luis Valley of southern Colorado and northern New Mexico from 1860-1890 depleted some of the flow of the Rio Grande that normally served New Mexican farmers in the Mesilla Valley and Texan and Mexican farmers in the E1 Paso-Juarez Valley of west Texas. These farmers, also plagued by periodic floods and natural droughts, registered complaints in the 1880's and 1890's against the upstream water diversions (Lester, 1977, p. 26-48). Anson Mills of E1 Paso, who was later to become the first U.S. Commissioner on the joint International Boundary Commission, had suggested in 1888 that an international dam be built 3 mi upstream of E1 Paso to store irrigation water for the farmers of Mexico and Texas. Irate Mesilla Valley farmers immediately protested that such a facility would inundate thousands of acres of their lower valley farmland and would provide no benefit to New Mexico (Mills, 1918, p. 261-278).

Just when it appeared that the U.S. and Mexico were about to build the E1 Paso dam in the middle 1890's, the Rio Grande Dam and Irrigation Company obtained a charter from the Department of the Interior to construct a private dam near Engle, New Mexico, approximately 150 mi by river upstream of E1 Paso. The Irrigation Company, afflicted by financial difficulties and years of litigation in the courts, was never able to construct the dam at the Elephant Butte site; and its charter expired in 1903 (Clark, 1975, p. 1019-1031).

The drought that produced record low discharges at the E1 Paso cross section in 1902 continued into the spring of 1903, prompting local farmers and the Mexican Government to once again complain to Washington. By 1904, the Reclamation Service of the Department of the Interior had completed its investigation of water availability, and strongly endorsed Elephant Butte as the only logical site at which a dam and reservoir could adequately serve all interested parties in the valleys below. This recommendation was effected by the 1906 Water Allocation Treaty between the U.S. and Mexico that provided for the creation of the Elephant Butte Dam and guaranteed Mexico an annual 60,000 acre-ft of water to be delivered to the head of the Acequia Madre in Juarez (Hundley, 1966, p. 28-30).

Elephant Butte Dam was completed in 1916 at a cost of approximately $5 million. At the time of completion it was the world's largest dam and created the second largest man-made water impoundment in the world. Downstream irrigators, organized into water-user associations, were to repay most of the dam's cost through long-term, interest-free loans. The early water associations were replaced in 1919 by the quasi-public Elephant Butte Irrigation District. In 1940, a hydroelectric facility with a generating capacity of 24,300 kilowatts was added to the project (Day, 1970, p. 58-62).

According to a 1974 silt survey conducted by the Bureau of Reclamation, Elephant Butte Reservoir retains approximately 80.1 percent, or 2,109,400 acre-ft, of its original storage capacity of 2,634,000 acre-ft. Sedimentation rates in the reservoir have been considerably below those estimated at the time the dam was constructed. Caballo Dam was added 22 mi downstream of Elephant Butte in 1938 to regulate water releases from Elephant Butte and to harness flood discharges from several large tributary arroyos. A silt survey conducted in 1958 indicated that Caballo still retained 99.997 percent of its original storage capacity of 344,000 acre-ft. Together, the two dams have been remarkably successful in providing flood protection and irrigation water to the valleys below. In 1915-one year before Elephant Butte Dam-irrigated farmland in southern New Mexico was 38,876 acres; today it is approximately 85,000 acres (Bureau of Reclamation annual records, E1 Paso, Texas).

Continue down gorge of Rio Grande. **0.1**

176.2 Stop sign; *turn right onto NM-51.* **0.1**

176.3 Descending to canyon floor; cuts ahead in progressively older Mesaverde beds. 0.3

176.6 Powerhouse road to right. Upper Pleistocene terrace gravels locally cap bedrock units downstream from this point. **0.8**

177.4 Crossing bridge over Rio Grande. **0.3**

177.7 Mesaverde beds in cuts to right. Across river to left dark-colored Mancos shales (Upper Cretaceous) crop out at the mouth of Mescal Canyon. A slice of folded and broken San Andres Limestone (Permian) within the Hot Springs fault zone forms the ridge west of the canyon mouth (Kelley and Silver, 1952). **0.2**

177.9 *Prepare for right turn* ahead. Steeply dipping Mesaverde beds mark upthrown part of Hot Springs fault zone. **0.1**

178.0 *Turn right onto NM-135.* **0.1**

178.1 Hot Springs fault zone follows arroyo valley to right, with upper Santa Fe piedmont alluvium (west) downthrown against Mesaverde beds (east). Roadcuts ahead on right in deformed Santa Fe beds capped with undeformed river-terrace gravel of late Pleistocene age. **0.9**

179.0 Contact (conformable?) of upper Santa Fe fluvial facies on piedmont facies in cut to right. **1.1**

180.1 Stop sign; *turn left onto NM-52.* This completes Stop S7 tour loop of Elephant Butte area and the road log section from the New Mexico-Texas State line.

ELEPHANT BUTTE RESERVOIR TO SOCORRO

by J. W. Hawley, C. E. Chapin, and G. R. Osburn
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180.1 Junction of NM-52 and NM-135 at Elephant Butte State Park. *Proceed north on NM-52.* **1.1**

181.2 NM-Spur 52 to left; *continue straight* (north) on NM-52. **0.8**

182.0 *Bear left* on NM-52; right fork to Hot Springs Landing. Cross broad ridge cut in sandy beds of the upper Santa Fe fluvial facies. About 1 mi northeast of this junction is the Summit 1 Mims exploratory well, drilled between 1950 and 1954 (sheet 2, hole p). The hole penetrated 1,986 ft (605 m) of basin fill, interpreted as Santa Fe, and 4,209 ft (1,283 m) of Cretaceous to Pennsylvanian rocks. Estimated depth to Precambrian basement is 7,985 ft (2,434 m) or 3,415 ft (1,041 m) below sea level (Foster, this guidebook, hole p). **1.4**

183.4 Curves ahead; route ascends dissected scarp cut in distal part of the upper Santa Fe piedmont facies. These loamy to gravelly beds, with paleosol zones, were deposited at the toe of a huge alluvial-fan complex that overlaps sandy fluvial deposits of the ancestral Rio Grande. **1.2**

184.6 Stop sign; *continue straight across US-85 and curve right on 1-25 north approach ramp.* **0.2**

184.8 *Merge with 1-25;* San Mateo Mountains at 12:00. From here to mile 198.0 the route ahead crosses the Cuchillo plain, the distal part of a huge coalescent fan surface that spreads out from upper reaches of the ancestral Cuchillo and Alamosa Creeks in the Cuchillo and San Mateo ranges. This relict piedmont slope and floor of Engle Basin (Kelley, 1952) was graded to ancestral-river base levels more than 330 ft (100 m) above the present river-valley floor. The surface generally correlates with the Jornada I and La Mesa geomorphic surface to the southeast (Stops S1b-S4) and the Palomas surface to the south (Stop S6). The surface is of complex origin, being mainly erosional near the mountain fronts and mainly constructional in areas such as this one near the basin axis. **4.2**

189.0 Milepost 88; aircraft direction station to left. Near this point is the Gartland 1 Brister exploratory well, drilled in 1951 and 1955 (sheet 2, hole q). The hole penetrated 1,450 ft (442 m) of Santa Fe Group basin fill, 90 ft (27 m) of McRae? Formation, and 7,045 ft (2,147 m) of Cretaceous to Pennsylvanian rocks. Estimated depth to Precambrian basement is 8,805 ft (2,684 m) or 3,955 ft (1,205 m) below sea level (Foster, this guidebook, hole q). The hole is reported to have penetrated a monzonite sill from 4,350 to 5,110 ft (1,326 to 1,578 m) in the Yeso Formation (Jahns, 1955a). About 3 mi west of this point is a second test hole, Gartland 1 Garner that penetrated 6,524 ft (1,989 m) of basin fill, possibly all Santa Fe Group (sheet 2; Foster, this guidebook, hole r). Westward thickening of fill may indicate northward extension of the Palomas structural basin, bounded on the east by the Mud Springs block. **1.0**

190.0 Underpass. View ahead of northern Cuchillo plain and San Mateo Mountains beyond north wall of Monticello Canyon (fig. S28). **0.1**

190.1 Descending into Monticello Canyon of Alamosa Creek. As much as 300 ft (90 m) of upper Santa Fe fan gravels are exposed in cuts on both sides of the canyon. **0.9**

191.0 Milepost 90; cuts in upper Pleistocene terrace gravel of Alamosa Creek. **0.4**

191.4 Bridge over Alamosa Creek. *Prepare for right turn ahead at crest of grade.* **1.1**

192.5 *Take Exit 92-Mitchell Point road.* **0.2**

192.7 **STOP S8, Mitchell Point interchange (optional),** northeastern Cuchillo plain at Mitchell Point, 1-25

FIGURE S28—The Cuchillo plain (western Engle Basin), southern San Mateo Mountains, and Nogal Canyon cauldron (Oligocene); view is to northwest across Monticello Canyon of Alamosa Creek. About 300 ft of upper Santa Fe piedmont gravels are exposed in north canyon wall. The massive cliffs are exposed in north canyon wall. The massive cliffs on Vicks Peak—the high point at the south end of the San Mateos—are cauldron-facies Vicks Peak Tuff just inside the west margin of the cauldron. The cauldron margin swings southeastward from Vicks Peak towards the viewpoint and is marked by a series of rhyolite domes of which Peñasco Peak at the right center is most prominent. The high cuesta to the right of Peñasco Peak is just outside the cauldron and is capped by thin, outflow facies of Vicks Peak tuff resting on about 600 ft of lithic-rich latite welded tuffs that form the dark, east-dipping ledges. These older tuffs probably came from another cauldron buried by Nogal Canyon cauldron (photo by G. R. Osburn).

interchange. *Park near intersection at east edge of interchange. Assemble at stop sign on overpass* for discussions of ranges flanking the Engle and northern Palomas Basins (figs. S26 and S29).

MOUNTAINS AND BASINS WEST OF 1-25

by C. E. Chapin

To determine the orientation of points discussed, 12:00 is looking north-northeast up 1-25 (fig. S29). The west shoulder of the rift, the Black Range, forms the southwestern skyline at 6:30-8:30. The Animas Hills at 6:30-7:00, Salado Mountains at 8:00, and Cuchillo range at 8:30-9:30 are east-tilted intrarift horsts that parallel the Black Range but lie about 10 mi (16 km) to the east and are separated from the Black Range by a series of narrow north-trending grabens. Tilting and erosion has exposed Paleozoic sedimentary rocks and numerous stock intrusions along these narrow horsts. The Copper Flat porphyry copper deposit in the Animas Hills northeast of Hillsboro occurs in a stock dated at 73.4 ± 2.5 m.y. (Hedlund, 1974). Andesitic detritus in the Late Cretaceous-early Tertiary McRae Formation at Elephant Butte Reservoir (Stop S7b) is another indication of Laramide magmatism in this area. A siliceous, low-grade fluorspar deposit of more than 2 million tons averaging 19 percent CaF_2 is present in the Salado Mountains near a nepheline-monzodiorite stock dated at 59.9 ± 2.4 m.y. (Lamarre, 1974). Cuchillo Mountain at 9:00 is composed of a monzonitic laccolith dated at 48.8 ± 2.6 m.y. (Chapin, Jahns, and others, 1978) intruded into Paleozoic limestones. In the northern Cuchillo range, beryllium, tungsten, and iron deposits occur in contact-metasomatized Paleozoic sedimentary rocks along the margins of granitic intrusions. The northernmost of these intrusions, a fine-grained aplitic granite, has been dated at 29.2± 1.1 m.y. (Chapin, Jahns, and others, 1978). The stratigraphy and ore deposits of the Cuchillo range have been studied extensively by Jahns (1944, 1955b) and Jahns and others (1978).

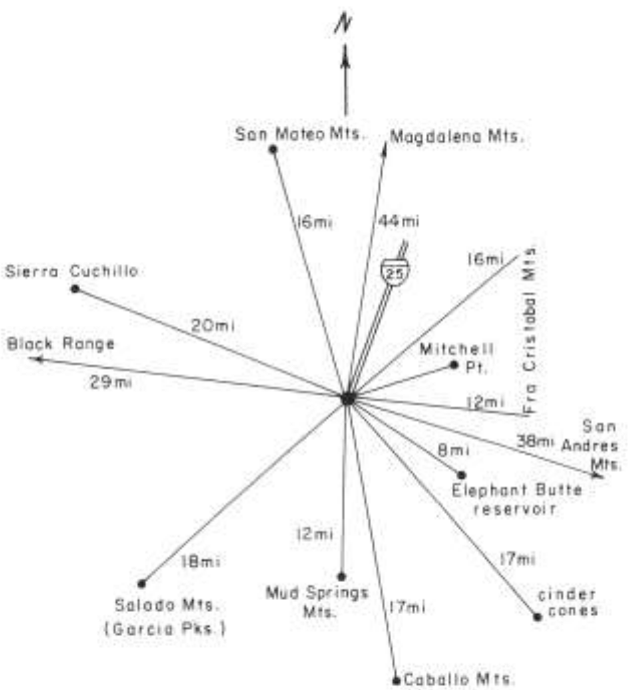


FIGURE S29—Panoramic index of features seen from Stop S8 at Mitchell Point interchange (I-25) in western Engle Basin.

At 10:00, Vicks Peak, elevation 10,252 ft (3,125 m), forms the bold south end of the San Mateo range. The spectacular cliffs forming the south face of Vicks Peak consist of about 1,000 ft (300 m) of cauldron-facies Vicks Peak Tuff on the western margin of the Nogal Canyon cauldron (Deal and Rhodes, 1976; Deal, Stop S9, this guidebook). The southeastern margin of the Nogal Canyon cauldron lies along the north side of the high mesa at 11:30 and extends southwestward through the Peñasco Peak rhyolite dome at 11:00. The dark hills to the left of Peñasco Peak are also rhyolitic intrusions along the cauldron margin. The low hills this side of Peñasco Peak appear to be remnants of silicic lavas resting on Paleozoic limestones outside the cauldron. The high mesa behind the microwave tower consists of latitic lava flows and volcaniclastic sedimentary rocks of the Red Rock Ranch Formation (Farkas, 1969) at the base overlain by 600-800 ft (183-244 m) of lithic-rich, latitic ash-flow tuffs of the Rock Spring Formation (Farkas, 1969) that form the prominent ledgy outcrops. The mesa is capped by 200-300 ft (61-91 m) of outflow-facies Vicks Peak Tuff, which dips eastward away from the cauldron. The Nogal Canyon cauldron appears to overlap and partly bury an older cauldron to the west that was the source of the ash-flow tuffs in the Rock Spring Formation. The Red Rock Ranch and Rock Spring Formations are correlative with the Spears Formation to the north and the Rubio Peak Formation to the southwest. All are early Oligocene latitic lava flows, tuffs, breccias, and volcaniclastic sedimentary rocks, which all underlie the silicic ash-flow tuffs capping the Datil-Mogollon volcanic field. Plant fossils in lacustrine sediments of the Red Rock Ranch Formation are similar to those of the Florissant Lake Beds in Colorado. The Red Rock Ranch flora is one of the data points used by Axelrod and Bailey (1976) in interpreting the Cenozoic climate and altitude along the Rio Grande rift.

THE FRA CRISTOBAL RANGE FROM MITCHELL POINT EXIT (STOP S8)

by Sam Thompson 1I1
New Mexico Bureau of Mines and Mineral Resources, Socorro, New Mexico

Lying 11 mi (18 km) northeast of the 1-25 Mitchell Point exit (fig. S29), the Fra Cristobal Range trends north-south about 15 mi (24 km) and is about 5 mi (8 km) wide. Elevations rise to over 6,800 ft (2,075 m) along the crest of the range, compared to 4,600 ft (1,400 m) in the Jornada del Muerto on the east side and to 4,400 ft (1,340 m) in the Rio Grande Valley (Elephant Butte Reservoir) on the west side of the range. For orientation of points discussed, 12:00 is looking north-northeast up 1-25.

The northern part of the Fra Cristobal Range, from 1:002:00 (N. 45° E.-N. 85 ° E.), consists of Precambrian, Cambrian-Ordovician, and Pennsylvanian rocks (McCleary, 1960). The Precambrian outcrops are brownish; they form rugged escarpments up to 1,700 ft (520 m) high on the western front and consist mostly of granitic and metamorphic rocks (Condie and Budding, in press). Pennsylvanian rocks of the Magdalena Group are about 1,500 ft (460 m) thick and consist of grayish, evenly bedded limestones and mudstones forming the crest of the range (McCleary, 1960). North of Fra Cristobal Peak at 1:15 (N. 60° E.), Pennsylvanian rocks rest unconformably on Precambrian rocks; southward, a Cambrian-Ordovician sequence of Bliss sandstones, E1 Paso limestones, and Montoya dolostones ranges up to 300 ft (90 m) in thickness where it is preserved beneath the pre- Pennsylvanian erosion surface (Kelley and Silver, 1952; Jacobs, 1956; Warren, 1978).

The general Laramide structure of the northern part of the range is that of an asymmetrical anticline, with the Precambrian core thrust eastward over Pennsylvanian or older Paleozoic rocks (McCleary, 1960). The alternating limestones and mudstones of the Pennsylvanian were thrown into a north-south trend of chevron synclines overturned to the east in front of the thrust zone. In the Amphitheater Canyon area, from 1:30-2:00 (N. 65° E.-N. 80° E.), the axes of the Laramide anticline and of a syncline to the west (overturned to the east) form the southern plunge of the core (Jacobs, 1956). The steep dip in the Pennsylvanian at the south end, 2:00 (N. 80° E.), is on the Hellion monocline (Warren, 1978).

Although not seen from this locality, the conglomeratic, lower part of the McRae Formation, which is probably Late Cretaceous in age, rests unconformably on Precambrian at the north end of the range (Kelley and McCleary, 1960). This relationship indicates that in this range a phase of Laramide deformation was completed before the end of Late Cretaceous time.

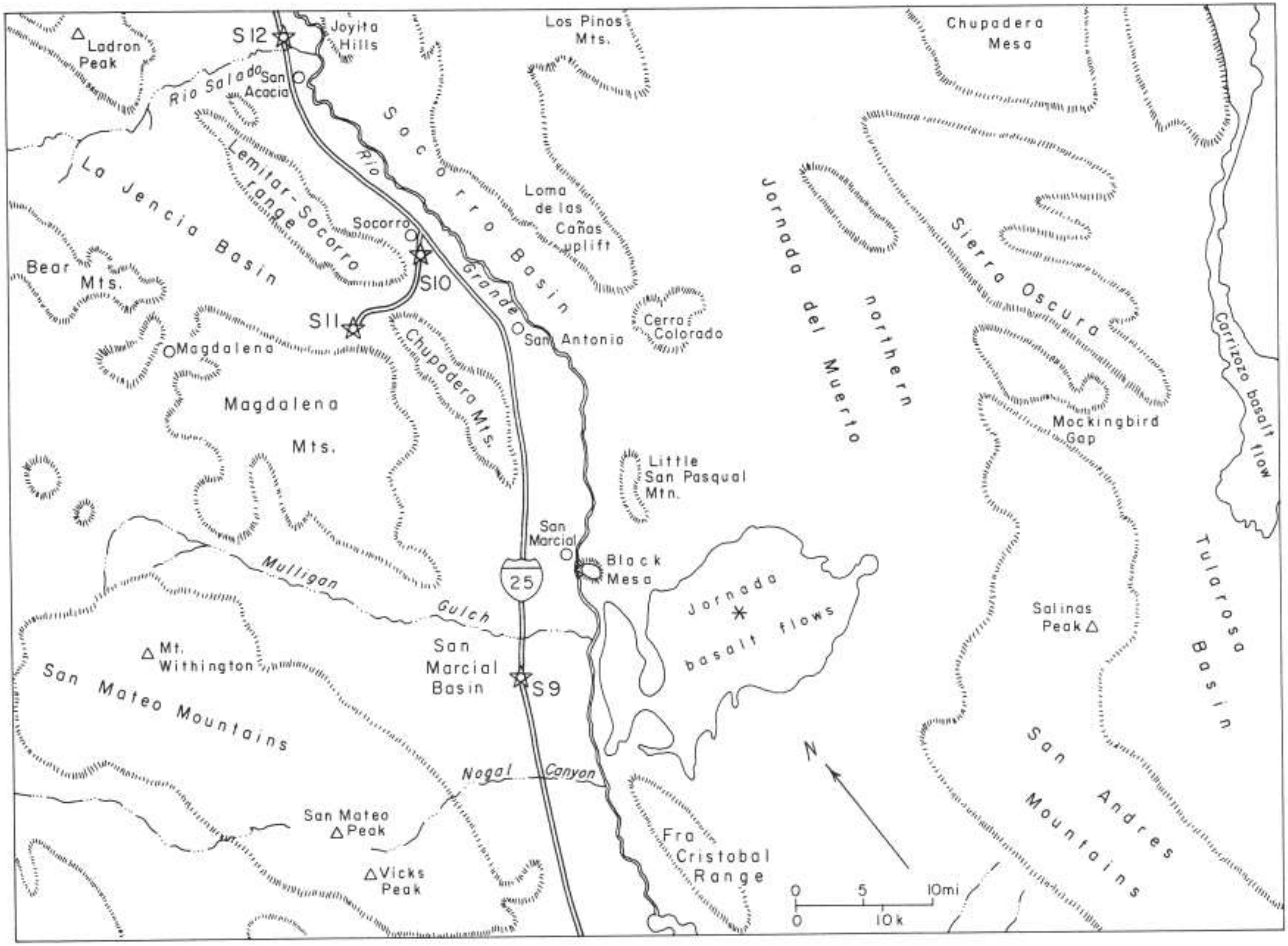
The Basin and Range deformation in the northern part of this range is characterized by normal block faulting with minor strike-slip movement and some broad, open folding. The Fra Cristobal fault zone forms the boundary with the Jornada del Muerto depression on the eastern side of the range. Gently dipping Pennsylvanian rocks are exposed on the up-thrown side, and Cretaceous rocks probably are present beneath a thin Quaternary cover on the downthrown side. On the western side of the range, the Hot Springs fault zone (Walnut Canyon fault of Warren, 1978) forms the boundary with the Rio Grande depression. The fault along the mountain front is marked in places by a silicified ridge that shows up very well on aerial photographs. Precambrian is exposed on the upthrown side, and some small blocks of Pennsylvanian (about 1:00, N. 50° E., north of Fra Cristobal Peak) and possible Permian (San Andres?, about 1:30-1:45, N. 70° E. in the Amphitheater Canyon area) are mapped on the down-thrown side (McCleary, 1960; Jacobs, 1956). However, these blocks may be horses in the fault zone. In the deepest part of the adjoining Rio Grande depression (Engle Basin), the Precambrian basement may lie several thousand feet below the surface and probably is overlain by the Paleozoic, Cretaceous, lower Tertiary, and a thick valley fill of upper Tertiary to Quaternary rocks.

In the southern part of the Fra Cristobal Range, from 2:00-2:45 (N. 85° E.-S. 75° E.), Permian rocks form a 1,400-ft (425-m) sequence along the crest: Abo red beds, Yeso sandstone-limestone-gypsum, and San Andres limestone in prominent cliffs (Thompson, 1955, 1961). Some normal faulting is evident within the range, even from this distance, and is attributed to the Basin and Range deformation of middle to late Tertiary age. Most of the beds dip gently, and folding generally is absent. Some tight, isoclinal folds in the incompetent Yeso Formation are present in a small area immediately north of Walnut Canyon, to the east (about 2:15); however, these folds are not discernible from here. Because their northwest-trending axes are truncated by the boundary fault, the folds are inferred to be of Laramide age. Some late Cenozoic gravity-slide structures over the incompetent beds are indicated in other localities (Warren, 1978).

Along the bounding normal faults at the southern end of the range, at 2:45 (S. 75° E.), the San Andres (Permian) is up-thrown against Upper Cretaceous Dakota and Mancos on the west and Mesaverde on the east. These faults intersect and die out southward into the Fra Cristobal anticline (Thompson, 1955, 1961). The Cutter sag (Kelley and Silver, 1952; Bushnell, 1953) forms the structurally low area from 3:00 to 4:30 between the Fra Cristobal and Caballo uplifts and consists of exposures of Dakota, Mancos and Mesaverde (Upper Cretaceous), and McRae Formation (Upper Cretaceous to lower Tertiary). The western boundary of the sag is defined by the Hot Springs fault with middle to upper Tertiary Santa Fe Group downthrown to the west in the Rio Grande depression (see Stop S7).

Two aspects of this western fault boundary of the Cutter sag remain controversial. First, is the boundary a Hot Springs fault zone that extends northward to form the western margin of the Fra Cristobal uplift (Thompson, 1955, 1961); or does an individual Hot Springs fault die out abruptly northward, while an individual Walnut Canyon fault (to the east) forms

FIGURE S30—SKYLAB-4 PHOTO (a) AND INDEX MAP (b) OF THE SAN MARCIAL-JORNADA DEL MUERTO-SOCORRO BASIN AREA, Stops S9 to S12 (photo SL4-A4-030 courtesy of Technology Application Center, University of New Mexico, scale approximately 1:500,000).


Ladron Peak
S12
Joyita Hills
Los Pinos Mts.
Chupadera Mesa
Rio Salado
San Acacia
Socorro Basin
Rio Grande
Lemitar-Socorro range
La Jencia Basin
Loma de las Cañas uplift
Jornada del Muerto
northern
Sierra Oscura
Socorro
S10
Bear Mts.
S11
San Antonio
Cerro Colorado
Carrizozo basalt flow
Magdalena
Chupadera Mts.
Magdalena Mts.
Mockingbird Gap
Little San Pasqual Mtn.
San Marcial
Black Mesa
Mulligan Gulch
25
Jornada basalt flows
Salinas Peak
Tularosa Basin
Mt. Withington
San Marcial Basin
S9
San Mateo Mountains
N
San Andres Mountains
Nogal Canyon
San Mateo Peak
Fra Cristobal Range
Vicks Peak
0 5 10mi
0 10k

the margin of the uplift and terminates abruptly southward at a scissor point on the transverse fault (Warren, 1978)? The critical area for resolving this question lies northeast of Black Bluffs at 3:00 (S. 65 °-70 ° E.). Second, was there any lateral movement along the Hot Springs fault in this area? Some hints of left-lateral drag are indicated in the Cretaceous beds along the fault, and a large right-lateral drag fold is mapped along a parallel fault south of Black Bluffs (Flying Eagle Canyon area; Thompson, 1955, 1961). Although only vertical displacements are indicated in the volcanic rocks (Warren, 1978), these rocks are late Pliocene in age (2-3 m.y.; Bachman and Mehnert, 1978) and were formed after the main Basin and Range deformation in middle to late Tertiary time (29-3 m.y.; Chapin and Seager, 1975).

Many of the volcanic-vent locations appear to be controlled by the positions of the major faults. The near perfect cone on Crater Hill, at 2:00 (N. 80° E.) in front of the range, may mark the position of the buried major fault in the boundary zone between the Fra Cristobal uplift and the Rio Grande depression. This cone may be the source of the basalt flows (dated at 2.9 m.y.; Bachman and Mehnert, 1978) in the Mitchell Point area along the narrows of the Rio Grande at 1:45 (N. 70° E.). Other flows in the Fra Cristobal area also appear to extend several miles from the vent sources (Warren, 1978).

Continue north on 1-25. 2.0

194.7 Low hills on left are just south of Nogal Canyon cauldron. 3.3

198.0 Milepost 97. Crossing dissected northern edge of Cuchillo plain. 3.5

201.5 Underpass; Red Rock interchange. 0.5

202.0 Milepost 101. At 9:00, roadcut along old US-85 at end of ridge exposes closely spaced, nearly vertical sheet jointing in densely welded Vicks Peak Tuff. Sheet jointing of this type is characteristic of cauldronfacies tuffs in several cauldrons in the Magdalena and San Mateo ranges. Old US-85 apparently lies very close to the eastern margin of the Nogal Canyon cauldron, which is largely concealed by piedmont gravels in this area. **0.4**

202.4 Cliffy outcrops along box canyon of San Jose Arroyo at 10:00 are Vicks Peak Tuff dipping 10-20° E. **1.0**

203.4 Crossing dissected piedmont plain, on upper Santa Fe Group, east of the San Mateos. Low hills at 10:30 to 11:30 are outflow-facies Vicks Peak Tuff overlying latitic tuffs and lava flows of the Rock Spring Formation along the northeast margin of the Nogal Canyon cauldron. Peñasco Peak rhyolite dome on the southern margin of the Nogal Canyon cauldron visible at 8:00, Vicks Peak at 9:00. The northern Jornada del Muerto Basin at 1:00 to 2:00 lies east of the Rio Grande Valley and west of the San Andres and Oscura ranges. **0.6**

204.0 Milepost 103. Crossing valley of Cuervo Arroyo cut in upper Santa Fe piedmont gravels. **1.8**

205.8 San Mateo Peak on crest of San Mateo range at 9:00 is outside the northwest side of Nogal Canyon cauldron. Reddish, hydrothermally altered rocks forming low ridges to right of San Mateo Peak lie along the northern margin of the Nogal Canyon cauldron. The low hills along the east flank of the San Mateo range from 9:00-10:00 are cauldron-facies Vicks Peak Tuff. The Nogal Canyon cauldron did not resurge; consequently, its geomorphic expression is that of low hills of monotonous Vicks Peak Tuff partly surrounded by a discontinuous ring of higher hills made up of ring-fracture domes (such as Peñasco Peak), pre-cauldron volcanic rocks capped by thin outflow-facies Vicks Peak Tuff, and windows of Paleozoic rocks. **1.9**

207.7 Descending into Nogal Canyon. As much as 200 ft (60 m) of upper Santa Fe piedmont gravels are exposed in canyon walls and roadcuts ahead. Paleosol zones in the section are characterized by strong reddish horizons of clay accumulation over carbonate-enriched horizons. **0.3**

208.0 Nogal Canyon bridge; milepost 107. **0.7**

208.7 Ridges of Paleozoic limestones in middle distance at 9:00 are along northern rim of Nogal Canyon cauldron. For about the next 16 mi the route crosses the moderately dissected central plain of San Marcial Basin (Kelley, 1952). The Mulligan trough segment of the basin extends northwest between the San Mateo and Magdalena (11:00) ranges. The San Marcial Basin merges with the northern Jornada del Muerto east of the entrenched valley of the Rio Grande. The Jornada Basin is bordered on the east by the Oscura Mountains (2:00) and the San Andres range (Salinas Peak at 3:00). Sierra Blanca, elevation 12,003 ft (3,659 m), is on the distant skyline at 2:30 beyond Mockingbird Gap, between the San Andres and Oscura Mountains. 2.3

211.0 Milepost 110. Magdalena Mountains at 11:00-11:30, Chupadera Mountains at 12:00, Black Mesa of San Marcial at 1:00, and basalt flow on Jornada del Muerto plain at 2:30. The Jornada flow, which descends almost to floodplain level on the east slope of the river valley, has been K-Ar dated at 0.76 ± 0.1 m.y. by Bachman and Mehnert (1978, no. 27). The basalt may rest on an early-stage surface of valley entrenchment that was partly buried and then exhumed in late Pleistocene time. **1.6**

212.6 Underpass. Rest area and Stop S9 ahead. **0.9**

213.5 Underpass. **1.1**

214.6 *Take exit* to rest area. **0.2**

214.8 **STOP S9, San Marcial Basin.** Fort Craig rest area near milepost 114 in San Marcial Basin. Assemble north of picnic shelters (northbound trip) for discussions of the San Marcial and northern Jornada Basins and flanking ranges (figs. S30 and S31).

OVERVIEW OF CENOZOIC FEATURES, SAN MARCIAL BASIN by C. E. Chapin

To determine the orientation of points discussed, 12:00 is to northeast up 1-25 (figs. S31 and S32). Vicks Peak is at 7:00; Nogal Canyon cauldron is from 6:00-7:00; and San Mateo Peak and Blue Mountain are high points on crest of San Mateo range north of Vicks Peak. The long ridge projecting eastward from the San Mateo range to the right of Vicks Peak marks the north rim of the Nogal Canyon cauldron. San Juan Peak (the pyramid-shaped summit on the flank of the San Mateo range at 8:30) is made up of light-colored stratified tuffs that overlie quartz-latite lavas and Vicks Peak Tuff from the Nogal Canyon cauldron. The northern San Mateo range (8:45-9:30) is the resurgent dome of the Mt. Withington cauldron, 25 mi (40 km) wide (fig. S32). The broad, low saddle in the San Mateo range at 8:30-8:45 reflects the approximate position of the moat on the south side of the Mt. Withington cauldron. A complex series of silicic flows and domes, unwelded local tuffs, breccias, and tuffaceous sedimentary rocks is exposed in this area (Deal, this stop).

A complex of at least seven overlapping and nested cauldrons (fig. S32) extends northeastward from the Mt. Withington cauldron to Socorro, a distance of about 40 mi (64 km). The cauldrons range in age from 32 to 26 m.y. and are distributed along an incipient transform fault formed by the en echelon stepping over of the Rio Grande rift across the northeast-trending Morenci lineament. During the initial opening of the Rio Grande rift, the axis of extension south of the Morenci lineament was along the Winston graben (fig. S32); north of the Morenci lineament, the axis of extension was along the east side of the Albuquerque-Belen Basin, approximately 60 mi (96 km) to the northeast. These two en echelon axes of extension are connected by a transverse shear zone, or incipient transform, across which the direction of rotation and step faulting changes 180 degrees. North of the transform, the beds are tilted to the west away from the Albuquerque Basin and downfaulted to the east towards the basin. South of the transform, the beds are tilted to the east and downfaulted to the west towards the Winston graben. This persistent eastward rotation of fault blocks is visible across the Magdalena (10:30) and Chupadera (11:30) ranges. The hogbacks are capped by resistant ash-flow tuffs, which are repeated over and over again by step faults downthrown to the west. Socorro Peak is visible at 11:00 as a low saddle-shaped mountain between the Magdalena and Chupadera ranges. Socorro Peak lies just north of the transform and is composed of west-tilted late-Miocene domes and flows. Note the mesas along the west side of the Chupadera range capped by late Pliocene(?) flat-lying basalts. Similar basalts along the east flank of the Chupadera range are tilted as much as 30 degrees to the east.

To the east of the Rio Grande, Little San Pasqual Mountain is visible at 1:00. Black Mesa, also at 1:00, is capped by a basalt flow that overlies sands approximately 300 ft (90 m) thick of the ancestral Rio Grande. The flow has a K-Ar age of 2.2 ± 0.10 m.y. (Bachman and Mehnert, 1978, no. 26). The cluster of low hills on the Jornada plain at 2:00 are cones at the center of an extensive basalt field. A flow on the western edge of the field, K-Ar dated at 0.76 m.y. by Bachman and Mehnert (1978), descends nearly to the level of the Rio Grande floodplain. The Sierra Oscura (1:00-2:00) and the San Andres Mountains (2:30-3:30) lie on opposite sides of another transverse shear zone that marks the intersection of the Rio Grande rift with the Santa Rita lineament. The prominent saddle at 2:00 is called Mockingbird Gap. North of Mockingbird Gap, Paleozoic limestones capping the Oscura range dip east; south of the gap, the same limestones capping the San Andres range dip west. This curious rotation of beds in opposite directions across a lineament is characteristic of areas where the Rio Grande rift broke across major, preexisting flaws in the lithosphere (Chapin and others, 1978).

GEOLOGY OF SAN MATEO MOUNTAINS

by Edmond G. Deal

Eastern Kentucky University, Richmond, Kentucky

Rocks exposed in the San Mateo Mountains to the west and northwest of the highway here are mainly Oligocene ash-flow tuffs that were erupted from two major collapse cauldrons (Deal and Rhodes, 1976). The Nogal Canyon cauldron in the south end of the range is slightly older than the Mt. Withington cauldron in the north end of the mountain range, but both structures probably are about 30-32 m.y. old (fig. S33). The Mt. Withington cauldron went through a process of collapse, resurgent doming, and moat filling, generally following a typical caldera cycle (Smith and Bailey, 1968). Few details of the structural evolution of the Nogal Canyon cauldron are known.

Paleozoic sedimentary rocks form low foothills along the south and east margin of the south end of the San Mateo Mountains and are overlain by a thick sequence of early Oligocene lavas and tuffs of intermediate composition. The basal part (Red Rock Ranch Formation) of the sequence is composed of dominantly andesitic to latitic lava flows that are lithologically similar to the basal volcanic sequence in the Magdalena area. Breccias interbedded with these lavas in the Sierra Cuchillo, just southwest of the San Mateo range, suggest close proximity to a stratovolcanic cone (Maldonado, 1977). The upper part (Rock Spring Formation) of the intermediate sequence consists mainly of welded quartz latitic ash-flow tuff. Little is known of the distribution of these tuffs, but thicknesses of about 3,300 ft (1,000 m) (Farkas, 1969) strongly suggest that their source may have been a cauldron now largely buried by the younger felsic volcanics that fill the Nogal Canyon cauldron.

The Nogal Canyon cauldron has a diameter of 9.3-12.5 mi (15-20 km). The cauldron is filled with at least 2,150 ft (650 m) of very crystal-poor (1-2 percent phenocrysts) rhyolitic ash-flow tuff (Vicks Peak Rhyolite Tuff). Deposits of this tuff outside the cauldron do not seem to have been widespread and in some areas fill only canyons. The upper part of the tuff grades upward into a flow-banded mixed lava, the Springtime Canyon Quartz Latite, that is dominated by dark, porphyritic quartz-latitic material but also contains a rhyolitic component. Cauldron collapse occurred coeval with ash-flow eruptions. Whether resurgent doming occurred is not known.

The Mt. Withington cauldron, which dominates the northern end of the range, is about 18.7-25 mi (30-40 km) in diameter. This structure is probably a composite cauldron that underwent several major episodes of collapse but utilized essentially the same set of ring fractures during each collapse. Pre-Tertiary rocks are completely buried at the north end of the San Mateo range. Eruptions of crystal-poor tuff (A-L Peak Tuff), which initiated cauldron subsidence, left deposits about 2,000 ft (600 m) thick within the cauldron; but deposits are thinner or missing on the cauldron rim and are widespread outside the cauldron. Ensuing eruptions of moderately crystal-rich ash-flow tuff (Potato Canyon Rhyolite) resulted in catastrophic collapse of the Mt. Withington cauldron and deposition of at least 5,000 ft (1,500 m) of additional tuff within the cauldron; very little tuff escaped to be deposited in surrounding areas. Strong resurgent doming elevated the floor of the deeply subsided cauldron to its approximate original structural level. The cauldron moat was then filled by thin ash-flow tuffs erupted from centers outside the Mt. Withington cauldron and by rhyolitic domes, lavas, pumiceous tuffs, and epiclastic debris (Beartrap Canyon Formation) from sources within the moat.

The north end of the San Mateo range roughly corresponds to the resurgent dome of the Mt. Withington cauldron, and the low topographic pass that separates the northern and

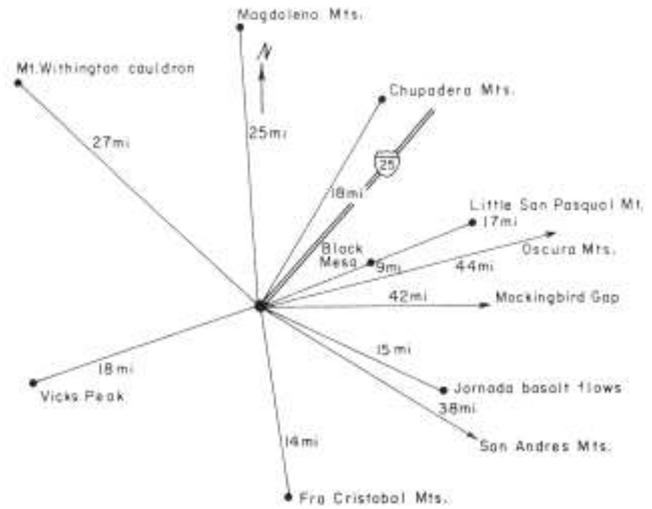


FIGURE S31—PANORAMIC INDEX OF FEATURES SEEN FROM STOP S9 AT FORT CRAIG REST AREA, SAN MARCIAL BASIN.

southern ends of the range roughly corresponds to the southern segment of the cauldron moat. The present topographic relief of the range has been accentuated by Basin and Range faulting, which began long after the eruptions of the Mt. Withington and Nogal Canyon cauldrons had ceased.

Continue north on 1-25. **1.4**

216.2 Underpass, NM-107 interchange. **0.6**

216.8 Roadcuts ahead are in upper Santa Fe alluvium with thin veneer of upper Pleistocene piedmont-slope and arroyo-terrace gravels. These deposits cap graded erosion surfaces associated with episodes of Rio Grande Valley entrenchment. **1.3**

218.1 Crossing Mulligan Gulch. **0.5**

218.6 Crossing Mulligan Gulch arroyo. Upper Santa Fe alluvium in cuts ahead. **1.4**

220.0 Milepost 119. For next 5 mi, roadcuts are in uppermost Santa Fe Group basin fill comprising a sequence of several fining-upward layers of alluvium, each capped with a well-developed paleosol. Buried soil profiles are characterized by reddish horizons of clay accumulation over nonindurated zones of carbonate accumulation. Valley-border erosion surfaces, cut into the upper Santa Fe beds, are locally capped with thin gravelly deposits of late Quaternary age. **2.0**

222.0 Black Mesa at 3:00 forms east border of Rio Grande Valley. **2.0**

224.0 Chupadera Mountains in foreground at 11:00 to 12:00. **1.6**

225.6 San Marcial underpass. **0.2**

225.8 Red layer on hill at 1:00 is autobrecciated and oxidized top of latitic lava flow in the early Oligocene Spears Formation. The low hills to the right of 1-25 from 1:00 to 4:00 are composed mostly of latitic lavas dipping southeasterly off the Chupadera uplift. **0.4**

226.2 Volcanic conglomerates containing clasts of red sandstones of Abo Formation (Permian) and a latitic ash-flow tuff (34.5± 1.3 m.y., K-Ar, biotite) of the Spears Formation are exposed in roadcut on left. 1.0

227.2 Volcanic conglomerates of Spears Formation exposed in low, gently sloping roadcut on right; latitic lava flows of Spears Formation cap butte at 3:00. **0.1**

227.3 Chupadera range, a late Miocene intrarift horst, ahead on left. The first high ridge at 11:30 consists of about 300 ft (100 m) of flow banded A-L Peak Tuff overlying latitic lava flows of the Spears Formation. The Hells Mesa Tuff (32 m.y.), which normally separates the Spears and A-L Peak, is missing in the southern Chupadera range. Lineated pumice in the flow-banded A-L Peak indicates an east-southeast transport direction away from cauldron sources in the Magdalena-San Mateo area (see Stop S9). **1.7**

229.0 Milepost 128. Little San Pasqual Hills at 3:00 on east side of Rio Grande Valley. The west-facing cliffs are Pennsylvanian limestone and shale, with Permian rocks forming dip slopes to the east. Conglomerate and sandstone of the Baca Formation (lower Tertiary) crop out in small hills about 1 mi northwest of the uplift. Geddes (1963) shows that the Little San Pasquals are a faulted anticlinal structure, probably resulting from Laramide folding and subsequent block faulting continuing up to the time of deposition of youngest Santa Fe beds. Geddes' (1963) interpretation of gravity survey data indicates the presence of at least two large normal faults between the hills and the river valley, with the valley center being underlain by thick Santa Fe basin fill. **0.6**

229.6 Cienega Springs at 9:30 is a major water hole at the northwest end of the Pedro Armendaris Grant, a Spanish land grant that extends southward along the Rio Grande Valley to Truth or Consequences. The highest peak in the Chupadera range at 10:30 is capped by A-L Peak Tuff, which directly overlies Precambrian rocks and thin remnants of altered and silicified Paleozoic limestones and sandstones. Approximately 1,500 to 2,000 ft (460 to 600 m) of the Oligocene volcanic section is missing in this area. Possible causes are: 1) erosion along the south margin of the Sawmill Canyon cauldron (fig. S32) prior to eruption of the A-L Peak Tuff and/or 2) the existence of a Laramide uplift that was beveled to its Precambrian core by the late Eocene erosion surface but remained topographically high until middle Oligocene time. **1.8**

231.4 Roadcuts for next 2.5 mi in early Miocene fanglomerates equivalent to the Popotosa Formation of the Socorro area. Uplift of the Chupadera intrarift horst in late Miocene to Holocene time and attendant erosion has exposed the basal sedimentary section of the rift basin. Fanglomerates of similar age in the Socorro area are red and extremely well indurated. The differences in color and induration are believed to be due to an ancient geothermal system in the Socorro area that caused extensive alkali metasomatism (Chapin and others, 1978). **0.5**

231.9 Good view of southeast-dipping fanglomerates in badlands topography to right and left. **2.1**

234.0 Milepost 133. Route descends long grade into the "Socorro constriction" (Kelley, 1952) on the western side of the Socorro Basin. The basin is flanked on the west by the Chupadera-Socorro-Lemitar range and on the east by the Loma de las Canas-Cerro Colorado uplift. Cuts for the next 4 mi are in upper Santa Fe piedmont alluvium with a discontinuous cover of upper Quaternary gravel capping valley-border erosion surfaces. **0.4**

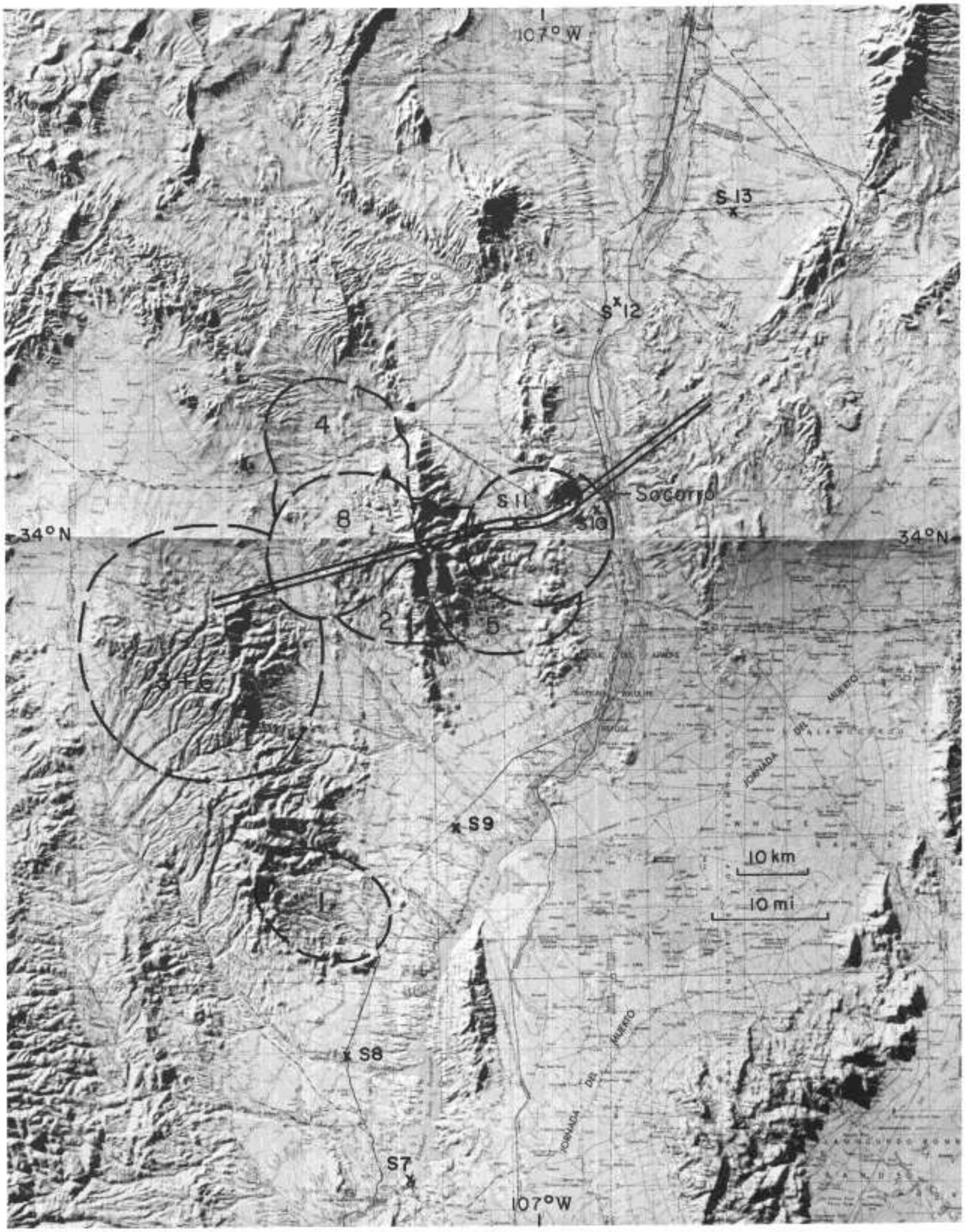


FIGURE S32—OVERLAPPING AND NESTED CAULDRONS AND A TRANSVERSE SHEAR ZONE (DOUBLE LINE) IN THE SOCORRO-MAGDALENA AREA. Base is composite of Socorro and Tularosa 2-degree quadrangles (Army Map Service plastic relief maps). From oldest to youngest, the cauldrons and their ash-flow sheets are: 1) Nogal Canyon—Vicks Peak; 2) North Baldy—Hells Mesa; 3) Mt. Withington—A-L Peak Tuff, gray-massive member; 4) Magdalena—A-L Peak Tuff, flow-banded member; 5) Sawmill Canyon—A-L Peak Tuff, pinnacles member; 6) Mt. Withington—Potato Canyon Tuff; 7) Socorro—tuff of Lemitar Mountains; 8) Hop Canyon—tuff of South Canyon. Nogal Canyon and Mt. Withington cauldrons modified from Deal and Rhodes (1976) (from Chapin, Chamberlin, and others, 1978, fig. 2, with permission).

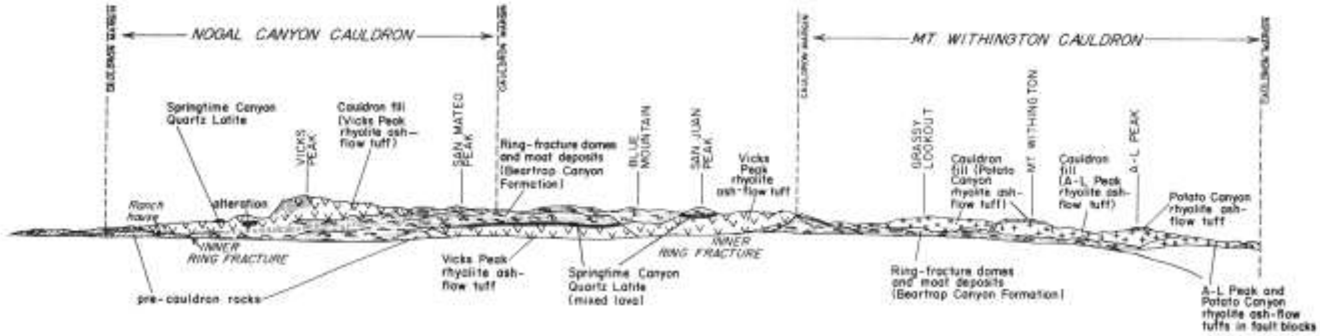


FIGURE S33—DIAGRAMMATIC NORTH-SOUTH CROSS SECTION OF SAN MATEO MOUNTAINS, INCLUDING NOGAL CANYON AND MT. WITHINGTON CAULDRONS (courtesy of E. H. Deal and W. P. Elston, 1978).

234.4 Socorro Peak at 11:00. The Cerro Colorado hills rise above the Jornada del Muerto plain at 2:30. Sierra Oscura is on the distant skyline at 3:00. The Cerro Colorado uplands are formed on rhyolitic to andesitic volcanic and volcaniclastic rocks of Oligocene age. These units overlie the Baca Formation (Eocene), which to the northwest is underlain by coal-bearing upper Cretaceous rocks of the Carthage district, a Triassic red bed sequence, and Permian carbonate and elastic rocks. **0.6**

235.0 Milepost 134. High peak at 8:30 is capped by dark-colored A-L Peak Tuff, erupted from cauldrons in the Magdalena area. Light-colored, poorly-welded tuffs dip southeast and rest on silicified Mississippian limestone and sandstone that, in turn, overlies Pre-cambrian granite and schist. The Precambrian rocks form low, rounded hills at 9:00-10:00. Note strongly tilted Pliocene(?) basalt, capping high level remnants of basin fill as well as Precambrian rocks along the mountain front. **3.0**

238.0 Milepost 137. For about the next 10 mi, upper Pleistocene gravels cap the valley-border erosion surfaces that are cut on intertonguing piedmont and axial river facies of the upper Santa Fe Group. The ancestral Rio Grande deposits, discontinuously exposed in roadcuts from here to Socorro, mainly consist of sand and pebbly sand with some interbedded loam to clay. 2.0

240.0 Milepost 139. San Antonio exit, US-380, ahead. From 12:30 to 2:30 high mesas in the vicinity of Loma de las Canas are capped by Permian carbonate rocks. This upland forms a structurally high area on the east side of the rift from which the entire volcanic section has been stripped. Low bluffs east of the river at 2:00 are formed on gravelly sand and conglomeratic sandstone deposited by the ancestral Rio Grande. These upper Santa Fe fluvial beds contain a large mass of pumice boulders that are possibly derived from the Jemez volcanic center. If this correlation is correct, the youngest Santa Fe basin fill (Camp Rice, Sierra Ladrones, upper buff equivalents) would postdate initial eruption of the Bandelier Tuff sequence about 1.4 m.y. ago (Smith and others, 1970).

San Antonio is named for a mission founded in 1629 by Fray Antonio de Arteaga and Fray Garcia de Francisco de Zuñiga (Pearce, 1965). The town is the birthplace of Conrad Hilton. **0.3**

240.3 San Antonio overpass. South margin of Socorro cauldron (Stops S10 and S11) is west of this point along Nogal Canyon in the Chupadera Mountains. Pleistocene piedmont and valley-border surfaces, grading eastward from the base of the Chupaderas to bluffs along the Rio Grande, are offset by several faults that trend south-southeast toward this area from the foot of Socorro Peak (Sanford and others, 1972). **1.0**

241.3 Roadcuts and arroyo exposures from here to Socorro show complex intertonguing of piedmont gravel and river sand facies. Units comprise youngest Santa Fe basin fill (Sierra Ladrones Formation) and older (middle to upper Pleistocene) valley fill. **0.7**

242.0 Milepost 141. Magdalena range on western skyline, Socorro Peak at 11:00, and Ladron Peak on distant skyline behind Lemitar Mountains at 11:30. Socorro Peak forms north rim of Socorro cauldron, with cauldron moat from 10:00 to 11:00 and resurgent dome from 9:00 to 10:00. Four-million-year-old basalt of Sedillo Hill caps mesa in moat area at 10:30. Piedmont fault scarp at 11:00 shows displacement of youngest Santa Fe and older valley fill units. These features will be discussed at stops S10-S12 in the Socorro to Santa Fe section of the southern rift road log. **1.3**

243.3 Relay tower on left. High hills, mesas, and cuestas on the skyline east of the Rio Grande (Loma de Las Canas uplift) consist mostly of Permian (San Andres, Yeso, and Abo) formations. Pliocene to lower Pleistocene, fluvial and piedmont facies of the upper Santa Fe Group crop out in the bluffs and benches that form the eastern border of the river valley. **2.2**

245.5 Underpass; Luis Lopez Road. **1.9**

247.4 Socorro airport on left; crossing Socorro Canyon fan. The surface here is probably of pre-Wisconsinan, late Pleistocene age. Geomorphic-surface components of the fan between here and the Socorro interchange are probable correlatives of the Tortugas and Picacho units in northern Mesilla Valley (Stops S2 to S3). However, late Quaternary faulting and warping in both areas hampers even short-range correlations that are based mainly on landscape position. **0.9**

248.3 *Take Exit 148.* **0.7**

249.0 *Enter Socorro.* The name (Spanish for help, aid) was given by Don Juan de Oñate on June 14, 1598, to the Piro pueblo of Teypana (near the present city) because of aid given to the colonists by the Indians. A mission church was built before 1628 by Fray Garcia de Zuñiga. The community was abandoned after the 1680 Pueblo Rebellion and was not reestablished until 1815 or 1816. Between 1867 and 1890, Socorro was the center of one of the richest mining areas in the country (Pearce, 1965). New Mexico Institute of Mining and Technology, including the New Mexico Bureau of Mines and Mineral Resources, is located here. 0.7

249.7 Railroad crossing. 0.1

249.8 Intersection of California and Spring streets, junction of US-60 and US-85 (Business 1-25), and assembly point for second segment of southern rift tour. End of E1 Paso to Socorro road log. *Stop for night.*

SOCORRO TO EL PASO

This log is adapted from more detailed road logs for the northbound route by Lovejoy, Seager, Hawley, Chapin, Chamberlin, and Osburn. The emphasis is on geologic and geomorphic features seen from a southbound perspective between the formal tour stops. Discussions at stops S9-S1, other long technical entries, and historical notes are not included. Such items are noted at appropriate places in the road log, and they are cross referenced to corresponding mile points in the northbound log.

Mileage

0.0 Intersection of California and Spring Streets and junction of US-60 and US-85 (Business 1-25). *Proceed south on US-85 to 1-25 interchange. 0.1*

0.1 Railroad crossing. 1.0

1.1 *Merge with 1-25.* Gravelly arroyo-fan and terrace deposits, which overlap and intertongue with sandy fluvial beds, are exposed in roadcuts and arroyo banks ahead. These units of the upper Quaternary, valley-fill sequence unconformably overlie sandy basin fill of the upper Santa Fe Group (here Sierra Ladrones Formation) deposited in part by the ancestral Rio Grande. 0.9

2.0 Crossing Socorro Canyon fan. The surface here is probably of pre-Wisconsinan, late Pleistocene age. Quaternary piedmont and valley-border surfaces, grading eastward from the base of the Chupadera Mountains to bluffs along the Rio Grande, are offset by south-southeast-trending faults that extend from the foot of Socorro Peak toward San Antonio (Sanford and others, 1972). Correlation of geomorphic surfaces along the Rio Grande Valley is made difficult by late Quaternary faulting and warping, particularly where such correlations are based mainly on landscape position. 1.8

3.8 High hills, mesas, and cuestas on the skyline east of the Rio Grande are part of the Loma de las Canas uplift. They are capped by Permian limestones of the San Andres and Yeso Formations. The uplift forms a structurally high area on the east side of the rift from which the entire volcanic section has been stripped. Pliocene to lower Pleistocene fluvial and piedmont facies of the Sierra Ladrones Formation crop out in the bluffs and benches that form the eastern border of the river valley. 0.2

4.0 Along the route for the next 7.5 mi upper Pleistocene gravels cap valley-border erosion surfaces that are cut on intertonguing piedmont and axial river facies of the upper Santa Fe Group. The ancestral Rio Grande deposits, discontinuously exposed in roadcuts from here to mile 12 consist mainly of sand and pebbly sand with some interbedded loam to clay. 4.0

8.0 Low bluffs east of the river at 10:30 are formed on gravelly sand and conglomeratic sandstone, correlated with the fluvial facies of the Sierra Ladrones Formation (to north) and Camp Rice Formation (to south). These upper Santa Fe beds contain a large mass of pumice boulders that are possibly derived from Bandelier-Cerro Toledo volcanics of the Jemez center. If this correlation is correct, the youngest Santa Fe basin fill (upper Camp Rice, Sierra Ladrones, and upper buff equivalents) would postdate initial eruption of the Bandelier Tuff sequence about 1.4 m.y. ago (Smith and others, 1970). 1.7

9.7 San Antonio overpass. South margin of Socorro cauldron (Stops S10 and S11) is west of this point along Nogal Canyon in the Chupadera Mountains. 0.6

10.3 Mileage sign-Truth or Consequences 62; Las Cruces 138. Oscura Mountains on skyline at 9:00 beyond Cerro Colorado. Salinas Peak, elevation 9,040 ft (2,755 m), at 10:30 south of the Oscuras, is the highest peak in the San Andres Mountains. The broad intermontane-basin (or bolson) surface between the Rio Grande Valley and the Oscura-San Andres range is the Jornada del Muerto plain. The Jornada del Muerto Basin (discussed at Stops S4 and S2) extends southward from this area more than 120 mi (190 km). The Magdalena Mountains form the western skyline, from 2:00 to 3:00, behind the southern Chupadera Mountains (12:00 to 3:00).

Little San Pasqual Mountains (mile 19.3) are on the edge of the Jornada del Muerto Basin at 5:00. The Cerro Colorado hills rising above the northern Jornada plain at 3:00 are formed of rhyolitic to andesitic volcanic and volcaniclastic rocks of Oligocene age. These units overlie the Baca Formation (Eocene), to the northwest, which is underlain by the coal-bearing Upper Cretaceous rocks of the Carthage district, a Triassic red-bed sequence, and Permian carbonate and elastic rocks. 0.4

10.7 Cuts in upper Santa Fe fluvial facies capped with arroyo-terrace gravel. 1.7

12.4 Cuts for about the next 4 mi are in uppermost Santa Fe piedmont deposits comprising gravelly to loamy alluvium with buried soils (paleosols). The beds have a discontinuous overlay of gravelly alluvium capping valley-border erosion surfaces of late Quaternary age. The uppermost Santa Fe beds beneath the piedmont plains of this region were deposited episodically as sheetlike, fining-upward sedimentation units. Depositional episodes were followed by long intervals of stability and soil formation. Buried soil profiles are characterized by reddish horizons of clay accumulation over nonindurated zones of carbonate accumulation. 1.6

14.0 Mile 135. High peak at 1:30 is capped by dark-colored A-L Peak Tuff, erupted from cauldrons in the Magdalena area. The underlying light-colored, poorly welded tuffs dip southeast and rest on silicified Mississippian sandstones and limestones, which in turn overlie Precambrian granites and schists. The Precambrian rocks form low, rounded foothills at 1:30 to 3:00. The light-colored tuff unit probably accumulated in preexisting topographic lows, since the densely welded A-L Peak Tuff rests directly on Paleozoic rocks just to south.

Approximately 1,500-2,000 ft (460-600 m) of the Oligocene volcanic section is missing in this area. Possible causes are: 1) erosion along the south margin of the Sawmill Canyon cauldron prior to eruption of the A-L Peak Tuff and/or 2) the existence of a Laramide uplift that was beveled to its Precambrian core by the late Eocene erosion surface but that remained topographically high until middle Oligocene time. Transport directions in arkosic channel sands of the Baca Formation (Eocene) north of Magdalena indicate a source region for Precambrian detritus somewhere to the south-southeast.

Note basalt-capped mesa at 2:30 on crest of Chupaderas in saddle at head of valley. This unit may be correlative with the 4-m.y.-old basalt of Sedillo Hill seen at Stops S10 and S11. **2.2**

16.2 Roadcuts for next 2.3 mi are in early Miocene fanglomerates equivalent to the Popotosa Formation of the Socorro area. Uplift of the Chupadera intrarift horst in late Miocene to Holocene time, and attendant erosion has exposed the basal sedimentary section of the rift basin. Fanglomerates of similar age in the Socorro area are red and extremely well indurated. The differences in color and induration are believed to be the result of an ancient geothermal system in the Socorro area that caused extensive alkali metasomatism (Chapin and others, 1978). **1.1**

17.3 Milepost 131. Good view of the southeast-dipping fanglomerates in badlands topography to right and left. **2.0**

19.3 Little San Pasqual Mountains rise above the Jornada plain at 9:00 on east side of Rio Grande Valley. The west-facing cliffs are Pennsylvanian limestone and shale, with Permian rocks forming dip slopes to the east. Conglomerate and sandstone of the Baca Formation (lower Tertiary) crop out in small hills about 1 mi northwest of the uplift. Geddes (1963) shows that the Little San Pasquals are a faulted anticlinal structure, probably resulting from Laramide folding and subsequent block faulting continuing up to the time of deposition of youngest Santa Fe beds. Geddes (1963) interpretation of gravity-survey data indicates presence of at least two large normal faults between the hills and the river valley, with the valley area being underlain by thick Santa Fe basin fill.

From 11:30 to 1:00 southeast-dipping volcanics form low hills at the south end of the Chupadera Mountains. Cienega Springs at 3:00 is a major water hole at the northwest end of the Pedro Armendaris Grant, a Spanish land grant that extends southward along the Rio Grande Valley to Truth or Consequences. The high ridges of the Chupadera range beyond the springs consist of about 300 ft (100 m) of flow-banded A-L Peak Tuff (28.5 m.y.) overlying latitic lava flows of the Spears Formation (lower Oligocene). The Hells Mesa Tuff (32 m.y.), which normally separates the Spears and A-L Peak, is missing in the southern Chupaderas. Lineated pumice in the flow-banded A-L Peak indicates an east-southeast transport direction away from cauldron sources in the Magdalena-San Mateo area (see Stop N9). **2.3**

21.6 Roadcut on right in upper Santa Fe piedmont alluvial facies with buried soils (paleosols). **1.1**

22.7 Volcanic conglomerates of Spears Formation (lower Oligocene) exposed in low, gently sloping roadcut on left; latitic lava flows of Spears Formation cap butte at 9:00 to 11:00. **1.0**

23.7 Volcanic conglomerates containing clasts of red sandstones of Abo Formation (Permian) and a latitic ash-flow tuff (34.5 ± 1.3 m.y., K-Ar, biotite) of the Spears Formation exposed in roadcut on right. **0.3**

24.0 Milepost 125. Black Mesa at 9:30 to 10:00 forms east border of Rio Grande Valley. The capping basalt flow, which overlies about 300 ft (90 m) of fluvial sand (Sierra Ladrones correlative), has a K-Ar age of 2.2 ± 0.10 m.y. (Bachman and Mehnert, 1978, no. 26).

For next 7 mi, roadcuts are in uppermost Santa Fe Group basin fill comprising a sequence of several fining-upward layers of alluvium, each capped with a well-developed paleosol. Valley-border erosion surfaces, cut into the upper Santa Fe beds, are locally capped with thin gravelly deposits of late Quaternary age. **0.4**

24.4 San Marcial underpass. For about the next 16 mi the route crosses the moderately dissected central plain of the San Marcial Basin (Kelley, 1952). The Mulligan trough (or graben) segment of the basin extends northwest between the San Mateo (12:00-2:00) and Magdalena ranges. The San Marcial Basin merges with the northern Jornada del Muerto east of the entrenched valley of the Rio Grande. **0.7**

25.1 Crossing arroyo valley. The low hill to left marks the southern exposed segment of the Chupadera Mountain uplift and is composed mostly of latitic lavas (Spears Formation). **5.9**

31.0 Descending into Mulligan Gulch. Upper Santa Fe alluvium exposed in valley walls and roadcuts ahead. **0.3**

31.3 Crossing broad floor of Mulligan Gulch. Basalt flow on Jornada del Muerto plain at 9:00. This flow, which descends almost to floodplain level on the east slope of the river valley, has been K-Ar dated at 0.76 ± 0.1 m.y. by Bachman and Mehnert (1978, no. 27). The basalt may rest on an early-stage surface of valley entrenchment that was partly buried and then exhumed in late Pleistocene time. **1.1**

32.4 View down axis of Fra Cristobal Range (Stop S8) at 10:30. **1.3**

33.7 Underpass, NM-107 interchange. *Prepare to exit* for rest area and Stop S9 ahead. **1.2**

34.9 *Take exit* to rest area. **0.2**

35.1 **STOP S9, San Marcial Basin.** 1-25, Fort Craig rest area. *Assemble south of picnic shelters* for discussions of the San Marcial and northern Jornada Basins and flanking ranges. See mile 214.8 entry in E1 Paso to Socorro log. **1.4**

36.5 Underpass. **0.8**

37.3 Underpass. The route continues across the dissected piedmont plain of the southern San Marcial Basin. **2.9**

40.2 Crossing arroyo valley with gravel stockpiles on right. Ridges of Paleozoic limestones in middle distance at 2:30 are along northern rim of Nogal Canyon cauldron. Vicks Peak, elevation 10,252 ft (3,125 m), is on the skyline beyond the ridges. San Mateo Peak, elevation 10,139 ft (3,090 m), located north of Vicks Peak at 2:45, is outside Nogal Canyon cauldron on its northwest side. Reddish, hydrothermally altered rocks forming low ridges to east of San Mateo Peak also lie along the northern margin of the Nogal Canyon cauldron. The low hills along the east flank of the San Mateo range (1:00 to 2:30) are cauldron-facies Vicks Peak Tuff. The Nogal Canyon cauldron did not resurge; consequently, its geomorphic expression is one of low hills composed of monotonous Vicks Peak Tuff. The low hills are partly surrounded by a discontinuous ring of higher hills made up of ring-fracture domes (such as Peñasco Peak), pre-cauldron volcanic rocks capped by thin outflow-facies Vicks Peak Tuff, and windows of Paleozoic rocks. **1.0**

41.2 Fra Cristobal Range at 9:00 to 10:30. Note prominent fault scarp on western base of range. The route ahead passes through a constricted basin segment, the Pankey channel of Kelley (1952), connecting the San Marcial Basin with the Engle Basin to the south. 0.3

41.5 Descending into Nogal Canyon. As much as 200 ft (60 m) of upper Santa Fe piedmont gravels are exposed in canyon walls and roadcuts ahead. In this section paleosol zones are characterized by strong reddish horizons of clay accumulation over carbonate-enriched horizons. 0.5

42.0 Milepost 107; Nogal Canyon bridge. 1.0

43.0 Milepost 106. For next 9 mi the route crosses upper Santa Fe piedmont deposits that are locally cut by deep valleys of major arroyos. 1.3

44.3 Crossing valley of Chaunti Arroyo. 1.7

46.0 Milepost 103. Crossing valley of Cuervo Arroyo. 0.2

46.2 Sierra-Socorro County line; Vicks Peak at 3:00. **1.1**

47.3 Cliffy outcrops along box canyon of San Jose Arroyo at 3:00 are Vicks Peak Tuff dipping 10-20 degrees to the east. 0.7

48.0 Milepost 101. At 3:00, roadcut along old US-85 at end of ridge exposes closely spaced, nearly vertical sheet jointing in densely welded Vicks Peak Tuff. Sheet jointing of this type is characteristic of cauldronfacies tuffs in several cauldrons in the Magdalena and San Mateo ranges. Old US-85 apparently lies very close to the eastern margin of the Nogal Canyon cauldron, which is largely concealed by piedmont gravels in this area. 0.5

48.5 Red Rock underpass; entering Engle Basin. 1.5

50.0 The route ahead crosses dissected northern edge of Cuchillo plain. 2.0

52.0 Milepost 97. For the next 13 mi the route crosses two large, undissected areas of the Cuchillo plain. These surfaces are remnants of the distal part of a huge coalescent fan that spread out from upper reaches of the ancestral Cuchillo and Alamosa Creeks heading in the Cuchillo and San Mateo ranges. This relict piedmont-slope and floor of the Engle Basin was graded to ancestral-river base levels more than 330 ft (100 m) above the present river-valley floor. The Cuchillo plain generally correlates with the Jornada I and La Mesa geomorphic surfaces to the southeast (Stops S1 b-S4) and the Palomas surface to the south (Stop S6). The surface is of complex origin, being mainly erosional near the mountain fronts and mainly constructional near the basin axis, as it is here.

Near Mitchell Point, 5.5 mi to the southeast, a basalt tongue in the lower part of the Santa Fe Group fluvial facies has been K-Ar dated at 2.9 ± 0.3 m.y. (Bachman and Mehnert, 1978, no. 28). These ancestral Rio Grande beds are overlapped by and intertongue with the fan deposits that extend beneath this surface. The sequence appears to correlate with the lower part of the Camp Rice section near Rincon (Stop S4) as well as with much of the Sierra Ladrones Formation of the Socorro-San Acacia area (Stops S10-S12). **2.8**

54.8 Overpass. Low hills on right are just south of Nogal Canyon cauldron. 2.3

57.1 *Take Exit 92;* Mitchell Point road. **0.2**

57.3 **STOP S8, Mitchell Point interchange (optional).** Northeastern Cuchillo plain at Mitchell Point (1-25) interchange. Park near intersection at west edge of interchange. Assemble at east end of overpass for discussions of ranges flanking the Engle and northern Palomas Basins. See mile 192.7 entry in E1 Paso to Socorro log. **0.2**

57.5 Descending into Monticello Canyon of Alamosa Creek. As much as 300 ft (90 m) of upper Santa Fe gravelly alluvium are exposed in cuts on both sides of the canyon. **1.1**

58.6 Crossing bridge over Alamosa Creek. **0.2**

58.8 Cuts in upper Pleistocene terrace gravel of Alamosa Creek. **1.2**

60.0 Underpass at milepost 89. *Continue south* on 1-25 across Cuchillo plain. **0.8**

60.8 Aircraft direction station to right; Mud Springs Mountains at 1:00. Near this point is the Gartland 1 Brister exploratory well, drilled in 1951 and 1955 (sheet 2, hole q). The hole penetrated 1,450 ft (442 m) of Santa Fe Group basin fill, 90 ft (27 m) of McRae? Formation, and 7,045 ft (2,147 m) of Cretaceous to Pennsylvanian rocks. Estimated depth to Precambrian basement is 8,805 ft (2,684 m) or 3,955 ft (1,205 m) below sea level (Foster, this guidebook, hole q). The hole is reported to have penetrated a monzonite sill from 4,350 to 5,110 ft (1,326 to 1,578 m) in the Yeso Formation (Jahns, 1955a). About 3 mi west of this point is a second test hole, Gartland 1 Garner, that penetrated 6,524 ft (1,989 m) of basin fill, possibly all Santa Fe Group (Foster,this guidebook and sheet 2, hole r). Westward thickening of fill may indicate northward extension of the Palomas structural basin that is bounded on the east by the Mud Springs block. **0.9**

61.7 Basalt-capped mesas east of Elephant Butte Reservoir from 9:00 to 11:00 are in the Cutter sag between the Fra Cristobal and Caballo Mountains. **3.1**

64.8 *Take Exit* 83; route to Elephant Butte State Park. 0.2

65.0 *Turn left on NM-55; continue east through underpass. Prepare for left turn ahead.* **0.5**

65.5 Junction of US-85 and NM-52. *Turn left on NM-52* and continue southeast toward Hot Springs Landing and Elephant Butte. **0.2**

65.7 Starting descent into Rio Grande Valley. The route crosses dissected basin-fill terrain cut in distal part of upper Santa Fe piedmont facies. These loamy to gravelly beds, with paleosol zones, were deposited at the toe of the huge alluvial-fan complex of ancestral Alamosa and Cuchillo Creeks. To the east and south the distal piedmont facies overlaps and intertongues with sandy fluvial deposits. 0.5

66.2 Badlands to right and left in upper Santa Fe alluvium. **1.0**

67.2 Near piedmont and fluvial facies contact. Route ahead crosses broad ridge cut on sandy deposits of the late Pliocene to middle Pleistocene Rio Grande. **0.8**

68.0 Junction; Hot Springs Landing to left. *Continue south* on NM-52. About 1 mi northeast of this junction is the Summit 1 Mims exploratory well, drilled between 1950 and 1954 (sheet 2, hole p). The hole penetrated 1,986 ft (605 m) of basin fill, interpreted as Santa Fe, and 4,209 ft (1,283 m) of Cretaceous to Pennsylvanian rocks. Estimated depth to Precambrian basement is 7,985 ft (2,434 m) or 3,415 ft (1,041 m) below sea level (Foster, this guidebook, hole p). **0.8**

68.8 Junction NM-52 and Spur-52 to Truth or Consequences. *Continue straight* on NM-52 toward Elephant Butte and **STOPS S7a and S7b, Elephant Butte Reservoir and Dam.** See miles 172.8 to 181.1 entries in E1 Paso to Socorro road log. After Stop S7 excursion, *return to this point; continue southwest via Spur-52 and US-85 to 1-25.* Road log from here to New Mexico-Texas State line adapted from northbound log by Hawley and Seager. **0.8**

69.6 Roadcuts in upper Santa Fe fluvial facies. **0.4**

70.0 Ascending to terrace surface. Upper Pleistocene gravels of ancestral Cuchillo Creek in roadcuts. **0.4**

70.4 Stop sign; junction of Spur-52 and US-85. *Turn left on US-85; continue south* on high terrace of Cuchillo Creek. **0.4**

70.8 Contact of terrace gravels on conglomeratic sandstone and sand of the upper Santa Fe fluvial facies. **0.3**

71.1 Crossing valley of Cuchillo Creek. In bluffs downstream (to left) basal, upper Santa Fe fanglomerate is overlain by fluvial facies sand and gravel. 0.2

71.3 Bridge. Stream-terrace gravel caps upper Santa Fe fluvial facies in cuts ahead. **0.5**

71.8 Junction with 1-25 approach route; *turn right.* North Truth or Consequences interchange ahead; *keep left for southbound ramp to Las Cruces.* Intersection; *turn left onto 1-25-South entrance ramp.* Large roadcuts at this interchange are in sandy strata of the upper Santa Fe fluvial facies. **2.1**

73.9 Badlands to right are formed on piedmont-slope to basin-floor facies of upper Santa Fe Group that overlaps and interfingers with sandy fluvial beds. Carbonate-cemented limestone gravel forms a thin mantle capping piedmont erosion surfaces.

The city of Truth or Consequences to right was formerly known as Hot Springs. Springs in the center of town issue warm mineralized waters (temperatures from 98-114° F) from fissures at the base of a Pennsylvanian (Magdalena Group) limestone hill that lies along the southeast extension of the Mud Springs uplift. In 1950 the city voted to adopt the name of the then popular radio show "Truth or Consequences." In return, the show's master of ceremonies, Ralph Edwards, agreed to bring his program to the annual fiesta held in the city. The community is often simply designated by the initials T or C (Jahns, 1955a; Pearce, 1965). **0.2**

74.1 Nearly vertical beds of Pennsylvanian limestone in roadcuts mark the southeast prong of the Mud Springs block. Undeformed upper Santa Fe beds bury the bedrock in this area. The route leaves the Engle Basin and enters the Palomas Valley of the Rio Grande. The river valley is located near the east edge of the Palomas structural basin, adjacent to short, steep piedmont slopes ascending to the western escarpment of the Caballo uplift. The basin is bounded on the west by the Animas-Hillsboro blocks that form the foothill belt flanking the high Mimbres-Black Range chain on the western skyline (Kelley, 1952, 1955). **0.4**

74.5 Good view of northeast-tilted Mud Springs Mountains to right. This southeast-trending block of Precambrian to Pennsylvanian rocks (Kelley and Silver, 1952) abuts against the Caballo uplift along the southwest-trending Hot Springs faults. The route ahead descends into the valley of Williamsburg (Mud Springs) Arroyo. Roadcuts are in conglomeratic mudstone to sandstone of the (basal upper?) Santa Fe Group. **1.2**

75.7 Milepost 76. Crossing Williamsburg (Mud Springs) Arroyo valley. **0.1**

75.8 *Cross bridge.* Eastward-tilted upper Santa Fe beds in roadcuts on right; deformation is related to offset of the Palomas Basin block (ahead) along the Mud Springs fault zone. The arroyo valley to the north follows this northwest-southeast-trending zone. Precambrian rocks that form the core of the Mud Springs uplift are exposed along the Rio Grande about 2 mi east of this point as well as to the north in the mountains (Kelley and Silver, 1952). **0.9**

76.7 Williamsburg underpass and exit, at milepost 75. East-tilted mass of the Caballo Mountains at 7:00 to 11:00. Upper Santa Fe alluvium is exposed in bluffs to right. These piedmont toeslope deposits were derived mainly from two large tributary stream systems (ancestral Cuchillo and Palomas Creeks) that head to the west in the Black and Cuchillo ranges. **2.0**

78.7 Large roadcuts in upper Santa Fe piedmont facies. **0.3**

79.0 Descending into valley of Palomas Creek. Upper Pleistocene terrace gravels of the creek cap Santa Fe beds in roadcuts and valley walls ahead. **0.7**

79.7 Milepost 72. Crossing Palomas Creek Valley; Palomas Gap through northern Caballo range at 9:00. A test well near here **(B.** Iorio No. 1 Fee) "was drilled to 2,100 ft (640 m) and plugged back to 1,550 ft (472 m) for a flow of 30 gallons a minute of water having a temperature of 32° C (90° F). In this well the Santa Fe formation had a thickness of 1,165 ft (355 m)" (Kelley and Silver, 1952, p. 189). The hole bottomed in the mid-Tertiary Thurman Formation. **0.4**

80.1 Las Palomas underpass. Badlands ahead carved on distal piedmont facies of upper Santa Fe basin fill. From this point south to Caballo Dam (mile 91.7), thick sections of upper Santa Fe piedmont deposits are exposed in walls of deeply incised arroyo valleys. Most of these valleys were cut by streams heading in the Black Range and adjacent parts of the Animas-

Hillsboro uplift. In highway cuts and nearby arroyo exposures for the next 7.5 mi, piedmont gravels intertongue with fine-grained basin-floor deposits that have been interpreted as river floodplain as well as playa facies (Davie and Spiegel, 1967). The exposed basin fill in this area is tentatively correlated with Sierra Ladrones Formation (north) and the Camp Rice Formation (south). 0.9

81.0 Crossing valley of King Arroyo; cuts ahead in upper Pleistocene terrace deposits. Good view across Rio Grande Valley of the Caballo frontal escarpment. Low sun-angle illumination highlights a prominent piedmont scarp that extends along the foot of the range just below apex areas of high-level fans and pediments. 1.9

82.9 Maroon clay over gray sand of upper Santa Fe fluvial(?) facies in cuts ahead. 0.4

83.3 Ascending long grade rising to summit of high-level valley-border surface. Cuts ahead in distal piedmont-alluvial facies of upper Santa Fe, which overlaps and interfingers with fluvial beds to north and east. Tour stop ahead on right. 1.0

84.3 *Take rest area exit.* **0.2**

84.5 STOP S6, Caballo Reservoir. See mile 157.3 entry in Denver to Alamosa road log. After stop, *continue south* on 1-25. **0.2**

84.7 Milepost 67. Route descends across stepped sequence of Pleistocene terraces of Arroyo Seco. **0.7**

85.4 Arroyo Seco bridge. Cuts ahead in upper Santa Fe basin fill. Gravelly piedmont alluvium intertongues with and overlaps basin-floor sand to clay. **1.6**

87.0 Animas Arroyo bridge. During highway construction the carapace and limb bones of a giant tortoise were collected from near the base of the deep roadcut ahead. **0.7**

87.7 Exit 63; NM-90 to Hillsboro and the Black Range; *continue south* on 1-25. **0.4**

88.1 Exposures of upper Pleistocene arroyo terrace deposits in roadcuts and valley walls ahead. **0.6**

88.7 Milepost 63. Crossing low valley-border surfaces underlain by Holocene arroyo deposits. Lower end of Caballo Reservoir to left. Just east of the lake, placer gold deposits have been developed in upper Santa Fe fan deposits derived from Precambrian granitic terrane that forms the lower slopes of the Caballo escarpment (Kelley and Silver, 1952). **1.9**

90.6 Cuts ahead in upper Santa Fe piedmont facies. **0.8**

91.4 Caballo Dam at 10:00. Red Hills from 10:00 to 11:00 form the northern end of a foothill belt southwest of the main Caballo mass. Apache Valley lies between the two upland areas. Andesitic to latitic volcaniclastic and epiclastic rocks of Eocene age, with a basal Paleozoic-derived fanglomerate unit, form the oldest fill in Apache Valley. This is the Palm Park Formation of Kelley and Silver (1952), and it is overlain by a sequence of rhyolite tuffs and related epiclastic rocks that they designated the Thurman Formation. The type area (Rincon Hills) of these units at the south end of the Caballo range has been mapped by Seager and Hawley (1973). In the Red Hills, red Precambrian granite is overlain by faulted lower Paleozoics, with both units being overlapped by the Eocene fanglomerates of the basal Palm Park Formation. Farther east, the early Tertiary fanglomerates were deposited on successively younger units up to the Cretaceous. **0.3**

91.7 Crossing Percha Creek diversion channel to Caballo Reservoir. Percha Creek is the main drainage line from the central Black Range. **0.4**

92.1 Underpass; old US-85. Fluorspar mine in northern Red Hills at 11:00 **0.6**

92.7 Milepost 59. Bluffs ahead on left are tilted, basal upper Santa Fe conglomerates capped with sandy fluvial facies. **0.6**

93.3 Cross Rio Grande; roadcuts ahead in Holocene fan deposits. **2.4**

95.7 Milepost 56. Cuts for next 2.3 mi are in upper Santa Fe fluvial and piedmont facies locally capped with upper Quaternary deposits of the valley-border sequence. **0.6**

96.3 Contact of fluvial facies on basal conglomerate zone of upper Santa Fe Group in roadcut to left. 1.0

97.3 Nakeye, Round, and Flat Top Mountains at 9:00 to 10:00 are a southern continuation of the Red Hills uplift. These tilted fault blocks comprise lower Paleozoic limestones, sandstones, and shales with an overlying, upper Paleozoic carbonate and clastic sequence that is capped by Permian red beds of the Abo Formation (Kelley and Silver, 1952). **0.4**

97.7 Milepost 54. Derry Hills, ahead on left, are a complex fault block with overturned structures in the eastern part. The exposed section includes Percha Shale (Devonian), Pennsylvanian limestone of the type Derry Series (King, 1973), and Permian red beds of the Abo Formation. 0.3

98.0 North edge of Derry Hills block. Dark-red Abo sandstone and mudstone to right and left. 0.3

98.3 Roadcut on right in Pennsylvanian limestone; cut ahead on left in Abo red beds. **0.8**

99.1 Silicified rock of Derry Hills fault zone to left. Pennsylvanian carbonate rocks are exposed in the upthrown (eastern) block. Derry Hot (warm) Springs, to west of highway ahead, is along the fault zone. **0.2**

99.3 Pennsylvanian limestone in roadcut to left unconformably overlies Percha Shale (upper Devonian). **0.3**

99.6 Pennsylvanian rocks to left form southern end of Derry Hills. **0.6**

100.2 Highway roadcuts from here to E1 Paso are in Santa Fe Group or younger valley fill. **0.4**

100.6 Underpass; Garfield-Derry interchange. **0.1**

100.7 Milepost 51. Road log from here to New Mexico-Texas State line is adapted from logs in the New Mexico Geological Society guidebook, Las Cruces Country (Seager, Clemons, and Callender, 1975). **0.3**

101.0 Entering Doña Ana County. For the next 5 mi the route crosses a complex of older valley-border surfaces that are partly constructional and partly erosional. Valley fill caps surfaces cut on upper Santa Fe fluvial and piedmont facies. A few of the deeper arroyo valleys may cut through the upper Santa Fe into the Rincon Valley Formation of the lower Santa Fe Group. **1.4**

102.4 To left, up arroyo, are faulted and folded Paleozoic rocks of the outlying Round-Nakeye-Flat Top mountain block of the southwestern Caballo uplift. **2.3**

104.7 Milepost 47. Route starts descent into the southern end of the Palomas Valley. Panoramic view of south-central New Mexico region. Red House Mountain at 9:00 to 10:00 is at the southern end of the Caballo range. High spires on skyline at 11:30 are the northern Organ Mountains, east of Las Cruces and Stop S2. Low flat-topped mountain in the Rio Grande Valley that is in line with the Organs is San Diego Mountain, overlooking Stop S5. The Robledo Mountains on the skyline at 12:00 are south of the Leasburg Dam-Radium Springs area (Stop S3) at the mouth of Selden Canyon. The broad domal uplift from 12:15 to 1:30 in the middle distance is Sierra de las Uvas. This uplift is capped by upper Oligocene-lower Miocene (Uvas) basaltic andesite over rhyolitic volcanics (Bell Top Formation) and forms the high central mass of the Good Sight-Cedar Hills volcano-tectonic depression (Seager, 1975b; Clemons, 1976). The Good Sight Mountains, from 1:30 to 3:30, form the western limb of the synclinal trough within the depression that flanks the Uvas dome. The Good Sights are also capped with basaltic andesite, overlying a sequence of Oligocene rhyolitic volcanics that wedges out westward over andesitic to latitic volcanics of the Rubio Peak Formation (Palm Park equivalent). Nutt Mountain (Sunday Cone) at 3:15 is an Oligocene rhyolite intrusive body in the northern Good Sight Mountains. Cooke's Peak on the western skyline beyond Nutt Mountain is at the southern end of the ranges (Black, Mimbres, and Cooke) that form the western rift boundary in this area (Chapin and Seager, 1975).

The high mesa from 1:00 to 3:00 on the far side of the valley is underlain by about 300 ft (90 m) of upper Santa Fe fluvial deposits over lower Santa Fe playa sediments (reddish unit at base of bluffs west of river). A Blancan vertebrate fauna has been collected from the basal part of the fluvial section in this area. The southern end of the Palomas Basin is at the apex of the large fluvial-fan-delta complex constructed by the ancestral Rio Grande. This upper Santa Fe unit (mainly gravelly sand to conglomeratic sandstone in south-central New Mexico) extends into Texas and Chihuahua and makes up the bulk of the upper Santa Fe Group (Camp Rice and Fort Hancock Formations) in this region. From here north, the zone of ancestral-river deposits in the upper Santa Fe section (Sierra Ladrones Formation and equivalents) narrows to a belt 2.5-5 mi (4-8 km) in width, and the Pliocene to middle Pleistocene basin-fill section is dominated by piedmont-slope rather than fluvial facies. 2.2

106.9 Cuts on left for the next mile are in upper Pleistocene river-terrace deposits that are inset against upper Santa Fe beds. Molluscan faunas from older valley-fill units between Caballo Dam and E1 Paso have been described by Metcalf (1967, 1969). Correlation of surfaces and deposits (morphostratigraphic units) in the valley-fill sequence is based, in part, on three factors: 1) physical tracing of units, 2) studies of molluscan faunas, and 3) comparison of soils preserved on stable geomorphic surfaces (Hawley, 1965, 1975b; Hawley and Kottlowski, 1969). **1.8**

108.7 Milepost 43. Highway curves to left. Entering Rincon segment of the Rio Grande Valley. The route ahead crosses a broad zone of upwarped, tilted, and faulted basin fill of the lower Santa Fe Group (see Stops S4 and S5). In many places near the valley-axis, upper Santa Fe fluvial deposits have been removed by erosion. Roadcuts for the next 5.5 mi are in complexly intertonguing arroyo-fan and river deposits. Sediments were deposited during at least two major intervals of valley entrenchment and partial back filling. These beds are angularly unconformable on the playa and alluvial-flat facies of the Rincon Valley Formation (upper Miocene), a correlative of the upper Popotosa Formation in the Socorro area. **1.7**

110.4 Underpass; Hatch interchange. 2.0

112.4 Crossing valley of Johnson Spring Arroyo. Road up arroyo leads to type areas of Palm Park (upper Eocene) and Thurman (Oligocene-lower Miocene) Formations, about 2.5 mi north of highway. High bench at 9:00 on skyline is the Rincon geomorphic surface with the very strong caprock caliche described at Stop S4. This upfaulted surface may be as old as 1-2 m.y. **1.9**

114.3 Crossing broad arroyo valley. Rincon Hills, at 8:30 to 12:00, are formed on units of the Thurman Formation (Oligocene to early Miocene), a sequence of rhyolitic volcanic and tuffaceous sedimentary rocks and basaltic andesites that are overlapped to the south by basal units of the lower Santa Fe Group (Seager and Hawley, 1973). The telephone relay tower at 10:30 is on conglomeratic sandstone to mudstones of the Hayner Ranch Formation (lower to middle Miocene; lower Popotosa equivalent). The light-reddish badland-forming unit to the right, left, and in road-cuts ahead is the basin-floor facies of the Rincon Valley Formation. This fine-grained, gypsiferous facies grades northward into coarse fanglomerates derived in part from the southern Caballo uplift. In ridges and benches at the base of the Rincon Hills, the Rincon Valley Formation is overlain by light-gray fluvial sandstones of the Camp Rice Formation (Pliocene-Pleistocene). The exposed Rincon Valley-Camp Rice sequence in this area has been broadly folded and offset by faults. **0.4**

114.7 Milepost 37. Cuts ahead in Rincon Valley mudstone to sandstone that has been tilted and faulted. *Prepare to exit ahead.* **1.0**

115.7 *Take Rincon exit, milepost 36. Continue south through Rincon Valley on NM-140 to* **STOP S5 at San Diego Mountain.** See miles 105.5 to 125.5 in E1 Paso to Socorro road log. After Stop S5 excursion, *return to this interchange; take 1-25 South (Las Cruces) approach ramp.* **0.4**

116.1 Approach ramp from Rincon merges from right; *continue east* across ATSF Railroad and Rincon Arroyo bridges. **0.4**

116.5 Ascending long grade from arroyo channel to floor of the Jornada del Muerto Basin. About 250 ft (75 m) of Camp Rice fluvial deposits (here upper? Pliocene to middle Pleistocene) are exposed in slopes and roadcuts ahead. This facies consists mainly of pebbly channel sand, with coarse gravel near the top and thin loamy layers at intervals throughout the section. The latter probably represent overbank deposits. Paleosols present in a number of the loamy units indicate periods of non-deposition and surface stability. **0.6**

117.1 Roadcut in Camp Rice channel and floodplain deposits. **1.1**

118.2 The route ascends to the floor of Jornada del Muerto

Basin and La Mesa geomorphic surface. *Prepare to take Upham exit ahead.* Note the strong, partly indurated horizon of soil-carbonate accumulation in uppermost sandy deposits of the Camp Rice (upper Santa Fe) fluvial facies. This soil-carbonate zone forms a caliche caprock layer that occurs within several feet of the ground surface in large areas of the southern Jornada del Muerto Basin. 0.5

118.7 *Take Upham exit, milepost 33. Continue north* across Jornada plain on graded road to **STOP S4, Rincon overlook.** See miles 100.1 to 102.7 in E1 Paso to Socorro road log. After Stop S4 excursion, *return to this interchange; take 1-25 South (Las Cruces) approach ramp.* **0.4**

119.1 Approach ramp merges from right; continue southeast on 1-25 across the Jornada plain. For the next 13 mi the highway closely follows E1 Camino Real, the Chihuahua-Santa Fe trail established in 1598 by Mate and the first European colonists (Gregg, 1954; Moorhead, 1958). **0.6**

119.7 San Andres range on eastern skyline from 8:00 to 10:30; Organ Mountains at 11:30; and Doña Ana Mountains at 12:00. **3.9**

123.6 Overpass. San Diego Mountain at 3:00 rises to west of the Precambrian core of the Tonuco uplift (see Stop S5). Outcrops of Bliss Sandstone (Cambro-Ordovician), overlain by several hundred feet of E1 Paso Limestone (Ordovician), form the dark band on the east side of the uplift. A thick section of lower Tertiary sedimentary and volcanic rocks, including the Palm Park Formation, is unconformable on the E1 Paso Group. Patches of silicified Camp Rice conglomerate and sandstone locally overlie Precambrian rocks in the central Tonuco uplift. The silicified Camp Rice also caps the prominent bench on the northeast flank of the uplift, where it has been downfaulted at least 100 ft (30 m) along the east Tonuco boundary fault. **0.4**

124.0 Rest area on east side of highway; Robledo Mountains at 1:00. **3.1**

127.1 Relay tower at 9:00. Doña Ana Mountains at 3:00. High Mt. Summerford ridge at the north end of the Doña Anas is the exposed part of a monzonitic to syenitic laccolith dated at 35 m.y. (Seager and others, 1976). **1.3**

128.4 *Exit to rest area (optional stop).* See mile 90.1 entry in E1 Paso to Socorro section of the road log. **1.7**

130.1 On drainage divide between Rio Grande watershed and internally-drained (bolson) segment of the Jornada del Muerto. A buried Tertiary bedrock high connecting the Doña Ana and Tonuco-Selden Hills uplifts passes beneath this point. Caliche-capped Camp Rice fluvial sand (exposed in roadcuts) and the basin floor have been upwarped in this immediate area. This Pleistocene deformation, with about 330 ft (100 m) displacement, is related to movement along the Jornada fault zone that forms the northeastern boundary of the Tonuco-Selden Hills and Doña Ana blocks (Seager, 1975a). **1.1**

131.2 Roadcuts in Camp Rice fluvial sand. Descending long grade into the northern Mesilla Valley between the Doña Ana and Robledo Mountains. Slopes ahead have thin cover of upper Quaternary alluvial and eolian deposits on Camp Rice fluvial facies. Uvas basaltic andesite caps high mesas of Sierra de las Uvas at 3:00. **0.2**

131.4 Fort Selden-Radium Springs exit 1 mi; Leasburg State Park and Stop S3 next right. **1.0**

132.4 *Take Fort Selden-Radium Springs exit. Continue west* across low river terrace to **STOP S3, Leasburg Dam-Radium Springs overlook.** See miles 82.0 to 86.4 in E1 Paso to Socorro road log. After Stop S3 excursion, *return to this interchange via Fort Selden ruins; take 1-25 south (Las Cruces) approach ramp.* **0.6**

133.0 Approach ramp merges from the right; *continue south* on 1-25 along eastern border of Mesilla Valley. Mt. Summerford forms north ridge of the Doña Anas at 9:00. Low ridges to west of peak are on Hueco Limestone (Permian). **0.6**

133.6 In arroyo to right, with the dam, upper Pleistocene valley fill overlaps basal Camp Rice sandstone and conglomerate that is angularly unconformable on Palm Park laharic breccias and mudstones. A small fault block of Hueco Limestone (Permian) is located just east of dam.

For about the next 7 mi the route crosses upper Quaternary alluvial deposits that are associated with at least three major intervals of valley entrenchment and partial back filling. Piedmont surfaces inset below high-level remnants of the Camp Rice Formation extend along the bases of the Doña Ana and Robledo uplifts. These surfaces include members of the Tortugas, Picacho, and Fort Selden sequence of middle to late Quaternary valley-border surfaces that are partly erosional and partly constructional in origin. The Tortugas and Picacho surfaces are graded to former river base levels, about 70-90 ft (24 m) and 120-130 ft (37 m), respectively, above the present floodplain (Hawley and Kottlowski, 1969; Metcalf, 1967). Fort Selden surfaces (latest Wisconsinan-Leasburg and Holocene-Fillmore) are graded to base levels near the present valley floor. Major episodes of river-valley entrenchment have been correlated with glacial maxima in the Rio Grande headwaters area of Colorado and northern New Mexico. Waning parts of glaciations and interglacial intervals (like the Holocene) have been times of major aggradation of both the river floodplain and (at least) the lower parts of tributary arroyo systems (Kottlowski, 1958; Hawley, 1975b).

Roadcuts ahead are mainly in Picacho alluvium that exhibits intertonguing of arroyo-fan and river facies. Picacho and Tortugas deposits in the northern Mesilla Valley have been warped and faulted, most noticeably along the eastern fault-zone boundary of the Robledo-Picacho block, with offsets in the range of 10-100 ft (3-30 m). Major featues of valley-fill units from here to E1 Paso are shown in fig. S12 (mile 74.0, E1 Paso to Socorro road log). **3.9**

137.5 Arroyo crossing; good view of central Doña Anas at 9:00. The northern and central parts of the mountains are largely underlain by a stock or sheet of upper Eocene andesite, with andesitic flows, laharic breccias, and other volcaniclastics dipping off its western flank. The stock may be the source of part of the Palm Park Formation, a major (upper Eocene) volcaniclastic and epiclastic unit in the Las Cruces-Caballo region. The southern, highest part of the range is carved on a partly exposed Oligocene cauldron complex about 6-8 mi (10-13 km) in diameter. A 2,500-ft (750-m) thick ash-flow tuff below Doña Ana Peak is associated with the eruption that initiated the cauldron cycle. Younger cauldron fill includes rhyolite flows and domes, bedded tuff and breccia, and ash-flow tuffs. The northwestern edge of the cauldron is exposed east of here near the center of the range. This edge consists of swarms of rhyolite, monzonite, and ignimbrite dikes that separate precauldron (upper Eocene) rocks of the cauldron wall from ash-flow tuffs and associated rocks of its interior. **0.7**

138.2 Overpass. At 9:00 western foothills of Doña Ana Mountains are composed of intrusive flow-banded rhyolite and a thick, massive, welded ash-flow tuff that fills the Doña Ana cauldron (about 35 m.y.). The dissected pediment at the foot of the mountains is cut mainly on ash-flow tuff. This erosion surface has been exhumed from beneath a Camp Rice Formation cover (Seager and others, 1976). **2.5**

140.7 Milepost 11. The southern Robledo Mountains from 9:00 to 10:00 are a south-tilted horst capped by Lower Permian limestone and intertonguing red beds (Hueco-Abo units) that dip beneath a sequence of lower Tertiary sediments and Eocene volcaniclastic rocks near Picacho Mountain. The prominent piedmont platform extending along the base of the Picacho-Robledo block comprises Tortugas and Picacho members of the valley-border sequence.

From here to the Texas State line (mile 173.2) the route is on thin, sandy alluvial and eolian deposits primarily associated with Holocene (Fillmore) units of the Fort Selden valley-border surface. These sediments rest on a broadly-undulating erosion surface cut in sandy Camp Rice deposits or on remnants of gravelly alluvium associated with Picacho fans and terraces. Carbon-14 dates on charcoal recovered from deposits of tributary arroyo systems indicate that the river base level has been essentially stable for the past 7,500 (Carbon-14) years, with expansion of arroyo-mouth fans taking place at the expense of riverfloodplain width (Hawley, 1975b). **1.3**

142.0 Overpass, Doña Ana interchange. Picacho (upper Pleistocene) fan alluvium forms low ridges on left. The village of Doña Ana, to left, is the oldest community in the Mesilla Valley. Doña Ana was permanently settled in 1843 as the administrative center for an 1839 Mexican land grant. **0.7**

142.7 Milepost 9. Picacho Mountain across valley at 3:00 is the exhumed root of a flow-banded rhyolite dome intruded through andesite-latite laharic breccia and other volcaniclastics of the Palm Park Formation (Eocene). Goat Mountain, on the Jornada del Muerto Basin rim at 9:00, is a mid-Tertiary microsyenite plug. **1.9**

144.6 Logs of water wells and gravel-pit exposures 2-3 mi east of this point show the following Santa Fe section: upper, caliche-capped rounded gravel of mixed siliceous composition and sand, about 60 ft (18 m) thick; pebbly sand, partly calcite-cemented, with silt and clay beds, as much as 200 ft (66 m) thick; and basal, partly gravelly clay, loam, and sand, as much as 400 ft (130 m) thick, over andesitic volcanic rock. An early to middle Pleistocene vertebrate fauna *(Mammuthus, Equus,* and *Cuvieronius)* of Irvingtonian provincial age has been collected from the upper gravel-and-sand unit 2-3 mi to the east. At least the upper 260 ft (80 m) are Camp Rice Formation fluvial facies (Hawley and others, 1969; King and others, 1971). **0.5**

145.1 North Las Cruces-US-70 interchange ahead; *continue straight* on 1-25. **0.5**

145.6 Underpass, US-70 interchange. **0.3**

145.9 Crossing Alameda Arroyo and outlet channel for U.S. Army Corps of Engineers flood-control structure. The 2.5-mi-long earthfill structure on the left diverts rainstorm runoff (Alameda and Las Cruces Arroyo watersheds) that formerly flowed through downtown Las Cruces. **2.1**

148.0 Picacho fan remnant on right with water tank. Mural on tank depicts Spanish colonization of New Mexico in 1598. Lohman Avenue interchange ahead; *continue straight* on 1-25. **0.3**

148.3 Underpass; Lohman Avenue. New Mexico State University and Stop S2 next right. **1.7**

150.0 *Take University Avenue exit (NM-101); stay in left lane of exit ramp for left turn ahead onto University Avenue eastbound. Continue east* to Stop S2 via Dripping Springs Road and Tortugas Mountain. **STOP S2, Tortugas Mountain and Organ caldera.** See miles 55.5 to 64.1 in E1 Paso to Socorro road log. After Stop S2 excursion *return to this interchange; take 1-25 South (El Paso) approach ramp.* **0.6**

150.6 Approach ramp merges from right; *continue south* on 1-25. New Mexico State University, Pan-American Center to right. **0.1**

150.7 Crossing Tortugas Arroyo; solar-energy research house on left adjacent to golf course. Slopes between highway and Tortugas ("A") Mountain at 9:00 are formed on sand and gravel of the Camp Rice fluvial facies with a thin veneer of upper Quaternary (Fort Selden-Picacho) alluvium-colluvium and eolian deposits. Clary 1 State oil test (sheet 2, hole c), about 1 mi south of Tortugas Mountain, was drilled to a total depth of 2,585 ft (790 m). The test encountered Santa Fe basin fill to at least 586 ft (180 m), and lower Permian (possibly also upper Pennsylvanian) strata below 1,420 ft (433 m). Lower Permian rocks may also have been penetrated between 586 and 1,420 ft (180 and 433 m). Estimated depth to Precambrian basement is 7,494 ft (2,285 m) or 3,254 ft (992 m) below sea level (Foster, this guidebook, hole c). **0.7**

151.4 I-10 East (E1 Paso); junction ahead. *Stay in left lane.* Las Alturas Estate subdivision at 10:00. A reasonably large area of hot water (200° C) at depth in this area has been outlined using geochemical and geophysical techniques (Swanberg, 1975). Geothermal resources of the area are discussed at Stop S3. **0.5**

151.9 *Take left fork for 1-10 East (El Paso) exit.* **0.4**

152.3 Underpass. **1.0**

153.3 *Merge to left with I-10.* Crossing Fillmore arroyo. **0.2**

153.5 Southern Organs from 9:00 to 11:00; Bishop Cap at 11:00; Franklin Mountains at 12:00 (area of Stop S1). Low bluffs to left are Picacho (upper Pleistocene) fan alluvium that partly fills a broad valley cut in sandy Camp Rice strata. **1.3**

154.8 Milepost 147. Fort Fillmore (1851-1862) ruins 1 mi to west near edge of floodplain. **0.8**

155.6 Black Mountain at 1:30 is a basalt cinder cone that rises above the central plain of Mesilla Bolson (La Mesa geomorphic surface). On west side of Mesilla Valley at 3:00, upper Pleistocene basalt flows from the Santo Tomas center cap an older (Tortugas?) valley-border surface (Hoffer, 1971). The Santo Tomas cinder cone on La Mesa rim has been nearly obliterated by cinder-quarry operations. Olivine basalts of the Santo Tomas-Black Mountain basalt field have KAr ages in the 0.226-0.025-m.y. range (Hoffer, 1971, 1973, 1976). Oldest flows associated with valley-border surfaces are in the 0.2-0.25-m.y. range. Timing of initial valley entrenchment is discussed at Stop S1b. 2.2

157.8 Crossing Peña Blanca Arroyo and apex of large alluvial fan of Holocene age. Tilted mass of light-colored ash-flow tuff at 9:00 forms part of the Organ caldera fill. Low ridges ahead on left are remnants of a late Pleistocene (Picacho) alluvial fan spreading out from a valley cut in Camp Rice fluvial deposits. 2.4

160.2 Underpass; Mesquite interchange. **0.5**

160.7 Mileage sign-Anthony 13, E1 Paso 32 mi. Bishop Cap, at 9:00, is the highest peak of a series of fault-block ridges of Paleozoic rocks that range in age from Ordovician to Pennsylvanian (Seager, 1973). The rocks form part of the southern rim of the Organ caldera discussed at Stop S2. Fillmore Pass, from 2:00 to 3:00, between Franklin and Organ Mountains, is underlain by thick fill of late Pliocene-early Pleistocene Rio Grande (lower Camp Rice Formation) that once flowed through the gap into Hueco Bolson (see Stop S1a). **0.7**

161.4 Crossing Bishop Cap Arroyo; feedlot on right. Vado Hills at 11:30 are the northernmost of a series of Eocene andesitic intrusions located in the southern Mesilla Valley. These plutons also include Cerro de Cristo Rey and Three Sisters (Assembly Point; Stop S1 b; Garcia, 1970). 1.4

162.8 Small hill of andesite projects through more than 330 ft (100 m) of Santa Fe Group basin fill in feedlot area to right. **0.3**

163.1 Quarry on left in andesite of Vado Hills. **0.8**

163.9 Underpass; Vado interchange. 2.8

166.7 Culvert; New Mexico Port of Entry exit ahead on right. *Continue south* on I-10. North tip of Franklin Mountains at 9:00. **1.3**

168.0 Milepost 159, opposite New Mexico Port of Entry weighing stations. New Mexico segment of the Franklin Mountain chain (upper Paleozoic carbonate rocks) at 9:00 to 11:00 and Texas part of Franklins (Stop S1) at 11:00 to 12:00 are separated by Anthony Gap. **1.3**

169.3 Underpass; north Anthony interchange. The apparent contorted bedding pattern on steep western dip slope of the northern Franklin range is an erosional pattern in well-stratified Pennsylvanian rocks and was not caused by folding (Kottlowski, 1960; Harbour, 1972). **0.8**

170.1 Foothills at 11:00, below northern peak of the southern Franklin block, are formed on a south-plunging syncline of Hueco Limestone (Lower Permian) (see Stop S1b). **0.8**

170.9 Crossing E1 Paso Natural Gas Co. pipeline. Trenches cut for the pipeline, northwest of Anthony Gap at approximately 10:00, expose high-level Camp Rice piedmont deposits with interbedded volcanic ash. As discussed at Stop S1b, this rhyolite ash may have been derived from the 0.7-m.y. B.P. eruption of the Long Valley caldera near Bishop, California. Towards the basin, the piedmont deposits overlap and intertongue with Camp Rice fluvial beds. This facies change can be seen in the valley-rim bluffs about 2.5 mi east of I-10. **0.6**

171.5 Underpass. **1.7**

173.2 Texas State line. Log from here to E1 Paso adapted in part from E1 Paso-Franklin Mountains-State line section of E1 Paso to Socorro road log by Lovejoy and Hawley. **0.2**

173.4 Underpass; Anthony interchange. **0.3**

173.7 Texas Tourist Information Bureau and rest area ahead on right. At 9:00 well-bedded carbonate rocks in foothills south of Anthony Gap are Hueco Limestone (Permian), forming west limb of south-plunging syncline discussed at Stop S1b. This is the Anthony "landslide" block of Lovejoy (1975b). **0.8**

174.5 La Tuna Federal Correctional Institution at 3:00. The upper dissected benchlands along the west base of the Franklins are primarily erosion surfaces cut on upper Santa Fe basin fill (piedmont gravels overlapping and intertonguing with fluvial facies). High-level deposits of piedmont gravel are associated with the mid-Pleistocene Jornada I surface, La Mesa pediment of Kottlowski (1958), and form the uppermost Camp Rice beds. In the area crossed by I-10, surfaces cut on the Santa Fe Group are mantled with arroyo-terrace and fan gravels that are associated with graded surfaces formed during at least three intervals of river-valley entrenchment and temporary stabilization of floodplain base levels. Geomorphic surfaces of the valley-border sequence in the E1 Paso area have been designated (in order of decreasing age and relative elevation) Kern Place, Gold Hill, and low terraces (Kottlowski, 1958; Hawley, 1965; Metcalf, 1969). These surfaces correlate with the Tortugas, Picacho, Fort Selden sequence of the northern Mesilla Valley (mile 133.6). Molluscan faunas and morphostratigraphic units in the valley-fill sequence have been described by Metcalf (1969). Surficial deposits along the route from here to E1 Paso are commonly cemented with soil-carbonate accumulations, forming strong caliche zones. **1.1**

175.6 Border Steel Rolling Mills on right. Anthony's Nose at 9:00, elevation 6,927 ft (2,100 m), is capped with Fusselman Dolomite (Silurian). Well-bedded units at the base of the Franklins are Mississippian and Pennsylvanian carbonate rocks. **0.5**

176.1 Underpass; Vinton interchange. 1.1

177.2 Milepost 4. Mt. Riley and East Potrillo Mountains on skyline at 3:00 are on west edge of Mesilla Bolson (see Stop S1b). **1.9**

179.1 Exit to Canutillo and Trans-Mountain Highway. The Trans-Mountain route leads to **STOP S1b, Tom Mays Memorial Park,** in the limestone foothills west of the Franklins, and across the range (through Smuggler's Gap and Fusselman Canyon) to **STOP Sla, Wilderness Park Museum.** Stops S1a and S1b are on northbound to westbound segments of the Franklin Mountains tour loop. The loop begins at the Holiday Inn Assembly Point in downtown E1 Paso and follows the Rim Road-Scenic Drive route around the south tip of the range. See miles 00.0 to 27.0 in E1 Paso to Socorro road log. The southbound segment of the Franklin Mountain tour loop continues on I-10. **0.8**

179.9 Approach ramp from Canutillo interchange merges on right. At 9:00 North Franklin Mountain (Cabeza de Vaca Peak, elevation 7,192 ft-2,192 m), capped with Precambrian rhyolite, forms the high point of the range as well as the highest structural point in Texas (Adams, 1944). Smuggler's Gap (9:30), between North (9:00) and South (10:00) Franklin Mountains, is at the upper end of Fusselman Canyon. Precambrian rocks of the North Franklin Mountain-Fusselman Canyon area (Stops Sla to S1 b, miles 13.1 to 17.4 northbound log) are described by McAnulty, Sr. (1968), McAnulty, Jr. (1968), Denison and Hetherington (1969), and Harbour (1972). Foothills of Hueco Limestone (Permian) along the base of the range west of Smuggler's Gap are considered by Harbour (1972, section E-E ') to be in place, but by Lovejoy (1975b) to be remnants of landslide blocks that overlie Cretaceous rocks. Structural features of the Franklin west slope are discussed at Stop S1b (mile 21.8 northbound log). **1.4**

181.3 Underpass. **1.0**

182.3 Three Sisters Peaks from 9:00 to 10:30 are mid-Eocene andesite porphyry intrusions in Cretaceous shale and limestone (Garcia, 1970). **0.3**

182.6 Dam to left between north and middle "Sisters"; Smuggler's Gap on skyline at 9:00. West of gap at base of range Ordovician (lower E1 Paso Gap) limestone of the Franklin block is in fault contact with Cretaceous rocks (Harbour, 1972). The displacement is in the order of 7,000-8,000 ft (about 2,135-2,440 m) down on the west. This segment of the Western Boundary fault zone is not obviously expressed in the surface topography. **0.9**

183.5 Underpass. Cerro de Cristo Rey (Cerro de Muleros) uplift at 11:30-12:00 across the Rio Grande. The peak is 0.2 mi north of the New Mexico-Chihuahua boundary. The uplift consists of a central andesite laccolith, a confocal, contemporaneous felsite sill on the west and south sides of the laccolith, and an annulus of deformed Cretaceous marine strata (Lovejoy, 1976d). The andesite pluton, as well as the other intrusive andesites in the E1 Paso-Vado Hills area (miles 161.4-190.5), is considered to be contemporaneous with the nearby Campus Andesite intrusion K-Ar dated at 47.1 ± 2.3 m.y. (Hoffer, 1970). According to Lovejoy (1976d, p. ix) "the pluton formed after tectonism ceased in the Sierra de Juarez of the Chihuahua tectonic belt, perhaps early during the tectonism that produced the Basin and Range province.. . . Although the pluton is situated on the Texas lineament (with long axis of the pluton and minor structures in the uplift trending N. 60° W., parallel with the Texas lineament trend) evidence is lacking for any activity along the Texas lineament." **0.9**

184.4 Mesa Street overpass. For the next 2.6 mi the route crosses a complex of Kern Place and Gold Hill valley-border surfaces. **0.4**

184.8 Andesite crops out in walls of small arroyo east of highway. **0.9**

185.7 Reddish Precambrian rhyolite is exposed on west face of South Franklin Mountain (peak at 9:00, with aircraft guidance towers). The frontal fault trace in the Western Boundary zone is along the base of the range from 9:30 to 10:30 and beyond the tall (Fortune-Life) building at 10:00 (fig. S1 b). West-dipping lower Montoya Group (Ordovician) carbonate rocks in the range block are opposite Cretaceous rocks of the down-thrown block, indicating a stratigraphic separation of about 6,000 ft (1,830 m). Huge slide blocks, starting with the Crazy Cat block to the south (Assembly Point and mile 1.1-northbound), can be traced north from Crazy Cat Mountain (11:15, with microwave tower) and Flag Hill (10:45) to the Thunderbird foothill area below South Franklin Mountain (figs. S2a, b; Lovejoy, 1975b, 1976b, c). These blocks cover the traces of the Western Boundary zone. **0.8**

186.5 Underpass; Sunland Park Drive. *CAUTION, DANGEROUS INTERSECTIONS! Keep left; continue on I-10.* **0.5**

187.0 Loop 16 underpass; ascending long grade. Roadcuts ahead are in upper Santa Fe bolson-floor facies with a thin mantle of piedmont gravel associated with the Kern Place surface. The high, dissected benchlands along the western base of the mountains are primarily erosion surfaces, cut on upper Santa Fe basin fill, which are capped with thin piedmont gravels of the middle Pleistocene Jornada I surface (La Mesa pediment of Kottlowski, 1958). **1.5**

188.5 The Crazy Cat slide block (10:30), with microwave tower on summit, is a brecciated mass of carbonate rocks-Fusselman Dolomite (Silurian) over Montoya Group (Ordovician)-8,000 ft (2,500 m) long north-south, 5,000 ft (1,500 m) wide, and about 330 ft (100 m) thick (Lovejoy, 1976b). The slide breccia lies across the Western Boundary fault zone and is faulted less than 16 ft (5 m)-probably less than 6 ft (2 m). The age of the slide is not known, but it is older than Blancan-age bolson-floor deposits of the Santa Fe Group. **0.9**

189.4 Underpass; Executive Center Boulevard. ASARCO smelter ahead on right is just east of the international boundary. **0.5**

189.9 Underpass; ASARCO slag tramway. The route ahead approaches the inner Rio Grande Valley. The northwest part of Ciudad Juarez, Chihuahua, is across the river to the right. **0.5**

190.4 Cut on left exposes intrusive contact of 47-m.y. Campus Andesite with Cretaceous shale (Hoffer, 1970). The andesite crops out in roadcuts ahead and is a part of a small pluton that forms hills in and around the campus of the University of Texas at E1 Paso. **0.6**

191.0 University of Texas at E1 Paso to left; Shuster Avenue-Sun Bowl Drive ahead on right. *Continue straight* on I-10. **0.4**

191.4 Overpass; Shuster Avenue. **0.5**

191.9 Underpass; Porfirio Diaz Avenue. *Keep right for next exit-downtown* E1 Paso. **0.5**

192.4 *Take El Paso-Downtown exit.* **0.2**

192.6 Stop sign at intersection of Wyoming Avenue and Santa Fe Streets. Assembly Point at Holiday Inn is one block ahead on right: Wyoming Avenue between E1 Paso and Oregon Streets. End of Socorro to E1 Paso section of road log. Hasta la vista!

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Southern rift guide 2,
Socorro-Santa Fe, New Mexico

Much of the tour route from Socorro to Santa Fe is in the central part of the large Albuquerque Basin, with the initial segment in the smaller Socorro and La Jencia Basins. The concluding part of the southern rift tour is in the Santo Domingo and Santa Fe extensions of the Albuquerque and Española Basins, respectively. Several excursions are made from central basin areas to piedmont slopes and foothills of adjacent uplifts. From Socorro to San Felipe Pueblo (mile 199.8) the main route on 1-25 closely follows the inner valley of the Rio Grande. Between San Felipe and Santa Fe the route ascends from the river floodplain to the high piedmont surface at the base of the Sangre de Cristo Mountains, the southernmost range of the Rocky Mountain chain.

The region crossed includes the core area of early investigations of the "Rio Grande depression" by Kirk Bryan (1938) and his students. From south to north the route crosses or is near areas studied by Denny (1940, 1941), Wright (1946), Bryan and McCann (1937, 1938), and Stearns (1943, 1953a, b).

This section of the guide is introduced by A. L. Sanford's paper reviewing geophysical studies in the Socorro area. His discussion is related to features seen at the first four stops (S10-S13). Guidebook entries at these stops and in the connecting road log emphasize the middle and late Cenozoic evolution of the ranges within and flanking the Socorro, La Jencia, and southernmost Albuquerque Basins. As in the area traversed to the south (Stops S2, S3, S6, S8, S9), much of the discussion centers on mid-Tertiary and younger cauldron structures and their relation to the evolution of the rift.

From Stop S12 (near San Acacia) north to Santa Fe, major emphasis is placed on dating and correlating geomorphic surfaces (erosional and constructional) that characterize the later stages of rift evolution. Discussions at Stop S12 and Stop S16 (Albuquerque) stress interpretation of pedogenic (soil) features in relation to 1) lengths of surface-stability intervals and 2) relative and absolute ages of episodic movement on intrarift faults.

Northeast of the San Acacia-Rio Salado area (Stop S12) the route enters the Albuquerque Basin, the major rift segment in central New Mexico. The southern part of the basin (from Stops S13-S14) is bounded on the east by the Manzano-Los Pinos range and on the west by the Ladron and Lucero uplifts. The western rift border is also the eastern margin of the Colorado Plateau province. Thick sections of Precambrian and upper Paleozoic rocks are exposed in these structurally high boundary ranges. At Stop S13 in southeastern Albuquerque Basin (as at Stops S1b, S6, and S8) discussions stress the major influence of Laramide precursors on the development of the present Basin and Range forms. Stop S13 is also near the COCORP lines (Oliver and Kaufman, 1976) briefly discussed by Sanford in the following section.

Stops S14-S16 are on a high tableland remnant of upper Santa Fe basin fill, the Llano de Albuquerque, that extends almost the full length of the central Albuquerque Basin. The Llano ranges from about 300-600 ft (100-200 m) above the flanking valleys cut by the Rio Puerco (west) and Rio Grande (east). Discussions at Stop S14 relate to 1) deep drill holes and basin-fill thickness, 2) Pliocene-Pleistocene volcanics of the nearby Cerro de los Lunas, Cat Hills, and Wind Mesa centers, and 3) history of final basin aggradation (uppermost Santa Fe deposition) and initial river-valley entrenchment. The timing of the latter events is interpreted from a K-Ar-dated volcanic sequence and volcanic-ash and soil-geomorphic correlations. Stops S15 and S16 are on 1-40 west of Albuquerque. They are at the western and eastern escarpments (in Spanish, cejas or cejitas), respectively, that border the Llano de Albuquerque. Structures of the western rift-Colorado Plateau boundary and upper Santa Fe stratigraphy are discussed at Stop S15. This stop is on the Llano rim at the crest of the Ceja del Rio Puerco first described in the classic papers by Bryan and McCann (1937, 1938).

Stop S16 overlooks the river valley and provides a panoramic view of the Sandia, Manzanita, and northern Manzano ranges. As at Stop S13, structural evolution of the eastern rift boundary and influence of Laramide precursors are stressed. Discussions also relate to methodology used for estimating timing and amounts of episodic movement on a nearby Quaternary fault. A combined geologic and pedologic approach has been used in evaluating a sequence of buried calcic paleosols formed in the deposits on the downthrown side of the fault.

Stops S17 and S18 are on the northern Sandia piedmont east of 1-25. Stop S17 is selected for on-site presentation of gravity-profile data collected during a recent geophysical survey by the U.S. Geological Survey. The stop is located directly over one of the linear zones of steep gravity gradient that delineate master faults within and along the boundaries of the rift. At Stop S18, located opposite the northwest corner of the Sandia block, discussions center on the system of right-echelon faults and intervening ramps involved in the eastward shift of the rift margin across the transitional zone (Santo Domingo subbasin) that separates the Albuquerque and Española Basins. Recent work on the large San Felipe volcanic field (including Canjilon Hill maar) is also discussed. This sequence of basaltic volcanics has K-Ar ages of 2.5-2.6 m.y.

Stops S19 and S20 offer contrasting views of the Santo Domingo subbasin at the eastern edge of the Albuquerque Basin. The structural setting includes 1) an east-dipping block of Mesozoic to middle Tertiary rocks (Espinaso Ridge extension of the Sandia block) that forms a northward-plunging half graben, and 2) an eastern boundary-fault zone (La Bajada-Rosario) at the base of La Bajada escarpment. The escarpment rises to the basalt-capped plateaus (Cerros del Rio-Mesita de Juana Lopez) of the western Santa Fe embayment and the Cerrillos Hills-Ortiz Mountain belt of monzonite porphyry intrusions.

Stop S19 is on a high point in the landscape that offers a panoramic view of much of the north-central New Mexico region. The stop is near the type area of the Ortiz erosion surface of Bryan and McCann (1938) and overlooks the La Bajada escarpment, which extends from Galisteo Creek to the mouth of White Rock Canyon of the Rio Grande. Stop S20 is in the northeastern part of the Santo Domingo subbasin at the base of La Bajada escarpment. This stop is opposite the mouth of Cañada de Santa Fe, which cuts into a Pliocene basalt-capped section of Tertiary to Mesozoic rocks. The broad plain on which Stop S20 is located in part of the type La Bajada surface of Bryan (1938). Discussions at Stops S19 and S20 and connecting road log entries deal with 1) the strati-graphic sequence exposed in La Bajada escarpment, 2) the origin and ages of the Ortiz-La Bajada sequence of geomorphic surface, and 3) the style and timing of structural deformation along La Bajada and related faults in the northern Sandia uplift to Santa Fe embayment region.

The final stop (S21) of the northbound tour is in the Cerrillos Hills area, above La Bajada escarpment. The site overlooks the Santa Fe embayment at the south end of the Española Basin and provides a panoramic view toward Santa Fe, at the base of the Sangre de Cristo Mountains. Discussions relate to 1) the Mesozoic to middle Tertiary section of the La Bajada area, 2) middle Tertiary monzonitic intrusives and associated rocks of the Cerrillos Hills and Ortiz Mountains, and 3) events associated with upper Santa Fe deposition and subsequent stages of piedmont-slope development along the Sangre de Cristo front.

The southbound segment of the Socorro-Santa Fe guide includes a short log (from Bernalillo to near San Ysidro in the Jemez Creek Valley) that connects the main north-south log with the Jemez Mountain road log by Bailey and Smith. Emphasis of the Bernalillo-San Ysidro log and Stop S22 is on the nearly complete Santa Fe section exposed along the Rincones de Zia escarpment, which descends from the northern end of the Llano de Albuquerque to Jemez River.

CHARACTERISTICS OF RIO GRANDE RIFT IN VICINITY OF SOCORRO, NEW MEXICO, FROM GEOPHYSICAL STUDIES

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The Rio Grande rift has many unusual geological and geophysical characteristics in the area between Bernardo and San Marcial, New Mexico. In that area many geophysical investigations have been conducted. This paper summarizes the geophysical aspects of these studies that are significant to an understanding of this part of the rift.

Properties of the crust

GENERAL STRUCTURE—A north-south crustal profile of the Rio Grande rift through the Socorro region has been published by Sanford, Mott, and others (1977). Important features of the profile are 1) an upper crustal layer approximately 19 km thick with a velocity of 5.8 km/sec, 2) a lower crustal layer with a velocity of 6.5 km/sec and thickness of approximately 17 km beneath Socorro, and 3) a northward dip of about 2 degrees on the Moho, which overlies upper-mantle rock with a velocity of 7.9 km/sec. The most unusual characteristics of the general structure of the crust are the abnormally low upper-crust and upper-mantle velocities. The upper-crust velocity, 5.8 km/sec, is significantly lower than the 6.15 km/sec found beyond the margins of the rift. The low upper-crust velocity is probably caused by the pervasive fragmentation of the upper crust of the rift by normal faults (O'Connell and Budiansky, 1974). On the other hand, the low upper-mantle velocity is probably related to the mechanism that has produced crustal extension for the past 25-29 m.y. (Chapin and Seager, 1975).

Changes in crustal thickness to the east and west of Socorro have been calculated from regional-gravity and seismic-refraction studies of mining explosions located at Tyrone, New Mexico, and Morenci, Arizona (Sanford, Mott, and others, 1977). Recently, the crustal structure east of the rift was determined from a seismic refraction profile extending northward from a large chemical explosion in the northern part of White Sands Missile Range (Olsen and others, 1977). These data indicate little change in Moho depth to the east of the Rio Grande rift but an increase in depth to the west. The gravity data (assuming the change in the Bouguer anomalies is totally the result of a 0.2 g/cm^3 density contrast across the Moho) give an 8° dip S. 60° W., whereas the seismic data give 3.4° dip S. 40° W. and 1.1° dip S. 63° W. Regardless of which dip is used to the west, the geophysical data do not support the existence of a sharp, symmetrical mantle upwarp beneath the rift in the Socorro vicinity.

MAGMA BODIES IN THE CRUST—An unusual feature of the crust beneath the rift in the Socorro vicinity is seismic evidence for the existence of magma bodies. Two types of magma bodies have been detected. The first is an extensive (more than 1700 km') sill-like body occurring at depths of 18-22 km. The second type of magma body is composed of small intrusives located above the southern end of the extensive magma layer (fig. 1).

Extensive mid-crustal magma body—The initial evidence for an extensive magma body at mid-crustal depths came from an analysis of the arrival times and amplitudes of two reflection phases on microearthquake seismograms (Sanford and Long, 1965; Sanford and others, 1973). These two reflections, S to P and S to S, are impulsive and have the same general frequency content as the direct S-phase. Recordings by instruments with a broad frequency response show that the S to S phase contains a wide range of frequencies—from 3 to 15 Hz (Rinehart, 1976). This observation indicates that the reflecting discontinuity is sharp and singular. In addition, the absolute strength of the reflections as well as the ratio of their amplitudes indicates that the discontinuity producing the reflections is underlain by magma (Sanford and others, 1973; Sanford, 1977b).

The minimum geographical extent of the magma has been determined from the geographical distribution of S to S reflections on microearthquake seismograms (Rinehart, 1976; Sanford, Mott, and others, 1977; Sanford, 1977b) and from exceptionally strong P-wave reflections on high-resolution seismic reflection profiles (Oliver and Kaufman, 1976; Brown and others, 1977). These latter reflections on the COCORP (Consortium on Continental Reflection Profiling) profiles have about the same depth and dip (6° northward) as the S-wave reflections from the top of the magma layer.

The available observational data indicate that the magma body is very thin relative to its extent. P-wave residuals for teleseisms and mining explosions (Yousef, 1977; Fischer, 1977; Tang, 1978) do not support the existence of a thick magma layer even after station corrections are applied. Analysis of the Gasbuggy refraction data (Toppozada and Sanford, 1976) indicates that time delays for P_n arrivals passing through the magma layer cannot be much greater than 0.1 second. A layer of magma (full melt) 0.6 km thick would be sufficient to produce a 0.1-second time delay. Finally, no clearly defined reflection phases from the bottom of the magma layer have been identified on microearthquake seismograms. If such reflections exist, they must occur so closely in time to the reflections from the top of the magma body that they cannot be easily identified.

Small shallow magma bodies—Three types of observations suggest the existence of small magma bodies above the southern end of the mid-crustal magma layer: 1) the screening of SV waves (vertically polarized S waves), 2) the spatial distribution of Poisson's ratio, and 3) the spatial distribution of microearthquake hypocenters (Sanford, 1976).

For many microearthquakes in the Socorro vicinity, SV waves are absent or extremely weak on seismograms for one or more stations in the array (Shuleski, 1976; Sanford, Rinehart, and others, 1977). About 40 percent of these observations can be explained by the fault mechanism of the microearthquakes; the remaining 60 percent apparently result from SV screening by molten or partially molten rock bodies (Kubota and Berg, 1968; Matumoto, 1971). Four shallow magma bodies west and southwest of Socorro can account for most of the observed screening. Although the precise location, shape, and volume of the intrusives have not been determined, approximate locations for segments of the crust containing the shallow magma bodies are given in fig. 1.

From an analysis of S-P times and P travel times for microearthquakes, the spatial distribution of Poisson's ratio in the upper crust has been found (Caravella, 1976). Several pie-shaped segments in the upper crust with Poisson's ratios greater than 0.29 have been located near Socorro. Although these high Poisson's ratios could result from compositional changes in the crustal rocks, they can also be explained by the same general distribution of shallow magma bodies used to account for SV screening.

An analysis of the spatial distribution of microearthquake foci shows activity surrounding, but not within, the crustal segments containing the shallow magma bodies (Sanford, Rinehart, and others, 1977). Above these regions, microearthquake foci are never deeper than about 2 1/2 km, whereas in adjacent areas, activity occurs to depths of 8 km or more. Earthquake activity is not expected in segments of the crust containing magma because high temperatures produce stable sliding rather than stick-slip movement along faults.

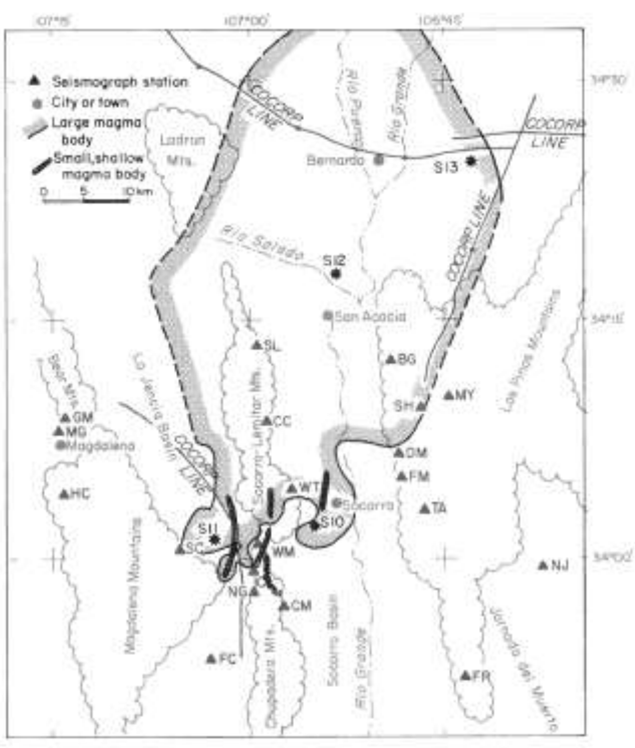

FIGURE 1—Geographical extent of the extensive magma body. A solid line indicates the boundary is closely defined; a dashed line denotes some uncertainty of its location. Positions of the COCORP lines and the shallow magma bodies (heavily hachured areas) are also shown.

To date we at New Mexico Tech have only looked for shallow magma bodies above the southern end of the extensive magma body. Thus we cannot be certain that this region is the only one where magma may leak upward through the crust from the deeper magma body.

Natural seismicity

The pattern of natural seismic activity in space and time suggests recent intrusion of magma into the crust in the vicinity of Socorro. Elastic strain is being released in this region by large numbers of earthquakes, most occurring in swarms. Earthquake swarms are observed in the vicinity of active volcanoes and in regions that have had volcanic activity in recent geologic times (Richter, 1958).

Descriptions of the seismic activity in the Socorro vicinity since 1960 have appeared in a number of publications (Sanford and Holmes, 1961; Sanford and Holmes, 1962; Sanford, 1963; Sanford and Singh, 1968; Sanford and others, 1972; Singh and Sanford, 1972; Sanford, Mott, and others, 1977). The principal characteristics of the seismic activity are listed below:

1) Unlike the Albuquerque-Belen Basin to the north, elastic strain is being released in the Socorro area by hundreds of earthquakes, nearly all in the microearthquake range (local magnitudes less than 3.0).
2) The seismic activity is diffusely distributed over a 2,000 km^2 area roughly centered on the deep, extensive magma body.
3) The activity within this area does not correlate closely with the spatial distribution of known major faults.
4) A composite fault-plane solution for microearthquakes in the Socorro area indicates that the microearthquakes are the result of downdip movement on faults with near north-south strike.
5) Approximately 75 percent of the microearthquake activity is occurring in swarms (defined as six or more shocks from the same focal region in 24 hours).

A characteristic of historical as well as of recent seismic activity is the occurrence of a majority of earthquakes in swarms. One of the historical swarms from 1906 to 1907 was major, comparable in magnitude to the famous 1965-67 Matsushiro swarm, which Stuart and Johnston (1975) attribute to magmatic intrusion at shallow depth. During the 1906-07 Socorro swarm, shocks were felt almost every day and at times reached a frequency of one perceptible tremor an hour. Three shocks of this swarm reached a Rossi-Forel intensity of VIII at Socorro and were felt over areas of about 275,000 km^2 (Reid, 1911; Sanford, 1963). The local magnitudes of these quakes is estimated to be near 6.

Rift structure

A gravity survey (fig. 2) indicates that the long, narrow Socorro Basin is composed of three linked structural depressions. The two depressions adjacent to the Socorro-Lemitar Mountains are asymmetrical. Narrow fault zones with large displacements, perhaps as great as 3.5 km, border the western margins of these downdropped crustal blocks. From their deepest points west of the Rio Grande, these depressions rise

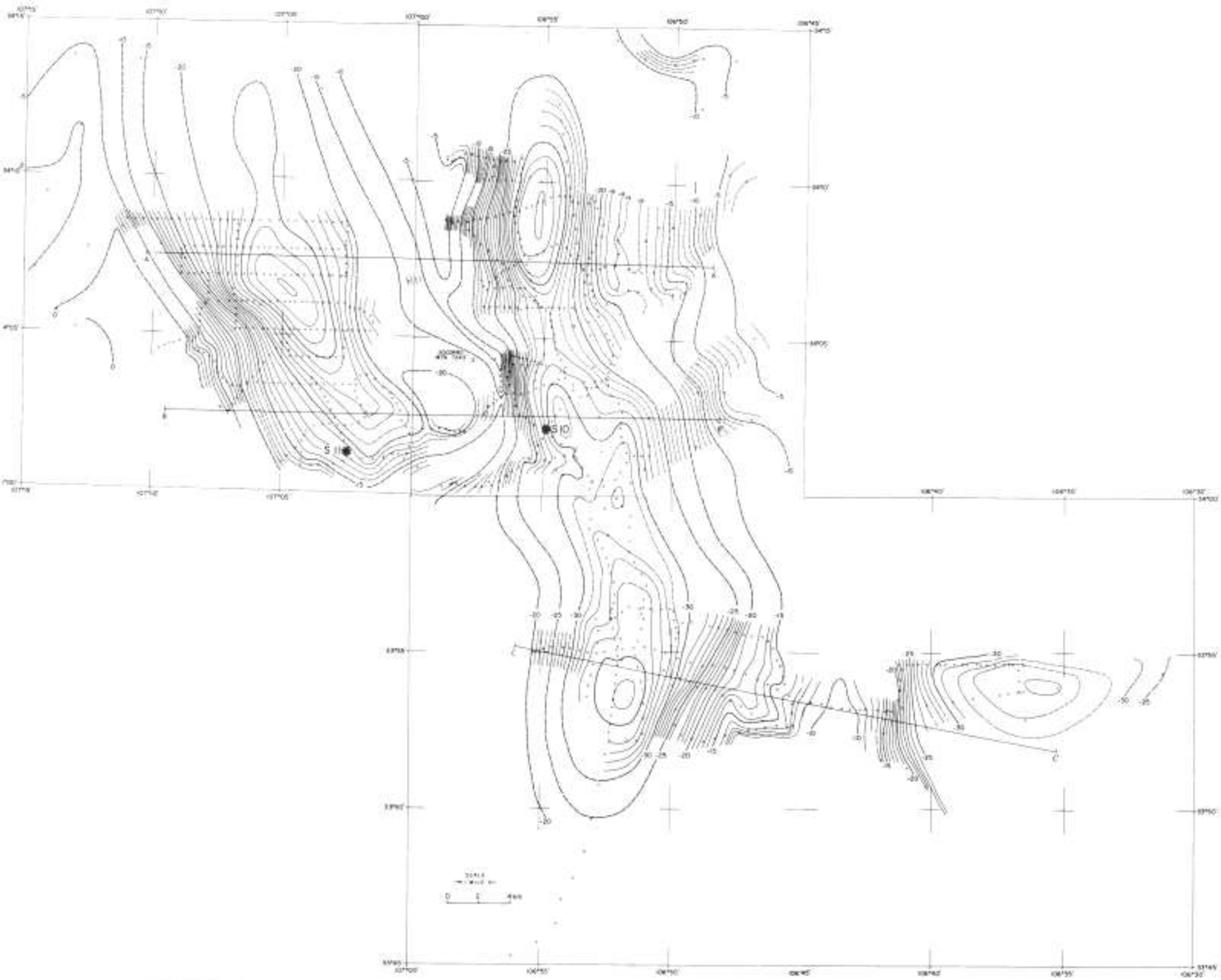

FIGURE 2—BOUGUER GRAVITY MAP OF THE SOCORRO AREA; terrain and regional corrections have been applied (from Sanford, 1968).

fairly gradually to the east, probably by a combination of step faulting and tilting. Some interpretations of the gravity data also indicate the possibility of buried horst blocks beneath Socorro Basin.

La Jencia Basin is not as narrow as Socorro Basin nor as structurally asymmetrical. However, the total structural relief for La Jencia Basin is comparable to that for the structural depressions comprising the Socorro Basin-on the order of 3 km. Thus the geophysical data are compatible with geologic information indicating a broader basin in the Socorro area prior to uplift of the Socorro-Lemitar Mountains 9-10 m.y. ago (Denny, 1941; Chapin and Seager, 1975).

The gravity data also support geologic mapping that indicates the existence of a large caldera south of Socorro Peak (Chapin and others, 1978). The gravity anomalies north of Socorro Peak are substantially more positive than those to the south, although the topographic relief is similar. These observations can readily be explained by low-density deposits in the moat region of the caldera. Gravity coverage in the Jornada del Muerto Basin east of the Rio Grande Valley is not great. Recently Schlue (1978) completed a gravity survey in this basin that extends detailed coverage northward from 33°55 ' N. to 34°00 'N. between 106 °37 'W. and 106 °42 'W. His study indicates the basin is open further to the north than shown in fig. 2.

Fig. 3 shows a previously unpublished Bouguer gravity map covering a section of the rift that includes the transition from the Albuquerque-Belen Basin to the Socorro Basin. The map, based on work by Wongwiwat (1970), Oralratmanee (1972), and others, does not have the regional gravity removed. Inclusion of the regional gravity does not seriously affect a qualitative interpretation of near-surface geology from the map, because the regional variations in gravity are not great east of longitude 107° W. (Sanford, 1968). In addition, no terrain corrections were applied to the observations. With the exception of gravity stations in the northeast corner of the map, this correction is negligible.

The gravity map clearly shows the structural constriction between the Albuquerque-Belen Basin and the Socorro Basin. The Bouguer anomaly on the saddle between the two basins is about 15 milligals positive relative to the basins. The gravity map also indicates complex horst-and-graben structure beneath the southern end of the Albuquerque-Belen Basin. Details of the complex structure are particularly well shown on detailed seismic reflection profiles 1 and 1A (COCORP data). Two major horst structures revealed by these geophysical surveys appear to be subsurface extensions of the Ladron and Joyita uplifts.

Other geophysical observations

Additional geophysical observations of importance in the Socorro area are high temperature gradients and heat flows and surface uplift, all possibly related to the intrusion of magma into the crust. Temperature gradients as high as 241 ° C/km and heat flows as high as 11.7 HFU (heat-flow units) have been measured in the Socorro Mountain block (Reiter and Smith, 1977; Sanford, 1977a). Although movement of warm ground water upward along fracture zones is a possible explanation for the high temperature gradients (Reiter and others, 1978), two observations other than the seismic studies suggest these gradients are the result of magmatic intrusion into the upper crust. First, gradients as high as 184° C/ km have been measured about 2 km west of the major frontal fault bordering the eastern margin of the Socorro Mountains (Sanford, 1977a). Second, the residence time of the water passing through Socorro Peak is extremely short-approximately four years (Holmes, 1963); this residence time suggests that the water would not have had time to redistribute heat from great depths in the crust.

Uplift of the Socorro area in very recent time has been established by Reilinger and Oliver (1976) from an analysis of level-line data for the period 1909-1952. Their results for a single north-south line indicate surface uplift roughly coincident with the extent of the extensive magma body. The maximum average rate of uplift, about 6 mm/yr, has occurred approximately 20 km north of Socorro.

ACKNOWLEDGMENTS-Many of the studies described in this paper were conducted by undergraduate and graduate research assistants at New Mexico Tech. Where possible, I have acknowledged their work in the text; otherwise it appears in the references. The geophysical work in the Socorro vicinity has been supported by a number of organizations over the past 20 years but primarily by the State of New Mexico and the National Science Foundation.

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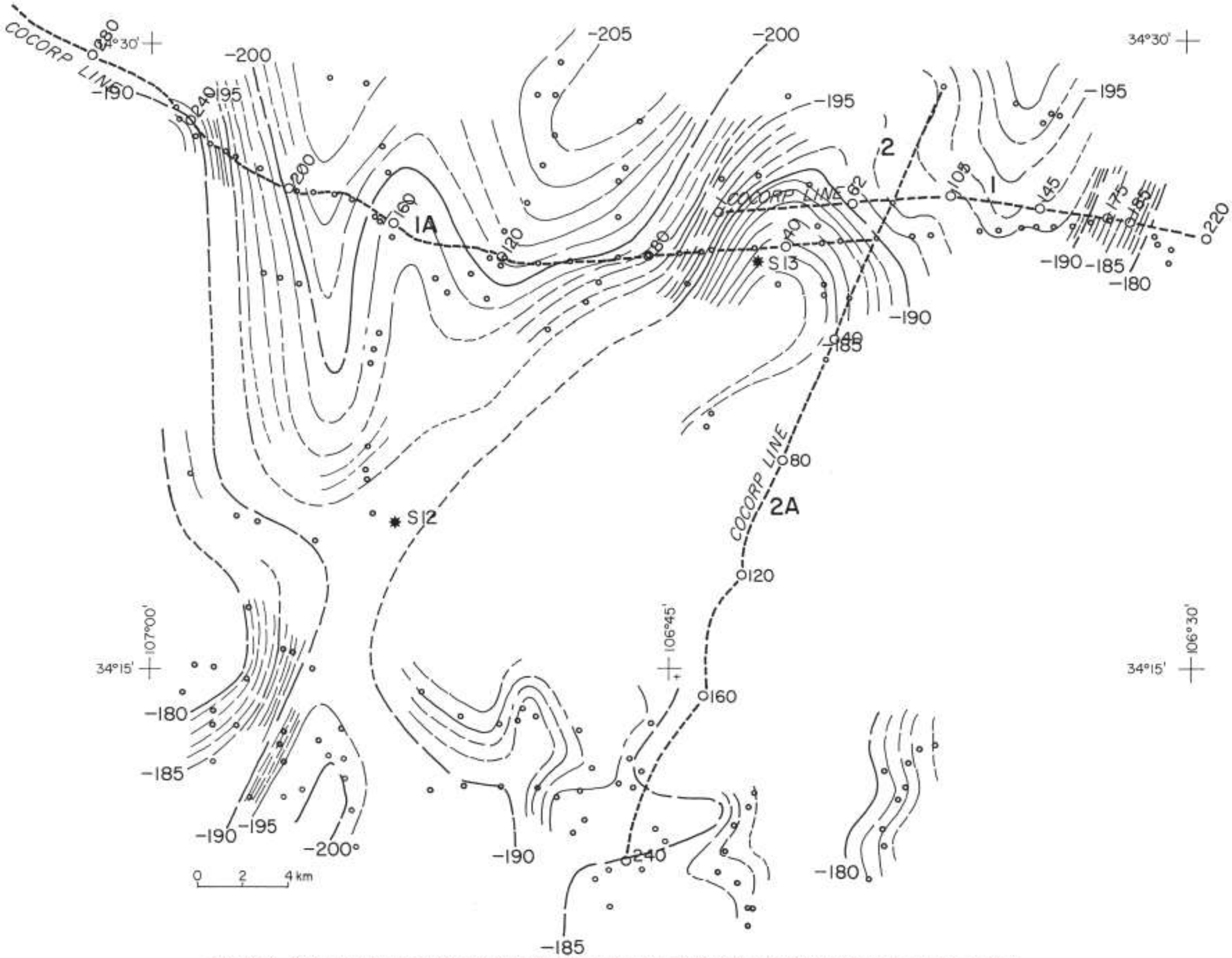

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SOCORRO TO RIO SALADO

by C. E. Chapin, R. M. Chamberlin, and J. W. Hawley

Mileage

0.0 Junction of US-85-US-60 at California and Spring Streets in south Socorro. *Proceed west on US-60; stay in left lane.* **0.5**

0.5 Stop sign at intersection of Spring Street and Business US-60. *Bear left on US-60 West.* **0.4**

0.9 Crossing tracks of railroad spur to Grefco perlite mine. Leaving inner valley of the Rio Grande and ascending to surface of late Pleistocene Socorro Canyon fan. **0.3**

1.2 Socorro High School to left on fan surface. *Prepare for left turn ahead at tour stop.* **0.7**

1.9 *Turn left into parking lot* of National Guard Armory. **0.1**

2.0 **STOP S10, Socorro.** Socorro National Guard Armory on north side of US-60. Discussion of geology and geophysics of the Socorro area as related to evolution of the Rio Grande rift as well as to precursor volcanic-tectonic features of the Datil-Mogollon volcanic field. (figs. S34-S37). Road-log and tour-stop entries from here to mile 23.2 are compiled primarily from log by Chapin, Jahns, and others (1978). Refer to paper by Sanford in the preceding section for a summary of geophysical studies in the area including Stops S10-S13. Fig. S38, from Cordell (1978) shows cross-state gravity and elevation profiles at 34 ° north latitude (about 2 mi south of this stop).

A major volcanic feature west of the Rio Grande Valley in this immediate area is the Socorro cauldron, of late Oligocene age, centered on the Chupadera Mountains to the southwest. The cauldron is a nearly circular structure, about 12 mi (20 km) in diameter. About 2,900 ft (900 m) of the cauldron-facies tuff of Lemitar Mountains (27 m.y.) is exposed on a resurgent dome making up the low reddish hills at 9:0010:00. The Luis Lopez manganese district is located on the resurgent dome; other manganese mines and prospects occur around the edges of the cauldron. The Socorro cauldron occurs at the northeast end of a string of partly overlapping cauldrons that extend southwestward through the Magdalena and San Mateo Mountains (Stops S8 and S9; fig. S32). In the following discussion of the cauldron area, 12:00 will be looking northwest, perpendicular to US-60.

The northern margin of the Socorro cauldron is exposed on the steep east-facing escarpment of Socorro Peak ("M" Mountain) at 12:30 (fig. S39). To the north at 1:30, Polvadera Mountain (in the Lemitar range) is a west-dipping hogback comprising dark-colored Oligocene ash-flow tuffs and andesite flows

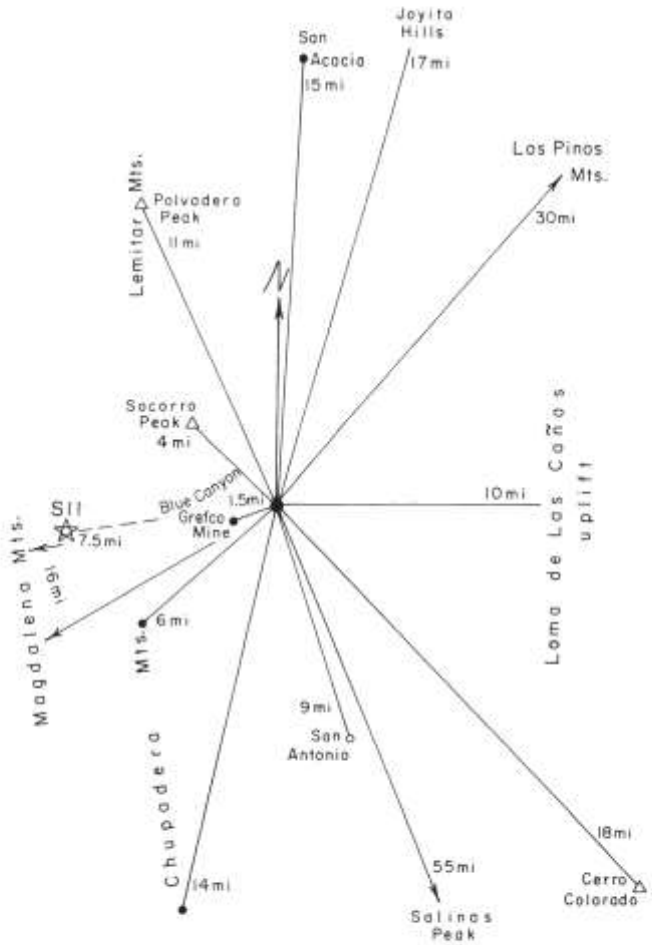


FIGURE S34—PANORAMIC INDEX OF FEATURES SEEN FROM STOP S10, SOCORRO NATIONAL GUARD ARMORY.

(skyline) above light-gray Pennsylvanian limestones and reddish Precambrian granite. Equivalent Pennsylvanian rocks exposed on the east face of Socorro Peak are truncated on the south by the ring fracture zone of the Socorro cauldron. Beneath the bold cliffs (below and to the right of the "M"), reddish-brown, poorly welded, lithic-rich tuffs and dark-colored andesite flows of the moat deposits (unit of Luis Lopez) directly overlie the light-gray, well-stratified Pennsylvanian limestones. Approximately 2,0003,000 ft (600-900 m) of Oligocene volcanic rocks were removed from the cauldron margin before it was overlapped by moat deposits. The abrupt truncation of Pennsylvanian limestones marks the buried topographic margin of the cauldron (considerable faulting is also present along the margin). The moat deposits decrease in thickness by at least 650 ft (200 m) across this margin. Landslide breccias of intermixed Madera Limestone (Pennsylvanian) and Spears Formation (early Oligocene) form dark-purplish-gray outcrops near the base of the escarpment (at bottom of ridge to left of the well-stratified Madera outcrops). These landslide deposits, which mark the topographic caldera wall, abruptly wedge out to the north (fig. S39). North of Blue Canyon (12:00), the high, reddish-brown ridge is a rhyolite dome that probably marks a point on the ring fracture zone (or structural margin) of the cauldron. The conspicuous light-colored outcrops along the base of the dome are propylitically altered tuffs related to early eruptions of this vent. Volcanism continued along the moat of the Socorro cauldron for several million years after caldera collapse (27-20 m.y. B.P.).

Volcanism was apparently quiescent in the Socorro area between about 20 and 12 m.y. ago. During this interval, the northern portion of the Socorro cauldron was buried beneath fanglomerates and playa deposits of a broad early-rift basin. The bold, dark-colored cliffs below and to the right of the "M" are composed of west-dipping fanglomerates and mudflow deposits of the lower Popotosa Formation (basal Santa Fe Group), which unconformably overlie moat deposits. From 12 to 7 m.y. ago, rhyolitic to rhyodacitic domes and flows spread across the northern half of the Socorro cauldron, blanketed thick playa claystones, and lapped onto bedrock highs along the cauldron margin and on the resurgent dome to the south. These silicic domes and flows form the skyline of Socorro Peak. The youngest of the late Miocene domes (7 m.y.) is the Grefco perlite deposit at 10:00. The high flat-topped mesa on the skyline at 10:30 is an 8-m.y.-old rhyodacite dome, probably truncated by an early Pliocene pediment that graded to the ancestral Rio Grande. Basalt flows erupted from vents at Sedillo Hill, 4 mi to the west, and flowed eastward down this pediment surface and onto the ancestral Rio Grande floodplain. The low basalt-capped mesas on both sides of the Grefco mine (10:00) are downfaulted remnants of these basalts. Light-colored friable sands of the ancestral Rio Grande are exposed in roadcuts leading to the water tank on top of the mesa. The overlying basalt, dated at 4.0 ± 0.3 m.y. by Bachman and Mehnert (1978), provides the oldest age yet obtained for the ancestral Rio Grande. Machette (1978b) has named the ancestral Rio Grande sands and their interfingering piedmont-slope deposits the Sierra Ladrones Formation. These sands underlie much of Socorro Valley and provide an important, shallow aquifer.

The Socorro Armory is located on a large alluvial fan constructed in middle to late Quaternary time by streams flowing out of Socorro Canyon. The surface here is interpreted to be of late Pleistocene age, probably pre-Wisconsinan, based on: 1) its intermediate position in the stepped sequence of graded surfaces and morphostratigraphic units bordering the Rio Grande (Hawley and others, 1976), and 2) the presence of moderate to strong soil horizons of clay and carbonate accumulation in surficial deposits. The surface of this fan segment appears to grade to levels (along the bluffs bordering the inner river valley) about 120-140 ft (36-43 m) above the present floodplain. Fan alluvium overlaps and probably interfingers with fluvial deposits associated with an earlier interval of river-valley entrenchment and partial back filling.

As noted in the E1 Paso to Socorro log (Stops S1b-S3 and entry at mile 240.3 near San Antonio) surfaces and associated alluvial fills of valley-border sequences exhibit 1) complex changes in facies character reflecting axial-river versus tributary-alluvial and colluvial environments, 2) various erosional-constructional combinations of graded surfaces, and 3) a variety of features associated with structural deformation. The deformational features range from prominent fault scarps (miles 3.2, 3.4, 16.0, and 17.4) to subtle forms related to warping of broad areas (Sanford and others, 1972; Sanford, this guidebook).

Foster and Luce (1963) and Sanford and others (1972) reviewed the historical development and use of geomorphic-surface terminology in the Socorro-Bernardo area (Stops S10, S12, and S13). As defined and interpreted by Bryan (1932, 1938) and Denny (1941), the stepped sequence of surfaces in this area comprises the following series of valley-flanking erosion surfaces or pediments (including elevations of projected grades above the present floodplains): Ortiz(?)-370-400 ft (115-120 m), Tio Bartolo-250 ft (75 m), Valle de Parida-150 ft (45 m), and Cañada Mariana-50-75 ft (15-25 m). Sanford and others (1972) use the following elevation ranges for valley-border surfaces seen at Stops S10 and S13: Tio Bartolo-200-275 ft (61-84 m); Valle de Parida, with 2 members at 140-180 ft (43-55 m) and 100-120 ft (30-37 m); and Cañada Mariana-40-90 ft (12-27 m). Denny (1967) has reexamined his own early studies of piedmont (valley-border) surfaces in the San Acacia area. He suggests that interpretations of these stepped-surface sequences should involve studies of present geomorphic processes. Moreover, he cautions against interpreting such sequences simply as erosion surfaces related mainly to successive climate-controlled (Davisian) stages of river-valley entrenchment, with each stage being followed by long intervals of base-level stability and erosion. No attempt is made in this road log to correlate surfaces and surficial deposits of the valley-border sequence with the type Tio Bartolo, Valle de Parida, and Cañada Mariana surfaces (mapped by Denny, 1941). Structural deformation, complex facies changes, lithologic similarity of units in stratigraphic sequences (both cut-and-fill and stacked units), and common poor exposure all combine to hamper local—as well as regional—correlation of geomorphic surfaces. Anything other than broad-brush correlation of morphostratigraphic units (Hawley and Kottlowski, 1969; Hawley and others, 1976) is impossible without detailed information on fill stratigraphy, genesis of surface forms (for example, erosional or constructional), soil development, and structural deformation. Aside from recent work by Lambert (1968) at Albuquerque (Stops S15-S18) and by Machette (1978b) near San Acacia (Stop S12), no detailed studies on the geology of post-Santa Fe valley-fills have been made in the Socorro and Albuquerque-Belen Basins.

Two thermal springs (Socorro and Sedillo Springs) and a third, man-made spring (Cook Spring) occur along the base of the escarpment from 10:45-11:45 and provide a large part of Socorro's water supply. The waters are a sodium-bicarbonate type with low dissolved solids and temperatures of about 90-91 ° F (Hall, 1963). Tritium studies by Holmes (1963) indicate a probable transit time of about four years from recharge along the east flank of the Magdalena Mountains to discharge at the springs. The springs are located where the range-bounding fault cuts moat deposits of the Socorro cauldron and a transverse shear zone of the Morenci lineament (Chapin and others, 1978). This shear zone separates two domains of tilted blocks undergoing rotation and step faulting in opposite directions. At the north, the beds are tilted to the west and downfaulted to the east; at the south, the beds are tilted to the east and downfaulted to the west. Note the reversal in dip from east to west in going from the Chupadera Mountains at 9:00 to the Lemitar Mountains at 1:00. The twisting motion across the lineament is represented in the brittle near-surface rocks by a zone of jostled blocks about a mile wide; in the deep crust, the strain must be relieved by shearing parallel to the lineament. The location of the thermal springs may reflect increased fracture permeability along the shear zone.

The transverse shear zone has been a major control of magmatism, both past and present. The seven overlapping and nested cauldrons (32-26 m.y.) are aligned along the zone (fig. S32). The area of 12-7-m.y.-old silicic volcanism is approximately bisected by the shear zone; the two youngest domes lie on or close to the zone; the vents for the 4 m.y.-old basalts are near it; the 18-km-deep, sill-like magma body outlined by Sanford and associates (using reflections from micro-earthquakes) ends against the zone (Chapin and others, 1978; Sanford, this guidebook); and the shallow, dike-like magma bodies located by Sanford and associates (using screening of SV waves, changes in Poisson's ratio, and the distribution of microearthquake hypocenters) are distributed along the zone. The transverse shear zone apparently forms a barrier to lateral movement of magma at mid-crustal depths but allows magmas to bleed upward along it and fill tension fractures at shallower depths.

Comparison of aeromagnetic, topographic, and geologic data reveals a quiet zone 5-8 mi in width extending southwestward from Socorro through the Magdalena range (Chapin and others, 1978). Aeromagnetic anomalies in the Magdalena range are both to the north and south but muted along this zone, which cuts across the highest part of the range. In the Socorro Peak area, the aeromagnetic anomalies are very subdued and seemingly independent of both terrain and surface geology. The quiet zone probably represents an upwarp of the Curie temperature isotherm to shallower depths, thus cancelling some of the aeromagnetic signature of the deeper crust. The structural grain of the aeromagnetic data is north trending to the north of the transverse shear zone and northeast trending to the south of it. The Morenci lineament seems to be a major structure in the Precambrian basement.

Red mine dumps of the Socorro Peak silver district are visible along the base of the escarpment between 12:30 and 1:00. The veins are in downfaulted late Miocene rhyodacite flows overlying red, gypsiferous upper Popotosa claystones. The silver ores were discovered in 1867, a few years after discovery of the Kelly district near Magdalena. When the railroad reached Socorro in 1881, mining and the town boomed. Socorro was a major supply point for several other mining districts and became the most populous town in New Mexico. The New Mexico School of

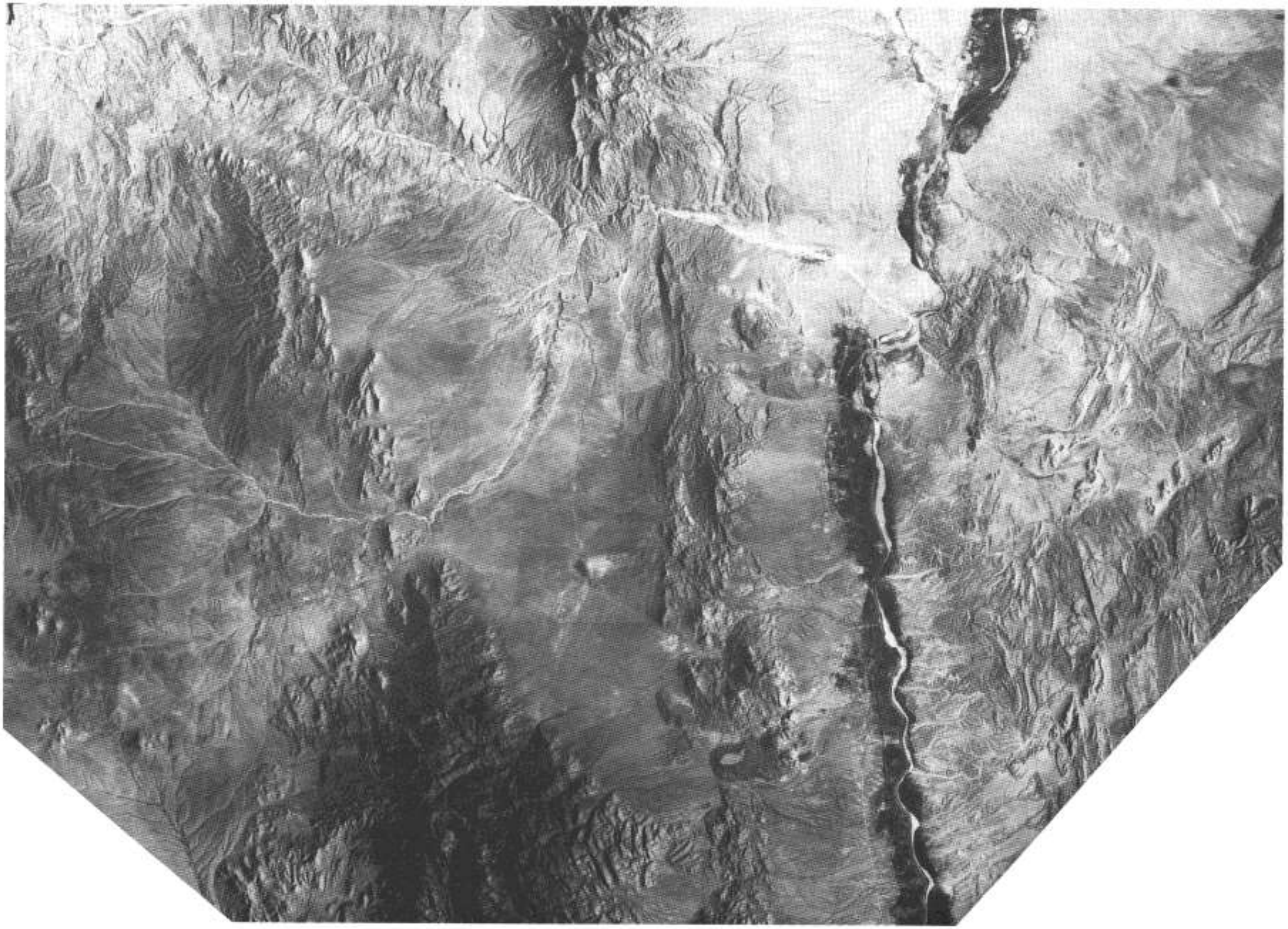
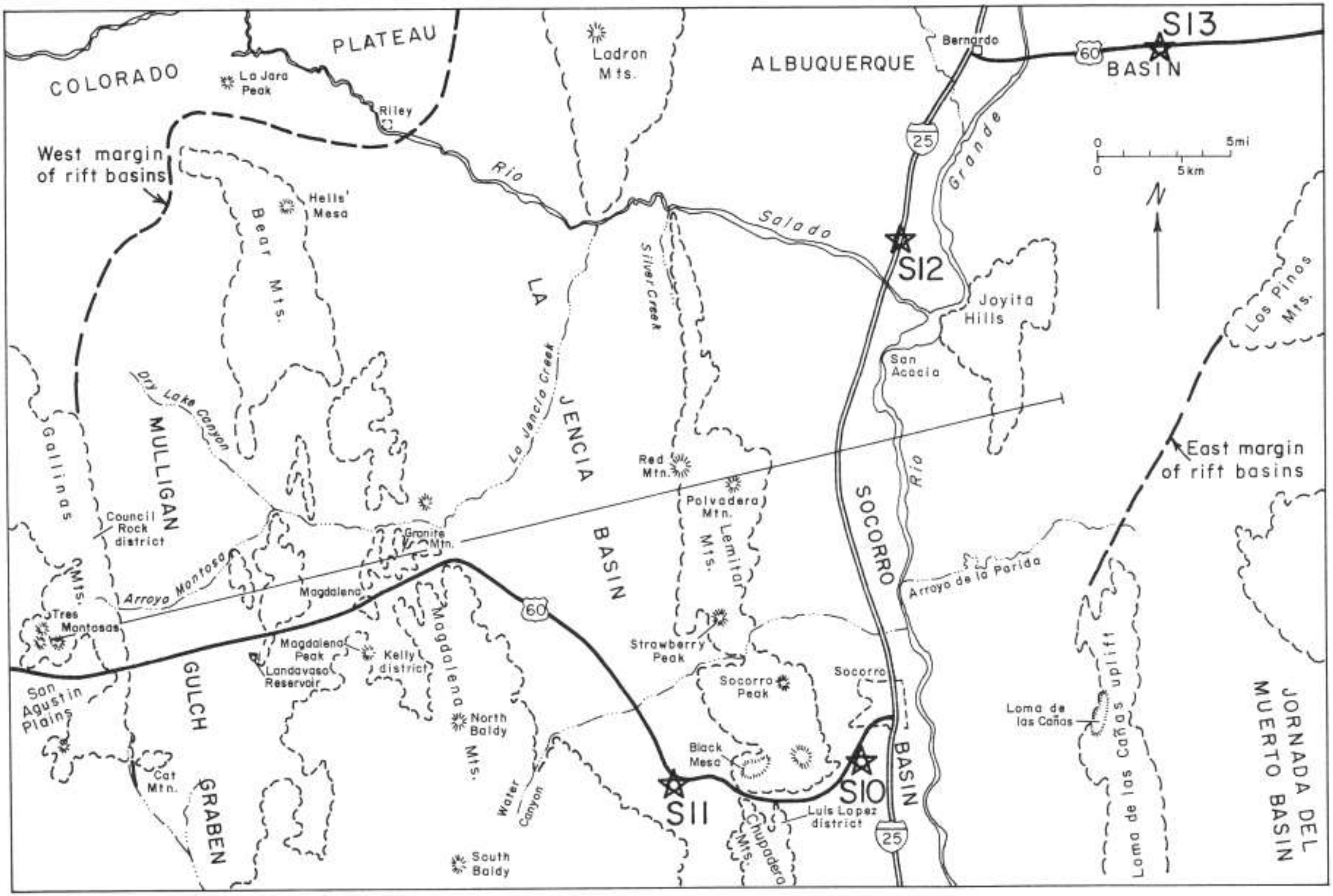


FIGURE S35—SKYLAB-3 PHOTO (a) AND INDEX MAP (b) OF THE SOCORRO-LA JENCIA BASIN AREA, STOPS S10 TO S13 (photo SL3-85-018 courtesy of Technology Application Center, University of New Mexico; photo scale approximately same as map scale).


COLORADO
PLATEAU
La Jara Peak
Riley
Ladron Mts.
ALBUQUERQUE
BASIN
Bernardo
60
S13
West margin of rift basins
Rio Salado
Hells' Mesa
Bear Mts.
25
Rio Grande
0 5mi
0 5km
N
S12
LA JENCIA BASIN
Silver Creek
La Jencia Creek
Joyita Hills
Los Pinos Mts.
San Acacia
Dry Lake Canyon
MULLIGAN GULCH GRABEN
Gallinas Mts.
Red Mtn.
Polvadera Mtn.
Lemitar Mts.
SOCORRO BASIN
East margin of rift basins
Council Rock district
Granite Mtn.
Arroyo Montosa
Magdalena
Arroyo de la Parida
Tres Montosas
Magdalena Peak
Kelly district
Landavaso Reservoir
Magdalena Mts.
Strawberry Peak
Socorro Peak
Socorro
San Agustin Plains
North Baldy
Loma de las Cañas
Loma de las Cañas uplift
JORNADA DEL MUERTO BASIN
Cat Mtn.
Black Mesa
S10
S11
Water Canyon
Chupadera Mts.
Luis Lopez district
South Baldy

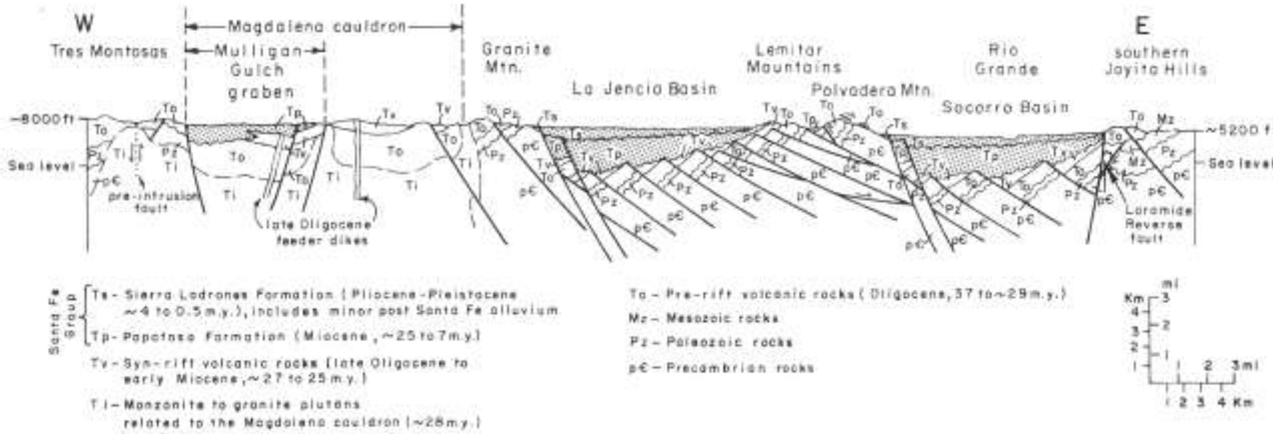


FIGURE S36—DIAGRAMMATIC WEST-EAST CROSS SECTION OF THE RIO GRANDE RIFT IN THE SOCORRO-MAGDALENA AREA, FROM TRES MONTOSAS TO THE JOYITA HILLS; the approximate line of section is shown on fig. S35b. Unconformable relationships and fault density of buried early-rift faults in the La Jencia and Socorro Basins are inferred from relationships exposed in uplifted basin floor in Lemitar Mountains. Note small "overturned" graben west of Polvadera Mountain and "klippe-like" erosional remnant of pre-rift volcanics (To) east of the mountain. The Sante Fe Group is shaded for emphasis of basin-fill features. The indicated thickness, about 1,000 ft (300 m) of the Sierra Ladrones Formation in the Socorro Basin is a minimum; gravity data (Sanford, this guidebook) suggest that this unit (Ts) may be 2,000-4,000 ft (610-1,220 m) thick in the area east of Socorro Peak.

Mines was established here in 1889. Most of the mines closed in the mid-1890's when the price of silver declined. Total value of production from the Socorro Peak district was estimated by Lasky (1932) at only $760,000 to $1,000,000, probably not much more than was spent getting it out. **0.6**

2.6 Road to Grefco mine on right. Resurgent dome of Socorro cauldron at 12:30; southern Chupadera range at 12:00 (south of Socorro cauldron). Piedmont slope along east flank of Chupadera range (12:30-1:00) formed by late Pliocene-Pleistocene fanglomerates unconformably overlying upper Popotosa Formation (late Miocene) and Pliocene-Pleistocene ancestral Rio Grande deposits of the Sierra Ladrones Formation. The piedmont slope is offset about 100 ft (30 m) at 12:00 (west of gravel pile) by a fault scarp trending south-southeast from the Socorro Peak escarpment (see mile 16.0). 0.2

2.8 Bridge over Socorro flood-control channel. Light-colored sands of the ancestral Rio Grande (Sierra Ladrones Formation) exposed at point of ridge. Pale-red, ledge-forming outcrops are piedmont-slope facies of the Sierra Ladrones Formation shed from the eastern Magdalena range. **0.4**

3.2 Approaching fault scarp cutting inset terrace gravels of late Pleistocene age. The same fault zone offsets lower Pliocene basalt flows at 3:00; strongly rotated basalt blocks near the base of the ridge cover the fault zone and may be related to it. Magdalena range at 12:30. **0.2**

3.4 Crossing fault scarp. Drill roads cut in gray perlite at 2:30. Red mudstones of the upper Popotosa Formation overlie the perlite dome and are visible in the upper cuts. Light-yellow sands of the ancestral Rio Grande visible to lower right of waste dump for perlite fines. **0.7**

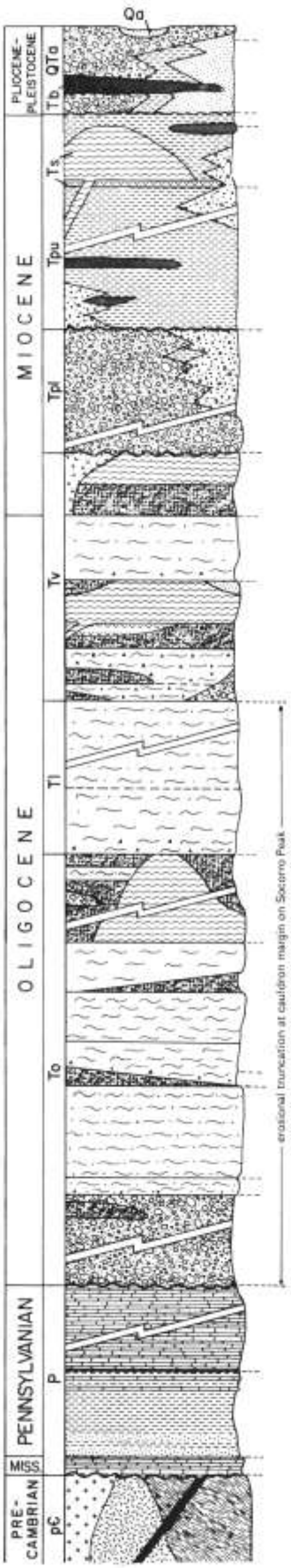
4.1 Road to site of old Great Lakes Carbon perlite mill on right. At 3:30 through small saddle is a view of northerly aligned necks and the vent on "M" Mountain, all part of the 7-12-m.y.-old rhyolite of Socorro Peak. **0.3**

4.4 At 3:00, the reddish-brown craggy outcrops are part of a northwest-tilted fault block of cauldron-facies tuff of Lemitar Mountains. The tuff is unconformably overlain by east-dipping lower and upper Popotosa. At 3:00, the high mesa is the 8-m.y.-old rhyodacite dome that was beveled by an early Pliocene erosion surface; note columnar jointing. Black Mesa at 2:00 is a remnant of the late Pliocene (4 m.y.) basalt of Sedillo Hill that flowed across the early Pliocene erosion surface, here cut on upper Popotosa clay-stones. The combination of a resistant basalt cap overlying incompetent claystones has resulted in a mantle of slump blocks and colluvium around Black Mesa that effectively masks most of the claystone. 0.6

5.0 Dirt road to windmill on right. At 2:30 on the north side of Socorro Canyon is a small exposure of dark-red gypsiferous claystones overlain by light-gray silts and non-gypsiferous muds tentatively correlated with the overbank facies of the Sierra Ladrones Formation. At 11:30, South Baldy, elevation 10,783 ft (3,540 m), the highest point in the Magdalena range, is the point where the transverse shear zone crosses the crest of the range. 0.2

5.2 For the next half mile, the old and new roadcuts to the left expose red non-gypsiferous muds, light-gray silt, and fine sand of the Sierra Ladrones Formation over-bank facies, capped and partly masked by slope wash from the overlying piedmont-slope gravels. 0.9

6.1 Crossing east-bounding fault of Chupadera range; roadcuts in moat volcanics collectively named the unit of Luis Lopez. Massive, reddish-brown andesite to rhyodacite lavas are overlain by light-gray, bedded rhyolite tuffs. The depositional contact between the two members is repeated by a minor fault in the road-cut on the right. An altered rhyolite flow caps the west side of the hogback and is unconformably overlain by remnant patches of lower Popotosa Formation, in turn unconformably overlain by red mudstones and buff sandstones of the upper Popotosa in the next roadcut on the right. 0.4



Post Santa Fe Alluvium: (0-50', 15 m) ALLUVIUM, SLUMP BLOCKS, and COLLUVIUM: inset deposits of gravel, sand, & mud along the Rio Grande & its tributaries. Fan, piedmont-slope and playa deposits of La Jencia bolson. Extensive slump & colluvial deposits on slopes around Socorro Pk., Strawberry Pk., & Black Mesa mantle mudstones of upper Popotosa Fm.

Sierra Ladrones Formation: (0-1000', 305 m) PIEDMONT-SLOPE, RIVER CHANNEL and FLOOD PLAIN DEPOSITS, and BASALT FLOWS: buff to pale-rd., poorly indur., fangl. w/ mixed clasts of all major rock types shed off present highlands. Fangl. intertongue w/ lt.-gry., friable, well-sorted, fn.-med.-gnd. sands of ancestral Rio Grande. Flood plain deposits are rd. & grn. mudst. & siltst. Basalt of Sedillo Hill (4 m.y.) underlies piedmont-slope facies & overlaps ancestral Rio Grande sands & piedmont facies near Grefco mine.

Rhyolite of Socorro Peak: 7-12 m.y. (0-800', 244 m) SILICIC DOMES, FLOWS, and TUFFS: pale-rd.-gry. to lt.-gry. rhyolite & rd.-brn. to lt.-gry. rhyodacite flow-banded lavas, domes, necks, & tuffs. Tuffs interbedded w/ clayst. of upper Popotosa at Socorro Spring, W. of Blue Canyon, Kelly Ranch (12 m.y.), and N. of Sedillo Hill.

Upper Popotosa Formation: (0-2500', 762 m) CLAYSTONES, MUDSTONES, SILTSTONES, SANDSTONES, CONGLOMERATES, and BASALT FLOWS: Dk.-rd. maroon gyp. playa clayst. & mudst. w/ thn. bds. of yel.-brn. to grn.-gry. clayst. North of Strawberry Pk., playa deposits intertongue w/ buff, cgl. ss w/ hydro. altered clasts derived from Magdalena area. At Grefco mine, mudst. intertongue w/ pale-rd. cgls. derived from E. of Rio Grande and w/ perlite-rich cgls. shed from Grefco dome. Basalt flows interbedded w/ playa deposits near Pound Ranch, Strawberry Pk., & Hwy. 60.

Lower Popotosa Formation: (0-1500', 457 m) MUDFLOW DEPOSITS, FANGLOMERATES, and minor LACUSTRINE DEPOSITS: rd.-brn., v. well-indur., heterolithic, crs. cgls. w/ abun. clasts of underlying volc. units & locally grading downward into ancient colluvial breccias. Gry. siltst., mudst., & thn. fresh-water ls. intertongue w/ lt.-gry. to prpl.-gry. cgl. ss. in Socorro Pk.-Blue Canyon area. Facies relationships reflect late-stage topography of Socorro caldera.

Lavas of Water Canyon Mesa: 20 m.y. (0-600', 183 m) INTERMEDIATE to SILICIC LAVAS and TUFFS: rd. silicic lavas & tuffs underlain by intermed., dk.-gry. to dk.-rd.-brn., dense lavas; intruded and overlain by flow-banded wht. rhyolite domes & flows.

Tuff of South Canyon: 26 m.y. (0-600', 183 m) ASH-FLOW TUFFS: multiple-flow, simple cooling unit of rhyolite ash flow tuffs. Lower zone of lt.-gry., poorly to densely welded, xl.-poor tuff w/ "botryoidal" pumice & lithic-rich lenses. Upper zone of med.-gry. to prpl.-gry., mod. to densely welded, mod. xl.-rich tuff w/ chatoyant sanidine & euhedral qtz.

Unit of Luis Lopez: (0-2000', 610 m) ASH-FLOW TUFFS, ANDESITE LAVAS, RHYOLITE DOMES and TUFFS, minor LANDSLIDE DEPOSITS and TUFFACEOUS SANDSTONES: Moat fill of Socorro cauldron. Lt.-gry., pumiceous, lithic-rich, poorly welded, rhyolite ash-flow tuffs intertongue w/ andesite flows, vent agglomerates, & minor andesitic laharic breccias. Pale-rd., orng.-rd., & lt.-gry. flow-banded rhyolite lavas, domes and tuffs cap sequence. Contemporaneous tongue of La Jara Peak Basaltic Andesite (0-800', 244 m) in Lemitar Mts.

Tuff of Lemitar Mountains: 27 m.y. (0-400', 122 m outflow; 700-2900', 213-884 m cauldron) ASH-FLOW TUFFS: multiple-flow, comp. zoned, simple to compound cooling unit of densely welded tuff. Lt.-gry. to pale-rd., xl.-poor lower member 200-800 ft (61-244 m) thk. in Socorro cauldron but only locally present as thn. lenses on outflow sheet. Md.-rd., xl.-rich, qtz. & biotite-rich, 2-feld. upper member 0-400 ft (122 m) outflow facies, 350-2900 ft (107-884 m) cauldron facies. Contact sharply gradational & welded. Xl.-rich clots common at top. Lithic-rich zones w/ Precambrian & andesite clasts widespread S. of Tower mine.

Unit of Sixmile Canyon: (0-2000', 610 m) ANDESITE to BASALTIC ANDESITE LAVAS, RHYOLITE LAVAS and DOMES, ASH-FLOW TUFFS, LAHARIC BRECCIAS, and SANDSTONES: post-collapse fill of Sawmill Canyon cauldron. Drk.-gry. mafic lavas intertongue with & surround other rock types. Heterolithic breccias along cauldron walls. Contemporaneous tongue of La Jara Peak Basaltic Andesite (0-500', 152 m) in Lemitar Mts.

A-L Peak Tuff: 32 m.y. (0-700', 213 m outflow; 2000+', 610+ m cauldron) ASH-FLOW TUFFS: composite sheet w/ basal gray-massive, middle flow-banded, & upper pinnacles members. All densely welded, xl.-poor, l-feld., rhyolite, ash-flow tuffs. Sources are Mt. Withington, Magdalena, & Sawmill Canyon cauldrons. Tongue of La Jara Peak Basaltic Andesite (0-200', 61 m) usually separates flow-banded & pinnacles members.

Lava Flows: (0-300', 91 m) ANDESITE to BASALTIC ANDESITE: unnamed tongue of dense prpl.-rd. flows locally present in SW Lemitar Mts.

Hells Mesa Tuff: 32-33 m.y. (0-500', 152 m outflow; 3000+', 915 m cauldron) ASH-FLOW TUFFS: rhyolite, multiple-flow, simple cooling unit, densely welded, xl.-rich, qtz.-rich, 2-feld., mass. tuffs. Pk. to rd. brn. when fresh, gry. when propyl. altered. Weathers to blocky bldrs. Basal tuffs similar to tuff of Granite Mtn.; abrupt increase in qtz. 10-25 ft above base.

Spears Formation – tuff of Granite Mountain: (0-100', 30 m) ASH-FLOW TUFFS: qtz.-latite, multiple-flow, simple cooling unit, densely welded, xl.-rich, lithic-rich, qtz.-poor, mass. tuffs; rd.-brn. when fresh, dk.-grn.-gry. when propyl. altered.

Spears Formation – volcaniclastic unit: 37-33 m.y. (0-1500', 457 m) CONGLOMERATES, MUDFLOW DEPOSITS, SANDSTONES, LAVAS, and ASH-FLOW TUFFS: volcaniclastic apron of latite to andesite comp., becomes coarser & contains more volc. units up & to south.

Madera Limestone: (500-1500', 152-457m) LIMESTONES: thk., homo. sequence of gry. to blk. micrites w/ a few thn. bds. of med.-crs.-gnd. qtz. ss. Up. 200-300 ft (61-91 m) is rd., grn., & gry. micrites grading up. into arkosic bds. of Abo Fm. Nodular micrites abun. throughout.

Sandia Formation: (550-650', 168-198 m) SHALES, QUARTZITES, and LIMESTONES: gry. to blk., sdy., carb. sh. and siltst. w/ thn. bds. of gry. to brn., med.-crs.-gnd. qtz. ss. (abun. near base) & gry., med.-gnd. micritic ls. (gradational w/ Madera).

Kelly Limestone: (0-90', 27 m) LIMESTONE: lt.-gry., med.-crs.-gnd., thk.-bdd. crinoidal biosparrites.
Caloso Formation: (0-30', 9 m) LIMESTONES and CONGLOMERATES: basal arkosic cgl. overlain by gry., mass., sdy. or pbly. micrites.

Basement: ARGILLITES, QUARTZITES, VOLCANIC and PLUTONIC ROCKS: thk. sequence of low-grade metased. & metavolc. rocks intruded by granitic & gabbroic plutons, & diabase dikes.

FIGURE S37—COMPOSITE STRATIGRAPHIC COLUMN OF THE SOCORRO AREA. Thickness of units not to scale (from Chapin, Chamberlin, and others, 1978, fig. 3, with permission).

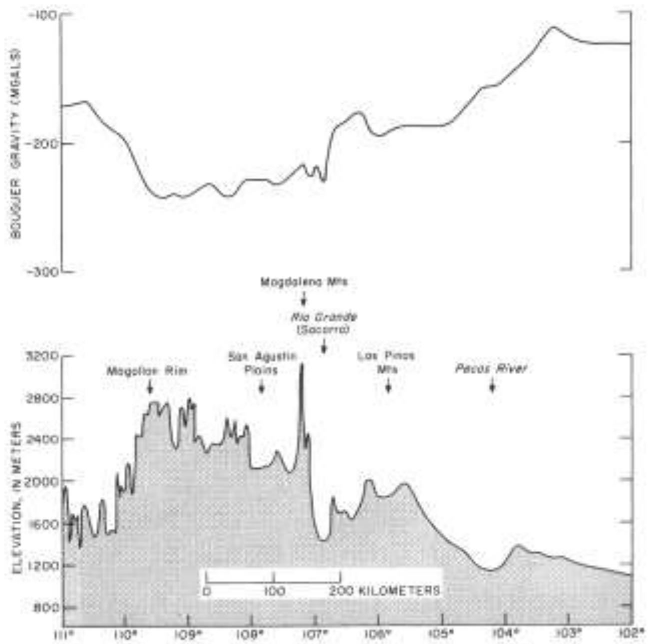


FIGURE S38—GRAVITY AND ELEVATION PROFILES ACROSS NEW MEXICO ALONG 34° NORTH LATITUDE (from Cordell, 1978, with permission).

6.5 Road to left leads to New Mexico Geological Society tour stop described by Chapin, Jahns, and others (1978). 0.1

6.6 Roadcut on left in basalt flow interbedded in red and green claystones of upper Popotosa Formation. 0.4

7.0 Crossing fault contact between upper Popotosa on east and volcanic moat-fill deposits (unit of Luis Lopez) on west. **0.1**

7.1 Bridge over Box Canyon. Entering large roadcut. Light-pink rock on right is a local ash-flow tuff of the moat and contains large rounded clasts of tuff of Lemitar Mountains and various andesites. The pumice is compressed but completely altered to clays that are removed during weathering to form small cavities. An andesite dike (23 m.y.) cuts the tuff at an oblique angle to the road (note slickensides on dike margin). To the west of the dike, red laharic breccias and fanglomerates of the lower Popotosa Formation overlie the ash-flow tuff and rest on andesitic dikes truncated by erosion. 0.3

7.4 Road to Luis Lopez manganese district on left. Andesite plug with steep sheet jointing intrudes moat deposits across Socorro Canyon at 2:30. **0.1**

7.5 Red and green upper Popotosa claystones unconformably overlie red fanglomerates of lower Popotosa in small gullies and cuts at 10:00. **0.1**

7.6 Andesitic dikes and lithic-rich ash-flow tuff unconformably overlain by dark-red Popotosa fanglomerates in cuts to right and left. **0.1**

7.7 Bridge over Six Mile Canyon Arroyo. 0.2

7.9 Road to telephone cable relay station on right. Vent area for late Pliocene (4-m.y.) basalt of Sedillo Hill at 12:30. Basalt flows are underlain by red mudstones of Popotosa Formation (hidden by slump and colluvium) and overlain by piedmont-slope deposits of the Sierra Ladrones Formation shed from the Magdalena range (basalt flows wedge out at 11:30). 0.5

8.4 Note extensive slumping of late Miocene rhyolite flows along south-facing escarpment of Socorro Peak at 3:00. Underlying red claystone is the cause. Silicic dome at 1:00 dated at 9 m.y.; dome on top of Socorro Peak dated at 11 m.y. (Burke and others, 1963). **0.7**

9.1 Ascending Sedillo Hill. Roadcuts on right are in red claystones of upper Popotosa Formation. **0.7**

9.8 Carbonate-cemented fan gravels of the upper Sierra Ladrones Formation (early? Pleistocene) in cut to right. 0.5

10.3 *Curve right at top of Sedillo Hill. Prepare to use turnout by litter barrel on right.* 0.2

10.5 **STOP S11, La Jencia Basin.** *Turn out at crest of Sedillo Hill.* This site is at the south end of La Jencia Basin on a high-level remnant of the piedmont plain extending from the base of the Magdalena Mountains. To the northwest of this point, the plain is cut by late Quaternary piedmont fault scarps. Fig. S40 shows the location of major points of interest and is keyed to the following outline of features west of the Rio Grande:

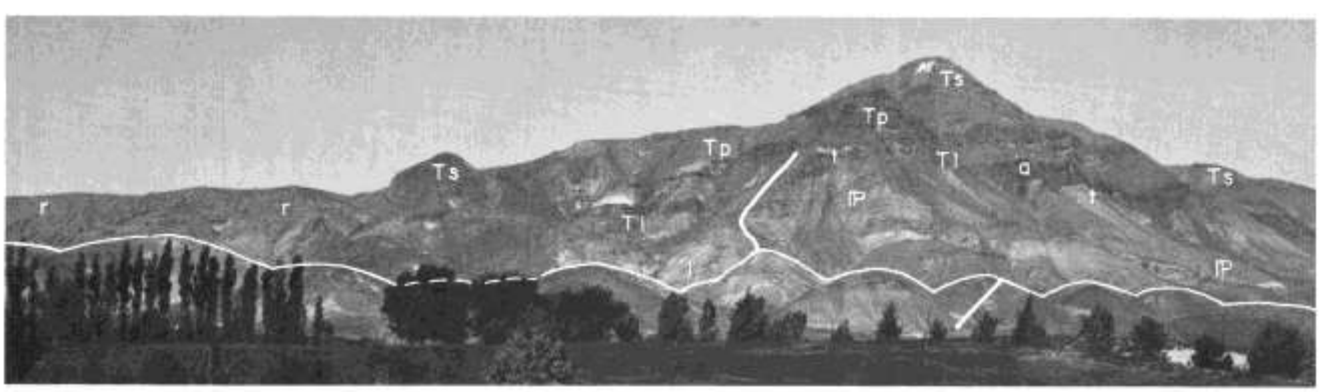


FIGURE S39—LOOKING WEST AT SOCORRO PEAK FROM THE NEW MEXICO INSTITUTE OF MINING AND TECHNOLOGY GOLF COURSE. Socorro Peak is a west-tilted late Miocene intrarift horst that has exposed the northern topographic wall (heavy line) of the Socorro cauldron. The cauldron wall truncates Pennsylvanian limestones and shales (IP) and is buried by late Oligocene moat-fill volcanic rocks (Tl) of the unit of Luis Lopez. A large rhyolite dome (r) north of Blue Canyon probably marks the main ring fracture of the cauldron. Other moat deposits include ancient landslide deposits (l), lithic-rich ash-flow tuffs (t), and andesite flows (a). Moat deposits are unconformably overlain by lower Popotosa fanglomerates (Tp). Rhyodacite to rhyolite intrusive necks and flows (Ts), the upper Miocene rhyolite of Socorro Peak, cut and overlie the Popotosa Formation. The cauldron wall is offset and strata are repeated in the low hills along the base of the escarpment by a major north-trending rift fault zone (light line) (photo by H. L. James; from Chapin, Jahns, and other, 1978, with permission).

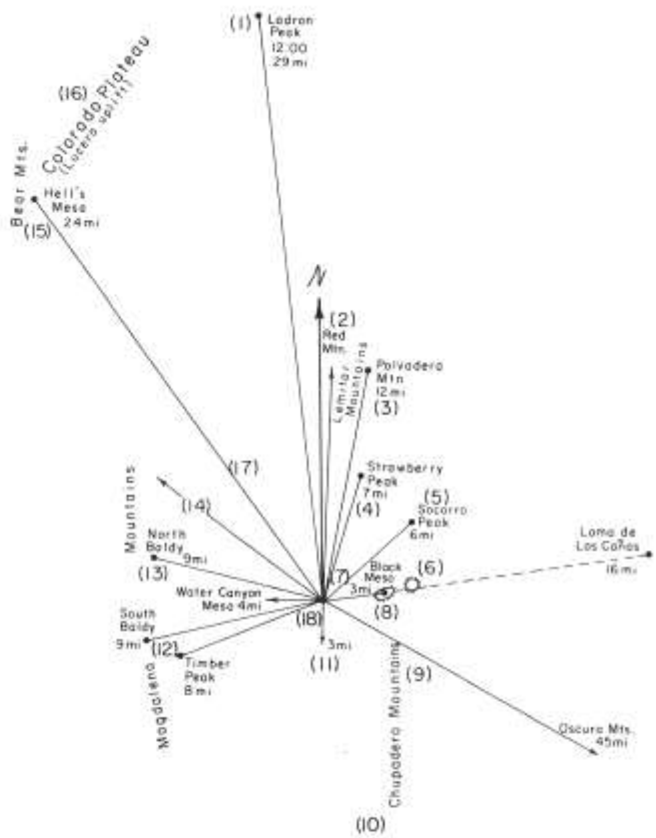


FIGURE S40—PANORAMIC INDEX OF FEATURES SEEN FROM STOP S11, SEDILLO HILL, AT SOUTHERN END OF LA JENCIA BASIN.

1) The peak of the Ladron Mountains on the northern skyline, elevation 9,176 ft (2,797 m), is on Precambrian rocks with upper Paleozoic rocks forming the western slopes of the uplift. Use this peak at 12:00 for orientation in locating the features seen from this stop.

2) Red Mountain at 12:15 is a hogback on the west slope of Lemitar range. Basal fanglomerates of the Popotosa Formation rest on upper Oligocene volcanic rocks and dip about 30 degrees westward into the La Jencia Basin (fig. S41).

3) Polvadera Mountain (peak formed by 32-m.y.-old Hells Mesa Tuff) at 12:30-12:45 is the high point of the Lemitar range. The range was uplifted through 4,000 ft (1,200 m) or more of Popotosa sediments. Field relationships indicate some uplift prior to 12 m.y. ago, with major topographic expression of the uplift, developing between 7 and 4 m.y. ago. Fig. S42 shows, diagrammatically, two stages in the structural evolution of the Lemitar uplift.

4) Just to the right of the Lemitars at 12:45 is Strawberry Peak, an 11.8-m.y.-old rhyodacite dome and remnant flow. The vent is on the southeast side of the peak.

5) At 2:00 rhyolite to rhyodacite flows and domes lead up to Socorro Peak and bury the northern Socorro cauldron margin.

6) Flat-topped beveled dome of 8-m.y.-old rhyodacite, just left of 3:00, is truncated by an early Pliocene erosion surface.

7) Note west dips in 4-m.y.-old basalt of Sedillo Hill at 1:30 in foreground. This flow remnant is north of the transverse shear zone and is being rotated westward with the Socorro Peak block.

8) Basalt on Black Mesa, immediately right of 3:00 and lying on the shear zone, is nearly horizontal.

9) Resurgent dome of Socorro cauldron at the north end of the Chupadera Mountains at 4:00-5:00.

10) Basalt correlative with the Sedillo Hill unit caps high mesas at 5:30 on west flank of Chupadera Mountains.

11) From 6:00-8:30 a field of east-tilted blocks of upper Miocene rhyolite lavas equivalent to those on Socorro Peak forms the eastern foothills of the Magdalena range.

12) Timber Peak-South Baldy-South Canyon area of the Magdalenas at 8:30-9:00 is west of Socorro cauldron margin and along the north margin of the Sawmill Canyon cauldron.

13) North Baldy area of Magdalenas and margin of North Baldy cauldron is at 9:30-10:00 on the skyline beyond the mouth of Water Canyon. The light-colored rocks just south of North Baldy are hydro-thermally altered Hells Mesa Tuff abutting against the

FIGURE S41—VIEW OF LEMITAR MOUNTAINS LOOKING NORTHWEST FROM TOP OF SOCORRO PEAK. Strawberry Peak at left, Ladron Peak at right rear, and Colorado Plateau on horizon. Hogback at right center is vertical A-L Peak Tuff. Oligocene volcanic rocks in Lemitar Mountains dip westward at 30-90 degrees into La Jencia Basin. Geologic sections in fig. S42 illustrate structural evolution of the Lemitar uplift.

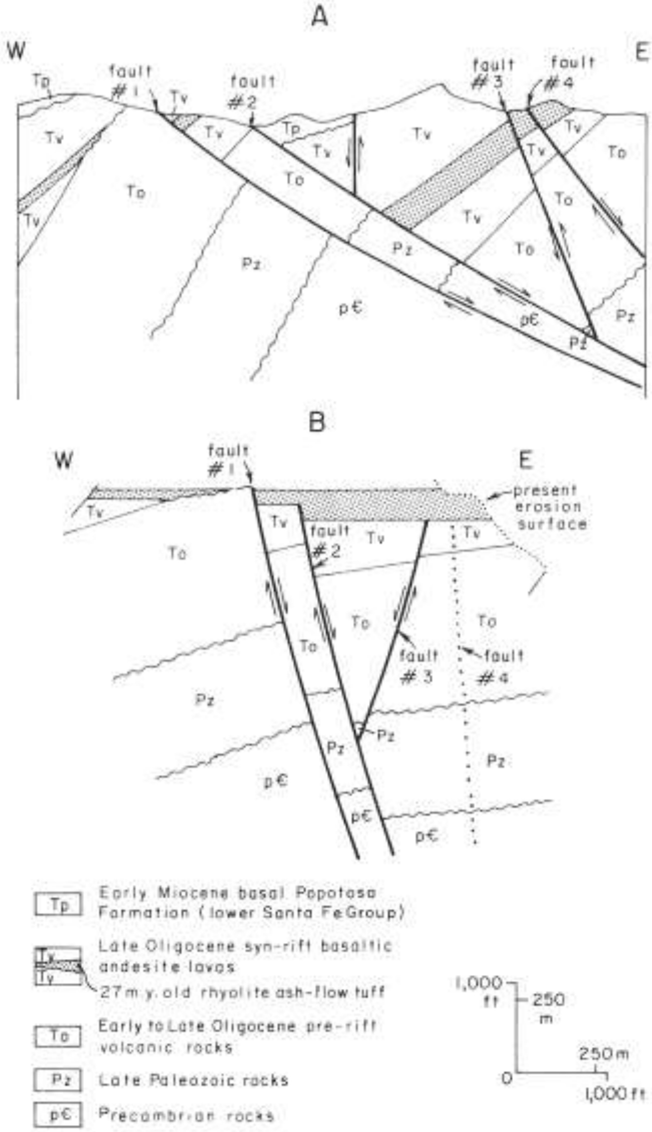


FIGURE S42—GEOLOGIC CROSS SECTIONS OF A KEY AREA IN THE WEST-CENTRAL LEMITAR MOUNTAINS. Together the sections illustrate the progressive nature of normal faulting (rifting) and concurrent block tilting through time; the sections also show that rifting had begun prior to 27 m.y. ago along closely spaced high-angle normal faults dominantly downthrown to the east. Section **A** is a present-day cross section illustrating the structural pattern typical of the entire range, which consists of an association of major displacement, downthrown-to-the-east, low-angle normal faults (#1 and #2) repeating steep 45-60°) west-dipping Oligocene volcanic strata. A few minor displacement high-angle reverse faults downthrown-to-the-west, such as #3, are associated with the steeply dipping strata. Angular discordances within formations and thickness changes across faults all indicate that rifting occurred contemporaneously with volcanism and later sedimentation (that is, rift faults are commonly growth faults). **B** is the same section as **A** reconstructed to the time immediately after eruption of a 27-m.y.-old rhyolite ash-flow tuff (tuff of Lemitar Mountains, which was erupted from the Socorro cauldron about 9 mi to the south). The ash-flow sheet forms a key structural datum within a thick pile of basaltic-andesite lavas. Low-angle normal faults of section **A** were originally high-angle normal faults, and fault #3 was originally a minor antithetic normal fault. Field relationships and K-Ar dating of volcanic strata provide evidence for the progressive (continuous but at varying rates) nature of rifting along three successive generations of normal faults dominantly downthrown-to-the-east. Low-angle normal faults (#1 and #2) have been inactive since about 20 m.y. ago. Moderately dipping-normal faults such as #4 were active about 12-7 m.y. ago and rifting is continuing on high-angle normal-faults (not shown) cutting Pliocene and Pleistocene strata along the east boundary of the Lemitar Range (section courtesy of R. M. Chamberlin).

topographic wall of the cauldron. Mudflow deposits of andesitic debris are interbedded in the Hells Mesa Tuff at this locality.

14) Precambrian rocks are exposed along the northeastern front of the Magdalena range from 10:00-10:30.

15) Bear Mountains at 10:45-11:00 form the northwest border of La Jencia Basin. Hells Mesa overlooking the Rio Salado Valley forms the prominent peak at the north end of the Bear range.

16) High mesas (including Sierra Lucero) of the southeastern Colorado Plateau margin are on the distant skyline at 11:00-11:30, northwest of Ladron Peak.

17) A COCORP (Consortium for Continental Reflection Profiling) seismic profile from east of Magdalena to Sedillo Hill closely parallels US-60 in the basin northwest of this stop. The profile indicates a structurally complex sub-fill basin floor.

18) A shallow magma body appears to underlie this tour stop at a depth of about 5 km (Sanford, this guidebook).

Looking east of the Rio Grande through the gap between Socorro Peak and Black Mesa, Abo Pass is at 2:30 on the far skyline between the Manzano range (north) and Los Pinos Mountains (south). South of Black Mesa, Chupadera Mesa is on the distant skyline at 3:30. Slopes east of these uplifts (Sacramento section of the Basin and Range physiographic province) are transitional to the Great Plains province-Pecos Valley section. The lower chain of mesa, cuestas, and hills from 2:30-4:00 (just east of the river valley) composes the Loma de las Canas uplift. These highlands form the eastern border zone of the rift. They are composed mostly of complexly faulted upper Paleozoic rocks, capped by the San Andres and Yeso Formations. The Mesozoic-lower Tertiary section and at least 2,000 ft (600 m) of Oligocene volcanic rocks have been stripped by erosion associated with uplift of the blocks. Thick sections of Mesozoic and lower Tertiary sedimentary rocks are preserved only in downfaulted blocks in the Carthage area (4:00) and on the eastern flank of the Joyita Hills (2:30). The east side of the Rio Grande rift is structurally higher than the west side through most of its length.

High ranges visible to the southeast beyond the northern end of the Jornada del Muerto Basin include Sierra Oscura at 3:45-4:15 beyond Cerro Colorado and the northern San Andres Mountains at approximately 5:00. If you had been standing here at 5:29 a.m. on July 16, 1945, you would have seen the blinding flash of light and the mushroom cloud from the first atomic bomb detonated at Trinity site at the base of the Oscura Mountains. *Retrace route to Socorro. 0.1*

10.6 Descending Sedillo Hill into Socorro Canyon. Panoramic view ahead across the Rio Grande Valley. 0.7

11.3 Los Pinos Mountains (east of Stop S13) at 11:30 through gap between Socorro Peak and basalt-capped Black Mesa in foreground (12:00). 0.8

12.1 Good view of extensive slumping on Popotosa claystone on slopes of Black Mesa ahead and on south-facing escarpment of Socorro Peak to left. 0.6

12.7 From 12:00-1:00 note north dip of dark reddish-brown volcanic rocks off resurgent dome of the Socorro cauldron. From 12:00-1:00 gentle northerly slope of ridge reflects exhumed late Oligocene to early Miocene erosion surface once buried by basal Popotosa mudflows. **1.1**

13.8 Box Canyon to right. 2.2

16.0 Route continues northeast on alluvial terrace surface of late Pleistocene age. The high-level erosion surface to right is cut on sand to clay of the Sierra Ladrones Formation and is capped with a thin veneer of middle(?) Pleistocene piedmont gravels bearing a strong soil. About 1.4 mi east of here (mile 17.4), this surface is downfaulted at least 100 ft (30 m) across a zone of piedmont fault scarps that extends south-southeast from the base of Socorro Peak to near San Antonio (mile 240.3, E1 Paso to Socorro log). The offset of the upper Pleistocene terrace gravels, on which the highway is located, is less than 10 ft (3 m). Holocene gravel exposed in arroyo walls north of the terrace fill is not deformed (Sanford and others, 1972). **0.9**

16.9 Good view to north of Socorro Peak at 10:30 and late Miocene, post-cauldron volcanic domes in moat of Socorro cauldron. Perlite is being mined from one such dome seen through gap west of basalt-capped ridge (with water tank) to left. Note tilting and step faulting of basalt along this ridge. **0.5**

17.4 Crossing late Quaternary fault scarp (see mile 16.0). **0.9**

18.3 Grefco perlite mine road to left. At 11:30 the Rio Grande enters Socorro Valley through a gap in the basalt flow east of San Acacia and southeast of Stop S12. Abo Pass on the skyline at 12:15 is between the Manzano (north) and Los Pinos Mountains and is east of Stop S13. **0.6**

18.9 Passing Stop S10, site at National Guard Armory. **1.1**

20.0 Railroad crossing. *Stay in right lane.* **0.3**

20.3 Intersection; *bear right on US-60 and Spring Street.* **0.5**

20.8 Stop sign, junction US-60-US-85 at Spring and California Streets. *Turn right on US-85 (Business 1-25); continue south to 1-25 interchange.* **0.2**

21.0 Railroad crossing. *Stay in left lane for approach to 1-25 North.* **0.6**

21.6 *Continue straight on approach ramp* for 1-25 North (Albuquerque). The route ahead crosses overpass and then loops from south to north on low fan-terrace surface bordering the floodplain. **0.5**

22.1 *Merge with 1-25 northbound.* **1.3**

23.4 Milepost 149. Historic downtown Socorro on left; see mile 249.0 entry in E1 Paso to Socorro road log. "Anthony, Tortugas," and Santa Fe Railroad (tracks first laid in 1881) to right. Analyses of 1909-1952 level-line data for this segment of the Santa Fe route indicates that a significant amount of deep-seated differential upwarping is occurring in the Socorro-San Acacia (Stops S10-S12) area (Reilinger and Oliver, 1976; Sanford, this guidebook). **1.3**

24.7 Underpass; *continue straight on 1-25* across Rio Grande floodplain. North Socorro exit to right. Entries from here to the Socorro-Valencia County line (mile 73.6) are compiled in part from logs by Foster and Luce (1963, p. 6-14). 0.5

25.2 Milepost 151. Socorro Peak at 9:00; Strawberry Peak at 9:30; Polvadera Mountain at 11:00 in the Lemitar range; and Ladron Mountains at 11:30. The low ridges north of Strawberry Peak are capped by basal Popotosa fanglomerates. **1.0**

26.2 Milepost 152 at flood-control canal crossing. **0.3**

26.5 Escondida overpass. Route ascends from valley floor onto remnants of older basin- and valley-fill alluvium. Erosion remnants of upper Santa Fe Group basin fill (Sierra Ladrones Formation of Machette, 1978) are capped with discontinuous mantles of post-Santa Fe valley-fill units. Roadcuts and arroyo-valley exposures ahead show complex intertonguing of piedmont and axial river (fluvial) facies in both the Sierra Ladrones Formation and the post-Santa Fe units of middle to late Quaternary age. As is observed in the Socorro Canyon-San Antonio area (Stop S10 and mile 16.0 entries), piedmont and valley-border surfaces in this area have been offset by faults as young as late Quaternary. **1.4**

27.9 Valley of Arroyo de la Parida east of the river at 3:00. Reddish fan gravels to fanglomerates (derived in part from Permian red beds in the Loma de las Canas uplift) interfinger westward with finer grained distal-piedmont to basin-floor facies that include tongues of gray pebbly sands deposited by the ancestral river. The sequence comprises the eastern piedmont and fluvial facies of the Sierra Ladrones Formation; intertonguing relationships were first described by DeBrine and others (1963). Vertebrate fossils collected from fluvial sands in the south bluff of the arroyo valley are of Blancan provincial age (mid-Pliocene to early Pleistocene, chart 1). The sparse fauna was originally described by Needham (1936). According to Bachman and Mehnert (1978, p. 288), the basal fluvial sand zone in the Arroyo de la Parida exposures rises "85 m [280 ft] in altitude northward over a distance of about 11 km [7 mi] along the east side of the Rio Grande, representing a gradient of about 7.7 m/km [about 40 ft/mi], compared with the existing gradient of about 1.0 m/km [about 5 ft/mi]." This upwarped part of the upper Santa Fe sequence extends north almost to San Acacia and coincides with the area where the preliminary studies of railroad level-line data by Reilinger and Oliver (1976) indicate high **(4-6** mm/yr) rates of present uplift. **0.7**

28.6 Crossing large arroyo; route for next 10 mi is on upper Pleistocene and Holocene fill associated with younger valley-border surfaces. **1.8**

30.4 Overpass, Lemitar-Polvadera interchange. **0.8**

31.2 Milepost 157. The east slope of the Lemitar Mountains at 9:00-10:30 includes Precambrian granites, schists, pegmatites, and diabase dikes. Just below the high point of the range, Polvadera Mountain, Pennsylvanian (Madera) limestones are in fault contact with Precambrian rocks. Near the south end of the range Mississippian and Pennsylvanian rocks overlie the Precambrian. The peak is formed on Oligocene volcanic rocks (rhyolite ash-flow tuffs and andesite flows) that overlie the Pennsylvanian and in places the Precambrian. The southern and northern ends of the range are overlapped by Santa Fe beds, including fanglomerate and playa mudstone facies of the Popotosa Formation (Miocene) and piedmont gravel and fluvial sand facies of the Sierra Ladrones Formation. **1.0**

32.2 Milepost 158. Gravel pits on right in Wisconsinan river-terrace deposits. Mastodon teeth have been collected from one of the pits by R. H. Weber. The low Joyita Hills, at 1:30 on the east border of the valley, are a complex fault block of Precambrian, upper Paleozoic, and lower to middle Tertiary rocks (Foster and Kottlowski, 1963). The Tertiary sequence includes a thin conglomerate of the Baca Formation (Eocene), which rests on an erosion surface cut nearly through the Triassic beds, and a thick sequence of Oligocene andesitic to rhyolitic volcanic rocks. Ash-flow tuffs derived from areas west of the rift are found east of the Joyita Hills (see Stop S13). **1.0**

33.2 Milepost 159. Light reddish-brown hills at north end of Lemitar Mountains (9:00-10:00) are formed on Popotosa fanglomerates. Lower hills in foreground are dissected piedmont facies of the Sierra Ladrones Formation (upper Santa Fe). **2.0**

35.2 Crossing San Lorenzo Arroyo at milepost 161. Ladron Mountains at 10:30 with Precambrian rocks (granite, gneiss, quartzite, and schist) forming the east face and peak of the uplift. **1.0**

36.2 Milepost 162. Back on river floodplain. Dark-reddish-brown hills at 9:00 are Cerritos de las Minas. They are formed on 26-m.y.-old basaltic andesite correlated with the La Jara Peak andesite (Machette, 1978b). The route ahead enters San Acacia quadrangle, first mapped by Denny (1940, 1941) and site of recent studies by Machette (1978b and this guidebook). **1.0**

37.2 Milepost 163. San Acacia underpass. **0.2**

37.4 Loma Blanca at 9:00 is rounded hill formed on sandy fluvial beds of the Sierra Ladrones Formation. The San Acacia constriction of the Rio Grande at 3:00 is cut into basal, basin-floor facies of the Sierra Ladrones Formation capped by basaltic (early Pliocene) andesite. These units are discussed at Stop S12. **0.8**

38.2 Milepost 164. Ascending from river-valley floor to low valley-border surface of late Pleistocene (Wisconsinan) age. This surface is formed mainly on thin fan deposits of the Rio Salado; these deposits bury an erosion surface cut on the lower piedmont facies of the Sierra Ladrones Formation. Denny (1941) mapped this surface as his Cañada Mariana pediment; he designated the slightly higher graded surface west of the highway at milepost 165 as Valle de Parida. Surfaces and surficial deposits are discussed by Machette at Stop S12. **1.8**

40.0 Crossing Rio Salado. Rest area and Stop S12 ahead on right. **0.6**

40.6 *Take rest area exit.* **0.2**

40.8 **STOP S12, Rio Salado rest area.** *Walk northeast of picnic area about 0.3 mi* to crest of dune-covered ridge for a view of the northern Socorro segment of the rift and the southern Albuquerque-Belen (or Albuquerque) Basin (figs. S43 and S44). From here north to Stop S20, about 20 mi west of Santa Fe, the tour route crosses an area recently mapped by Kelley (1977, scale 1:190,000). The area from here to south edge of Albuquerque is also included in the Socorro 2° sheet just compiled by Machette (1978c). The immediate area is covered by the new geologic map of the San Acacia quadrangle by Machette (1978b). Fig. S44 shows the location of major points of interest and is keyed to the following outline. Use 1-25 North as 12:00 for clock orientation of features seen from this stop:

1) Basaltic andesite of San Acacia in foreground at 6:00 has been dated at 4.5 m.y. (Bachman and Mehnert, 1978, no. 21). The flows are interbedded with the basal part of the Sierra Ladrones Formation. The gap in the andesite-capped bluffs through which the river flows is the narrowest segment of the inner Rio Grande Valley between White Rock Canyon (north of Stop S20) and Elephant Butte Dam (Stop S7b).

2) On skyline at 6:00 are east-dipping hogbacks of the Chupadera Mountains south of the transverse shear zone discussed at Stops S10 and S11.

3) Socorro Peak at 6:30 is capped by west-dipping silicic domes and flows of late Miocene (7-12 m.y.) age. The peak forms the north edge of Socorro caldera (Stop S10).

4) Strawberry Peak, at 6:45, is an 11.8-m.y.-old rhyodacite dome.

5) Polvadera Mountain at 7:00 is the high point of the Lemitar range. It is a west-tilted fault-block uplift north of the transverse shear zone. The east-facing escarpment of Precambrian and upper Paleozoic rocks is capped, in ascending order, by Spears volcaniclastic rocks and Hells Mesa and A-L Peak Tuffs, all of Oligocene age. Note smooth piedmont-slope grading east from the Lemitars to low (upper Quaternary) terraces and arroyo fans of the inner river valley. Absence of a prominent stepped sequence of older valley-border surfaces may reflect relatively recent downwarping of the Lemitar piedmont area. However, the terrain may simply reflect dominance of erosional processes in an area both underlain by sandy Sierra Ladrones fluvial deposits and located in a persistent topographic low between large fan complexes constructed by streams heading in the La Jencia Basin area north and south of the Lemitar Mountains.

6) Magdalena Mountains on skyline from 6:45-8:00. The transverse shear crosses the highest peak, South Baldy, just to right of Polvadera Mountain. South Baldy is along the north margin of Sawmill Canyon cauldron. North Baldy, the small point on the uniform crest of the northern Magdalena range, is on the north edge of North Baldy cauldron.

7) Dark ridges on skyline in the northern Lemitars from 8:00-9:00 are west-tilted Oligocene volcanic rocks and Miocene early-rift sedimentary rocks.

8) Long light-colored ridge (north-northwest trending) in foreground at 8:00-9:00 is Loma Blanca. This hill is an erosion remnant of east-dipping fluvial sand facies of the Sierra Ladrones Formation.

9) Large valley of Rio Salado, in the foreground at 9:00, drains a large area of the Datil physiographic section that is a transitional area between the Colorado Plateau and Basin and Range provinces (Hawley and others, 1976).

10) Bear Mountains, on skyline at 9:00, are another west-tilted fault-block uplift. This range is capped by

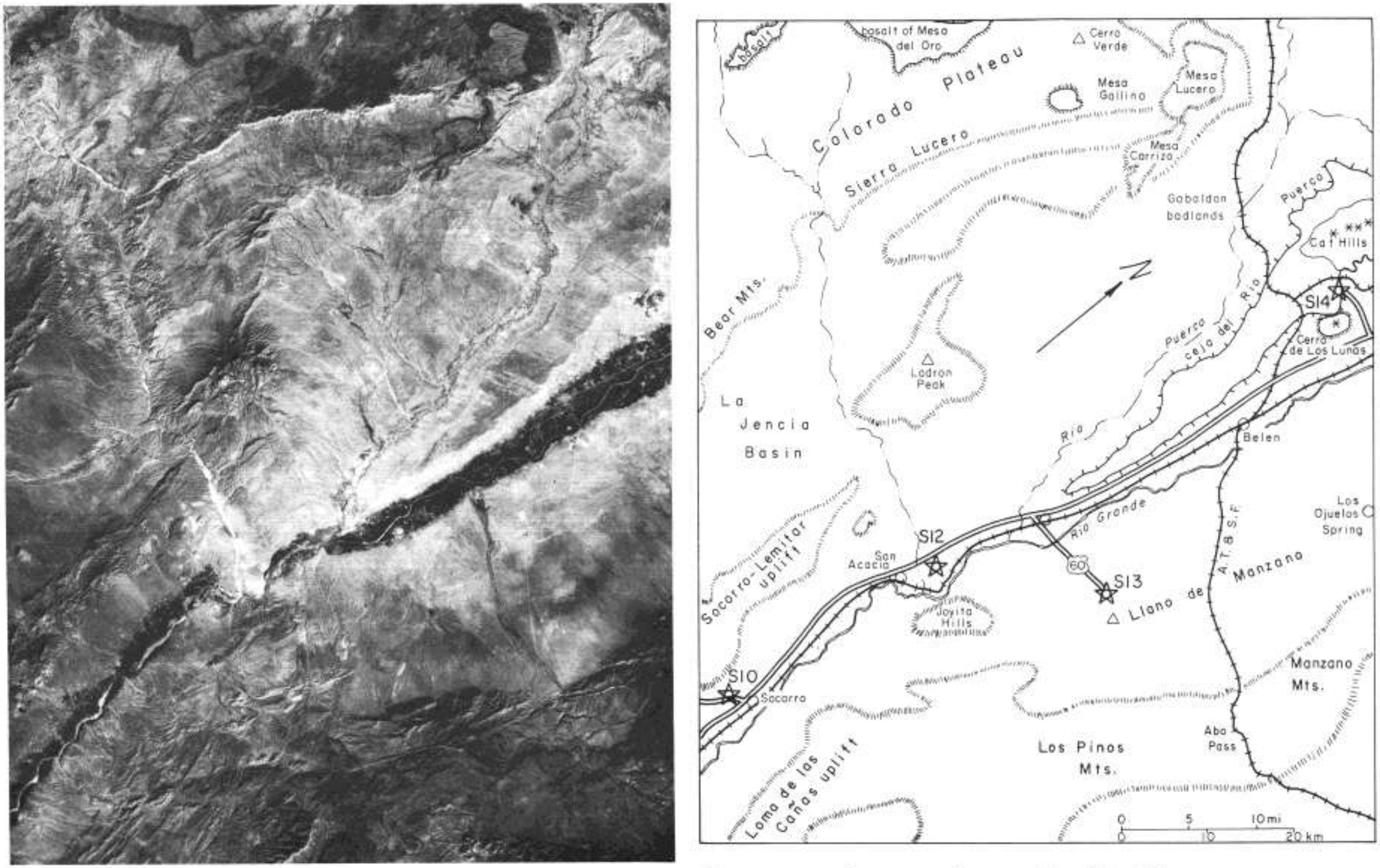


FIGURE S43—SKYLAB-3 PHOTO (a) AND INDEX MAP (b) OF THE NORTHERN SOCORRO-SOUTHERN ALBUQUERQUE BASIN AREA, STOPS S12 TO S14 (photo SL3-85-018 courtesy of Technology Application Center, University of New Mexico; photo scale approximately same as map scale).

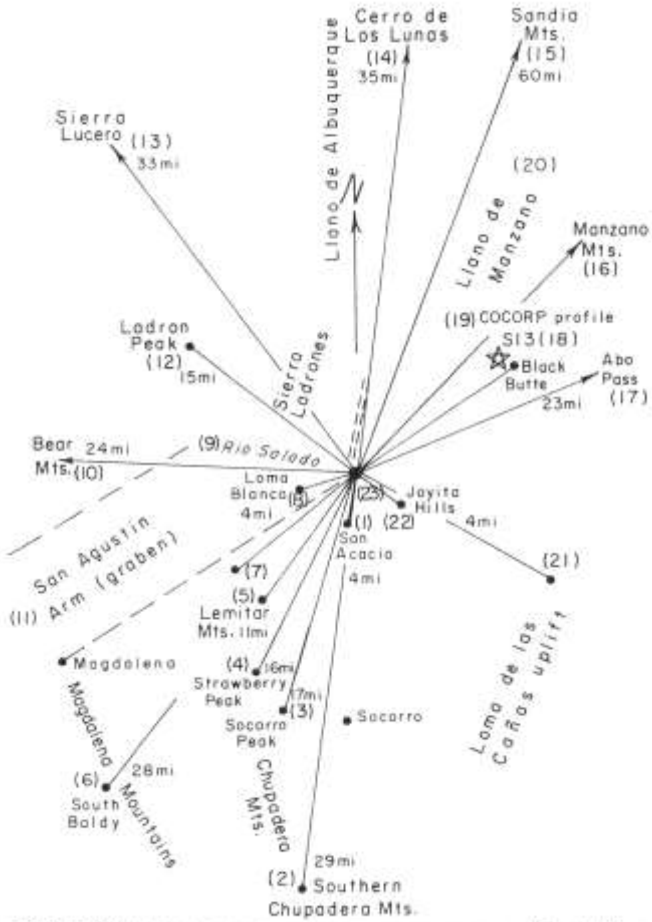


FIGURE S44—Panoramic index of features seen from Stop S12 at Rio Salado rest area, near San Acacia.

about 1,200 ft (360 m) of late Oligocene-early Miocene basaltic andesites erupted from an early rift-dike swarm.

11) The regional view to the southwest (8:00-9:00) is down the San Agustin arm of the rift. Paleozoic and Precambrian rocks are truncated by a major, northeast-trending fault at 8:00 on the north flank of Polvadera Mountain. These units are also truncated along the south flank of the Ladron Mountains (10:00). Between the two uplifts is a graben, about 6 mi (10 km) wide, that forms the type area of the Popotosa Formation (Denny, 1940). The low area between the north end of the Magdalenas (8:30) and the south end of the Bear Mountains (8:45) reflects a similar graben to the west.

12) Ladron Mountains at 10:00, with peak elevation of 9,176 ft (2,797 m). Precambrian rocks form the eastern slopes and crest of the mountains. Upper Paleozoic rocks form a dip slope along the west side of the uplift at the southeast corner of the Colorado Plateau. The Sierra Ladrones are low foothills on the southeast side of the Ladrons. They are formed on upper Santa Fe Group basin fill (type Sierra Ladrones Formation) in fault contact with the lower Santa Fe-Popotosa Formations.

13) The Lucero uplift, low on the skyline at 10:30, forms the eastern edge of the Colorado Plateau.

14) Looking beyond the notch formed by 1-25, cut at 12:00. Cerro de las Lunas volcano (Stop S14) is just visible on the far skyline. The southern prong of the Llano de Albuquerque extends south from Los Lunas volcano as a high-level 360-ft (110-m) mesa remnant between the valleys of the Rio Grande (east) and Rio Puerco (west). The confluence of the two rivers is about 6 mi (10 km) northeast of this stop.

15) The distant Sandia Mountains at 12:15 (Stops S16-S18) are a rift-bounding uplift that forms the east side of the northern Albuquerque Basin.

16) The Manzano Mountains at 1:00 to 2:00 (Stops S13, S14, and S16) form the eastern border of the central Albuquerque Basin.

17) Abo Pass at 2:00 is located between the Manzano range and the Los Pinos Mountains to the south. The structurally high Sandia-Manzano-Los Pinos chain includes a series of blocks of Precambrian rocks capped with upper Paleozoic sedimentary sequences. Laramide structures are prominently displayed in these eastward-tilted uplifts.

18) The dark butte at 2:00 on the distal part of the piedmont slope (upper Llano de Manzano surface) extending out from the Los Pinos front is Black Butte or Turututu (just east of Stop S13). This small fault block of Oligocene-early Miocene rhyolitic ash-flow tuffs derived from cauldrons in the Socorro-Magdalena area is capped by a 24-m.y.-old basaltic-andesite flow (Bachman and Mehnert, 1978, no. 19).

19) COCORP seismic reflection profiles extend across the rift from Abo Pass to north of the Ladron Mountains, crossing the Llano de Manzano, the piedmont slope north of Turututu, and the Rio Grande and lower Puerco Valleys near Bernardo (Oliver and Kaufman, 1976; Sanford, this guidebook).

20) The Llano de Manzano piedmont surface at 12:30-2:00 grades to a level about 260 ft (80 m) above the present Rio Grande floodplain. Machette (this stop) estimates that the surface stabilized and soil formation commenced about 280,000 years ago.

21) High mesas on the skyline at 3:00-4:00 are upper Paleozoic rocks capped by the Permian San Andres-Yeso-Abo sequence. As is noted at Stop S11, the east side of the Rio Grande rift is persistently higher structurally than the west side.

22) The low hilly bedrock terrain just east of the river valley at 2:45-4:00 comprises the Joyita Hills (mile 32.2). The west-tilted hogbacks of Precambrian to lower Miocene rocks reflect the location of the uplift north of the transverse shear zone. A very complete section of Oligocene volcanic rocks derived from Socorro-Magdalena centers forms the ridges on the east side of the uplift. Ridges in the Joyita Hills are capped by thin gravelly pediment veneers. Note the apparent upwarp of the southern extension of the Llano de Manzano surface as the Joyita Hills are approached. Northward upwarp of fluvial beds of the Sierra Ladrones Formation from the Arroyo de la Parida toward San Acacia has already been noted (mile 27.9; Bachman and Mehnert, 1978, p. 288).

23) In the foreground at 3:00 is the zone of modern uplift in the Socorro vicinity that is inferred from interpretations of railroad level-line data by Reilinger and Oliver (1976). Warping of young basin-fill and valley-border surfaces discussed above, as well as uplift and dissection of the Joyita Hills, may be related to the inferred modern uplift.

LATE CENOZOIC GEOLOGY OF THE SAN ACACIA-BERNARDO AREA

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The southern part of the Albuquerque-Belen Basin contains a well-exposed section of the Santa Fe Group (volcanic and sedimentary rocks of late Tertiary age), as well as older Tertiary volcanic rocks (Stops S10 and S11). The Santa Fe Group in the southern part of the Albuquerque-Belen Basin consists of the Popotosa and Sierra Ladrones Formations (Machette, 1978b). West of San Acacia (fig. S45), the basal part of the Popotosa Formation (Miocene) is interbedded with a locally derived, 26-m.y.-old andesite (Machette, 1978b). In this area the exposed eastern margin of the Popotosa Formation is in fault contact with younger rocks of the Sierra Ladrones Formation (Pliocene and Pleistocene).

The Popotosa Formation consists of well-indurated, grayish- to reddish-brown fanglomerates, locally derived breccias and mudflows, finer grained lithic sandstones, and gypsiferous playa deposits. Immediately south and east of the Ladron Mountains the fanglomerates of the Popotosa are composed mainly of clasts of Precambrian igneous and metamorphic rocks and lower Paleozoic sedimentary rocks. Farther south, west, and immediately to the north, the Popotosa is largely volcaniclastic. The Popotosa is at least 6,500 ft (2,000 m) thick west of San Acacia and may thicken considerably towards its source areas. The Popotosa Formation and older volcanic rocks are extensively faulted; locally they have dips of up to 60 degrees.

About 8 mi (13 km) west of San Acacia, the Sierra Ladrones Formation rests unconformably on Popotosa and older units; to the north, in the central part of the basin, these two formations probably constitute a continuous depositional sequence.

The Sierra Ladrones Formation consists of locally derived piedmont-slope and alluvial-fan sediments, as well as alluvial floodplain and axial-channel deposits of the ancestral Rio Grande. Near San Acacia, a 4.5-m.y.-old basaltic andesite is interbedded with fine-grained deposits of the lowest exposed part of the Sierra Ladrones Formation (Machette, 1978b). The uplifted, eastern part of the formation (early Pliocene at the surface) is nearly horizontal, whereas the western part includes sections with dips of up to 30 degrees. Most of the structure along the western flank of the Sierra Ladrones (foothills east of the Ladron Mountains) is associated with apparent low-angle (less than 45 degrees) extensional faulting of late Pliocene or Pleistocene age. The youngest beds of the Santa Fe Group are not present here. Near Bernardo, about 9 mi (15 km) to the north, younger beds of the Santa Fe Group form the Llano de Albuquerque, a constructional surface about 0.5 m.y. old (Hawley and others, 1976).

The oldest post-Santa Fe Group geomorphic feature in the southern end of the Albuquerque-Belen Basin is the Cliff surface (Bachman and Machette, 1977), an erosional surface cut on the Sierra Ladrones Formation. This surface probably represents the western margin of a middle Pleistocene paleohill (fig. S45). Using rates of pedogenic calcium-carbonate accumulation established for this region (Bachman and Machette, 1977), I estimate that the Cliff surface was formed about 440,000 years ago (table S1).

The Cliff surface is cut by the Cliff fault (fig. S46), a north-trending, west-dipping normal fault. This fault cuts the Pliocene part of the Sierra Ladrones Formation and places fine-grained, floodplain deposits on the west side against coarse-grained, stratigraphically lower, piedmont-slope deposits. These deposits have at least 100 ft (30 m) of vertical separation along the fault.

The next younger geomorphic surface in the southern part of the Albuquerque-Belen Basin is the Llano de Manzano. This surface was graded to a terrace level of the Rio Grande; a remnant of the terrace is preserved at the Volcano Cliffs, west of Albuquerque. Based on the carbonate content of relict soils developed on the Llano de Manzano, the terrace is estimated to have formed about 280,000 years B.P. To the southeast three major river terraces occur along the Rio Salado (fig. S45). The oldest terrace records the first contribution of Rio Salado sediments to the modern (that is, late Pleistocene) Rio Grande system about 220,000 years B.P. (Qt_1 fig. S46; Qag of Machette, 1978b). The youngest of the three terraces (Qt_2, fig. S46; Qae of Machette, 1978b) formed about 120,000 years B.P. (table S1).

The Cliff surface is characterized by strongly developed relict soil. Near the fault (fig. S46) the relict soil is composed of an upper and a lower soil separated by a thin wedge of colluvial deposits. Based on its carbonate content, the buried soil is believed to have formed between 440,000 years B.P. and 140,000 years B.P., a duration of 300,000 years (table S1). The upper soil is less well developed and, based on its carbonate content, has formed during the past 140,000 years.

Activity along the Cliff fault probably resulted in deposition of the colluvial apron as older sediments were eroded from the upthrown (eastern) block (fig. S46). The Cliff fault displaces the Qt_1 terrace (220,000 years B.P.) about 20 ft (6 m), but does not displace the Qt2 terrace (120,000 years B.P.). Although the Cliff fault probably has been recurrently active in Pliocene and Pleistocene time, the most recent activity occurred between 220,000 and 120,000 years B.P. If my interpretation of the soils of the Cliff and colluvium is correct, the most recent activity may be more accurately placed at about 140,000 years B.P.

About 3 mi (5 km) to the west of this stop, the Loma Blanca fault (Machette, 1978b) displaces Qt2 terrace deposits, with the east side downdropped about 20 ft (6 m). Directly to the northwest of this stop, along the eastern front of the Ladron

TABLE S1—ESTIMATED AGES OF SOME SOILS ON VARIOUS GEOMORPHIC SURFACES IN THE ALBUQUERQUE-BELEN BASIN, based on content of pedogenic calcium carbonate; * indicates that soil-age estimates are based on 124 g/cm² of calcium carbonate in the relict soil of the Llano de Albuquerque surface. A constant accumulation rate of 0.25 $g \cdot cm^{-2} \cdot kyr^{-1}$ is assumed.

Soil and associated geomorphic surface	Pedogenic carbonate content (g/cm² of soil column)	Estimated soil age (years)
Relict soil, Llano de Albuquerque	*98-124 (110 ave.)	*500,000
Relict soil, Llano de Manzano	65-75 (70 ave.)	280,000
Composite soil, Cliff surface	110	440,000
Upper soil, Cliff surface	35	140,000
Lower soil, Cliff surface	75	300,000
Relict soil, Qt_1 (upper terrace: Qag)	55	220,000
Relict soil, Qt_2 (lower terrace: Qae)	30	120,000

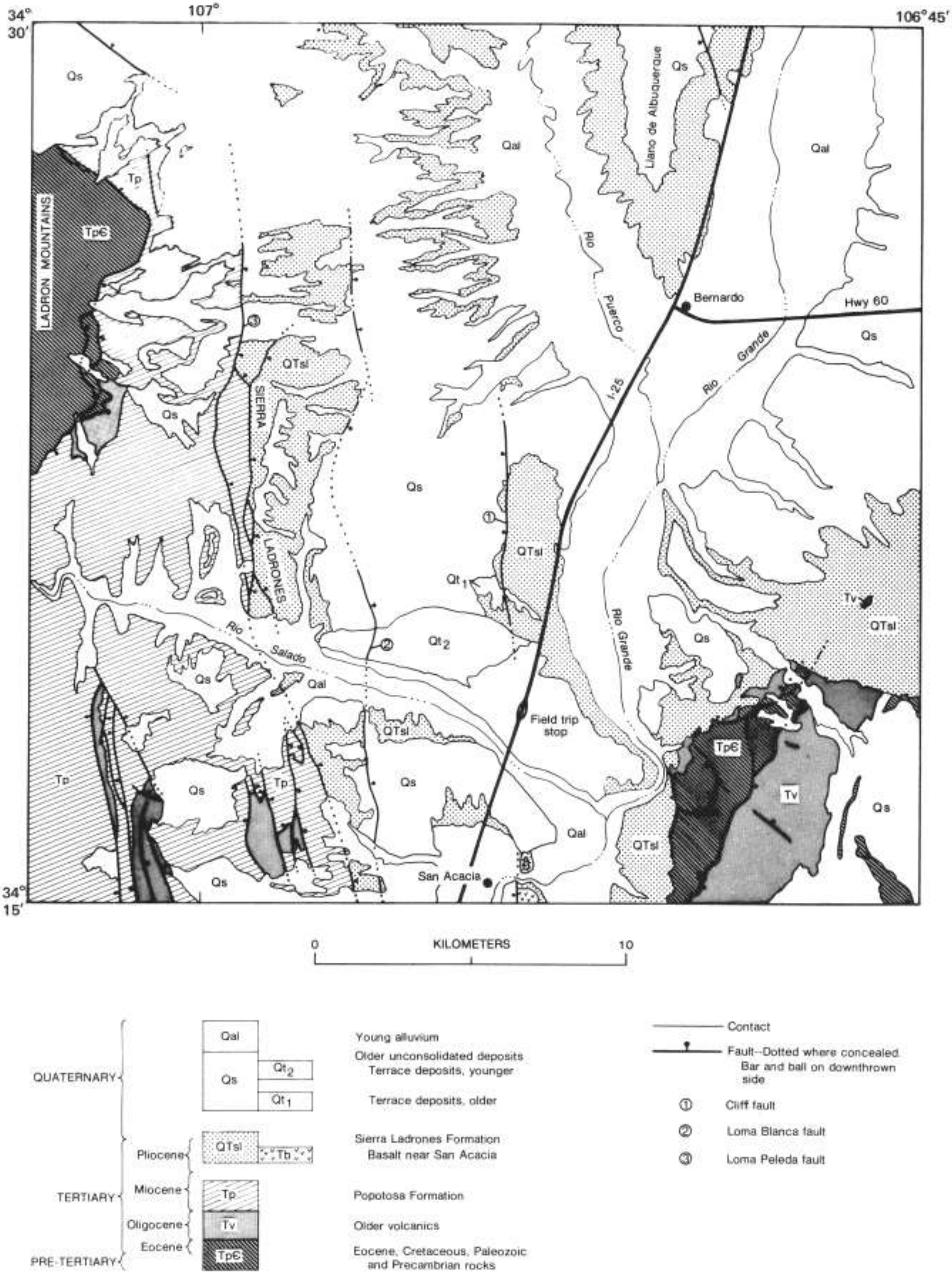


FIGURE S45—GENERALIZED GEOLOGIC MAP OF THE SOUTHWESTERN END OF THE ALBUQUERQUE BASIN FROM BERNARDO TO SAN ACACIA.

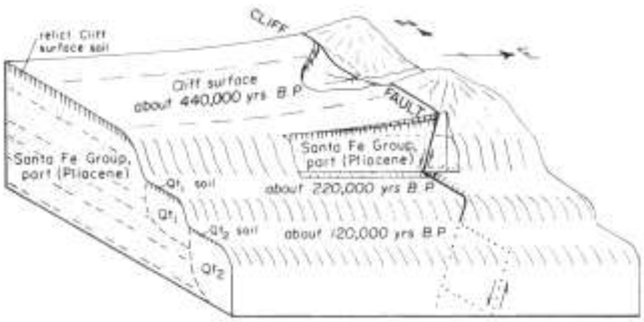


FIGURE S46—BLOCK DIAGRAM OF THE CLIFF FAULT, SAN ACACIA 7½-MINUTE QUADRANGLE, NEW MEXICO. The fault cuts lower buried soil (shown by vertical hachure pattern) of the Cliff surface and the oldest terrace deposit (Qt_1). Net vertical displacement of Qt_1 is about 20 ft (6 m). A younger terrace deposit (Qt_2) does not appear to be displaced by faulting. The southernmost exposure of the Cliff fault is located about 2.5 mi (4 km) north of Stop S12.

Mountains, extensive movement along the Loma Pelada and other faults has displaced many of the upper Quaternary deposits (fig. S45). The preservation of fault scarps in this area suggests that the most recent activity may be latest Pleistocene or early(?) Holocene.

The sand dunes at this road stop are of at least two ages: those that are active today and those that are older, stabilized dunes. The source of sand was the wide floodplain of the Rio Salado, although channel entrenchment in the last 80-90 years and invasion of salt cedar (tamarisk) may have restricted deflation of the floodplain. To the south of the Rio Salado, eolian sand is derived primarily from Rio Grande channel sands of the Sierra Ladrones Formation.

Return to rest area; continue north on 1-25. **0.7**

COMPILER'S NOTE-This concludes the log from Socorro to Rio Salado rest area by Chapin, Chamberlin, and Hawley.

RIO SALADO REST AREA TO RIO GRANDE BRIDGE (1-25)

41.5 Ascending to surface of major cut-and-fill terrace of the Rio Salado, here covered with stabilized veneer or eolian sand. The terrace fill (alluvial unit E of Machette, 1978b) has a well-preserved constructional surface 105-112 ft (32-34 m) above the Rio Salado. This is the Qt_2 surface discussed at Stop S12 that has an estimated age of 120,000 years. Denny (1941) maps this surface as a Cañada Mariana(?) pediment, but it may be equivalent to the 100-ft (30-m) cut-and-fill terrace he mapped along the Rio Salado several miles upstream. **1.0**

42.5 Starting descent into Rio Grande Valley west of La Joya. Cuts ahead in Sierra Ladrones piedmont facies, with gravel caps on ridges to right and left of Machette' s (1978b) alluvial unit F. The high ridge ahead on left is capped with alluvial unit G and is a remnant of the 220,000-yr.-old Qt, surface discussed at Stop S12. The surface projects about 210 ft (63 m) above the Rio Salado and is offset about 20 ft (6 m) by the Cliff fault. **0.2**

42.7 Bluffs to left are cut mainly in distal piedmont slope to basin-floor facies of the Sierra Ladrones Formation, although sandy axial-river zones crop out near the base of the section. On the basis of pebble-imbrication studies, Machette (1978b) interprets alluvial paleotransport directions as being from southeast to northwest in the lower part of the section exposed to the left. A possible source area would be east of the present river valley near the Joyita Hills. The ancestral river during this interval would thus have been west of here, probably in the Loma Blanca-Sierra Ladrones belt where the older fluvial facies is presently preserved. Kelley (1977) includes all exposed Santa Fe beds in this area in his undivided or middle red member of the Santa Fe Formation, which may include axial river facies. **1.3**

44.0 Overpass; La Joya State Wildlife Refuge to right. The town of La Joya is on the east side of the river at 3:00. Bluffs above the town are capped with thin fan and terrace gravels of Arroyo de los Alamos and Salas Arroyo (lower Palo Duro Canyon). These surface gravels rest on sandy fluvial beds here interpreted as an older river-channel deposit inset against the Sierra Ladrones Formation. The well-preserved fan-terrace surface is graded to a level about 130 ft (40 m) above the present floodplain. Denny (1941) also describes cut-and-fill terraces in the La Joya area. **0.9**

44.9 Cuts in Holocene alluvium on right. For the next 3 mi the route crosses low valley-border surfaces constructed by tributary arroyos graded to base levels near that of the present floodplain. **2.3**

47.2 Milepost 173. Rio Puerco Valley ahead on left. Ladron Mountains at 8:30-9:30, and Lucero Mesa at 9:30-10:00 on the western skyline. The south tip of the Llano de Albuquerque at 12:00 rises about 365 ft (120 m) above the Rio Grande floodplain. **0.5**

47.7 Crossing low terrace of the Rio Puerco (see mile 142.7). **0.6**

48.3 Crossing Rio Puerco. *Keep to right for exit on US-60.* **1.0**

49.3 *Take US-60 East exit.* **0.2**

49.5 Passing through Bernardo on US-60. **0.2**

49.7 Railroad overpass. *Continue east* across floor of Rio Grande Valley and State waterfowl area. **1.9**

51.6 Crossing Rio Grande. **0.5**

52.1 East edge of floodplain. Route ahead ascends terrace scarp. Gravel pits to right are in a unit here interpreted as an upper Pleistocene fluvial terrace deposit. To the south, toward Contreras, the basal contact of terrace gravels on reddish Santa Fe mudstones to sandstones is locally exposed. Axial river facies deposited during upper Santa Fe basin filling may be difficult to distinguish from inset fluvial terrace deposits associated with middle to late Quaternary valley cutting, particularly where such units are in direct contact. Inset terrace fills will be described in detail by Lambert in the Albuquerque-Bernalillo area (miles 177.4-179.4). **0.3**

52.4 Crossing terrace surface, which is about 90 ft (27 m) above the floodplain level and which has been mapped as Cañada Mariana pediment by Denny (1941). **0.3**

52.7 Junction with NM-43; *continue straight on US-60.* **0.6**

53.3 Scarp ahead ascends to high-level surface mapped as

Valle de Parida surface by Denny (1941), Ortiz by Kelley (1977), and Llano de Manzano by Machette (1978a). 1.3

54.6 On summit of high surface about 260 ft (80 m) above the river floodplain. Well-rounded siliceous gravel in the shallow pit to right indicates that this surface may be a remnant of an ancestral river-channel deposit. That the gravel is part of an inset fill associated with post-Santa Fe valley incision has not been established. The gravel may simply be a thin, locally-derived deposit reworked from older high-level fluvial gravels in the upper Santa Fe. **1.5**

56.1 Ascending steeper slope segment rising to highest graded-surface level of the valley-border sequence. Low hills of Tertiary basaltic volcanics to right. **0.8**

56.9 On crest of spur extending northwest from Black Butte. *Prepare for right turn ahead on road to relay tower.* **0.2**

57.1 **STOP S13, Black Butte.** Relay tower turnoff about 1.5 mi southwest of Black Butte (Turututu) near southern end of Albuquerque Basin. *Park vehicles south of US-60 on road to relay tower; assemble at cattle guard.* This is an optional stop to discuss the southeastern part of the Albuquerque Basin and the ranges flanking it on the east (figs. S43 and S47). Most of the following discussion of range geology is taken from Foster and Luce (1963b, p. 14). The east-central basin area is also discussed at Stop S16 near Albuquerque (Kelley, this guidebook). This stop provides a good vantage point for reviewing deep seismic-profiling research in this immediate area by the Consortium for Continental Reflection Profiling (COCORP).

Using US-60 East as 12:00, the Sandia Mountains are at 9:30; Manzanita Mountains at 10:00; Manzano Mountains at 10:00-10:45; Abo Pass at 12:00; and Los Pinos Mountains at 12:00-2:00. Black Butte at 1:30 in the foreground is a fault-block remnant of mid- Tertiary rhyolitic ash-flow tuff overlain by basaltic andesite with a K-Ar age of about 24 m.y. (Bachman and Mehnert, 1978, no. 19). To the southwest, the Magdalena Mountains are on the skyline at 4:00-5:00 beyond Socorro Peak and Lemitar Mountain. Ladron Peak is on the skyline slightly north of 6:00 and due west of the confluence of the Rio Grande and Rio Puerco. The Lucero uplift and Sierra Lucero are beyond and north of the Ladrons from 6:15-8:00. E1 Cerro de los Lunas volcanic center on the eastern edge of the Llano de Albuquerque (Stop S14) is slightly west of 9:00.

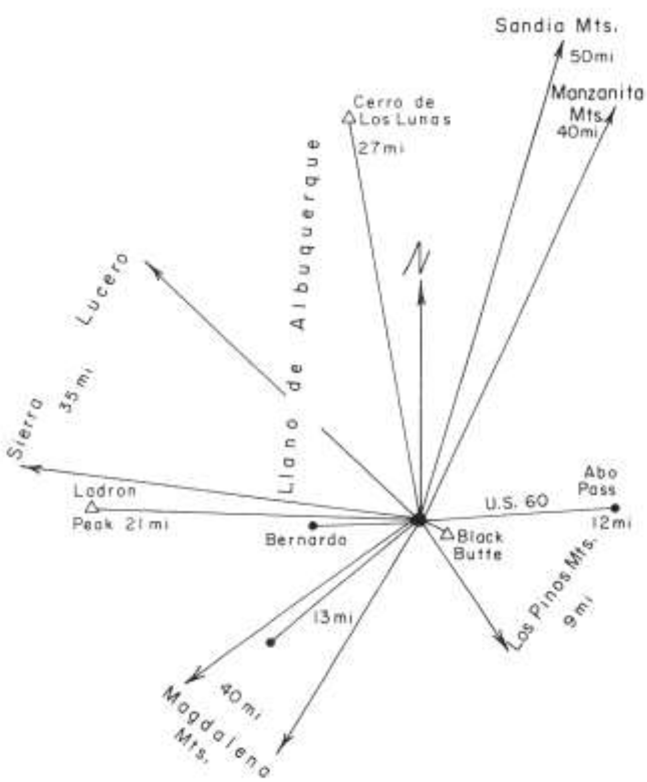


FIGURE S47—PANORAMIC INDEX OF FEATURES SEEN FROM STOP S13 NEAR BLACK BUTTE (TURUTUTU) IN SOUTHEASTERN ALBUQUERQUE BASIN.

The east-dipping fault blocks of the Sandia, Manzanita, and Manzano Mountains are capped by Pennsylvanian limestone, shales, and sandstones that unconformably overlie a complex series of Precambrian metasediments, metavolcanics, and granites (Kelley and Northrop, 1975; Reiche, 1949). Precambrian rocks form the bulk of exposures on the west-facing scarp of the uplift. Locally, remnants of Mississippian limestones underlie the Pennsylvanian.

Near the north end of the Los Pinos Mountains a sequence of more than 12,000 ft of Precambrian metamorphic rocks is exposed and includes quartzite, schist, and rhyolite (Stark and Dapples, 1946). Beyond Black Butte at 1:30, younger Precambrian granite forms the western Los Pinos escarpment. The granite is overlain unconformably by elastic rocks of the Sandia Formation. These are in turn overlain by elastic and carbonate rocks of the upper part of the Sandia Formation and the overlying Madera Formation (Pennsylvanian). At the base of the granite cliff near the south end of the Los Pinos uplift is a small exposure of Pennsylvanian limestone. This small outcrop leaves little space for retreat of the Precambrian cliff, which in this area approximates a fault scarp. The southern end of the Los Pinos uplift plunges to the southwest beneath cuestas and mesas of Pennsylvanian and Permian rocks. These uplands in turn continue southward to the Lomas de las Canas uplift east of the Socorro Basin.

Almost horizontal beds of Pennsylvanian rocks crop out at 12:00 just south of Abo Pass. These beds are a short distance to the east of the Montosa thrust fault that forms the contact between Precambrian and Pennsylvanian rocks in many parts of the Los Pinos and southern Manzano Mountains. The Manzanos consist of a complex sequence of metavolcanics, meta-sediments, and intrusive granitic stocks, all of Precambrian age (Reiche, 1949; Stark, 1956). These rocks are overlain by Pennsylvanian sediments similar to those in the Los Pinos Mountains and by remnants of Mississippian limestones.

As discussed by Kelley at Stop S16, about half of the Manzano structural relief is probably due to Laramide uplift on high-angle reverse faults that lie east of the crest of the range (Kelley, 1977, p. 37). The rift-bounding Manzano fault along the base of the range has given the extra west-side relief to the range. At the southern end of the Manzanos, the Manzano normal fault (and its southern continuation at the Los Pinos base) converges with the west-dipping Laramide (Montosa and Paloma) thrusts of the east side of the Manzano and Los Pinos ranges. The resulting thin strip of Precambrian rocks, between the overridden Pennsylvanian beds on the east and the rift fill on the west, has given rise to the low pass through Abo Canyon. South of the pass the faults diverge again, and the Los Pinos uplift is a horst between west-dipping (rift) normal and Laramide reverse faults.

This stop is on a ridge remnant of a high-level surface extending northwest from the base of Black Butte. The elevation here is about 350 ft (105 m) above the river floodplain, and this ridge crest is only about 20 ft (6 m) lower than the southern tip of the Llano de Albuquerque, 8.5 mi (14 km) to the west-northwest. This surface is less dissected to the north and east of the butte, and it is correlated by Kelley (1977) with the Ortiz pediment of Bryan (1938) and of Bryan and McCann (1938). Denny (1941) mapped the extensive piedmont surface east of Black Butte as Tio Bartolo pediment, and he included the surface at this stop with slopes descending to the Valle de Parida level. Machette (1978a) places much of the piedmont-slope complex from the mountain front to about mile 54.6 in his Llano de Manzano unit that postdates the Ortiz. Surface gravels here are probably a distal piedmont-slope facies, derived from the east, rather than an axial river deposit. The surficial deposits can be interpreted as being either the youngest part of the Santa Fe basin-fill sequence or the oldest part of the post-Santa Fe, valley-border sequence. Machette estimates the age of the Llano de Manzano to be about 280,000 years old on the basis of soil-carbonate-horizon dating (Stop S12, discussion by Machette).

Maps by Kelley (1977), Machette (1978c), and Sanford and others (1972) show that the high-level surfaces in this general area are cut by a number of piedmont fault scarps. Some show displacements down to the east along antithetic faults and indicate the presence of some intrarift horsts in the central basin area.

COCORP (deep seismic reflection) profiling using the VIBROSEIS technique was first conducted on a line extending from Abo Pass, about 15 mi (24 km) east of here, to a point north of US-60 nearly opposite this stop (Oliver and Kaufman, 1976). The line was later extended across the basin to a point north of the Ladron Mountains. Geophysical studies in the Socorro-southern Albuquerque Basin area (Stops S10-S13) are reviewed by Sanford in the first section of the Socorro to Santa Fe road log.

Retrace route to 1-25 at Bernardo. **7.4**

64.5 Railroad overpass. *Prepare for right turn ahead.* **0.2**

64.7 *Take 1-25 North (Belen) approach ramp.* 0.3

65.0 *Merge with 1-25.* From here to Los Lunas the route skirts the base of the eastern Llano de Albuquerque escarpment (Bryan and McCann, 1938). The summit of this narrow, 65-mi (105-km) mesa (Ceja Mesa of Kelley, 1977) is a remnant of the central plain of the Albuquerque Basin. The surface formed prior to entrenchment of the Rio Grande and Rio Puerco Valleys. The original piedmont-slope and basin-floor components that made up this ancient plain have been faulted, dissected by erosion, and partly buried by eolian and local alluvial-colluvial deposits. Extensive basalt flows are present to the north (Stops S14-S16), on both the summit and sideslopes of the mesa. All this considered, the broader summit areas of the Llano de Albuquerque, up to 8 mi (13 km) wide, are probably not aggraded or degraded significantly above or below the original (upper Santa Fe) constructional surface of the plain. The Llano is therefore similar in most respects to the extensive constructional plains of central intermontane basins south of Socorro, including the Jornada I and La Mesa surfaces, and their correlatives in the Hueco, Mesilla (Stops S1 and S2), Jornada (Stops S4 and S9), Palomas (Stop S6), and Engle (Stop S8) basins. The Llano de Albuquerque and associated deposits are discussed at Stops S14 and S15. **0.3**

65.3 Roadcuts ahead are in light-gray-brown sand and sandstone with lenses of pebble gravel and thin layers of reddish-brown clay to loam. The deposits are interpreted herein as fluvial tongues in upper Santa Fe basin fill. The entire 330-ft (100-m) section exposed from here to the top of the Llano escarpment is correlated by Machette (1978c) with the Sierra Ladrones Formation. Kelley (1977) includes most of the exposed section from here to E1 Cerro de los Lunas in his undivided-Middle red member of the Santa Fe Formation. However, he separates out the surficial zone of soil-carbonate (caliche) accumulation and a thin layer of gravelly to sandy sediments that he interprets as being associated with an Ortiz pediment surface truncating the upper Santa Fe sequence. Stratigraphic nomenclature and problems relating to identification and correlation of basin-fill surfaces are discussed at Stops S14, S15, and S19. **1.4**

66.8 The route from here to north of Belen (mile 87.5) is mainly on Holocene alluvium associated with low valley-border surfaces graded to near the present floodplain level. **1.7**

68.5 Milepost 179. Abo Pass at 9:00. Near this point the highway crosses the buried trend of a normal fault, downthrown to the west, that displaces the Sierra Ladrones Formation and the caliche cap of the Llano de Albuquerque at 1:00. Surface offset along the north-northwest-trending scarp is at least 50 ft (15 m). The fault was first mapped by Denny (1941, fig. 9) and is shown on maps by Kelley (1977) and Machette (1978c; fig. S45, this guidebook); however, the amount of displacement of upper Santa Fe beds is not reported in the literature. **0.6**

69.1 Roadcut to right in small knob of Sierra Ladrones fluvial facies, which is capped with pebbly sandstone underlain by interbedded reddish-brown clay and gray-brown sand to sandstone. The area of the Llano rim showing fault displacement of Sierra Ladrones beds and surface-capping caliche is in line with this knob and the windmill ahead on left. **0.4**

69.5 Milepost 180. In 1939 an oil test, Central New Mexico 1 Livingstone, was drilled from the Llano surface, elevation 5,074 ft (1,547 m), 1.7 mi west of this point. The 2,978-ft (916-m) hole penetrated an estimated 2,100 ft (640 m) of Santa Fe basin fill and bottomed in possible Cretaceous rocks (sheet 2 and Foster, this guidebook, hole u). 1.1

70.6 Low roadcuts for the next 0.5 mi in sandy fluvial facies of the Sierra Ladrones Formation. Facies composition of upper Santa Fe beds exposed in the escarpment to left has not been studied in detail. However, much of the section may be distal-piedmont to basin-floor facies laid down by western tributaries, rather than by a south-flowing river. The area traversed from here to Isleta is on the edge of the region, including the Rio Puerco Valley, described by H. E. Wright (1946), another of Kirk Bryan's students. **3.0**

73.6 Valencia County line; road curves left. Manzano range from 1:30-3:00. **0.7**

74.3 Crossing small floodplain embayment. About 330 ft (100 m) of weakly to moderately indurated, pebbly sand-to-clay beds of the Santa Fe Group are well exposed in high bluffs on left. **1.5**

75.8 Crossing irrigation canal with drop structures to left. **0.7**

76.5 Spur of Sierra Ladrones extending out from escarpment on left. **1.0**

77.5 Milepost 188. E1 Cerro de los Lunas Lunas volcanic center on east rim of Llano de Albuquerque at 11:45 is just south of Stop S14. Sandia Mountains at 12:30. **2.0**

79.5 Milepost 190. South Belen exit to right. **0.2**

79.7 Underpass. About 7 mi east of this point on the Llano de Manzano is the Grober 1 Fuqua oil test, drilled between 1937 and 1946 (sheet 2 and Foster, this guidebook, hole v). This 6,300-ft (1,920-m) hole penetrated 4,550 (1,387 m) of Santa Fe Group. The Santa Fe overlies an unknown thickness of beds tentatively correlated with the Baca Formation. According to an earlier interpretation of well data (Reiche, 1949, p. 1204), the section below 4,550 ft comprised 1,750 ft (535 m) of upper Cretaceous and probable Triassic rocks. **1.8**

81.5 Milepost 192. Water tank and Belen sanitary landfill on left. Titus (1963, p. 28-29) has described a 200-ft (60-m) section of upper Santa Fe beds that crop out in the escarpment badlands area at 9:00. The section is mainly sand and gravelly sand (including sandstone and conglomeratic sandstone lenses) with several prominent zones of interbedded clay, silt, and fine sand. Units are in upward-fining (channel sand and gravel to overbank silt-clay) sequences. A strong horizon of soil-carbonate accumulation engulfs the upper sedimentation unit. No angular unconformities are noted in the section. Preliminary studies of gravel character and sedimentary structures indicate that these units may have been deposited on the distal part of a broad piedmont alluvial plain sloping gently eastward toward the aggrading fluvial plain of the ancestral river. The log of a Belen city water well drilled near this base of the described section indicates that, for at least 500 ft (150 m), the gross lithologic character of the basin fill is similar to that of the bluff outcrop (Titus, 1963, tables 1 and 2). Well sample studies are needed to determine whether axial river deposits are present in the subsurface section. Deep oil tests in the area west and north of Belen are discussed at Stop S14. **2.0**

83.5 Milepost **194.** Spur of Santa Fe beds (interbedded sands, loams, and clays) extending out from escarpment on left. **El** Cerro Tome across valley at 1:30 is small andesitic volcanic center. Bachman and Mehnert (1978, no. 14) have K-Ar dated a plug from this center at 3.4 ± 0.4 m.y. The northern Manzanos (Reiche, 1949) form the skyline at 1:30-3:00 (fig. S48). The north-south-trending break in slope from 2:003:00 midway up the Llano de Manzano is the scarp of the Ojuelos or Hubbell Springs fault. The scarp marks the western edge of the Joyita-Hubbell bench of Kelley (1977, fig. 19; fig. S48, section D, this guidebook). This structural bench, upthrown on the east, is formed on pre-rift Permian, Triassic, and early Tertiary rocks. The bench is downfaulted to the west along the Manzano (frontal) fault. Basin-fill thickness increases abruptly west of the scarp. According to Kelley (1977; Stop S16, this guidebook) some movement along the 135-ft (40-m) high scarp has occurred in Holocene time. **1.7**

85.2 Railroad overpass. North Belen interchange ahead. **1.3**

86.5 Milepost 197. *Cerro de* los Lunas or Los Lunas

FIGURE S48—NORTHERN MANZANO MOUNTAINS AND EAST-CENTRAL ALBUQUERQUE BASIN; view is east across the Rio Grande Valley from southwest side of Cerro de los Lunas. The Manzanos (Mosca and Bosque Peaks north of center and Osha Peak to south) are capped with Pennsylvanian limestones, shales and sandstones. These strata overlie a complex series of Precambrian metamorphic and intrusive rocks that form the main range escarpment. The small hill in the Rio Grande Valley is El Cerro Tome, an andesitic plug of Pliocene age. The dark line midway up the piedmont slope east of El Cerro Tome (paralleling the mountain front) marks the western edge of the Joyita-Hubbell bench of Kelley (1977). The bench is formed on Permian, Triassic, and early Tertiary rocks and is terminated on the west by the Hubbell Springs fault scarp (Ouelos faults of Reiche, 1949). Andesite flows and landslide mass from Los Lunas volcano in center and left center. East-tilted Santa Fe beds with local veneers of alluvium-colluvium and eolian sand form slopes in foreground.

volcano, at 11:00-12:00. Note high surface (with relay tower) west of the central mass of andesitic volcanics. This surface truncates a thick west-tilted section of upper Santa Fe beds. According to Bachman and Mehnert (1978, fig. 4) these beds in turn overlap outlying bodies of mafic lavas (dark, low-lying hills southwest of the central mass); Bachman and Mehnert correlate the lavas with K-Ar-dated units (1.3 to 1.0 m.y., no. 13) sampled at three points on the central volcanic complex. Kelley (1977, p. 47) and Kelley and Kudo (1978) also consider that the central complex is early Pleistocene; however, they put the time of andesitic volcanism after 1) deposition and deformation of the Santa Fe beds and 2) initial cutting of the river valley. 1.3

87.8 Rounded hill on right is probably a remnant of an older river-terrace deposit. **0.7**

88.5 Milepost 199. E1 Cerro Tome across the valley at 3:00. Fig. S49 is a view from the southwest base to E1 Cerro de los Lunas (about 2 mi west of here) past E1 Cerro Tome to the northern Manzano Mountains. Southeast-tilted Santa Fe beds shown in the foreground of the picture overlap and contain fragments of andesites that crop out on the lower left. **1.0**

89.5 Milepost 200. Ascending from low valley-border surface of Holocene age to remnant of late Pleistocene river terrace. Note large landslide masses on south side of Los Lunas volcano. **0.8**

90.3 About 1 mi east of this point is the Harlan and others No. 1 exploratory well. Kelley (1977, table 9) reports that the base of the Santa Fe in this 4,223-ft (1,287-m) test hole is 2,835 ft (864 m) below the floodplain surface. **0.6**

90.9 Roadcut in pebbly sand terrace alluvium. This deposit is possibly equivalent to the Los Duranes unit (upper Pleistocene) that forms the Segundo Alto terrace fill in west Albuquerque (miles 125.9-128.1). **1.6**

92.5 Milepost 203. *Prepare to take exit ahead on right for Stop S14* (optional). **0.1**

92.6 *Take Los Lunas exit (NM-6).* **0.2**

92.8 Stop sign. *Turn left on NM-6; continue west across overpass.* Road-log entries from here to Albuquerque are compiled in part from guidebook by Kelley and others (1976, p. 7-12). The recent report by Kelley and Kudo (1978) should be consulted for detailed discussions and maps of volcanic features along the route. K-Ar-dated volcanic rocks and their relationship to basin and valley fills in this immediate area are also discussed by Bachman and Mehnert (1978) and Kudo and others (1977). **0.2**

93.0 Cattle guard. Los Lunas volcano at 11:00. **0.6**

93.6 Power-line crossing. The site of Shell Oil Company Isleta Central test well is located about 2 mi to the north (see Stop S14). **0.5**

94.1 The landslide at 10:00 has uncovered a section of the neck of the northern feeder conduit. Note that strong vertical ribbing in the plug transects thick flows on either side.

On northwest base of volcano at 10:30-11:00 also note west-dipping upper Santa Fe beds in the western flank of a faulted anticline. According to Kelley (Kelley and others, 1976, p. 11) the Ortiz pediment surface (early Pleistocene) truncates these beds, and eruption of the andesite cone appears to have taken place on the edge of an Ortiz-age mesa surface with flows descending down the mesa side slopes.

FIGURE S49—Southern slope of El Cerro de los Lunas about 2 mi west of mileposts 199 and 200 on I-25; view is to east across east-central Albuquerque Basin toward northern Manzano Mountains. High flat surface north of the Manzanos is the southern part of the Manzanita Mountains. El Cerro Tome at upper right is on east edge of river-valley floor. Southeast-tilted Santa Fe beds shown in the foreground overlap and contain fragments of andesites that crop out on lower left (below hammer and figure). This andesite unit is correlated by Bachman and Mehnert (1978, table 1, fig. 4) with andesites of the main Los Lunas center that they dated at 1.1 to 1.31 m.y. (see Stop S14).

The erosion surface on the tilted Santa Fe beds is mantled with sandy to loamy alluvial and colluvial deposits with scattered coarse fragments of andesite in the basal part, derived from the Los Lunas center, and lenses of rounded gravel. Two or three well-developed soil (paleosol) zones mark depositional breaks in the upper part of the erosion surface mantle, and lenses of silicic volcanic ash are present at the base of the mantle. **2.3**

96.4 Ascending to Llano de Albuquerque (summit of Ceja Mesa of Kelley, 1977). Cuts ahead in upper Santa Fe beds mapped as undivided Santa Fe Formation by Kelley (1977) and Sierra Ladrones Formation-Santa Fe Group by Machette (1978c). Kelley (1977) includes gravelly units exposed in the bluffs to the south, and along the railroad to the north, in the Ceja Member of the Santa Fe Formation. The Ceja is the general equivalent of at least the upper to middle part of the upper buff member of Bryan and McCann (1937). **0.1**

96.5 Approaching top of grade and Llano de Albuquerque surface; note strong zone of soil-carbonate accumulation (caliche) in roadcuts. *Prepare for left turn ahead at relay tower road junction.* **0.4**

96.9 **STOP S14, Cerro de los Lunas** (optional). East rim of Llano de Albuquerque northwest of E1 Cerro de los Lunas. *Park 0.2 mi up relay tower road to left; walk east to mesa rim.*

This stop offers a broad vista of the central Albuquerque Basin (figs. S43 and S50) as well as a close view of nearby volcanic features. Using the relay tower road as 12:00, Ladron Peak is on the southern skyline at 1:00. The Lucero uplift on the western skyline from 1:30-3:30 forms the eastern edge of the Colorado Plateau. From 2:30-3:30 basalt flows cap gently westward tilted Triassic and Permian beds of

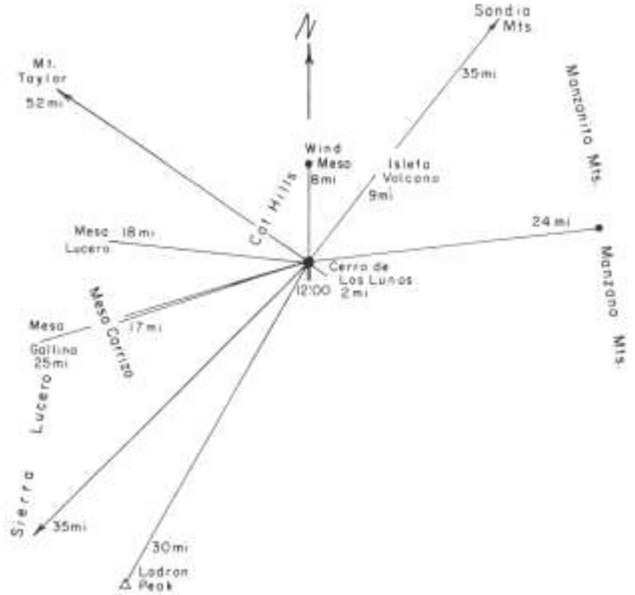


FIGURE S50—PANORAMIC INDEX OF FEATURES SEEN FROM STOP S14, LLANO DE ALBUQUERQUE RIM NORTHWEST OF EL CERRO DE LOS LUNAS.

the high, distant Sierra Lucero (Kelley and Wood, 1946). The flow on Mesa Gallina at the north end of Sierra Lucero (2:30) has a K-Ar age of 7.2 ± 0.6 m.y. (Bachman and Mehnert, 1978, no. 15). A lower basalt flow on Mesa Carrizo east of Mesa Gallina, at 2:15-2:45 on the east border of the Lucero uplift, has been K-Ar dated by Bachman and Mehnert (1978, no. 16) at 3.7 ± 0.4 m.y. This flow locally rests on thin deposits of basin fill and overlaps deposits of travertine of the Comanche fault zone. Mt. Taylor on the northwestern skyline (4:00) is a composite stratovolcano of Pliocene age (Crumpler, 1978). Structural features of the western rift boundary are discussed by Kelley at Stop S15 located on the Ceja del Rio Puerco about 16 mi (25 km) northwest of this point. The eastern rift boundary and the Sandia-Manzano ranges are discussed at Stops S13 and S16- S19.

Several deep oil tests have been drilled in the vicinity of El Cerro de los Lunas (sheet 2 and Foster, this guidebook, holes w, x, y, and z). The test well noted at mile 93.6, Shell 1 Isleta Central, was drilled in 1974 and 1975. This 16,346-ft (4,982-m) hole penetrated 12,040 ft (3,670 m) of Santa Fe basin fill with a thin overlay of Quaternary terrace deposits. Underlying Cretaceous rocks are part of a thick sequence of older sedimentary rocks, with estimated depth to Precambrian basement 18,410 ft (5,611 m) or 13,344 ft (4,067 m) below sea level (Foster, this guidebook, hole z). Another nearby deep test, Long 1 Dalies, is located on the Llano surface about 4 mi south-southwest of this stop (sheet 2, hole y). This hole, drilled in 1952-1953, bottomed in 8,495 ft (2,589 m) of Santa Fe basin fill without reaching its base. The section that was penetrated did include interbedded basalt flows and pumiceous tuffs (Foster, this guidebook, hole y).

Two other deep tests have been drilled about 10 mi southwest of here in the badlands area west of the Rio Puerco (sheet 2, holes w and x). Humble 1 Santa Fe (hole w) drilled in 1953 to a total depth of 12,691 ft (2,868 m), penetrated 6,145 ft (1,873 m) of Santa Fe and 3,760 ft (1,146 m) of Baca Formation before encountering Cretaceous rocks at 9,905 ft (3,019 m). Estimated depth to Precambrian basement is 19,300 ft (5,883 m), or 14,208 ft (4,331 m) below sea level (Foster, this guidebook, hole w). The second hole (x), Shell 2 Santa Fe, was drilled in 1974 to a total depth of 14,305 ft (4,360 m) and completed in Chinle Formation (Triassic). This well penetrated 7,780 ft (3,271 m) of Santa Fe and 3,230 ft (984 m) of Baca Formation before encountering Cretaceous rocks at 11,010 ft (3,356 m). Estimated depth to Precambrian is 20,200 ft (6,157 m), or 15,006 ft (4,574 m) below sea level (Foster, this guidebook, hole x).

Basaltic to andesitic volcanics of the Albuquerque Basin have recently been described by Kelley and Kudo (1978), and their report should be consulted for detailed information on the eruptive centers here and to the north along the tour route. The following discussion includes brief summaries on the volcanic units associated with centers near this stop (taken from Kelley and others, 1976, and Kudo and others, 1977). See Renault (this guidebook) for a general review of recent work on upper Cenozoic basalts and andesites of the rift region, as well as for information on composition of volcanics of the Wind Mesa, Cat Hills, and Los Lunas centers.

Two major centers of Pliocene to Pleistocene basaltic volcanism, Wind Mesa and Cat Hills, are located just north of this stop (fig. S51; fig. 10 of Kelley and others, 1976). Wind Mesa, the older of the two centers, is a low shield volcano near the edge of the Llano about 7 mi north of this stop. The field occupies an area of about 4 mil; and the eruptive sequence, nearly 200 ft (60 m) thick, comprises several flows of dark-gray to black, irregularly vesicular

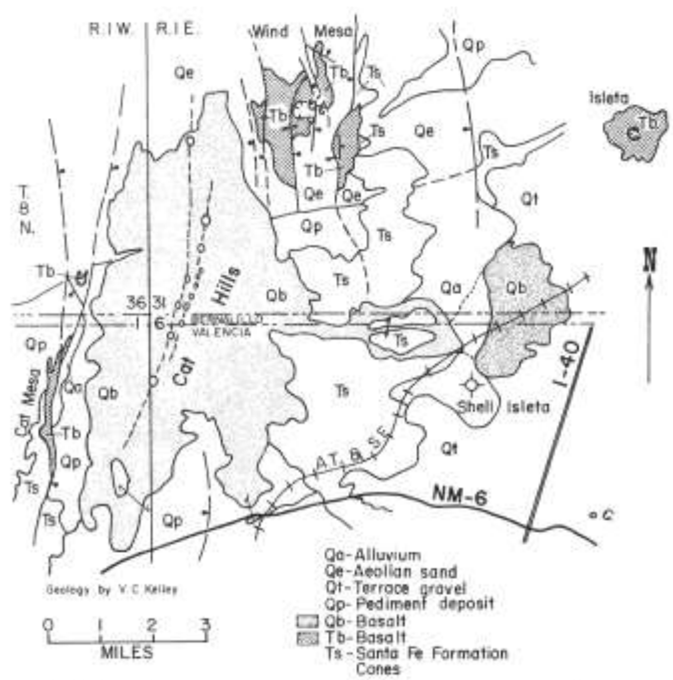


FIGURE S51—GEOLOGIC MAP OF CAT HILLS AND WIND MESA VOLCANIC FIELDS NORTH OF STOP S14 (Kelley and others, 1976, fig. 10).

basaltic andesite. The Wind Mesa field is considerably disrupted by several north-trending faults. The breakup resulted in a central graben adjoined by a horst on the west and two eastward-tilted blocks on the east.

The Cat Hills center consists of extensive flows and cones from a northerly trending fissure zone (fig. S51). Twenty-three cinder cones are aligned slightly east of north, and seven flow units occupying 26 mi' (67 km') have been mapped. The flows are all olivine basalts with alkaline affinities. The first two flows have the widest distribution and probably erupted from fissures. The oldest flow unit, Qb_1 of Kelley and Kudo (1978), has a K-Ar age of 0.140 ± 0.038 m.y. (Kudo and others, 1977). This unit was extruded onto a low segment of the late(?) Pleistocene terrace complex (mile 101.2) west of 1-40 and north of the Shell well site (fig. S51). The K-Ar age of the flow fits this geomorphic position.

Los Lunas volcano to the southeast consists of five flows and two vents, all andesite. As noted at mile 86.5, K-Ar age determinations on samples collected from three sites on the northeast and west flanks of the central peak have K-Ar ages ranging from 1.31 ± 0.05 to 1.01 ± 0.10 m.y. (Bachman and others, 1975).

There is disagreement between Bachman (Bachman and others, 1975; Bachman and Mehnert, 1978) and Kelley (1977; Kelley and others, 1976) on the sequence of events involved in deposition of the upper Santa Fe beds, emplacement of the andesites, and formation of the major upland surface of the Llano de Albuquerque.

As noted en route to this stop, there is an extensive erosion surface cut on the tilted Santa Fe section west of the main Los Lunas center. This surface is mantled with alluvial and colluvial deposits in which well-developed (buried and relict-surface) soils have formed. The basal part of this surface mantle, which crops out on the high mesa rim northeast of the relay tower, contains lenses of silicic volcanic ash as well as large fragments of andesite derived from the Los Lunas center. The ash is an air-fall unit of the Tsankawi Pumice Bed of Bandelier Tuff, Tshirege Member (Bachman and Mehnert, 1978). The Tsankawi unit has been dated at approximately 1.1 m.y. (Doell and others, 1968; Bailey and Smith, this guidebook).

Bachman (Bachman and others, 1975; Bachman and Mehnert, 1978) interprets the paleosol sequence in the upper part of the surface mantle as marking the culmination of aggradation and stabilization of the Llano de Albuquerque surface. He also correlates the dated andesites on the flanks of the central volcano with outlying andesite units southwest of the main center. These units, the "mafic flows" of Bachman and Mehnert (1978, p. 288-289, fig. 4), are overlapped by strata of the tilted Santa Fe section that crops out in the escarpment south of the relay tower (miles 86.5 and 88.5; fig. S49).

Bachman thus infers that Cerro de los Lunas is "a partly exhumed volcanic center (Bachman and others, 1975, p. 3)." According to this interpretation, extrusion of the 1-1.3-m.y.-old flows took place during final stages of aggradation of the central Albuquerque Basin, with local deformation and truncation of upper Santa Fe beds occurring during and shortly after emplacement of the andesites. Furthermore, according to Bachman, culmination of basin aggradation (final stages of Santa Fe deposition) occurred after deposition of the 1.0-1.1-m.y.-old ash lenses in the basal part of the erosion-surface mantle that underlies the paleosol zone. The angular unconformity below the mantle is thus regarded as a local feature related to Los Lunas volcanism rather than as an erosion surface of regional significance. The paleosol zone in the upper part of the mantle is correlated by Bachman with well-developed pedogenic caliches, such as the unit cropping out at this stop, that characterize stable parts of the Llano de Albuquerque surface. He dates this surface at about 0.5 m.y. on the basis of regional correlations of soil-geomorphic sequences (Hawley and others, 1976) and estimates of calcic-soil development (Bachman and Machette, 1977; Machette, 1978a; and this guidebook, Stops S12 and S16).

The contrasting interpretation by Kelley (Kelley and others, 1976, p. 9-12; Kelley and Kudo, 1978) is that the major eruptions of the Los Lunas center took place after tilting and truncation of the youngest Santa Fe section and after erosion of much of the inner valley. The outlying andesite limits are regarded as intrusive bodies in the Santa Fe rather than as a part of the Santa Fe sequence. Furthermore, the (pre-ash-fall) surface that truncates the tilted Santa Fe section is correlated by Kelley (Kelley and others, 1976, p. 11) with the Ortiz (erosion) surface of Bryan (1938) and Bryan and McCann (1938). Kelley interprets the surface mantle with the basal ash lenses as a post-Santa Fe veneer on the Ortiz erosion surface.

Problems and progress in determining the age and origin of surfaces on Santa Fe and younger deposits are also discussed at Stops S15, S16, and S19. The current research effort on ancient landscapes, surficial deposits and soils (here and elsewhere in the western states) reflects recent enactment of legislation that requires evaluation of all geologic factors that may relate to technological activities with long-term environmental impact (such as nuclear power-plant siting and disposal of radioactive and other hazardous wastes).

Retrace route to 1-25. **3.1**

100.0 Panoramic view of eastern Albuquerque Basin and Sandia-Manzanita-Manzano-Los Pinos mountain chain from 9:00-2:30. **0.8**

100.8 Cattle guard. 1-25 Los Lunas interchange ahead; *prepare for left turn* on east side of overpass. **0.2** 101.0 *Turn left on 1-25 North approach ramp.* **0.2**

101.2 Merge with 1-25. Continue north on surface of an alluvial terrace complex that is tentatively correlated with the Segundo Alto surface (late Pleistocene) in west Albuquerque. **1.5**

102.7 Milepost 205. The deep Shell Isleta Central oil test discussed at Stop S14 is located about 2 mi to the northwest. **1.0**

103.7 Milepost 206. Isleta volcano at 11:30. Flows in broad swale on plain to left are from Cat Hills center. As noted at Stop S14, the oldest flow (one of the two most extensive flows) has a K-Ar age of 0.140 ± 0.038

m.y. (Kudo and others, 1977). Thus, pre-Wisconsinan late Pleistocene is the youngest possible age of the surface on which the flow rests (chart 1). **1.4**

105.1 Entering Isleta Pueblo (1970 population: 1,783; area: 210,937 acres). "The original pueblo was located on the site of the present pueblo when Coronado visited the area in 1540. The Spanish established the Mission of San Antonio de Isleta by 1613. Plains Indian raids caused the Pueblo Indians living east of the Manzano Mountains to move to Isleta around 1675. The Isleta Pueblo did not actively participate in the Pueblo Revolt against the Spanish in 1680 and became a refuge for Spanish settlers. In spite of this, Governor Otermina captured the pueblo in 1681 and took 400 to 500 prisoners with him to E1 Paso where they settled at Ysleta del Sur. The remaining population abandoned the Pueblo of Isleta and fled to Hopi country. They returned in 1716, bringing their Hopi relatives with them. The present pueblo was built in 1709 by scattered Tigua families. Most of the Hopi later returned to Arizona, but have retained their ties with Isleta. Residents of Acoma and Laguna migrated to Isleta in the early 1800's because of drought and religious differences at their home pueblos. Isleta has incorporated a variety of pueblo people" (U.S. Dept. of Commerce, 1974, p. 350). Do not leave highway rights-of-way on reservation land without permission of the tribal governor. **1.5**

106.6 Crossing transcontinental route of ATSF Railroad. **1.0**

107.6 Underpass; Isleta Pueblo interchange. **0.1**

107.7 Milepost 210. Hill ahead on left (Kelley and Kudo, 1978; Kelley and others, 1976) is a compound volcano with a cone buildup, 1 to 1.25 mi in diameter, of five basalt flows. The base of the 300-ft (90-m) high volcano is within an earlier maar crater that is almost completely buried except on the northeastern and eastern sides. Basal flow units rest on a maar accumulation of basalt tuff-breccia. There are also several outlying basalt flows with no exposed connection to the volcano. The lowermost flows of the volcano may have been part of a lava lake that erupted in the maar. The second flow above the maar has a K-Ar age of 2.78 m.y. (Kudo and Kelley, 1977). The basalts of the Isleta center have alkali olivine affinities (Kelley and Kudo, 1978). See also Renault (this guidebook) for discussion of rift basalts. **0.3**

108.0 Outlying basalt mass in cut to left. **0.3**

108.3 Cuts for next 0.2 mi in lower flow sequence over Isleta tuff (Kelley and Kudo, 1978). Site of Stop 1 of Kelley and others (1976, p. 7) is ahead on right in gully where there are good exposures of the flow-maar contact. **0.7**

109.0 Albuquerque volcanoes at 11:00 in middle distance at east edge of the Llano de Albuquerque. Jemez Mountains, forming rim of Valles caldera, on far skyline at 12:00. Thin Santa Fe beds mantle basal basalt flow for the next 0.4 mi. **0.4**

109.4 Cuts in basal basalt flow on maar ring. Small gullied area ahead on left in tuff of Isleta maar. **0.7**

110.1 Entering first big cut with basalt flow of Black Mesa over tuff unit. The basalt of Black Mesa pinches out a short distance to the west, while tuffs of early Isleta maar interfinger eastward with fluvial sand and gravel of the ancestral Rio Grande (upper Santa Fe fluvial facies). The Santa Fe here is mapped as undivided-Middle red by Kelley (1977) and as Sierra Ladrones Formation by Machette (1978c). **0.3**

110.4 Crossing bridge over Coors Road. Second big roadcut ahead is through Black Mesa (of Isleta). Santa Fe river sand and gravelly sand is capped with beheaded basalt flow. The flow has no outcrop connection with Isleta volcano. A buried vent is suspected somewhere in nearby floodplain area to the south (Kelley and others, 1976; Kelley and Kudo, 1978). **0.6**

110.9 Crossing Rio Grande floodplain, through northern part of Isleta Reservation area. **0.3**

111.2 Crossing Isleta Boulevard. **0.5**

111.7 Milepost 214. West bridge abutment; Rio Grande channel ahead. End of Rio Salado rest area-Rio Grande bridge segment of log.

RIO GRANDE BRIDGE (1-25) TO BERNALILLO

by P. W. Lambert
U.S. Geological Survey, Albuquerque, New Mexico

112.2 East abutment of 1-25 bridge over Rio Grande. **0.4** 112.6 Bridge over ATSF Railroad. **0.1**

112.7 Exit 215, NM-47 (South Broadway). Road ascends from river floodplain on Holocene alluvial-fan apron. Scarp east of 1-25 is underlain by the Ceja Member of the Santa Fe Formation. Kelley (1977) has proposed the term Ceja to designate the upper, gravelly part of the upper buff member of Bryan and McCann (1937) and Lambert (1968). As previously noted, the Ceja Member is at least in part correlative with the Sierra Ladrones and Camp Rice Formations (charts 1 and 2). **0.8**

113.5 Road cut on right in the Ceja member. Albuquerque volcanoes and Volcano Cliffs (basalt-capped mesa) across valley at 10:30. The volcanoes consist of ten small basaltic cinder cones arranged along an almost perfectly straight north-trending fissure 3-4 mi long. Basalt, perhaps derived largely from the fissure rather than from the present cones, flowed mainly east and covers an area of about 22 mil. A K-Ar age of about 0.19 m.y. has been reported for one of the basalt flows (Bachman and others, 1975). See discussion by Machette at Stop S16 (mile 153.9). **1.5**

115.0 Roadcuts in the Ceja Member. **0.7**

115.7 Milepost 218. Road begins descent into valley of Tijeras Arroyo. Tijeras Arroyo drains an area of Precambrian, Paleozoic, and Mesozoic rocks within and east of the Sandia and Manzanita Mountains. The arroyo's course through the mountains is in a deep canyon that follows the Tijeras fault in places. Hills bordering both sides of Tijeras Arroyo are underlain by the Ceja Member. Early Pleistocene (late Blancan) vertebrate fossils (camel and horse) were collected from Ceja Member sediments near the top of the scarp on the south side of the arroyo about 1.5 mi east of 1-25 (Lambert, 1968). **1.0**

116.7 Milepost 219. Bridge over Tijeras Arroyo. **0.8**

117.5 Roadcuts ahead in Ceja Member. The scarp east of 1-25 leads up to a remarkably flat and undissected surface that is a northward extension of the piedmont plain west of the Manzano Mountains (Llano de Manzano of Machette, 1978a). The Albuquerque International Airport (Sunport) and Kirtland Air Force Base are located on this surface. All but the upper few feet of the scarp are underlain by sediments of the Ceja Member. At the top of the scarp, several feet of arkosic alluvial fan sediment derived from the Sandia and Manzanita Mountains overlie a pedogenic caliche developed in the top of the Ceja Member. The Ceja in the Sunport-Tijeras Arroyo area is similar to the Ceja Member elsewhere in the Albuquerque area except that it contains a greater proportion of clay, mud, and sand layers and a greater proportion of pebbles (silicic pumice, for example) derived from sources north of Albuquerque. In addition, sets of cross-strata dip mainly southeast to southwest. Locally, several relatively large bodies of clean channel sand and gravel are present within the member (Lambert, 1968, p. 103). These features suggest that the Ceja sediments in the Sunport-Tijeras Arroyo area accumulated in a basin-floor environment and probably represent a mixture of channel and overbank deposits of a south-flowing axial stream and distal deposits of its tributaries. **0.7**

118.2 Overpass-Rio Bravo Boulevard. Cut to right in sand and gravel of Ceja Member.

Entering Albuquerque (1970 population: 243,751). In 1706 New Mexico's colonial governor, Don Francisco Cuervo y Valdez founded a villa here that he named San Francisco de Alburquerque in honor of Don Francisco, Duque de Alburquerque and Viceroy of New Spain. When the governor placed the new villa of Alburquerque under the patronage of San Francisco, he selected the name of his own patron saint and that of the viceroy. The viceroy, however, fearing the displeasure of King Philip V of Spain (who had not authorized the villa), decided to rename it San Felipe de Alburquerque, honoring the patron saint of the monarch. Early in the 19th century, English-speaking people dropped the "r" in the second syllable. The city is the commercial hub of the state and the site of the University of New Mexico, founded in 1889 (Pearce, 1965, p. 5). **1.5**

119.7 Milepost 222. For the next 4 mi, 1-25 is routed along the outcrop belt of the alluvium of Edith Boulevard, a Rio Grande terrace deposit (upper Pleistocene), with a maximum thickness of 40-50 ft (12-15 m) (Lambert, 1968; see mile 178.3). In most places this alluvium (mainly gravel) has been removed or covered by construction activities, but remnants of the alluvium and the terrace it holds up are visible in places along the route, especially west of 1-25. East of 1-25 the alluvium of Edith Boulevard is buried by arkosic alluvial-fan sediments deposited by an ancestral Tijeras Creek. These pinkish-orange sediments are visible in bluffs east of 1-25. The southernmost exposures of the alluvium of Edith Boulevard on the east side of the Rio Grande are in this area. Either the belt of terrace deposits turned southwest and was later removed by lateral migration of the Rio Grande, or the alluvium is buried beneath the sediment of the Holocene alluvial-fan apron built westward from the high scarp east of 1-25. **1.0**

120.7 Gibson Boulevard overpass; airport to right. **1.4**

122.1 Central Avenue overpass. *Stay in left lane* for 1-40 westbound (Grants) exit. **1.4**

123.5 *Bear left* for 1-40 west. After merging with 1-40 the route is on Rio Grande floodplain. **2.4**

125.9 Rio Grande Boulevard overpass. Pink scarp ahead borders west side of the Rio Grande floodplain and is known locally as the Adobe Cliffs. The pinkish sediments exposed in the scarp are the alluvium of Los Duranes (Lambert, 1968), a thick, well-stratified sequence of channel sand and overbank mud deposited by the Rio Grande during a late Pleistocene aggradational phase. The alluvium is younger than the main outpouring of Albuquerque volcanoes basalt and is older than the alluvium of Edith Boulevard. The Los Duranes has a maximum exposed thickness of 131 ft (40 m). **1.4**

127.3 East abutment of 1-40 bridge across Rio Grande. Alluvium of Los Duranes is well exposed in Adobe Cliffs north of bridge. **0.2**

127.5 West abutment of Rio Grande bridge. Road begins ascent through roadcuts in alluvium of Los Duranes to Segundo Alto ("second high") surface, a 140-ft (43-m) high terrace, bordering the Rio Grande on the west. Locally, the surface is known as the West Mesa. **0.6**

128.1 West underpass under Coors Road. For the next mile the route is across the almost flat Segundo Alto surface. In the Albuquerque area the surface is about 8 mi long and 0.5 to 1 mi wide. The Segundo Alto surface is an alluvial terrace representing the upper limit of deposition of the alluvium of Los Duranes and is not an erosional terrace or a pediment. **0.3**

128.4 Cejita Blanca (scarp) from 10:00 to 1:00, Albuquerque volcanoes and Volcano Cliffs (basalt-capped mesa) from 1:00 to 4:00.

Cejita Blanca ("little white eyebrow") borders the Llano de Albuquerque on the east in the Albuquerque area and is underlain mainly by the Ceja Member. A thick pedogenic caliche developed in the top of the Ceja Member gives the scarp its name. In its present form Cejita Blanca is an erosional scarp, but the presence of several faults along the scarp suggests that it may have been initiated by faulting (see discussion by Machette at Stop S16 [mile 153.9]). Some of the sediments exposed beneath the basalt in Volcano Cliffs belong to the Ceja member; but some, especially those exposed along the easternmost edges of the mesa, appear to be a Rio Grande alluvium, pre-Los Duranes in age, that is inset in the Ceja Member (Lambert, 1976, p. 9). **0.8**

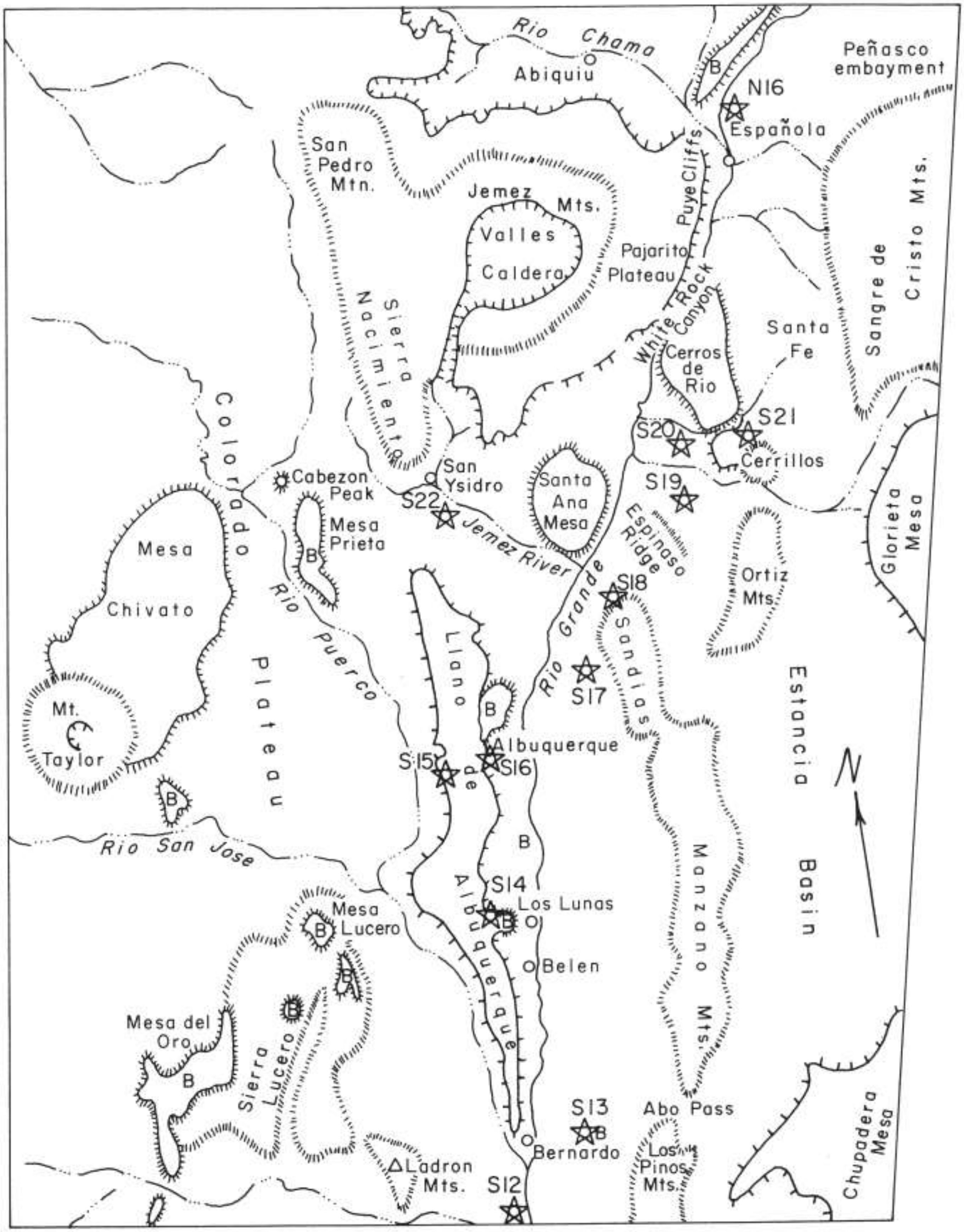
129.2 Milepost 154. Road begins ascent of alluvial-fan apron built eastward from base of Cejita Blanca. **2.0**

131.2 Milepost 152. Caliche at top of Cejita Blanca is visible at 1:00 and 2:00. A short distance ahead the road begins ascent of Cejita Blanca. **1.0**

132.2 Milepost 151; opposite Stop S16. Active sand dune, one of a series of dunes along Cejita Blanca, at 10:30. Roadcuts at right for next 0.2 mi exposed sediments of Ceja Member. **0.2**

132.4 West Mesa landfill at 1:00. Light-colored sediments at 2:00 are locally derived alluvium and intercalated caliches on downthrown side of County Dump fault (Lambert, 1968; Machette, 1978a). Gray hills at 3:00 are underlain by Ceja Member. The fault and associ-

FIGURE S52—LANDSAT-1 IMAGE AND INDEX MAP OF ALBUQUERQUE BASIN AND JEMEZ MOUNTAIN REGION, NORTH-CENTRAL NEW MEXICO, AREA OF STOPS S13 TO S22 (image E-1658-17091-5 courtesy of Technology Application Center, University of New Mexico; transmitted May 12, 1974; map and photo scale approximately 1:1,000,000).



[New Mexico Bureau Mines & Mineral Resources, Circular 163, 1978]

FIGURE S53—MT. TAYLOR VOLCANIC CENTER, TABLELANDS OF THE COLORADO PLATEAU, AND THE RIO PUERCO VALLEY; view is west from the Llano de Albuquerque at the top of Ceja del Rio Puerco at Stop S15. Mt. Taylor is a composite stratovolcano of Pliocene age. Mesas of the Colorado Plateau between the Rio Puerco and Mt. Taylor are capped mainly with Cretaceous sandstones. Along the western slopes of the valley opposite this viewpoint the margin of the rift is the antithetically faulted Puerco fault zone; the rift border lacks positive physiographic expression. In the low ridge immediately west of the Puerco, thinned intervals of the Santa Fe lie irregularly on, or are faulted against, pre-rift Cretaceous beds. East of the river, Santa Fe beds—including the Ceja Member at the top—are exposed in the 600-ft (200-m) Ceja del Rio Puerco (photo by P. W. Lambert).

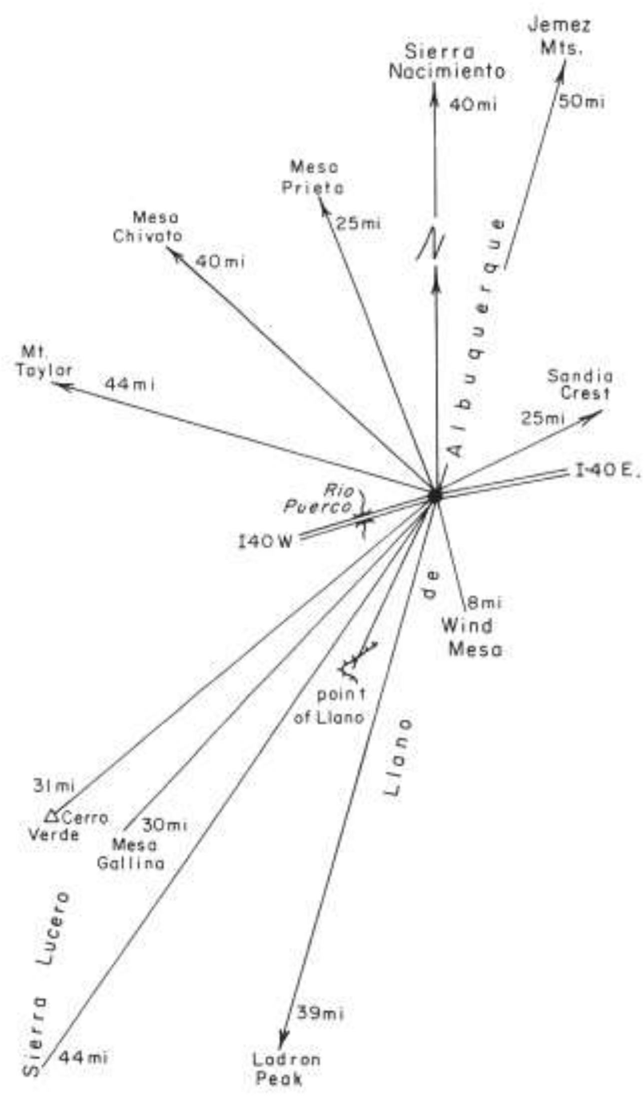


FIGURE S54—PANORAMIC INDEX OF FEATURES SEEN FROM STOP S15, CEJA DEL RIO PUERCO, ON I-25 WEST OF ALBUQUERQUE.

ated sediments will be discussed by Machette at Stop S16. 0.7

133.1 County Dump fault, or splinter fault associated with it, exposed near east end of roadcut at right. Light-colored sediments are on the downthrown (east) side of the fault, and grayish Ceja Member is on the up-thrown (west) side. *Prepare for right turn at next exit.* 0.2

133.3 *Take Central Avenue exit* (Exit 149). 0.3

133.6 Stop sign; *turn right and then bear left* (west). Travel west on frontage road along north side of 1-40. The exposure of the County Dump fault discussed at Stop S16 is located about 1.2 mi to the northeast on the power-line road that branches off the West Mesa land-fill road 0.1 mi east of this point. 0.2

133.8 Caliche developed in top of the Ceja Member is exposed in pits to left and right of road. For the next 4.5 mi the route crosses the Llano de Albuquerque (Ceja Mesa of Kelley, 1977), a former basin floor that is now preserved as a mesa summit between the Rio Grande on the east and the Rio Puerco on the west. The Llano is about 65 mi (105 km) long and up to 8 mi (13 km) wide and is generally bordered by precipitous scarps several hundred feet high. In the Albuquerque area the Llano slopes east and southeast with a gradient of 40-70 ft/mi, and is characterized by wide south- and southeast-trending valleys separated by gently rounded hills and ridges. The Ceja Member (discussed at Stop S15) underlies the Llano but is generally obscured by a thin veneer of locally reworked sediments and by eolian sand. Across the Llano de Albuquerque 1-40 travels through a partially stabilized, much subdued late Pleistocene dune field (Lambert, 1974). The field is composed of greatly elongated northeast-trending ridges of sand that T. S. Ahlbrandt (verbal communication, 1976) believes may represent the distended arms of migrating parabolic dunes. 1.2

135.0 Hill Top campground on right. Los Lunas volcano, 9:30; Wind Mesa, 9:30; Ladron Peak, 10:00; active sand dunes on west edge of Llano de Albuquerque, 10:30; Lucero Mesa, 11:00; Mt. Taylor, 1:30. 3.3

138.3 **STOP S15, Ceja del Rio Puerco.** At the top of the Ceja del Rio Puerco ("eyebrow of the Rio Puerco"),

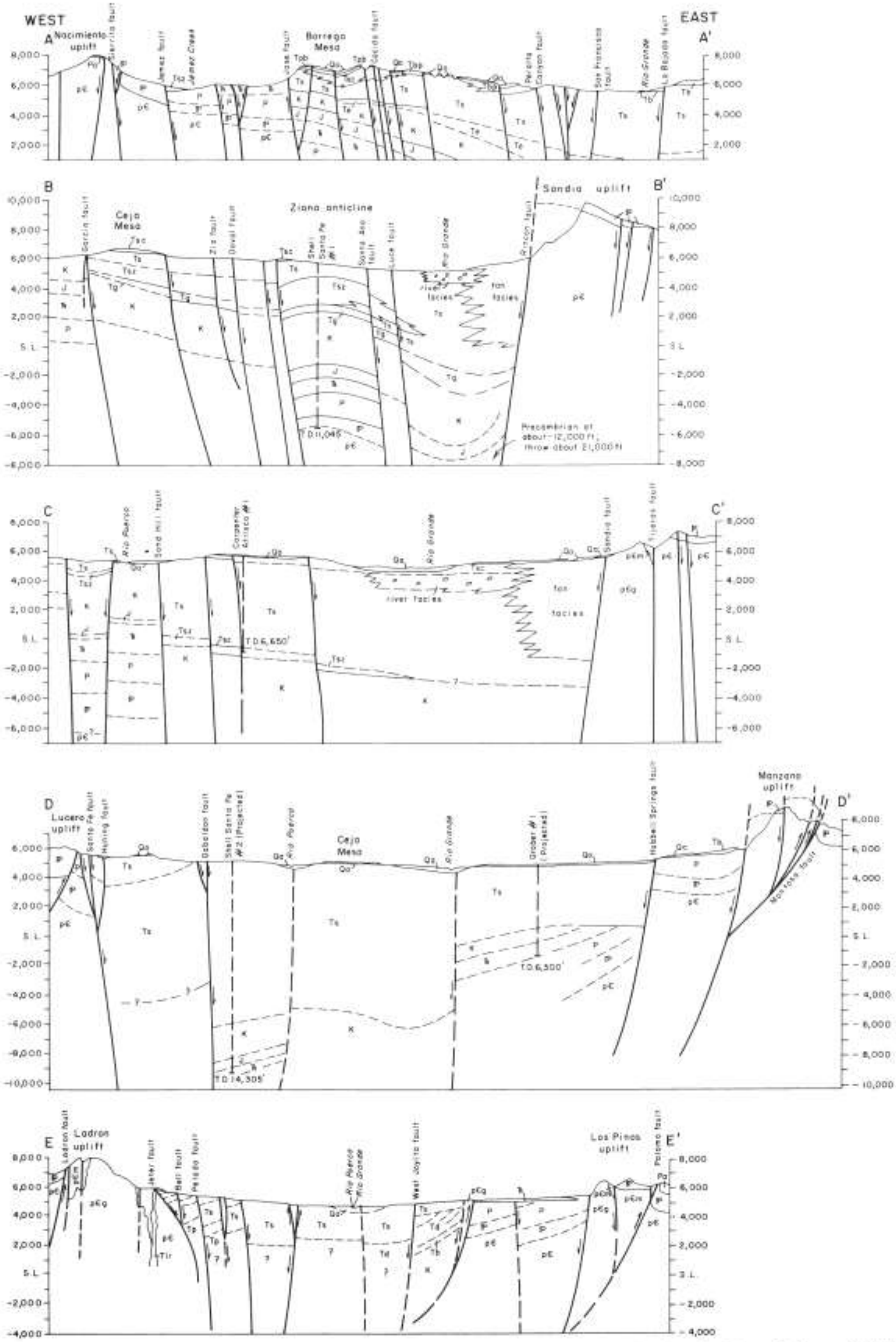


FIGURE S55—WEST-EAST STRUCTURE SECTIONS ACROSS ALBUQUERQUE BASIN. Abbreviations: pf, pfm, pfg—Precambrian undivided, metamorphics, and granitic plutons; IP—Pennsylvanian undivided, thin Mississippian locally present; P—Permian undivided; T̶R—Triassic undivided; J—Jurassic undivided; K—Cretaceous undivided; Tg—Galisteo Formation (Eocene); Td—Datil Formation (Oligocene); Te—Espinaso Formation (Oligocene); Tp—Popotosa (Miocene); Ts, Tsz, Tsc—Santa Fe Formation undivided, Zia member, Ceja Member; Tbp—Peralta Tuff Member of Bearhead Rhyolite; Tb—Basaltic flows; Qo—Ortiz pediment gravel; and Qa—alluvium undivided (from Kelley, 1977, fig. 20).

which is the scarp bordering the west side of the Llano de Albuquerque (figs. S52, S53, and S54). Assemble north of 1-40 frontage road for discussions of the rift border between the Colorado Plateau and the Albuquerque Basin and features of the western basin including the Llano de Albuquerque and associated upper Santa Fe basin fill (fig. S55 from Kelley, 1977, fig. 20). Fig. S56, from Cordell (1978), shows gravity and elevation profiles across the state at 35 ° north latitude (about 4 mi south of here).

WESTERN RIFT BORDER AND THE ALBUQUERQUE BASIN FROM THE CEJA DEL RIO PUERCO CREST ON 1-40

by V. C. Kelley

University of New Mexico, Albuquerque, New Mexico

The west rim of the Llano de Albuquerque (Ceja Mesa in Kelley, 1977) may be seen curving westward toward a point about 12 mi away (fig. S54). Directly west of that point across the Rio Puerco Valley is the northern end of the Lucero uplift, which forms the western border to the Albuquerque Basin southward for about 26 mi (41 km) to the 9,176-ft (2,797-m) pyramid-shaped Ladron Peak. The Ladron uplift is a large Precambrian mass that is bowed or horsted up from Mississippian and Pennsylvanian beds on the west and Popotosa and Santa Fe beds on the north, east, and south (fig. S55, *E-E ')*. The Lucero uplift is in many respects a rim of the Colorado Plateau, because dips to the west into the Acoma sag are mostly only a few degrees. The eastern margin of the Lucero is compound and commonly complex structurally in a narrow zone at the rift edge. An old fault, Comanche (on line with Gallina Mesa), is much curved and appears to be reverse, dipping into the Colorado Plateau. Comanche fault is most likely Laramide and may have culminated out of a very steep east-facing monocline. The rift-forming Santa Fe fault lies only 0.5-1 mi east of the reverse Comanche fault and drops upturned Santa Fe beds against Permian and Mesozoic beds of the deformed Colorado Plateau edge (fig. S55, *D-D ')*.

The northern end of the Lucero front merges into the Puerco fault zone, which is an antithetically faulted margin to the rift. From the northern end of the Lucero uplift northward along the Puerco fault belt to the southern end of the Nacimiento uplift, a distance of about 45 mi (72 km), the rift border lacks a positive physiographic expression. The rift-filling Santa Fe beds stand higher than the older Cretaceous east-dipping beds of the uplifted border (fig. S55, *B-B '* and C-C ').

In the low hills immediately west of the Puerco, at elevations 200-300 ft (60-90 m) lower than this stop, thinned intervals of the Santa Fe lie irregularly on or are faulted against pre-rift (Cretaceous) beds. East of the Rio Puerco the Santa Fe beds exposed in the Ceja del Rio Puerco slopes are nearly flat or at most dip only a few degrees easterly. One might therefore expect, barring faults, that the Cretaceous might only lie 400-500 ft (120-150 m) beneath this stop. However, exposures of tilted Santa Fe along the Rio Puerco Valley indicate thicknesses of 1,000-1,500 ft (300-450 m).

Projection of the Lucero-bounding Santa Fe fault may be made into this area (Kelley, 1977, geologic map and fig. 19) along the southwesterly course of the Rio Puerco to a junction with the Sand Hill fault in the Ceja del Rio Puerco some 6-8 mi north of the stop. In exposures of the Sand Hill fault,

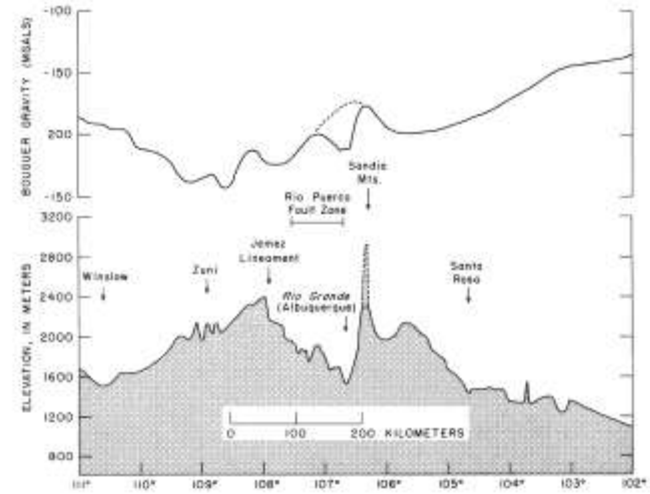


FIGURE S56—GRAVITY AND ELEVATION PROFILES ACROSS NEW MEXICO ALONG 35° NORTH LATITUDE. Dashed segment of gravity profile shows, schematically, residual broad positive anomaly upon which the more prominent gravity low, associated with graben fill, is superimposed (Cordell, 1978, with permission).

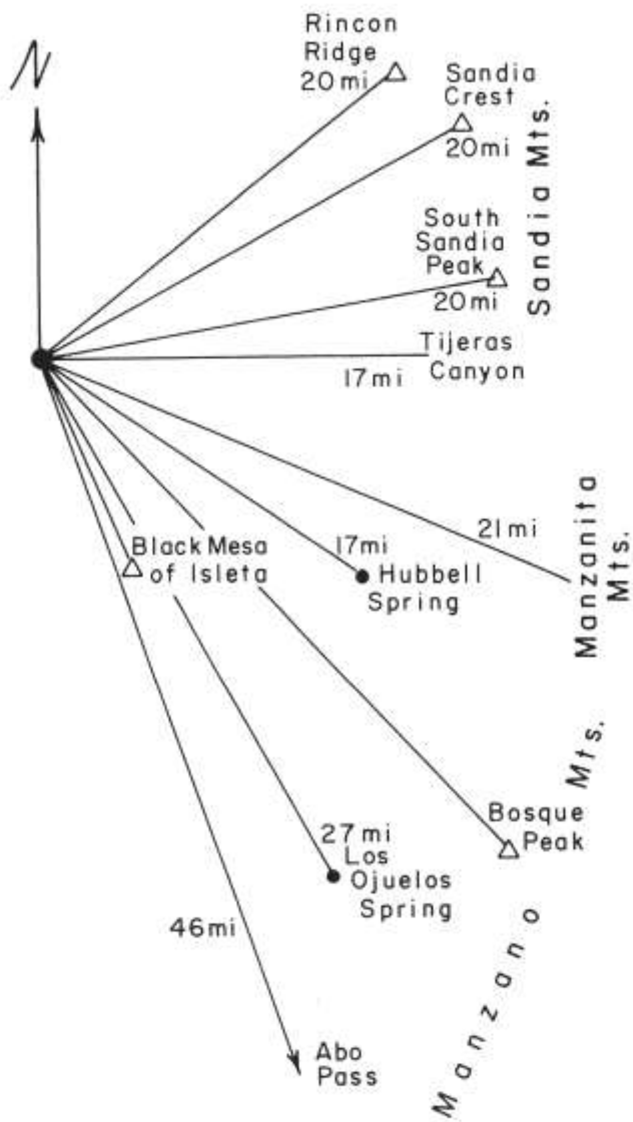


FIGURE S57—PANORAMIC INDEX OF FEATURES SEEN FROM STOP S16, ALBUQUERQUE OVERLOOK AT I-25 REST AREA WEST OF ALBUQUERQUE.

downthrow on the east does not appear to be large (fig. S55, C-C ').

In 1948 the Carpenter Atrisco #1 well was drilled on the Llano de Albuquerque along 1-40 only about 1.8 mi east of this stop (sheet 2, hole cc). This petroleum test hole was drilled to 6,650 ft (2,027 m) without reaching the bottom of the Santa Fe. Such large intervals do not exist in the outcrops to the west; furthermore, the Santa Fe strata that crop out just to the west of the Llano rim are uppermost beds. Therefore, one or more growth faults downthrown to the east between the outcrop and the well appear likely. Such a rapid increase in thickness is further supported by a marked gravity inflection very near the well location (Kelley, 1977, geologic map and fig. 19).

UPPER SANTA FE STRATIGRAPHY AND GEOMORPHIC FEATURES OF THE LLANO DE ALBUQUERQUE

by P. W. Lambert

The Ceja del Rio Puerco forms the east wall of the Rio Puerco Valley, and mesas of the Colorado Plateau form the west valley border. The Ceja Member of Kelley (1977) underlies most of the Llano de Albuquerque and consists mainly of interbedded pinkish-gray sandy-pebble gravel and gravelly sand. Grayish-pink sand, clay, and mudstone in the lower part of the scarp were considered to be lower Upper Buff formation by Lambert (1968), but Kelley (1977) has excluded these sediments from the Ceja Member. At the top of the scarp, several feet of active and inactive eolian sand overlie pedogenic caliche developed in the top of the Ceja unit. At the latitude of Albuquerque, the Ceja Member has a maximum exposed thickness of about 250 ft (75 m), and it appears to fill an asymmetric basin that was bounded on the east and southeast by the steep Sandia-Manzano uplift and on the west and northwest by a long, gentle basin slope. Clast composition and sedimentary structures indicate that the sediments in the vicinity of this stop were derived from sources to the west and north, probably in an area extending from Mt. Taylor to the Nacimiento Mountains. The location of the source area, the texture, the presence of upstream-inclined cross-strata, and the numerous small cut-and-fill structures all suggest that Ceja Member sediments in this part of the Ceja del Rio Puerco were deposited on an arid or semiarid alluvial plain (distal piedmont slope) by a network of east- and southeast-flowing subparallel shifting streams (Lambert, 1968) and that they are not the deposit of an ancestral Rio Grande. Throughout most of the Albuquerque area (for example, along the Ceja del Rio Puerco and the Cejita Blanca), the Ceja Member appears to be such a piedmont-slope or marginal basin-floor deposit. However, clean channel sand and gravel in the Ceja Member in the Albuquerque Sunport-Tijeras Arroyo area (mile 117.5) may be the deposits of a through-flowing ancestral Rio Grande. East of these possible axial stream deposits the Ceja Member appears to interfinger with arkosic alluvial-fan sediments derived from the Sandia-Manzano uplift.

Vertebrate fossils collected from the upper part of the Ceja Member in the vicinity of the Albuquerque Sunport indicate that that part of the member is early Pleistocene (late Blancan) in age (chart 1). Several lines of evidence suggest that the basin floor or slope represented by the Llano de Albuquerque is probably about 0.5 m.y. in age. The evidence includes 1) the age of the vertebrate fossils collected from the Ceja Member in the Sunport area (Lambert, 1968, 1969), 2) K-Ar and tephrochronologic dating of volcanic materials in and overlying the Upper Buff-Ceja-Sierra Ladrones units at the Los Lunas and Albuquerque volcanic centers (Bachman and Mehnert, 1978; Stop S14 discussion), and 3) pedologic dating of soil-geomorphic sequences (Bachman and Machette, 1977; Machette, 1978a). Both the Rio Grande and Rio Puerco Valleys have been excavated below the Llano de Albuquerque surface; if the age estimate above is correct, they are younger than mid-Pleistocene. For many years the Llano de Albuquerque has been considered a remnant of the widespread Ortiz erosion surface (Bryan, 1938; Bryan and McCann, 1938; Kelley, 1977), but recently Bachman and Mehnert (1978) have presented evidence that the Ortiz surface is about 3 m.y. old, much older than the Llano de Albuquerque. Aggradation of this central-basin plain presumably continued long after initial development of broad piedmont erosion surfaces in peripheral basin zones (for example, type Ortiz area-see Stops S19 and S20). After stop, *continue west on frontage road.* **0.4**

138.7 Cattle guard. Road ahead descends alluvial-fan apron that stretches west from base of Ceja del Rio Puerco. **2.1**

140.8 Fine-grained pinkish sediments in hills to right of road were mapped as undivided Santa Fe Formation by Kelley (1977). **1.5**

142.3 Cattle guard. Basalt of La Mesita Negra at right. **0.4**

142.7 Frontage-road bridge across Rio Puerco, the longest tributary entering the Rio Grande in New Mexico (see mile 48.3). In the mid-to-late 19th century, after a long period of aggradation, the Rio Puerco began to cut a steep-sided arroyo throughout most of its course. The process is continuing today at least in parts of the middle to upper reaches of the drainage basin. 0.3

143.0 Stop sign. *Turn left, cross 1-40 overpass, and prepare to enter 1-40 eastbound* (Albuquerque). **0.2**

143.2 *Turn right on 1-40 East* approach ramp. **0.3**

143.5 1-40 bridge across Rio Puerco. Note steep-sided arroyo. **1.9**

145.4 Sediments in roadcut on north side of 1-40 were mapped as undivided Santa Fe Formation by Kelley (1977). Cerro Colorado at 3:00 is a complex latite plug dome in Santa Fe beds (Wright, 1943). Ceja del Rio Puerco ahead. **2.1**

147.5 Roadcuts expose Ceja Member and caliche developed in upper Ceja sediments. **0.5**

148.0 Milepost 145. Top of Ceja del Rio Puerco. Llano de Albuquerque ahead. **1.3**

149.3 Low ridges on Llano to right (south) of 1-40 are parabolic(?) sand dunes. **2.8**

152.1 Exit 149, Central Avenue. *Continue east* on 1-40. 0.7

152.8 East edge of Llano de Albuquerque. Road begins descent on Cejita Blanca. *Prepare to take rest area exit.* **0.3**

153.1 Roadcut on right exposes locally derived sediments on downthrown side of County Dump fault. **0.5** 153.6 *Exit right to rest area.* **0.3**

153.9 **STOP S16, Albuquerque overlook.** At rest area west of Albuquerque overlooking the Rio Grande Valley. Assemble on dune-covered hill west of rest area for discussions of the eastern Albuquerque Basin, the rift-bordering Sandia-Manzano range, and Quaternary faulting at the east edge of the Llano de Albuquerque (figs. S57 to S59).

FIGURE S58—Oblique air view of northern Sandia Mountains from above Stop S16 area. Rio Grande and Albuquerque in foreground. The crest of the Sandias is capped with about 700 ft (210 m) of Pennsylvanian marine limestone. The bold escarpment consists mostly of 1,400-m.y. porphyritic granite.

FIGURE S59—Manzano Mountains and east-central Albuquerque Basin; view is southeast across Rio Grande Valley from near Stop S16. The southern tip of the Manzanita Mountains is on upper left. The Manzanos (Mosca and Bosque Peaks to north of center and Osha and Manzano Peaks to the south) are capped with Pennsylvanian limestones, shales, and sandstones. These strata overlie a complex series of Precambrian metamorphic and intrusive rocks that form the main escarpment of the range. Black Mesa of Isleta is at far right center (photo by P. W. Lambert).

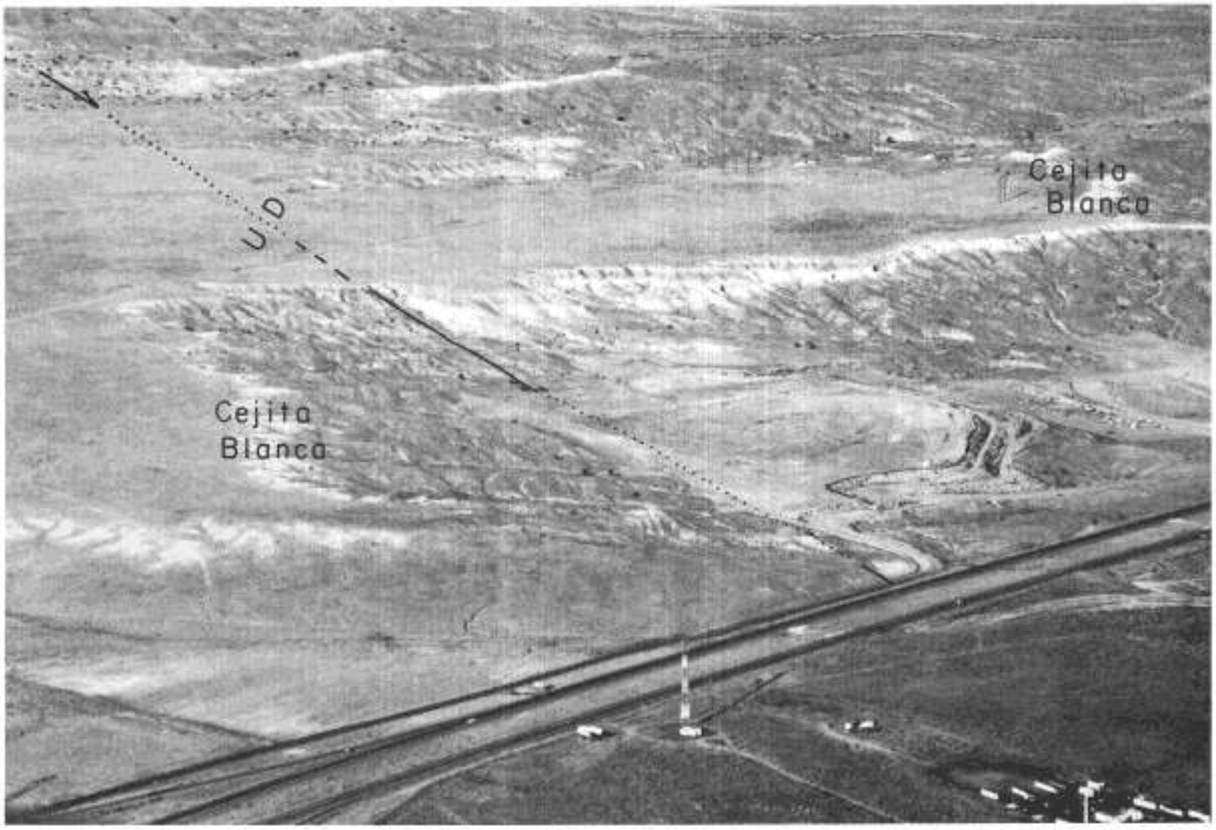


FIGURE S60—OBLIQUE AIR VIEW OF BERNALILLO COUNTY SANITARY LAND FILL AREA AND SITE OF COUNTY DUMP FAULT of Machette (1978a; Stop S16). View is to northeast from over western end of Central Avenue; I-25 crosses scene in foreground. Fault is shown by dashed and dotted line. White, soil-carbonate zone of Cejita Blanca rim caps gravelly to sandy beds of the Ceja Member. The zone separates into multiple paleosol horizons in wedge of colluvial and eolian deposits that mantles the downthrown block.

EAST RIFT BORDER AND THE ALBUQUERQUE BASIN FROM 1-40 ALBUQUERQUE REST AREA

by V. C. Kelley

At this stop one gets a grand vista of the 60-mi (100-km), bold, and nearly straight east-bordering uplifts of the Albuquerque Basin (figs. S52, S57). From north to south the uplifts are Sandia, Manzanita, Manzano, and Los Pinos. Faults bounding the rift closely follow the bases of the uplifts. The Sandia uplift (fig. S58) is tilted eastward at about 14 degrees. Its bold facade consists mostly of 1,400-m.y.-old porphyritic granite, which is veneered by some 700 ft (210 m) of Pennsylvanian marine limestone that can be seen along the skyline (fig. S55, *B-B ')*. At Stop S18 details of the northern end will be seen and discussed. The southern end of the range is almost due east at Tijeras Canyon through which 1-40 passes (fig. S55, C-C '). The Manzanita Mountains (fig. S57), south of 1-40, are the low, flat section that stretches for about 14 mi between the higher Sandia and Manzano uplifts. The Manzanitas are more a dissected plateau than an uplift, and the Pennsylvanian beds which form most of the front are flat-lying for many miles to the east.

The Manzano uplift (fig. S59; also discussed at Stop S13) is about 29 mi (47 km) in length; except for a few high Pennsylvanian caps, the escarpment consists of Precambrian granites and metamorphic rocks (fig. S55, *D-D')*. About the upper one-half of the relief is probably due to Laramide uplifting on high-angle reverse faults that lie east of the crest of the range (Kelley, 1977, p. 37). The rift-bounding Manzano fault along the base of the uplift has given the extra west-side relief to the range. At the southern end of the Manzanos (near Stop S13) the Manzano normal fault converges with the west-dipping Laramide Paloma and Montosa thrusts on the east side of the range. The resulting thin strip of Precambrian rocks, between the overridden Pennsylvanian beds on the east and the rift fill on the west, has given rise to a low pass through Abo Canyon. South of the pass, the faults diverge again and the Los Pinos uplift is a horst between the west-dipping (rift) normal and Laramide reverse faults (fig. S55, *E-E ')*.

Out about 3-6 mi from the bases of the Manzano and Manzanita uplifts there is a long structural bench (Joyita-Hubbell bench, Kelley, 1977, fig. 19). Along the northern part of this bench the western edge is marked by the Holocene Hubbell Springs fault and scarp, up to 135 ft (40 m) high. The upthrown bench is formed on pre-rift Pennsylvanian, Permian, Triassic, and early Tertiary rocks; it is veneered by pediment and alluvial fan gravels and possibly some thin Santa Fe beds. West of the Hubbell Springs fault the Santa Fe thickens abruptly and rapidly toward the Rio Grande (fig. S55, *D-D ')*.

BERNALILLO COUNTY DUMP FAULT

by M. N. Machette

The eastern edge of the Llano de Albuquerque surface is well displayed near the Bernalillo County dump, about 6 mi (10 km) west of Albuquerque. A strongly developed relict calcareous soil (called caliche by other authors) forms a resistant, light-colored cap and contributes to the prominent topographic scarp that borders the Llano de Albuquerque. Near the northwest corner of the Bernalillo County dump (figs. S60 and S61), a high-angle, east-dipping normal fault displaces the Llano de Albuquerque surface (Machette, 1976; 1978a). The surface, where constructional, is believed to be about 0.5 m.y. old (Hawley and others, 1976; see Stop S15). Here, the underlying basin-fill sediments, which are the youngest beds of the Santa Fe Group, are composed of coarse-grained sand and well-rounded pebble and cobble gravel (Upper Buff formation of Lambert, 1968). On the downthrown (east) side of the fault, four buried calcareous paleosols are formed in, and separated by, deposits of eolian sand and fault-scarp colluvium (fig. S62).

Fault-produced scarps that face in a leeward direction form effective traps for eolian sand. Thus, east-facing fault scarps on the Llano tend to be rapidly buried by eolian sand; the resultant stable geomorphic features are broad, generally north-south trending swales.

The total amount of pedogenic carbonate (in a soil-column of unit area) in the four buried soils (V, X, Y, and Z) and the surface soil (U) of the downthrown block is greater than that in the eroded Llano de Albuquerque soil at sample locality **a** (fig. S61). The composite section of buried soils represents a maximum content of pedogenic calcium carbonate, whereas relict soils, such as at locality f (fig. S61), are more typical of the Llano.

The model used for estimating soil ages (Bachman and Machette, 1977) assumes that pedogenic carbonate accumulated at a uniform rate throughout the duration of soil formation. Hence, the age of the soil is proportional to the pedogenic carbonate content (more complete discussion available in Machette, 1978a). Using soil ages thus derived, the history of the County Dump fault can be documented. Episodic movements occurred on this segment of the fault at the following times: 400,000 years B.P., more than 25.6 ft (7.8 m) net vertical displacement; 310,000 years B.P., 13.4 ft (4.1 m) displacement; 120,000 years B.P., 9.8 ft (3.0 m) displacement; and 20,000 years B.P., 6.9 ft (2.1 m) displacement (fig. S63). The total vertical displacement during the past 400,000 years amounts to about 56 ft (17 m). Short periods of stability (less than 10,000 years) would be represented by soils so weakly developed that they might not be distinguishable within the exposed section.

The uppermost soil (U) is weakly developed and characterized by small filaments and veinlets of calcium carbonate. Based on the pedogenic calcium carbonate content, this soil has been forming during the past 20,000 years. This soil and the deposit in which it is formed (fig. S63, unit E) are not cut by the fault.

The fault bifurcates north of the dump, but the major segment continues on a N. 6° E. trend (fig. S61). This trend is directly in line with the Albuquerque volcanoes, a string of seven small volcanoes and associated spatter cones. Bachman and others (1975) dated the oldest flows at 190,000 ± 40,000 years B.P. These flows mantle the eroded eastern edge of the Llano and form a structural bench overlying late Quaternary stream gravels of the Rio Grande. A sequence of younger flows is also present, one of which lies on the Segundo Alto (Lambert, 1968), a 140-ft (43-m) high Rio Grande terrace. The Segundo Alto is correlative with the 120,000-year-old Qt: terrace of the San Acacia area (Bachman and Machette, 1977). The Albuquerque volcanoes appear to have been episodically active from about 200,000 to at least 120,000 years B.P.; no doubt this volcanic activity has been intimately related to the County Dump fault and the other extensional faults that are so prevalent throughout the AlbuquerqueBelen Basin.

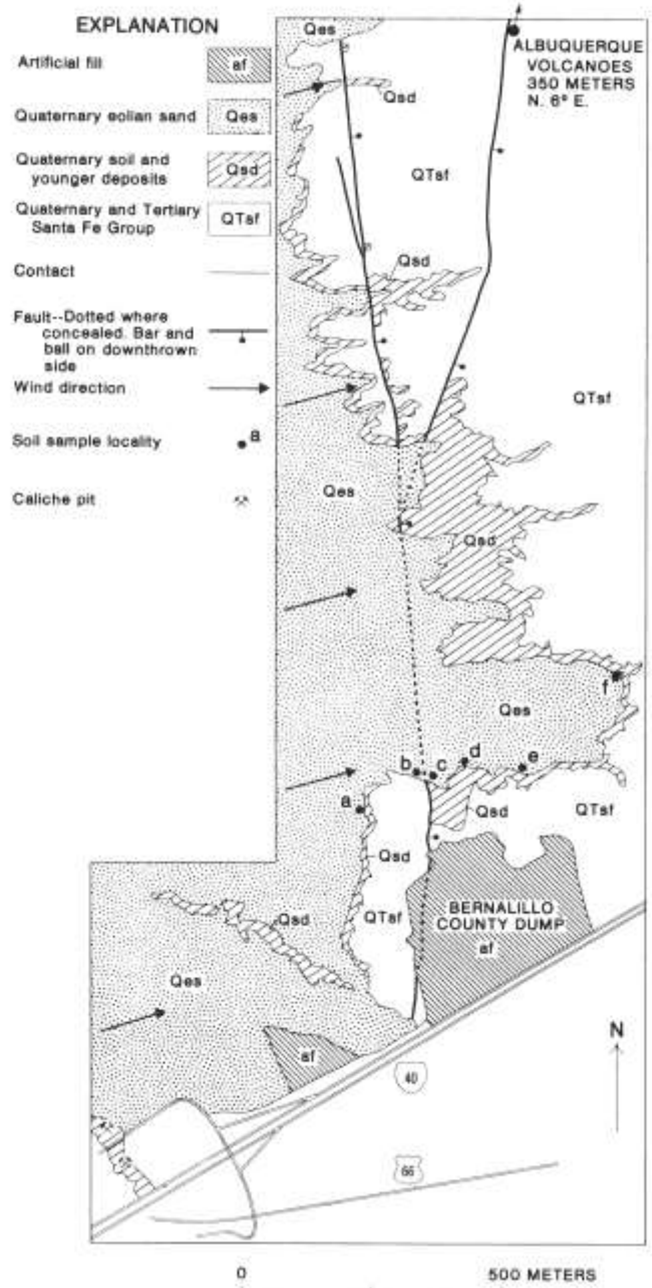


FIGURE S61—Geologic map of the area adjacent to the County Dump fault northwest of Stop S16 and about 6 mi (10 km) west of Albuquerque.

After stop continue east on I-40. **1.4**

155.3 Underpass; Albuquerque volcanoes at 9:00. **1.7**

157.0 Milepost 154. Route descends to Segundo Alto surface. **1.1**

158.1 Underpass; Coors Road. Route descends to floodplain. **0.6**

158.7 West abutment of I-40 bridge across Rio Grande. **1.3**

160.0 Rio Grande Boulevard overpass. **0.8**

160.8 8th-6th Streets exit. *Keep left; prepare to enter I-25 north.* **1.4**

161.2 *Take I-25 north exit.* **0.4**

161.6 *Merge with I-25.* **0.5**

162.1 Underpass, Candelaria Road. Route is crossing outcrop belt of alluviums of Edith and Menaul

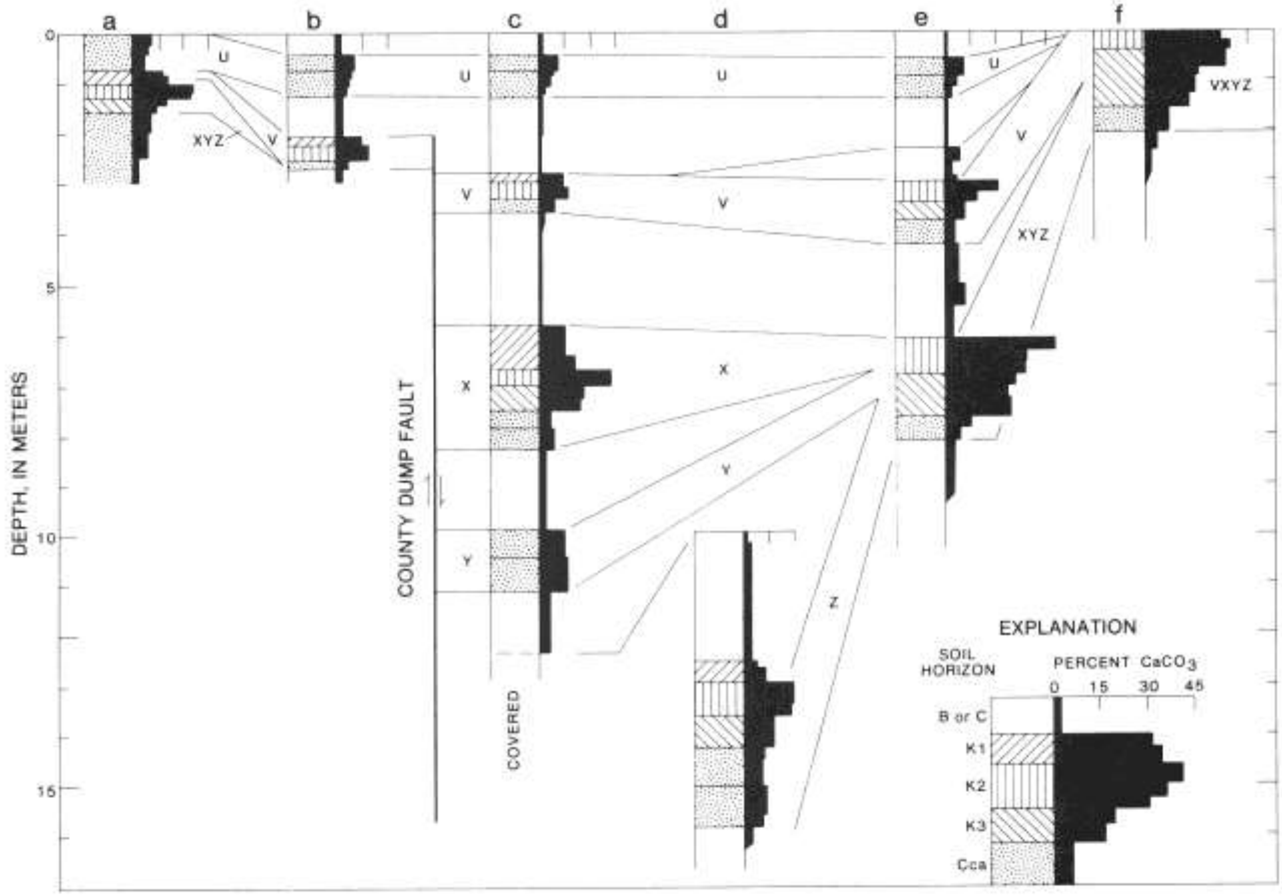


FIGURE S62—DIAGRAMMATIC CROSS SECTION THROUGH SOIL SAMPLE LOCALITIES a-f NORMAL TO THE COUNTY DUMP FAULT, showing correlation of soil parent materials, soil horizons, and carbonate distribution.

Boulevards (Lambert, 1968). The Menaul is a river-terrace deposit younger than the Edith. These terrace deposits are discussed at mile 178.3. **0.6**

162.7 The large flat areas west of 1-25 for the next mile are reclaimed gravel pits in the alluvium of Edith Boulevard. **1.0**

163.7 Underpass, Montgomery Boulevard and Montano Road. **2.0**

165.7 San Mateo Boulevard overpass. Route is now east of the outcrop belt of the alluviums of Edith and Menaul Boulevards and for the next 3.5 mi is across a distal, Holocene portion of the Sandia piedmont plain. **2.6**

168.3 Milepost 233. *Prepare to turn right in 0.7 mi.* On skyline at 3:00 is the contact between Precambrian igneous and metamorphic rocks and Paleozoic sedimentary rocks near top of Sandia Mountains. The steep spur of the Sandia Mountains at 1:00-2:00 is Rincon Ridge. It is composed of Precambrian metamorphic rocks intruded by pegmatite dikes. **0.7**

169.0 *SLOW. Take Exit 234 and prepare to turn right.* **0.3**

169.3 Stop sign. *Turn right (east) onto Tramway Road (NM-556).* **0.2**

169.5 Road ascends Sandia piedmont plain (Llano de Sandia of Machette, 1978a). The plain, known locally as the East Heights or East Mesa, is a partially dissected surface 7-8 mi wide that slopes westward from the Sandia Mountains to the inner valley of the Rio Grande. **1.8**

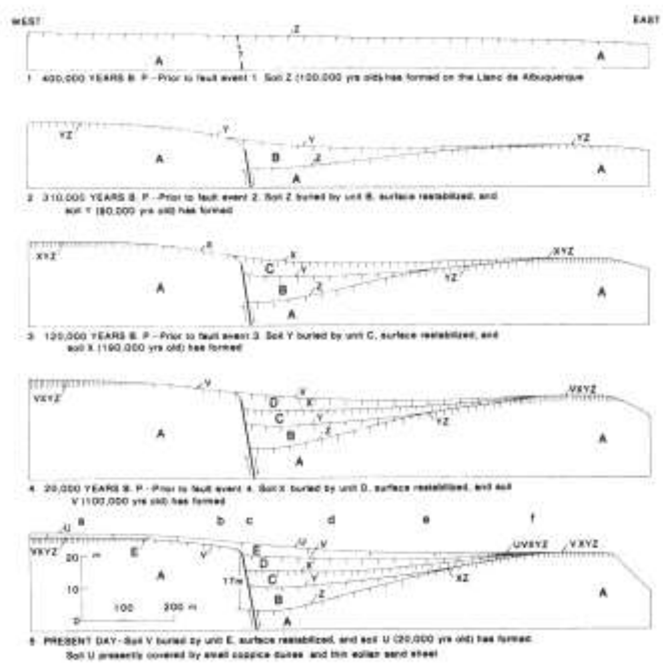


FIGURE S63—DIAGRAMMATIC CROSS SECTION, NORMAL TO THE COUNTY DUMP FAULT, illustrating fault history during the past 400,000 years.

171.3 **STOP** S17, Tramway **Road.** On Llano de Sandia about 2 mi west of Rincon Ridge of the northern Sandias (fig. S64). *Park vehicles on dirt road to right.*

Most of the Sandia plain is a coalesced alluvial-fan piedmont, but near the mountain front the piedmont consists mainly of alluvial fans and fan aprons together with some pediments and rock fans cut on granite. In places the piedmont surface has been dissected by subparallel west-flowing streams into a ridge and valley topography. Yellow to orange, upper Pleistocene alluvium underlies the low ridges, and Holocene alluvium underlies the grass- and shrub-covered alluvial terraces in the bottoms of the arroyos. The alluvium is predominantly arkosic sandy gravel and gravelly sand; fragments of mica schist and granite pegmatite are abundant in deposits west of Rincon Ridge.

Stearns (1953a, p. 475-476) describes the 5,024-ft (1,531-m) deep Norins Realty Co. exploratory well drilled about 2.5 mi south-southwest of here. According to the driller's log furnished by R. L. Bates, the upper 2,150 ft (655 m) is dominated by coarse, granite-derived basin fill interpreted by Stearns as "Santa Fe Formation." The lower 2,874 ft (876 m) penetrated includes mainly "gray sand" and "gray shale," which Stearns (p. 475) believes are "Tertiary, younger than Galisteo Formation and older than the Santa Fe Formation." These beds would thus be in the stratigraphic interval of the Zia Sand Formation of Galusha (1966) or the Lower gray member of Bryan and McCann (1937). The Galisteo-Zia-Santa Fe sequence (chart 2) is discussed in the Bernalillo to Santa Fe (Stops S18-S21) and Bernalillo to San Ysidro (Stop S22) road-log sections.

GRAVITY PROFILE ALONG TRAMWAY ROAD

by Lindrith Cordell
U.S. Geological Survey, Denver, Colorado

For this stop we have taken a side trip in order to study a geophysical cross section in the field. We are on one of the steep, linear gravity gradients that delineate the master boundary faults of the complex series of grabens along the axis of the Rio Grande rift (fig. S65). The surface is a dissected alluvial fan at the foot of the Sandia Mountains, about 3 mi (5 km) west of the eroded fault scarp. At the position labeled "Albuquerque" in fig. S65, a detailed gravity profile of the mountain front to the main north-south highway (1-25), extended on the basis of regional geophysical data (fig. S65), is shown in fig. S66. Individual observations are indicated by the black dots. In some cases these observations are projected a few tens of meters onto the line of the profile. The regional reconnaissance gravity map, a portion of which is shown in fig. S65, is discussed by Cordell (1976).

A density distribution compatible with the gravity profile is indicated on the bottom of fig. S66. Alluvial basin fill and pre-graben sedimentary strata are lumped together in a unit called "sedimentary rocks"; this unit has an estimated average density contrast with basement rocks of — 0.4 gm/cm^3. Basin fill, having a density contrast of about — 0.5 gm/cm^3, accounts for most of the low-gravity anomaly. The other density unit represents "basement rocks," and the derived interface represents the basement surface. The small steps are an artifact of the computer program, which used prismatic body elements.

The gravity data indicate a very large buried fault approximately at the site of the field-trip stop. A smaller buried fault is suggested about 1.2-2 mi (2-2.5 km) to the east. Regional gravity data (fig. S65) indicate that these faults may represent a left-lateral en echelon pair rather than two step faults: structural relief on the large fault at the field trip site probably decreases southward, whereas structural relief on the fault to the east increases southward.

Structural relief of the buried fault is at least 1-2 km. This structural relief occurs on a single large, steep fault (rather than on either a gently dipping fault or on a series of step faults) and that this and similar major, widely spaced faults delineated by gravity gradients constitute a system of master faults defining the Rio Grande rift.

Return to 1-25 north. 2.0

173.3 *Turn right (north) onto 1-25 approach ramp.* Route ahead is on upper Pleistocene and Holocene alluvial-fan deposits. 2.9

176.2 Here the route crosses the outcrop belt of the alluviums of Edith Boulevard and Menaul Boulevard (see mile 178.3). Low hill at right is composed of gravel of the Edith unit. Road ahead is on Holocene alluvial-fan deposits. 0.3

176.5 Sandia Pueblo at 3:00. Sandia (1970 population: 198; area: 22,884 acres) was established around 1300 A.D. It was one of the pueblos visited by Coronado in 1540-1541 when he headquartered his troops in the nearby pueblo of Mohi Tiguex (Coronado State Monument, Bernalillo), now in ruins (U.S. Dept. of Commerce, 1974, p. 373). **1.0**

177.5 Bridge across Sandia Wash. Gravel of Edith Boulevard unit is exposed on right side of road at north end of bridge (see mile 178.3). For the next 4 mi, 1-25 is routed along the scarp bordering the east side of the Rio Grande floodplain. The scarp has been formed by downcutting and lateral migration of the Rio Grande and subsequent dissection by its west-flowing tributaries. Red sandstone and mudstone of the Santa Fe Group (lower Santa Fe-red member of Spiegel, 1961; or Middle red member, Kelley and others, 1976) are exposed in the lower part of the scarp. Bailey and others (1969) correlate the "red member" with the Cochiti Formation (refer to Bernalillo to San Ysidro log). The Santa Fe beds are overlain by a sequence of upper Pleistocene terrace and alluvial-fan deposits that are described in the next road log entries. **0.8**

178.3 Milepost 239. The Bernalillo measured section of Lambert (1968, p. 267) is exposed in roadcuts just north of the milepost. The section extends from the base of the scarp west of the highway to the top of the roadcut east of the highway. The Middle red member crops out in the lower part of the scarp west of the highway. The alluvium of Edith Boulevard is exposed in the lower one-third of the roadcut east of the highway, a layer of orange alluvial-fan material in the middle one-third, and the alluvium of Menaul Boulevard in the upper one-third. East of the roadcut this alluvium is overlain by an unnamed alluvial-fan sand and gravel.

COMPILER'S NOTE—Lambert's (1978) alluviums of Edith and Menaul Boulevards are herein designated,

FIGURE S64—EAST-TILTED SANDIA UPLIFT AND LLANO DE SANDIA; view from Loma Barbon (mile 6.3 of Bernalillo to San Ysidro log) across Rio Grande Valley at Bernalillo. Stop S17 is on Llano de Sandia on far right center, and Stop S18 is on high piedmont surface just north of left center. The crest of the range above the bold escarpment of Precambrian rocks is capped by resistant limestone ledges of the Madera Formation over sandstone, shale, and limestone of the Sandia Formation (both Pennsylvanian). The upper Paleozoic section, locally including thin Mississippian rocks at the north and south end of the range, rests on a smooth erosion surface cut on Sandia Granite. Rincon Ridge, to right of center, is composed mainly of resistant quartz-mica schist and quartzite that are cut by a prominent swarm of pegmatite dikes. At the base of Rincon Ridge, late Quaternary displacement along the Rincon fault has offset upper piedmont slopes of the Llano de Sandia (photo by P. W. Lambert).

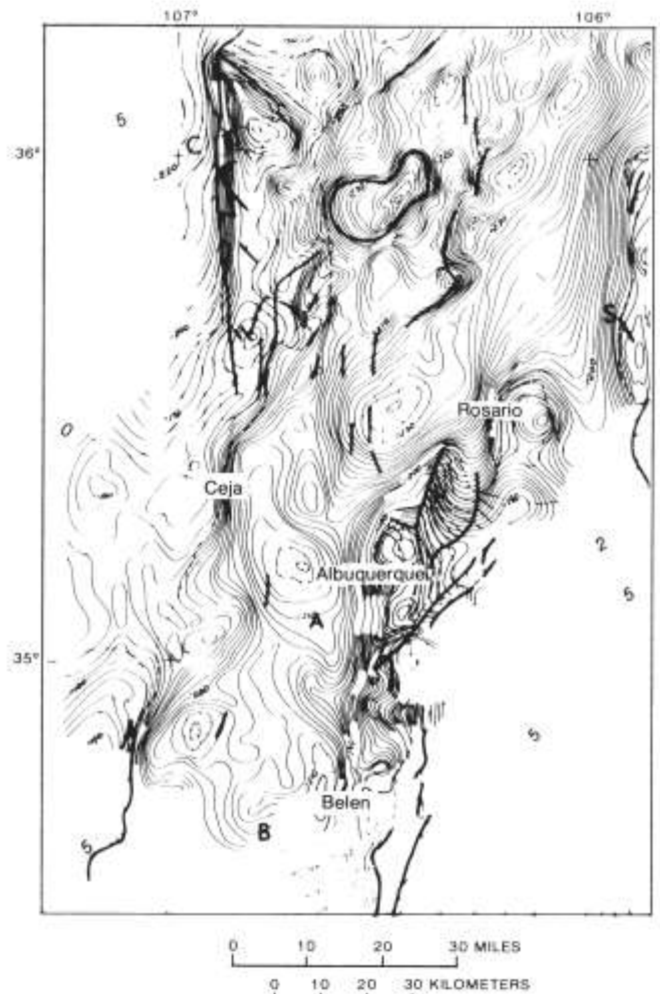


FIGURE S65—COMPLETE BOUGUER ANOMALY GRAVITY MAP OF PART OF RIO GRANDE RIFT IN NEW MEXICO. Solid contours show gravity at 2 mgal contour interval; dashed contours show basement elevation in thousands of feet (not known within the grabens, delineated by gravity lows). Heavy lines show major mapped faults. Albuquerque Tramway gravity profile shown by label "Albuquerque" (map modified from Cordell, 1976).

respectively, the Edith unit and the Menaul unit, or simply the Edith and Menaul.

The Edith unit is an upper Pleistocene Rio Grande terrace deposit with a maximum thickness of 40-50 ft (12-15 m); it is composed of gray sandy gravel and light-colored overband mud and sand. The gravel is characterized by abundant, well-rounded pebbles and cobbles of metaquartzite. The Edith is exposed along the east side of the Rio Grande between Albuquerque and Bernalillo and occurs on both sides of the river in Albuquerque. It overlies rock units of several different ages and contains a Rancholabrean (late Pleis-

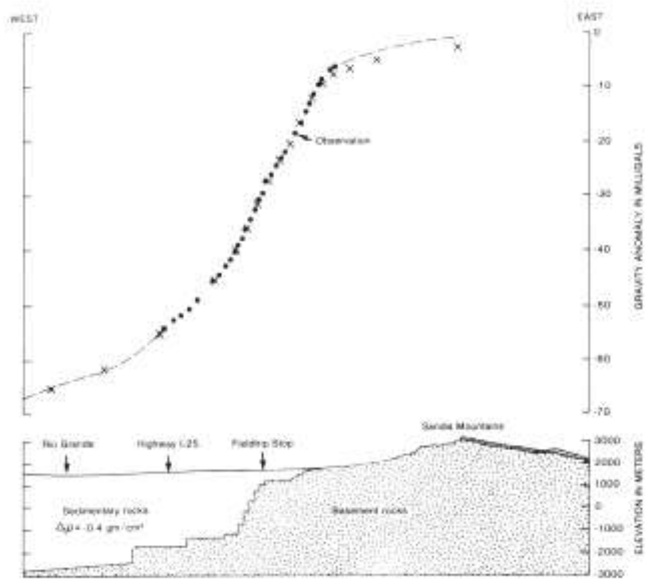


FIGURE S66—ALBUQUERQUE TRAMWAY GRAVITY PROFILE (upper figure) AND INTERPRETIVE MODEL (lower figure). Bouguer gravity minus an arbitrary datum shown at observation points (projected to profile line) by black dots. Gravity calculated from model shown by "x." Vertical and horizontal scales are the same on the lower figure. Paleozoic sedimentary rocks on the Sandia Mountains are shown by a dotted pattern.

tocene) fauna (chart 1). The Edith is not an axial stream deposit within the Middle red member, in contradiction to recent statements by Kelley and others (1976, p. 21) and Kelley (1977, p. 16).

The Menaul unit is a Rio Grande terrace deposit younger than the Edith and is composed of gray sandy-pebble gravel and overbank deposits. It is 10-25 ft (3-8 m) thick and overlies a wedge of alluvial fan sediment that rests on the Edith. Gravel in the Menaul contains less metaquartzite and more granite and intermediate volcanics than does gravel in the Edith unit. The Menaul crops out along the east side of the Rio Grande from a point 0.6 mi north of the Bernalillo measured section south to Albuquerque.

Hoge (1970, p. 75) believes that the Edith is younger than the Menaul and inset into it, but exposures in this vicinity clearly indicate that the Menaul physically, as well as stratigraphically, overlies the Edith. The coarseness of the Edith and Menaul suggests that these units were deposited during a glacial interval when the Rio Grande probably had a much greater discharge than at present. The roadcuts between here and Bernalillo mainly expose these upper Pleistocene units. The Middle red member is generally visible only in the bottoms of the deeper arroyos. In many places overlying sediments have been eroded off of the more resistant gravels of the Edith and Menaul units leaving well-developed stripped-structural surfaces. **0.6**

178.9 Large arroyo. The Menaul unit is absent north of this point. The belt of Menaul deposition was either west of this area or the unit was removed by erosion. **0.6**

179.5 Arroyo crossing. About 700 ft east of 1-25, just east of the high-tension line, a small normal fault offsets the Edith unit and overlying alluvial-fan deposits (fig. S67). The fault is not visible from the highway but is well exposed in a small tributary on the south side of the arroyo and in arroyos to the south. The fault strikes N. 12° E. and dips about 80° NW. It can be traced across the arroyos and intervening ridges for a distance of about 950 ft (290 m). Dip separation, as measured on the base of the Edith overbank sediments, is 17 ft (5 m). Because it offsets an upper Pleistocene terrace deposit, this fault is one of the youngest known faults in the Albuquerque area (see discussion of County Dump fault, Stop S16). **0.5**

180.0 Overpass, Exit 240. Bernalillo to left. *Prepare to take next (Placitas) exit.* **1.4**

End of Rio Grande bridge-Bernalillo segment of road log.

BERNALILLO TO SANTA FE

by J. W. Hawley and F. E. Kottlowski
New Mexico Bureau of Mines and Mineral Resources, Socorro, New Mexico

181.4 *Take Exit 242,* NM-44 east to Placitas (Stop S18). **0.5**

COMPILER'S NOTE-Road-log and tour-stop entries from miles 181.9-186.4 adapted from guidebook by Kelley and others (1976, miles 56.1 to 60.6, and 66.6).

181.9 Road tops surface of dissected alluvial fan. Excellent views of the plunging northern end of eastward-tilted Sandia uplift for next 2 mi ahead.

The route enters an area where the Tertiary geology was originally mapped by another of Kirk Bryan's students, C. E. Stearns (1953a, b; his Galisteo-Tonque area). The area is also the subject of recently published work on the Sandia Mountains (Kelley and Northrop, 1975) and the northern Albuquerque and Santo Domingo Basins (Kelley, 1977). **1.8**

183.7 At 12:00 knob near base of uplift is part of downthrown, north-dipping Pennsylvanian and Permian beds in a ramp structure occurring between the northward-running Rincon fault (along base of uplift from 12:00 to 2:30) and the San Francisco fault. The latter fault is 3 mi to east, beginning near the northern end of the sloping skyline of the Sandias (Kelley and Northrop, 1975, map 3). The Rincon fault was designated the Bernalillo fault by Stearns (1953a).

The low hills from 9:00 to 12:00 beyond the surface of the road are an eroded fault scarp. Stop S18 is at water tank on hill at 10:30. 0.6

184.3 Fanglomerate of Santa Fe exposed in arroyo walls and in gully to left of road. These beds dip about 9 degrees easterly toward the basin-bounding fault exposed in the roadcut around curves ahead. The dipping fanglomerates are part of the limb of a northerly plunging syncline in the Santa Fe and also a part of the Sandia structural ramp. 0.7

185.0 Basin-bounding fault in roadcut is between Santa Fe fanglomerates and Mancos Shale (Cretaceous). The fault here is a middle member of a splay of faults from the northern end of the Rincon fault and is termed Ranchos fault north of here (see Stop S18). 0.3

185.3 Knob at 9:00 has Ranchos fault near its top with olive-drab Mancos on this side and fanglomerate on top and west side. Ranchos fault passes just below the brown-and-white house on slope across valley at 2:00 and below hill with water tank (Stop S18). Note steeply north dipping Mancos in roadcut to right of road. *SLOW, prepare for left turn* at Ranchos de Placitas road ahead. 0.4

185.7 *Turn left on paved road into Ranchos de Placitas subdivision.* **0.1**

185.8 Ridge to right, north of road, is basal fanglomerate of Santa Fe. This fanglomerate lies beneath the limestone- and Precambrian-bearing fanglomerates that are much higher in the Santa Fe section. The basal fanglomerate of the ridge to the north has no limestone fragments and is made up mostly of red Permian sandstone boulders. It dips 30-45 ° N. and unconformably overlies Galisteo beds (Eocene) that dip 60-70° N. along the base of the ridge. Note step-faulted basalt flows of the San Felipe volcanic field across the Rio Grande Valley from 11:30 to 1:30. 0.3

186.1 Road forks. *Take right fork.* 0.1

186.2 Fork, *stay right on paved road.* 0.2

186.4 **STOP S18, Placitas overlook.** Intersection of Juniper Road and Cholla Lane. *Walk west to top of hill* with water tank for outstanding view (figs. S52 and S68). Structures of the northern end of the Sandia uplift and, especially, the ramp descent into the Rio Grande trough can be seen from this stop (figs. S69 and S70). After discussion, *walk to the arroyo to the north* to see the Ranchos fault, the downthrown younger fanglomerate of limestone fragments, the older reddish fanglomerate containing chiefly reddish sandstone

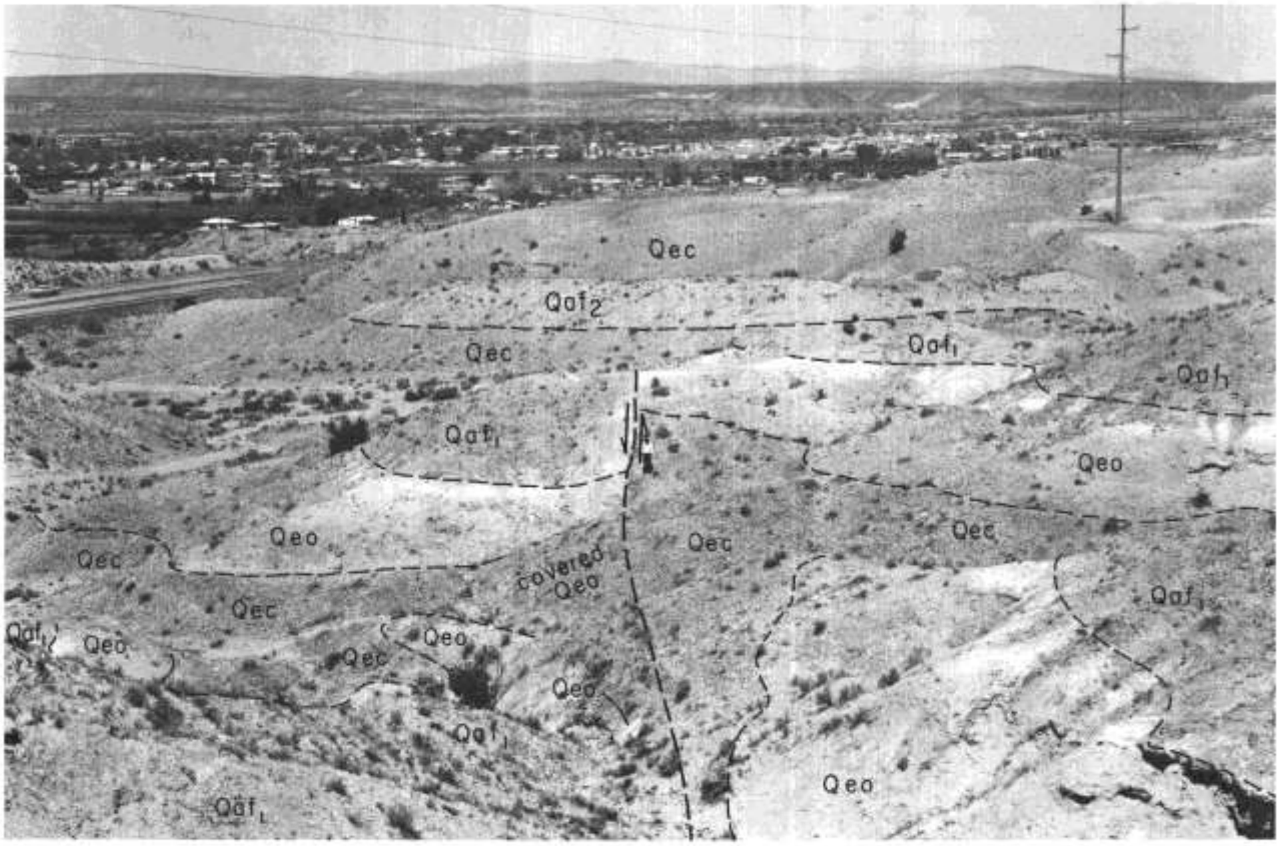


FIGURE S67—Small normal fault offsetting late Pleistocene terrace and alluvial fan deposits near mile 179.5. View is to north; man stands just to right (east) of fault. Prominent white bed is a diatomaceous silt at top of Edith overbank sequence. The fault can be traced to a point about 600 ft (180 m) south of the camera position. I-25 at far left; town of Bernalillo on Rio Grande floodplain in middle ground; and Jemez Mountains in background. From oldest to youngest the units shown are Qec, Edith channel deposits (pebble and cobble gravel); Qeo, Edith overbank deposits (clay and silt); Qaf_1, older alluvial fan deposits; Qaf_2, younger alluvial fan deposits.

fragments, and the underlying steeply dipping Galisteo Formation (Stearns, 1943; 1953a).

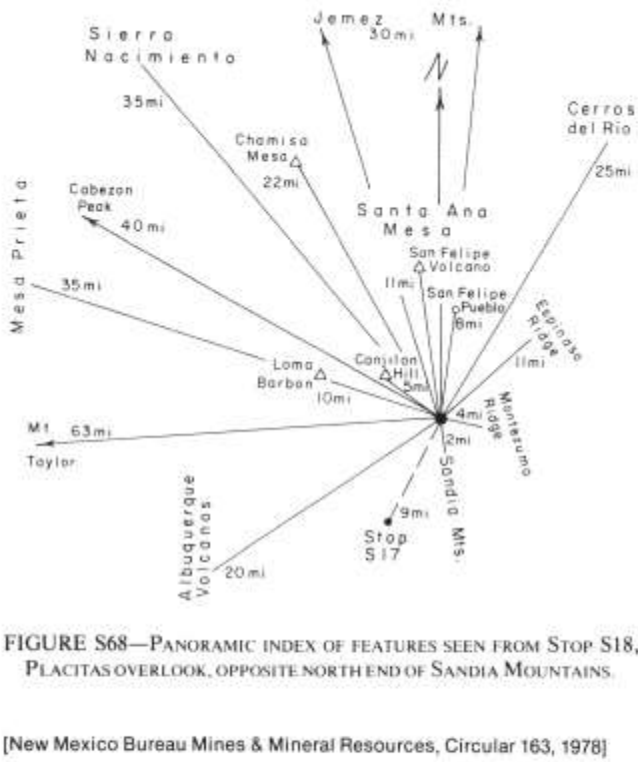


FIGURE S68—Panoramic index of features seen from Stop S18, Placitas overlook, opposite north end of Sandia Mountains.

FEATURES OF THE RIFT MARGIN NORTH OF THE SANDIA UPLIFT

by V. C. Kelley

This stop is situated at the northern end of the long, bold eastern border of the Albuquerque rift basin; it is also just off the northern plunge of the Sandia uplift. The uplift-bounding Rincon fault curves northeasterly about 3 mi to the south and branches into several splays, which are (from west to east) Valley View, Ranchos (beneath the stop), Escala, and Placitas. Of these, the Placitas fault is the most important because it connects the Rincon fault to the San Francisco fault across the Sandia ramp to the Montezuma salient, which forms the high skyline to the east (fig. S70). The San Francisco fault (near Stop S19) extends northward for some 27 mi (43 km) with diminishing throw into the southeastern corner of the Jemez Mountains. The northern part of the fault is in Santa Fe beds, and the trip route passes over the scarp (mile 207.1) shortly before the next stop.

As the San Francisco fault diminishes, a new fault—La Bajada (Stop S20)—picks up some 5-8 mi (8-13 km) to the east. This right jog in the rift is across the Hagan embayment in the southern Santo Domingo subbasin (Stop S19). The La Bajada fault scarp is as much as about 700 ft (215 m) high, and east of it is the Santa Fe embayment and plateau south of the

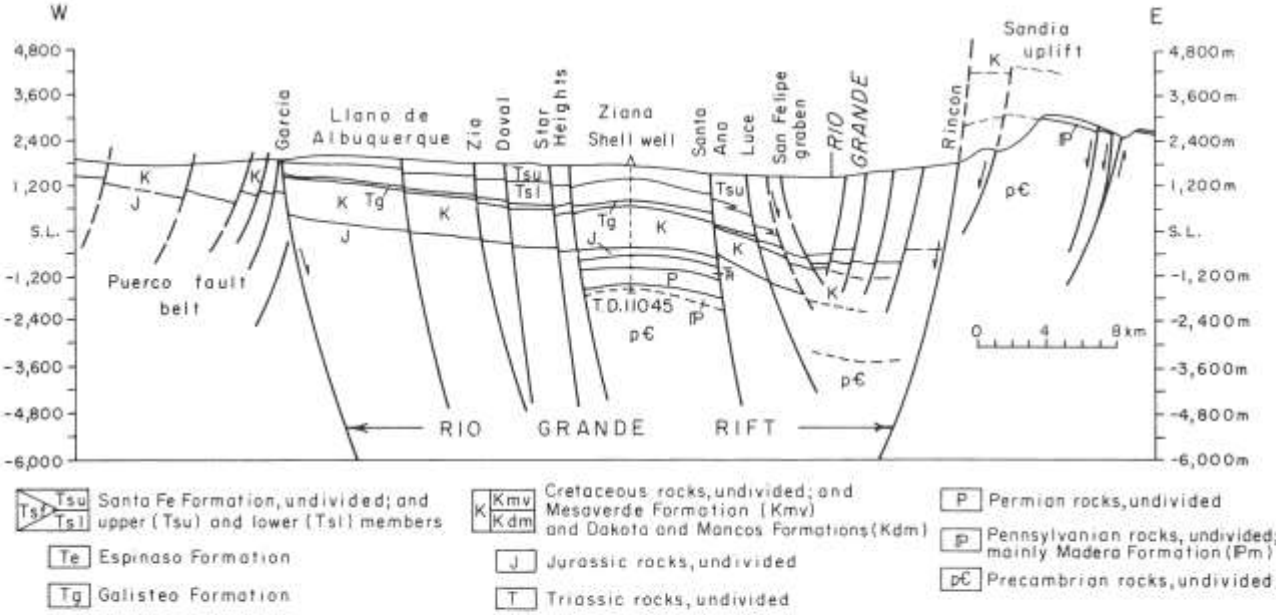


FIGURE S69—DIAGRAMMATIC STRUCTURE SECTION (NORTHWEST-SOUTHEAST) ACROSS THE NORTHERN ALBUQUERQUE BASIN from Puerco fault belt, opposite north end of Llano de Albuquerque, to Sandia uplift (modified from Kelley, 1977, fig. 20, BB').

Espanola Basin. The width of the zone of right-echelon shifting of the eastern rift boundary from La Bajada to the great Sangre de Cristo uplift is another 19 mi (30 km). In total, through three large faults (Rincon splays, San Francisco, and La Bajada) and northward-descending ramps, the rift margin is offset to the right some 32 mi (51 km) from this stop to the eastern border of the Española Basin. The three faults can be thought of as a right-echelon series of "relay" faults, as used by Goguel (1962, p. 128).

The accompanying structure section across the rift at the latitude of the northern end of the Sandia uplift shows predominantly easterly dips, including those in the Puerco fault belt and in the Sandia uplift (fig. S69).

This stop also offers a good vantage point for viewing the San Felipe basaltic volcanic field (Kelley and Kudo, 1978; fig. S71). The southern tip is located about 5 mi (8 km) northwest of this point, just south of the mouth of Jemez Creek. The nearly circular field, which forms much of Santa Ana Mesa extends about 13 mi (21 km) north-south and 10 mi (16 km) east-west; the field has an area of about 38 mil (100 km^2). San Felipe Peak, the main eruptive center, stands nearly 800 ft (240 m) above its projected base and is part of a northerly 7-mi (11-km) trend of about 20 cones. In addition, there are several low subfields; a 7-mi northerly trend of tiny cinder cones runs through the southwestern subfield. The first eruption was a stratified basalt tuff that spread mostly east from the main fissure zone. In the northeast it extends beyond the overlying flow and into upper Santa Fe beds. The first flow occurs nearly everywhere and, where exposed along the mesa edges, is generally 20-50 ft thick. Samples collected from this flow (Tb 4A of Kelley and Kudo, 1978) near Jemez Dam (at the southern tip of the field) have yielded K-Ar ages of 2.6 ± 0.2 m.y. (Armstrong and others, 1976, YU-JCD1) and 2.5 ± 0.3 m.y (Bachman and Mehnert, 1978, no. 9). The second flow is much less extensive but may be considerably thicker in the area of the main rise. Some of the central height may be due to buried buildup by early tuff rings. The third delineated flow is mostly along the main volcanic ridge, and the last event was the cinder-cone eruption. The San Felipe field is inter-Santa Fe; it probably was largely (if not completely) covered by continuing upper Santa Fe deposition. The flows are olivine basalt.

Canjilon Hill diatreme, 1 mi south of the southern tip of the main field (5 mi northwest of this stop; fig. S71) is probably

FIGURE S70—STRUCTURE SECTION FROM RIO GRANDE TROUGH TO HAGAN BASIN. Section extends east from Stop S18 area and crosses Montezuma salient and the structural downramp north of Placitas (from Kelley and Northrop, 1975, fig. 63, AA').

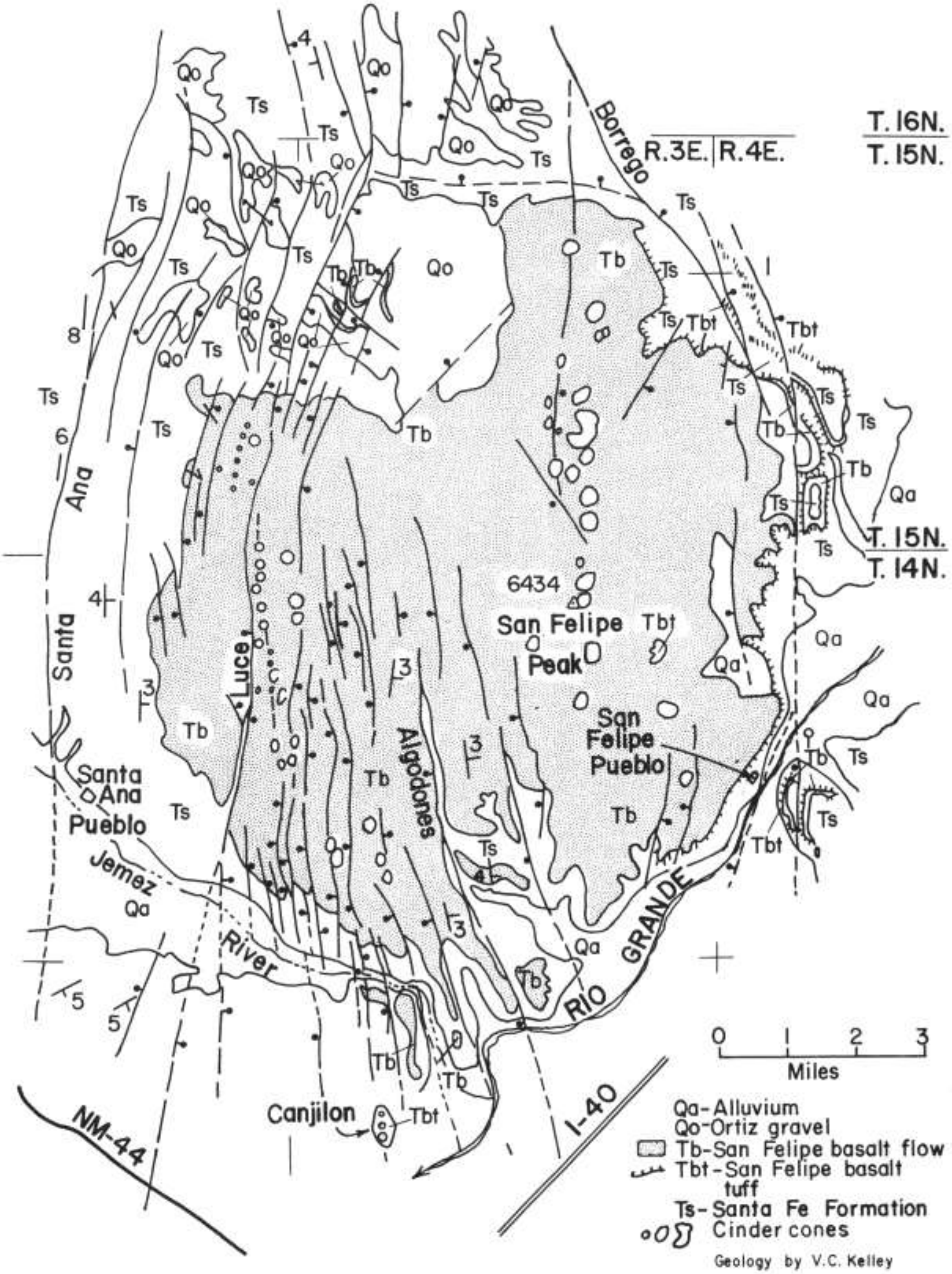


FIGURE S71—GEOLOGIC MAP OF SAN FELIPE VOLCANIC FIELD, Stop S18 (from Kelley and others, 1976, fig. 29).

an early phase outlier of the formerly more-extensive San Felipe field. The hill is on the western edge of the Rio Grande floodplain and is a good example of a dissected maar. This hill forms a small, oval mesa about 4,000 ft (1,220 m) long and 2,000 ft (610 m) wide, with its long axis oriented N. 5 ° W.; the hill consists of four principal parts, composing a small collapsed vent with basalt plugs and radial dikes in the eastern corner, and three sag-and-collapse basins aligned along the length of the structure, each with centroclinal maar deposits. The large southern collapse basin was filled with a lava lake, with the lake flow yielding a K-Ar date of 2.6 ± 0.09 m.y. (Kudo and others, 1977). There is close agreement between the three K-Ar age determinations made on basalts of the San Felipe center. As noted at mile 196.1, the main (first) San Felipe flow intertongues with the upper Santa Fe section in the bluffs east of the Rio Grande at San Felipe Pueblo, 8 mi (13 km) north of this stop. The axial river facies is also present in this section above and below the flow. The presence of ancestral Rio Grande deposits older than 2 m.y. has now been documented from here south to Fort Quitman, Texas, about 70 mi (110 km) below E1 Paso (see E1 Paso Assembly Point, Stops S1 and S7-S9, and mile 107.7 entry at Isleta).

Retrace route to 1-25. 0.7

187.1 Stop sign on NM-44. *Turn right.* **4.1**

191.2 *Bear right onto 1-25 approach ramp; continue north* toward Santa Fe. The large reddish roadcut to the right of the approach ramp exposes well-bedded sandstone of the Middle red member at the base overlain by a thin wedge gravel of the Edith unit. Red sand and unoriented sandstone blocks immediately overlying the Edith appear to be sediments derived from the Middle red member that caved and washed onto the Edith floodplain. Alluvial-fan sediment with some admixed Edith(?) gravel is exposed in the upper part of the roadcut. 0.3

191.5 *Merge with 1-25 north.* **0.6**

192.1 Milepost 243. Canjilon Hill diatreme (see Stop S18) forms irregular bluffs across river at 10:30. San Felipe volcano at 11:00. The San Felipe field of olivine basalt flows caps Santa Ana Mesa (9:30-12:00). 0.6

192.7 Bluffs to right are in Middle red member, consisting of reddish sandstone and mudstone with fanglomerate tongues. Inset river-terrace gravel (Edith) and deposits of graded alluvial slopes cap the ridges. 1.4

194.1 Milepost 245. Cuts ahead in gravel of Edith unit overlapped by fan deposits. **1.0**

195.1 On older surface of Las Huertas Creek fan. This surface is graded to an earlier valley base level about 120 ft (36 m) above the present floodplain. The mouth of Jemez Creek is across the river valley at 9:00. Santo Domingo subbasin of the Albuquerque Basin ahead, and Montezuma Ridge of Sandia uplift at 2:45. Just south of this point the route crosses the Algodones fault, which merges southward with the Rincon fault (Stop S18). This fault extends north across the river and forms the eastern margin of San Felipe graben, at 9:00 on Santa Ana Mesa (Kelley, 1977, p. 49). **1.0**

196.1 Junction; *continue straight* on 1-25. NM-474 to Algodones on left. San Felipe Pueblo is located along the river at the narrows between the bluffs at 11:30. Two basalt layers (single flow downfaulted to the west) crop out in the eastern bluff. The basalt is the basal flow (upper Pliocene) from the San Felipe center on Santa Ana Mesa (Stop S18), and it intertongues eastward with upper Santa Fe beds (Stearns, 1953a; Kelley, 1977; Kelley and Kudo, 1978). Spiegel (1961) mapped the deposits with the faulted basalt tongue as the "axial river gravel" unit in his "upper unnamed formation" of the Santa Fe Group. Smith and others (1970) include the deposits in a post-Santa Fe (Quaternary-Tertiary) "river gravel" unit that overlies the Cochiti Formation in this area. Kelley (1977; Kelley and Kudo, 1978) considers the beds as facies of his Middle red member in the Santa Fe Formation "main body." The 2.5-2.6-m.y. K-Ar age determinations on San Felipe basalts in the Jemez Dam-Canjilon Hill area (Stop S18; Armstrong and others, 1976; Kudo and others, 1977; and Bachman and Mehnert, 1978) indicate that these axial river deposits are in the uppermost part of the Santa Fe section (chart 2). They are of the same general age as the lower Camp Rice Formation between E1 Paso and Rincon (Stops S1 -S5), the upper Santa Fe fluvial facies at Elephant Butte (Stops S7-S8), Sierra Ladrones Formation near San Acacia (Stops S12-S13), and Puye and Ancha Formations in the Cerros del Rio-White Rock Canyon area to the north (Stops E14 and J10-J13). 1.3

197.4 Plains Electric Power Plant on left. San Felipe Pueblo in narrows at 11:00 (1970 population: 1,347; area: 43,853 acres). "According to tradition the [Keresan] Indians of the San Felipe were driven from their home on the Pajarito Plateau by enemy peoples and established a pueblo on the mesa overlooking the Rio Grande. The present pueblo on the west bank of the river was founded during the first half of the 18th century" (U.S. Dept. Commerce, 1974, p. 375). 0.9

198.3 East of low ridge up Maria Chavez Arroyo at 1:30 is a wide, northeast-dipping monocline that exposes nearly 3,000 ft of Middle red member of the Santa Fe (Kelley and others, 1976). About the upper 1,100 ft (335 m) of the section includes thick fanglomerates with clasts derived from most of the rocks now exposed in the Sandia uplift. According to Kelley (1977, p. 16), intertonguing mudstones in a zone 400-1,100 ft (120-335 m) below the top of section thicken to the northwest at the expense of fanglomerate beds and the unit grades into axial river deposits near 1-25. **1.0**

199.3 Crossing Arroyo de San Francisco. **0.2**

199.5 San Felipe Road to left; *continue straight* on 1-25. The Rio Grande Valley swings to the north toward the mouth of White Rock Canyon. The interstate highway, in its ascent to the Sangre de Cristo piedmont at Santa Fe, continues northeast across two major (right-echelon) fault scarps and adjacent basins. **0.5**

200.0 Roadcuts ahead for the next 1.4 mi are in crossbedded gravel and sand of the upper Santa Fe fluvial facies. **0.5**

200.5 Large cut on left in fluvial gravel and sand stained with iron oxide. In cuts ahead on right, and in exposures 0.5 mi to the southeast, similar Santa Fe beds are partly impregnated with manganese oxides. Note that beds in this area dip a few degrees to the northeast. **0.4**

200.9 Southern end of Sangre de Cristo Mountains from 11:30 to 12:30. Descending into valley of Tongue Arroyo. The Tongue (San Pedro Creek) watershed ineludes much of the eastern slope of the Sandia Mountains. 0.7

201.6 Crossing Tongue Arroyo. Espinaso Ridge at 2:00. Three miles upstream the Santa Fe is downfaulted (to west) against Jurassic beds along the San Francisco fault. 0.4

202.0 More Santa Fe axial river facies in cuts ahead. 0.2

202.2 Bed of volcanic ash with some pumice clasts is exposed in roadcut and gullies to right. This lenticular unit crops out at several places in the lower valley of Tongue Arroyo (Stearns, 1953a). The deposit probably includes air-fall as well as water-reworked facies; and is derived from the Bandelier-Cerro Toledo series of eruptions from 1.4 to 1.1 m.y. ago (Glenn Izett, U.S. Geological Survey, personal communication, December 1978). The ash postdates emplacement of the lower Bandelier unit (Guaje Pumice). 0.2

202.4 Roadcuts ahead in piedmont facies comprising sandy alluvium with conglomeratic sandstone lenses. This unit overlaps and appears to be gradational with the fluvial gravel and sand unit with the ash beds. The piedmont facies is unconformably overlain by a very thin erosion-surface veneer that contains some boulders. These units (chart 2) are discussed at Stop S20. 0.2

202.6 Espinaso Ridge on skyline from 1:00-2:30. The ridge is formed on coarse, latitic to andesitic volcanic breccias and fanglomerates of the Espinaso Formation (Oligocene; Stearns 1953a, b). Along the western base of the ridge, eastward-dipping Espinaso beds conformably overlie the Galisteo Formation (Stearns, 1943). **0.8**

203.4 Crossing Vega de los Tanos Arroyo, which flows around north end of Espinaso Ridge and heads in the southern Santo Domingo subbasin (Hagan embayment area) of the Albuquerque Basin. Road ahead ascends valley slope cut in upper Santa Fe piedmont facies (undivided Santa Fe Formation-Middle red member of Kelley, 1977). **1.4**

204.8 Route ascends to summit of a high-level erosion surface, correlated by Kelley (1977) with the Ortiz surface of Bryan (1938) and Bryan and McCann (1938). Optional stop turnout ahead on right. 0.3

205.1 Parking and optional stop areas to right and left. Monument on left erected by the Church of the Latter Day Saints to commemorate the Mormon Battalion explorations in 1846-1847 for a wagon route to the Pacific. At the north tip of Espinaso ridge (fig. S52) about 1 mi to the south at 2:30-3:00, the Espinaso Formation is overlain by basal Santa Fe beds (Abiquiu ? of Stearns, 1953a) correlated by Kelley with his Zia member of the Santa Fe Formation (see Bernalillo to San Ysidro road log and Stop S22). Dips of the section exposed along the ridge are all northeasterly at 10-25 degrees.

The Espinaso monocline is terminated on the northwest by the San Francisco fault, with the upper Santa Fe-Middle red member of Kelley (1977) downfaulted to the west against the Zia member and rocks of the underlying Espinaso-Galisteo-Mesozoic sequence. Diagonal cross faulting and left curving of the San Francisco fault suggest some left shift along this major boundary structure of the Rio Grande rift (Kelley and others, 1976; Kelley, 1977, p. 44; and this guidebook, Stop S18). The San Francisco fault crosses 1-25 about 1.5 mi northeast of this point, and it extends about 6-10 mi (9-16 km) before dying out in basin fill. The fault displaces the high-level erosion surfaces, to the east and south, that are correlated by Kelley (1977) with the Ortiz surface.

Bryan (1938) correlated the high-level surfaces in this immediate area with his type La Bajada surface, which is located in northeastern Santo Domingo Basin at the base of La Bajada escarpment (Stop S20). Unfortunately, the work in that area by Bryan and Upson has remained unpublished. Bryan believed that the La Bajada surface was the oldest part of the river-valleyborder sequence and was thus an erosional inset below the Ortiz. Kelley and others (1976, p. 28) consider that "there is no La Bajada surface that is different and younger than the Ortiz." According to Kelley's (1952, 1977) interpretation, discussed at Stop S19, differences in elevation and slope of these surfaces are due mainly to structural deformation including tilting as well as faulting. **1.2**

206.3 Crossing small arroyo past service stations; road ahead ascends dissected scarp of San Francisco fault. Erosion-surface veneers (pediment deposits), which cap east-tilted Santa Fe beds, are offset by the fault. These veneers are associated with Bryan's (1938) La Bajada surface and are correlated with gravels of the Ortiz surface by Kelley (1977). The gravel mantle on the type Ortiz surface has been designated the Tuerto gravel by Stearns (1953a; see Stop S19). **1.1**

207.4 Kearny Route historical marker on La Bajada-Ortiz surface: "General S. W. Kearny raised the American flag at Santa Fe on August 18, 1846, in a bloodless conquest of New Mexico. On September 25 he began his march to California. Here his route crosses U.S. 85." 0.3

207.7 Junction ahead; *prepare for right turn.* **0.3**

208.0 *Turn right on NM-22; continue south* on graded road to Stop S19. Road to left is to Santo Domingo Pueblo. **0.9**

208.9 Cattle guard. Low dissected fault scarp ahead, which offsets upper Santa Fe beds and La Bajada-Ortiz surface. **0.5**

209.4 Ascending another piedmont fault scarp. This zone of scarp splays out eastward from the main San Francisco fault (Kelley, 1977). **0.4**

209.8 **STOP S19, Hagan embayment.** *Park along road south of this point; assemble for discussions* of the northeastern Albuquerque Basin age (figs. S52 and S72). This stop, elevation 5,834 ft (1,778 m), provides a panoramic view of the region, including Albuquerque, Santa Fe, and the Jemez Mountains (fig. S72). The structural evolution of the north-central New Mexico region is discussed by Baltz (this guidebook).

The northwest skyline is dominated by Sierra Nacimiento and the Jemez Mountains, which form the southwestern prong of the Southern Rocky Mountains. The Jemez Mountains rim the Valles caldera and are described herein by Bailey and Smith. Espinaso Ridge, 2.5 mi to the southwest, has been described at mile 202.6. Dips in the basal Santa Fe (Zia) section are all northeasterly at 10-25 degrees. However, dips in the overlying Santa Fe section decrease

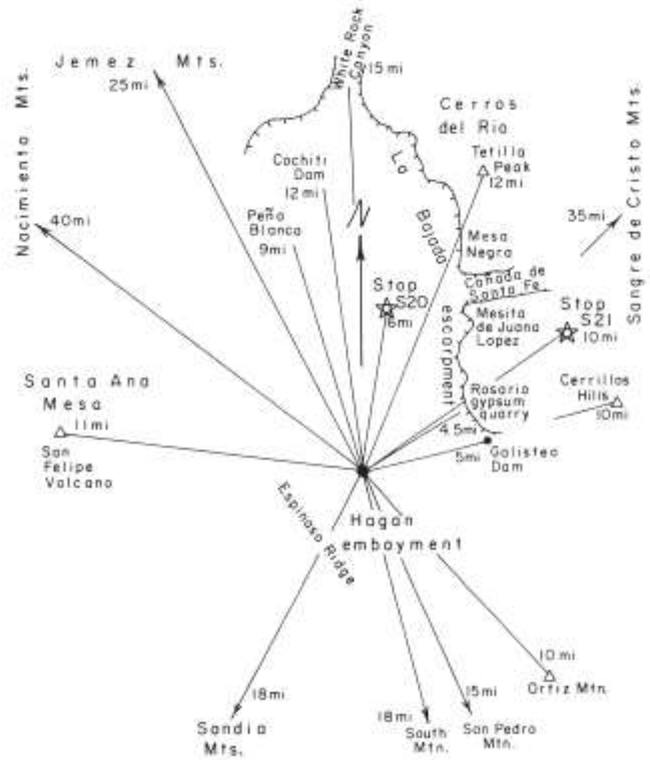


FIGURE S72—PANORAMIC INDEX OF FEATURES SEEN FROM STOP S19, HAGAN EMBAYMENT.

markedly a short distance east of the ridge and here are only a few degrees. The Ortiz Mountains, forming the southeastern skyline, are remnants of mid-Tertiary monzonite porphyry intrusions into the Paleozoic and Mesozoic sequence of the area. The Ortiz belt of laccolithic intrusions includes the San Pedro Mountains to the south-southeast and the Cerrillos Hills (Stop S21) to the east-northeast near 1-25. The northeastern skyline is dominated by the Sangre de Cristo Mountains (fig. S72), which form the southeastern prong of the Southern Rocky Mountains. The Sangre de Cristos are the eastern border of the Española Basin segment of the Rio Grande rift. The volcanic plateau in the middle distance north to northeast of the Santo Domingo subbasin is the Cerros del Rio field of basaltic to andesitic volcanics. The field includes a spectacular assemblage of phreatomagmatic features, particularly well exposed in the White Rock Canyon of the Rio Grande north of this stop (Aubele, this guidebook).

Upper Santa Fe beds exposed in the eroded slopes near this stop are in the southern prong of the Santo Domingo subbasin extending between Espinaso Ridge and the Ortiz trend of porphyry intrusions. This basin segment has been designated the Hagan embayment by Kelley (1952). It is an east-tilted half graben, with its eastern boundary being formed by the La Bajada fault of Kelley (1977)—Rosario fault of Stearns (1953a). Stop S20 in the Santo Domingo Basin, about 6 mi (10 km) north-northeast of this point, is located near the base of La Bajada escarpment.

The area directly south of this stop (underlain by Tertiary, Mesozoic, and upper Paleozoic rocks) along the eastern base of the Sandia uplift is also a half graben (Kelley and Northrop, 1975). The homoclinal stratigraphic succession that extends nearly 15 mi (24 km) from Sandia Crest to the Cerrillos Hills east of La Bajada comprises a relatively complete but "condensed" section of Mississippian to Pliocene rocks. In a sense, the east-tilted succession is all part of the Sandia uplift, which, as Kelley and Northrop (1975) have suggested, may have risen out of the early Santa Fe basin in Pliocene time.

This stop offers a good vantage point for discussing previous and present work on the stepped sequence of geomorphic surfaces that extend from the mountain fronts to the inner valley of the Rio Grande. For three-quarters of a century this area has been the site of a number of pioneering studies in geomorphology and Cenozoic stratigraphy. Of particular interest is the Ortiz erosion surface whose type area includes the Ortiz Mountain piedmont slopes seen from this point. An appropriate beginning for this discussion is a quotation from Bryan and McCann (1938, p. 7-8):

> The Rio Grande Depression is characterized by the presence of remnants of once broad erosion surfaces. These remnants stand at widely different elevations, and their degree of preservation is variable from place to place. However, they all slope toward the general position of the Rio Grande and belong to a succession of erosional surfaces representing successive stabilized grades of this master stream. In the region south of White Rock Canyon the oldest and highest of these remnants appear to be parts of the Ortiz surface, a widely developed and excellently preserved surface in the vicinity of the Ortiz Mountains, first described by Ogilvie [1905]. Although Ogilvie described but one surface in the type area, there appear, in fact, to be three, and it is the highest of these which is here named the Ortiz surface. It slopes outward on all sides away from the mountain and, if restored to its original condition, would be a low cone, the "conoplain" of Ogilvie. It cuts the hard rocks at the foot of the mountains and extends westward across the deformed Santa Fe. In places this surface is little dissected, and its gradient, projected toward the Rio Grande in the type area, reaches the river about 500 feet above its present grade.

Bryan (1938), with associates and students, correlated a number of extensive, high-level surface remnants in the Albuquerque Basin region with the type Ortiz surface. These remnants included basalt-capped surfaces of the Cerros del Rio-Cerrillos Hills area (Stops S20-S21) and Santa Ana Mesa (Stop S18), as well as the Llano de Albuquerque seen at Stops 514-S16. Bryan (1938) also made tentative correlations with surfaces such as the Jornada-La Mesa complex in southern New Mexico (Stops S1-S8). Notable subsequent work on the Ortiz surface and associated deposits near the type area includes the studies by Stearns (1953a) and Spiegel and Baldwin (1963). Work on possible correlatives in Albuquerque-Socorro area includes the earlier studies of Denny (1941; Stops S12-S13) and Wright (1946).

Important recent contributions on the subject of early-stage geomorphic surfaces have been made by Kelley (1977), Bachman and Mehnert (1978), and Machette (1978a). They have reviewed previous work and have discussed the problems of surface genesis and correlation. These include differentiating surfaces formed mainly by erosion from those resulting primarily from basin aggradation. As illustrated at Stops

S12 and S16, considerable progress is being made in use of pedogenic features for correlation and for establishment of reasonable ranges of surface age (Machette, 1978a). Bachman and Mehnert (1978) focus on use of K-Ar-dated basalts as a primary means of establishing a time frame for reconstructing geomorphic history of the central New Mexico region.

Kelley (1977, fig. 10) broadens the field of possible Ortiz correlatives by including in the Ortiz bracket some surfaces considered by other investigators to be part of the inset sequence of valley-border surfaces (for example, mile 205.1). However, the surface covered by basalts of the San Felipe (Santa Ana) center is excluded from the Ortiz by Kelley (1977). As most early investigators have done, he includes the Llano de Albuquerque (Stops S14-S16) in the Ortiz category. Kelley (1977) also proposes that complex surfaces such as La Bajada (Stop S20) and much of the Llano de Manzano (Stop S13) are Ortiz correlatives. He attributes many present differences in surface form and profile to post-Ortiz structural deformation, rather than to repeated intervals of surface regrading caused by changes in base-level and/or climate-vegetation controls on geomorphic processes.

On the other hand, Bachman and Mehnert (1978) propose that the Ortiz name be restricted to those surfaces that predate extrusion of upper Pliocene (2.5-2.8-m.y.) basalts, such as those of the Cerros del Rio field (mile 225.1) that are penecontemporaneous with the Ancha and Puye Formations (charts 1 and 2). The San Felipe (Santa Ana Mesa) flows, which are interbedded with upper Santa Fe fluvial facies (Stop S18), are another sequence considered post-Ortiz by Bachman and Mehnert (1978). Excluded from the Ortiz are early to middle Pleistocene surfaces of partly erosional and partly constructional origin, such as the Llano de Albuquerque and Llano de Manzano surfaces described by Lambert (1968; this guidebook) and Machette (1978a; this guidebook).

Retrace route to 1-25. **1.8**

211.6 Stop sign. *Turn right; continue northeast* on I-25US-85. Route ahead crosses several La Bajada-Ortiz surface remnants and associated alluvial veneers that cap upper Santa Fe basin fill. **1.6**

213.2 Route starts descent into valley of Galisteo Creek. Alluvial slope and terrace deposits (Quaternary) form discontinuous cover on Santa Fe beds. **2.0**

215.2 Galisteo Reservoir to right. **0.2**

215.4 Crossing Galisteo Creek. Rosario gypsum quarry at 3:00 is developed in Todilto Formation (Jurassic). **0.2**

215.6 Roadcuts ahead in Santa Fe conglomeratic sandstone with narrow strip of inset terrace deposits along Galisteo Creek. **0.3**

215.9 Overpass. Crossing main line of ATSF Railroad. **0.1**

216.0 Rosario gypsum plant to right; *continue east* on 1-25. stone (Cretaceous), the Jurassic section includes uppermost rounded ridges of Morrison sandstone over lavender mudstones, light-colored Todilto limestone and gypsum, and thin, reddish Entrada Sandstone. The base of the exposed sequence is in Triassic red beds. **0.3**

216.3 Reddish-brown alluvium derived from Galisteo red beds exposed in La Bajada escarpment covers downfaulted upper Santa Fe beds. **0.4**

216.7 *CAUTION! Dangerous intersection ahead. Prepare for left turn.* **0.3**

217.0 Crossing La Bajada (Rosario) fault with pinkish to brownish Santa Fe beds downthrown to the west. Cuts ahead in Eocene Galisteo Formation (red to brown mudstones to conglomeratic sandstones) at the base of La Bajada escarpment. **0.3**

217.3 *Turn left on NM-22.* **0.4**

217.7 Conformable contact of Espinaso Formation on Galisteo red beds is exposed up arroyo valley to right (Stearns, 1953a, b). **0.3**

218.0 Road curves to left. Espinaso Formation, cropping out in ridge to right, is overlain by light-colored sandy sediments of the Santa Fe Formation-Zia member of Kelley (1977). The Zia unit was mapped as Abiquiu (?) by Stearns (1953a). **0.2**

218.2 Power-line crossing. About 1.2 mi to the north is the mouth of Cañada de Santa Fe in the La Bajada escarpment, here about 450 ft (140 m) high. The route ahead descends on a broad alluvial plain extending toward the Rio Grande Valley from the base of the escarpment. **2.1**

220.3 Road ahead curves to right where it joins the old highway to Cochiti. *Turn left at curve; park on old section of highway to south.* **0.2**

220.5 **STOP S20 (optional), La Bajada escarpment.** This stop is located on a broad alluvial surface about 2.5 mi west of the mouth of Cañada de Santa Fe in La Bajada escarpment (fig. S73). Locations of major landmarks seen from this point are shown on fig. S74. Features of the Cerros del Rio volcanic field and the rocks exposed in the scarp to the north through White Rock Canyon of the Rio Grande are discussed by Aubele (this guidebook). The tectonic setting of the north-central New Mexico region, including this part of the northern Albuquerque Basin and the Española-San Luis Basin to the north, is discussed by Baltz (this guidebook). The Jemez Mountain and Española Basin areas to the north are described in guidebook sections, respectively, by Bailey and Smith, and Manley. Finally, the guidebook paper by Bridwell and the recent journal paper by Cordell (1978) deal with aspects of geophysical research in this region.

La Bajada fault forms the eastern border of the Santo Domingo subbasin and the northeastern boundary of the Albuquerque Basin (Kelley, 1977, p. 38). It is the easternmost of the series of three major right-echelon faults discussed at Stop S18. Besides La Bajada these are the Rincon (with its northern splays) and San Francisco faults. Toward its northern end La Bajada fault curves northwesterly toward the Jemez Mountains and becomes a part of the northern constriction or termination of the Albuquerque Basin. North and east of here the rift margin shifts into the Española Basin. The structural setting of that basin is described by Kelley (1978). Surface expression of La Bajada fault occurs in a belt about 23 mi (37 km) in length. Between the mouths of White Rock Canyon and Cañada de Santa Fe the escarpment rises as much as 700 ft (215 m).

Beds ranging from Triassic to Cretaceous are up-

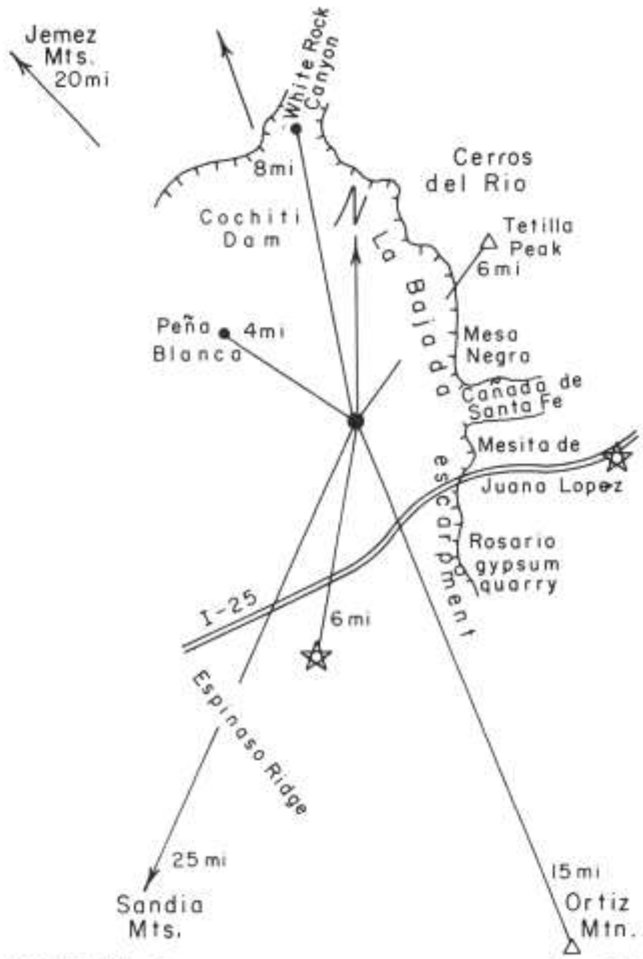


FIGURE S73—Panoramic index of features seen from Stop S20, west of La Bajada escarpment on NM-22.

thrown and tilted eastward up to 20 degrees along the eastern border of the subbasin, especially in the southern part. Along the route just traversed between 1-25 and Cañada de Santa Fe, the uplifted structure is complicated by diagonal faults which drop Galisteo, Espinaso, and Zia beds against Jurassic and Cretaceous beds. In the northern part, sands of Kelley's Zia member (Abiquiu? unit of Stearns, 1953a) are exposed in the scarp beneath thick basalt flows of the Cerros del Rio field (fig. S73). The northern end of the fault is covered by Bandelier Tuff (lower Pleistocene). South of Galisteo Creek (southeast of Stop S19), the southern end of La Bajada fault is covered by gravel of the Ortiz pediment (Tuerto gravel of Stearns, 1953a). Development of the fault in the area of burial suggests that the La Bajada fault continues to the south, curving into the eastern and southeastern boundary faults (Tijeras and Barro) of the Sandia block. Kelley and Northrop (1975, p. 86) have suggested that such north-south continuation of the La Bajada and Tijeras faults may have formed the border of the Rio Grande trough before rise of the Sandia uplift in Pliocene time.

In the escarpment close at hand (north of 1-25), upper Cretaceous rocks are unconformably overlain by a thick sequence of lower to middle Tertiary rocks. This sequence is in turn overlain by a northward-thickening wedge of Santa Fe beds and basalts of the Cerros del Rio field. The basal Tertiary unit is the Galisteo Formation (Stearns, 1943, 1953a, b). It consists of partly conglomeratic sandstones to mudstones with some fresh-water limestone and water-laid tuff. Vertebrates collected from uppermost Galisteo beds are of Duchesnean age (Stearns, 1953a), while an early Eocene age is reported for the lower beds (Robinson, 1957). Galusha and Blick (1971, p. 35) also consider that much of the uppermost sequence is late Eocene. The Duchesnean provincial age is assigned to the 37.5-40-m.y. interval on the Cenozoic radiometric time scale of Berggren and van Couvering (1974, fig. 1; chart 2).

As noted at mile 202.6, near Espinaso Ridge, the Galisteo is conformably overlain by intermediate-volcanic breccias and fanglomerates of the Espinaso Formation (Stearns, 1953a, b). The Espinaso is associated with intrusives of the Ortiz porphyry belt and related volcanics (Stop S21). K-Ar ages of these units are in the Oligocene range. In the lower Cañada de Santa Fe area, the Espinaso is unconformably overlain by or is in fault contact with a thick lower Santa Fe section, composed of tuffaceous sand, silt, and some limestone (fig. S73). This light-colored sandy sequence is the Santa Fe Formation-Zia member of Kelley (1977) and the Abiquiu (?) Formation of Stearns (1953a).

Basalts of the Cerros del Rio that cap La Bajada escarpment in this general area have K-Ar ages in the 2.8-2.5 m.y. range (Bachman and Mehnert, 1978, nos. 2-4 and 7). These basalts overlap and interfinger with piedmont and axial river facies of the Ancha and Puye Formations, considered by Spiegel and Baldwin (1963) to be the upper unit of the Santa Fe Group. Other workers have excluded these formations from the Santa Fe (Galusha and Blick, 1971; Kelley, 1977). However, it should be noted that Pliocene basin fill elsewhere in the southern rift has been traditionally in-

FIGURE S74—La Bajada escarpment and Mesa Negra at southern end of Cerros del Rio volcanic field and north of Cañada de Santa Fe; view is northeast across type La Bajada surface of Bryan (1938) from near Stop S20. Tetilla Peak, on center skyline, marks one of a large number of vent areas for Pliocene basalts of the Cerros del Rio area (Aubele, this guidebook). White Cliffs at escarpment base between Tetilla Peak and Cañada de Santa Fe are sandstones of Kelley's (1977) Zia member of the Santa Fe Formation (photo by P. W. Lambert).

eluded in the Santa Fe. These 2-5-m.y.-old units include at least the lower parts of the Upper buff-Ceja Member and the Sierra Ladrones and Camp Rice Formations. The Servilleta Formation (Pliocene) of the San Luis-northern Española Basin area is also an Ancha-Puye correlative (Stops N13-N16).

This stop offers a striking contrast in perspective when compared to the high physiographic settings of Stops S19 and S21. The alluvial plain in the immediate area of this stop forms a broad divide between the lower valleys of Galisteo Creek and the Santa Fe River. The plain grades to high-level surfaces bordering the inner Rio Grande Valley about 3.5 mi to the west-northwest. East of Peña Blanca the highest well-preserved surface remnant grades to a level about 300 ft (90 m) above the Rio Grande. This is Bryan's (1938) La Bajada surface. As mentioned at Stop S19 and mile 205.1 there are two contrasting viewpoints on the origin and age of geomorphic surfaces in this area. The first is Bryan's (1938) original interpretation of the La Bajada "pediment" as a Pleistocene erosion surface, considerably younger than the Ortiz, that was graded to an ancient Rio Grande base level about 300 ft (90 m) above the present floodplain. Kelley's (1952, 1977) proposal is that the La Bajada (and other surfaces in a similar physiographic position) should be considered as a probable downfaulted or downwarped segment of the Ortiz. A third viewpoint, of course, is that both interpretations may be correct within a given river-valley segment. The following observations must also be considered: 1) Stepped sequences of graded, valley-border surfaces are extensively preserved along the Rio Grande. 2) Not all such graded surfaces are strictly erosional, but may also include large areas of constructional forms such as alluvial fans and terraces. 3) Structural deformation has continued throughout latest Tertiary and Quaternary time with resultant displacement of all but the youngest Holocene surfaces in many parts of the rift. Features like the La Bajada escarpment and foot slopes deserve careful examination, and the details of valley-fill stratigraphy and pedogenic features should be worked out as has been done in the Las Cruces-Rincon area (Stops S2-S5) and the central and southern part of the Albuquerque Basin (Stops S12, S15, and S16).

Retrace route to 1-25. 3.2

223.7 Stop sign. *Turn left;* and *continue northeast* on 1-25. After turn, Dakota Sandstone (Cretaceous) is at 3:00. The Dakota is thin in this region and here rests on sandstone of the upper Morrison Formation (Jurassic). 0.1.

223.8 Roadcuts in Galisteo Formation. 0.2

224.0 Roadcuts in Galisteo conformably overlain by Espinaso Formation. To the east this sequence is faulted against Mancos Shale (Upper Cretaceous). 0.3

224.3 At the west end of roadcut yellowish Morrison sandstones are in vertical (fault) contact with Mancos Shale. Ahead on right Morrison sandstone and shale is cut by dark-reddish igneous dike. **0.1**

224.4 Sandstone in lower Mancos is exposed in roadcut to right. Note mantle of colluvium with basalt blocks on steep slopes. 0.5

224.9 Contact of thin upper Santa Fe beds (thin, light-reddish silt and clay) on Mancos Shale. The Mancos is cut by a limburgite dike. 0.2

225.1 Contact of basalt on a thin reddish-to-brown sandy layer that overlies a strong calcic paleosol formed in fine-grained "upper Santa Fe pediment" deposits. Basalt here is part of the flow sequence K-Ar dated at 2.8 ± 0.2 m.y. by Bachman and Mehnert (1978, no. 7). The surface on which the flow rests and the underlying alluvium (Ancha and Tuerto equivalent) are traceable to the southeast up the valley of Galisteo Creek. In that area the surface is at a level conforming to that of the type Ortiz erosion surface of Bryan and McCann (1938, p. 8, fig. 2) south of the Galisteo. 0.3

225.4 Summit of basalt-capped La Bajada escarpment; route ahead crosses Mesita de Juana Lopez. The low cone at 11:30 marks the central vent of flows forming the Mesita. 0.9

226.3 Overpass; Waldo interchange. 0.6

226.9 Milepost 268 at crest of hill; *prepare to take rest area exit.* Basalt cone at 9:00 and roadcuts in basalt ahead. Ortiz Mountain (monzonite porphyry) at 3:00. The extensive piedmont surface west of the mountain is the type Ortiz surface of Bryan and McCann (1938) and Ogilvie's (1905) conoplain landform. 0.7

227.6 *Exit right to rest area.* **0.2**

227.8 **STOP S21, La Cienega rest area.** *Walk to picnic shelter at northeast end of the rest stop.* Features seen from this point are indexed on fig. S75. 1-25 to the

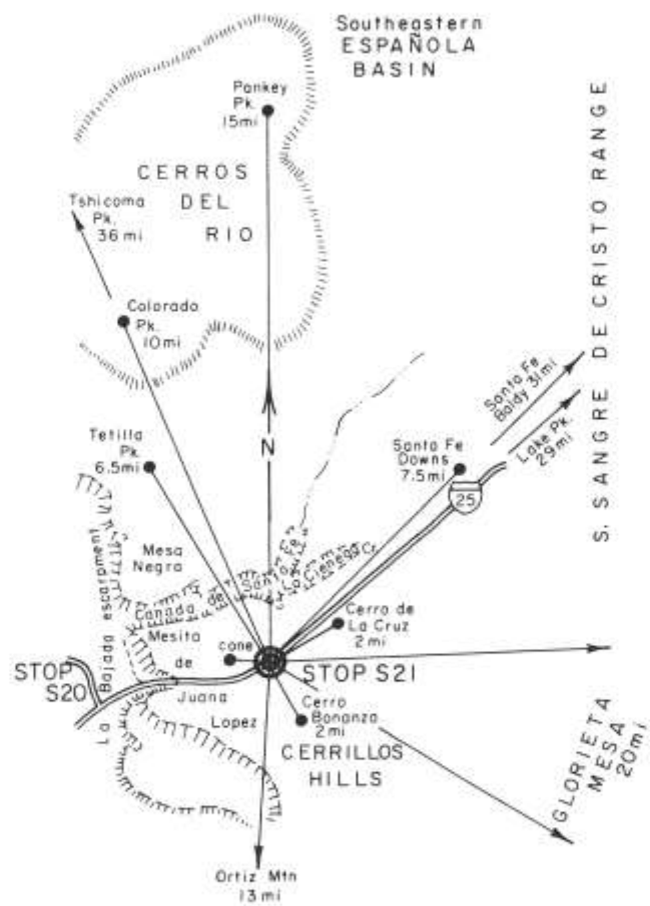


FIGURE S75—PANORAMIC INDEX OF FEATURES SEEN FROM STOP S21, LA CIENEGA REST AREA ON I-25 WEST OF SANTA FE.

northeast leads to Santa Fe, nestled at the foot of the Sangre de Cristo Mountains. Using highway as 12:00, Lake Peak caps the range at 12:00, elevation 12,409 ft (3,782 m); Santa Fe Baldy at 11:45, elevation 12,622 ft (3,847 m); and the Truchas Peaks at 11:30, elevation 13,102 ft (3,993 m). At 11:00 in foreground is La Cienega area of volcanic hills and low basalt-capped mesas; basalt cone of Tetilla Peak at 9:00, Cerros del Rio from 9:00-11:00; Jemez Mountains on skyline from 8:30-9:30. At the south end of the Sangre de Cristo Mountains is Glorieta Mesa on the far skyline at 1:30; cone-shaped peak at 12:30 in foreground is Cerro de la Cruz; Cerrillos Hills are at 3:00, with Cerro Bonanza the nearest high peak; Ortiz Mountains are in distance at 4:00.

At 12:00, Alamo Creek is the first valley just northeast of the nearest overpass; second overpass is road to La Cienega. The name Cienega (Spanish for "marsh") reflects the springs that occur along and east of the line of hills extending from east of this stop southward to the main part of Cerrillos. Ground water in the Santa Fe Basin to the east rises to the surface when blocked on its westward path by this chain of hills, which are the surface expressions of monzonite intrusives that have domed Paleozoic and Cretaceous strata.

In this area, the Galisteo Formation (Eocene) is unconformable on Mesaverde Formation (Upper Cretaceous). It is overlain by the Espinaso volcanic rocks, a complex sequence of volcanic flows and volcaniclastics and related intrusives (Ortiz porphyry belt); the sequence ranges from 34 to 25 m.y. in age (Bachman and Mehnert, 1978). These rocks are related to the zinc, lead, copper, silver, gold, and turquoise deposits of the Cerrillos. Unconformably above the Espinaso volcanics and intrusives is the Cieneguilla Limburgite, an augite-olivine-labradorite basalt; it caps Cerro de la Cruz at 12:30. Erosionally unconformable on the older rocks in this area is the youngest part of the Santa Fe Group, the Ancha Formation. As already noted, basalts of the Cerros del Rio field (Aubele, this guidebook) are interbedded with the Ancha.

Three physiographic surfaces that predate the entrenched system of arroyo valleys form part of the piedmont plains landscape to the east. They are developed on the Ancha Formation and are partly erosional and partly constructional in origin. The highest, the Divide surface, forms the low skyline north of Santa Fe at 11:30. Along the Santa Fe River a belt about 3 mi wide forms the lowest surface, the Airport surface; the red-roofed grandstands of Santa Fe Downs at 11:45 are near the south edge of the Airport surface. To the south is the slightly higher Plains surface, forming the interstream divides southward from 1-25.

Moraines occur at the base of the glacial cirques on Lake Peak and Santa Fe Baldy; Richmond (1963) identified pre-Wisconsin moraines, two moraines of **Bull** Lake Glaciation, three moraines of Pinedale Glaciation, and a neoglacial moraine. Rio Tesuque and Santa Fe River head in the cirques of these peaks. At the foot of the range where the rivers leave the mountains, four alluvial terraces and outwash deposits that postdate the Airport surfaces were mapped by Kottlowski and Baldwin (Spiegel and Baldwin, 1963). Two "low" alluvial terraces are upper Holocene, and the older of the two may be related to Neoglacial events. The "middle" terrace, 20-30 ft (6-9 m) above channels along the Santa Fe River, may be associated with the Pinedale Glaciation; and the "high" terrace, 45-60 ft (14-18 m) above channels, may correlate with Bull Lake deposits. **0.9**

228.7 Underpass. **0.5**

229.2 Crossing Alamo Creek. **0.9**

230.1 Cerro de la Cruz to right. **0.3**

230.4 Underpass; La Cienega interchange. **0.2**

230.6 The floor of the valley to left intersects the water table to form a well-vegetated, partly marsh area or cienega. Ground water here discharges from a zone in thin upper Santa Fe beds that rest on much less permeable bedrock units (for example, Mancos Shale). 2.3

232.9 Milepost 274. Crossing valley of Cienega Creek. Ahead, south of Santa Fe Downs, 1-25 is on the Plains surface, with Santa Fe Downs on the slightly lower Airport surface. 0.9

233.8 Santa Fe Downs to left. **1.1**

234.9 Milepost 276. Crossing valley of Arroyo Hondo. **1.2**

236.1 Cerrillos Road exit to right; *continue straight* on 1-25. **0.4**

236.5 Overpass; Madrid-Cerrillos Highway (NM-14). Route ahead is on the Plains surface between Arroyo de los Chamisos to the north and Arroyo Hondo to the south. Off of the highway are scattered pits of pumice (Jemez source), which is interbedded in the upper part of the Ancha Formation. **0.4**

236.9 Milepost 278. Santa Fe (Spanish for "holy faith"), elevation 7,000 ft (2,135 m), is the capital of New Mexico and the oldest European community in the United States west of the Mississippi River. It was founded as a villa by Don Pedro de Peralta in 1610, after the first Spanish governor and colonizer, Oñate, moved his headquarters here. Peralta was instructed to establish a capital for "The Kingdom of New Mexico," and he did so at the edge of the Sangre de Cristos where a Tano Indian village had been abandoned. Santa Fe was the only Spanish incorporated town north of Chihuahua until 1680. The capital was evacuated on August 21, 1680, when the Pueblo Revolt forced Governor Otermin and the colonists to flee down the Rio Grande to Guadalupe Mission at Paso del Norte, the present Ciudad Juarez. In 1692 and 1693, a good many of the colonists returned with the new governor, Don Diego de Vargas, who was able to enter the city without warfare. On August 18, 1846, American forces under General S. W. Kearny also occupied the city without firing a shot. Santa Fe is a cultural center with museums, research institutions, and historical monuments of Indian, Spanish, and pioneer-American interest (adapted from Pearce, 1965, p. 149). **2.0**

238.9 Milepost 280. To the southeast at the foot of the mountains, Arroyo Hondo has cut a canyon into the east edge of the Santa Fe plains. A facies of the Galisteo Formation that is rich in fragments of Precambrian rocks overlies the Precambrian in this canyon and is itself overlain by augite andesite flows and flow breccia of the Espinaso volcanics, K-Ar dated by

Bachman and Mehnert (1978) at 24-25 m.y. The Espinaso flows are in turn overlain by the Tesuque Formation, with the Bishops Lodge Member at the base. Northward, the Galisteo and Espinaso units pinch out, probably owing to pre-Santa Fe Group erosion, and the Bishops Lodge Member rests on Precambrian rocks or on Pennsylvanian strata. *Keep to right for next exit.* **1.9**

240.8 Crossing Santa Fe spur of ATSF Railroad; *take exit ahead.* Railroad cuts are in Ancha Formation, and highway is on remnants of the Plains surface. **0.1**

240.9 *Exit right to St. Francis Drive and US-84-285 North.* **0.2**

241.1 *Keep left* for St. Francis Drive. **0.8**

241.9 Overpass; *merge* with St. Francis Drive northbound. **0.4**

242.3 Pumice mill on left; valley of Arroyo de los Chamisos ahead. Tesuque Formation of the lower Santa Fe Group crops out in arroyo channel between road and railroad to left. **0.2**

242.5 Crossing arroyo; hill ahead is on Plains surface. **0.7** 243.2 Overpass (St. Michael's Drive); route ahead descends from Plains surface onto Airport surface. **1.0**

244.2 Traffic light (Cordova Drive); the route drops from the Airport surface onto middle or third terrace of the Santa Fe River. On the south side of the river, where the city extends onto the alluvial plain of the Santa Fe River, modern construction and erosion have obscured the relationships of the two lower terraces (dated between A.D. 1880 and 2230 B.P. in Rio Tesuque valley). The dissected hills north of and in the northern part of Santa Fe are mainly carved from the Tesuque Formation, discussed in detail on the Española Basin tour. **0.2**

244.4 Traffic light (Cerrillos Road); *continue straight on US-84-US-285 truck bypass.* **0.8**

245.2 Traffic light; intersection of St. Francis Drive and the Alameda at north edge of Santa Fe River. *Turn right for access to city center.* End of Socorro to Santa Fe (northbound) segment of southern rift tour.

SANTA FE TO SOCORRO

This log is compiled from more detailed road logs for the northbound route by Chapin, Chamberlin, Lambert, Hawley, and Kottlowski. The emphasis is on geologic and geomorphic features seen from a southbound perspective between the formal tour stops. Discussions at Stops S21 to S10, other long technical entries, and historical notes are not included. Such items are noted at appropriate places in the road log, and they are cross-referenced to corresponding mile points in the northbound tour guide.

Mileage

0.0 Traffic light; intersection of St. Francis Drive and The Alameda at north edge of Santa Fe River. *Go south on US-84-US-285 truck bypass.* On the south side of the river, where the city extends onto the alluvial plain, modern construction and erosion have obscured relationships of lower terraces (dated between A.D. 1880 and 2230 B.P. in Rio Tesuque Valley to the north). **0.7**

0.7 Traffic light; intersection of Cerrillos Road and St. Francis Drive. *Continue straight* on US-84-US-285 across middle or third terrace of the Santa Fe River. This surface may be associated with the Pinedale Glaciation of Wisconsinan age (chart 1). **0.3**

1.0 Traffic light (Cordova Drive). The route ascends from the middle terrace level to the Airport geomorphic surface (Spiegel and Baldwin, 1963). The Airport surface is the lowest of three piedmont surfaces (Pleistocene) that predate the entrenched system of arroyo valleys. They are developed on the Ancha Formation, the youngest unit of the Santa Fe Group, and are partly erosional and partly constructional in origin. The highest, the Divide surface, forms the low skyline north of Santa Fe (Stop El). Remnants of the intermediate Plains surface are crossed by the tour route south and west of this point (Stop S21). **1.0**

2.0 Overpass (St. Michael's Drive). Route is on remnant of Plains surface here preserved on a drainage divide north of Arroyo de los Chamisos. **0.5**

2.5 Crossing valley of Arroyo de los Chamisos. Tesuque Formation of the lower Santa Fe Group crops out in arroyo channel between road and railroad to right. **0.4**

2.9 Pumice mill on right. *Stay in right lane for 1-25 South.* **0.4**

3.3 *Bear right on 1-25 South approach ramp at underpass.* **0.7**

4.0 Crossing Santa Fe spur of ATSF Railroad. Railroad cuts are in Ancha Formation. To the southeast at the foot of the mountains, Arroyo Hondo has cut a canyon into the east edge of the Santa Fe plains. A facies of the Galisteo Formation that is rich in fragments of Precambrian rocks overlies the Precambrian in this canyon, and the facies is itself overlain by augite andesite flows and flow breccia of the Espinaso volcanics, K-Ar dated by Bachman and Mehnert (1978) at 24-25 m.y. The Espinaso is in turn overlain by the Tesuque Formation, with the Bishops Lodge Member by the base. Northward, the Galisteo and Espinaso units pinch out, probably owing to pre-Santa Fe Group erosion, and the Bishops Lodge Member rests on Precambrian rocks or on Pennsylvanian strata. **2.0**

6.0 Milepost 280. Route is on the Plains surface between Arroyo de las Chamisos to the north and Arroyo Hondo to the south. Off the highway are scattered pits in pumice deposits (Jemez source), which are interbedded in the upper part of the Ancha Formation. **2.3**

8.3 Overpass; Madrid-Cerrillos highway (NM-14). **1.5**

9.8 Crossing valley of Arroyo Hondo. Route ahead ascends to another small remnant of the Plains surface. **0.8**

10.6 Santa Fe Downs to right is on the Airport geomorphic surface. Cerros del Rio basalt field is at 3:00 (Aubele, this guidebook). **1.2**

11.8 Crossing valley of Cienega Creek. Ortiz Mountains (monzonite porphyry) in middle distance are discussed at Stops S19 and S21. Sandias (Stops S16-S18) are at 11:30. **2.0**

13.8 The floor of the valley to right intersects the water table to form a well-vegetated, partly marsh area or cienega. Ground water here discharges from a zone in thin upper Santa Fe beds that rest on much less permeable bedrock units (for example, Mancos Shale).

Prepare to take La Cienega exit ahead for excursion to Stop S21 (optional on southbound tour), located at rest area south of 1-25. **0.4**

14.2 *Take Exit 271 to* **STOP S21, La Cienega rest area** (optional). *Cross over 1-25 to southeast frontage road and proceed southwest on frontage road to rest area. After stop continue southwest on frontage road and rejoin 1-25 South at Waldo interchange* (Exit 267). **0.2**

14.4 Underpass; La Cienega interchange. *Continue west* on 1-25. **0.2**

14.6 Cerro de la Cruz (Calvary Hill) on left is capped by Cieneguilla Limburgite, an augite-olivine-labradorite basalt (upper Tertiary). Cerro Bonanza at 11:00 is at the north end of the Cerrillos Hills. The Cerrillos form the northern part of the Ortiz porphyry belt. Intermediate volcanics and related monzonite porphyry intrusives have K-Ar ages in the 34-25 m.y. range (Bachman and Mehnert, 1968). **1.0**

15.6 Crossing Alamo Creek. **1.5**

17.1 Opposite Stop S21. See mile 227.8 in Socorro to Santa Fe road log. Basalt-capped Mesita de Juana Lopez ahead. Low cone at 1:00 marks central vent for flows (upper Pliocene basalt) forming the Mesita. **0.9**

18.0 Crest of hill; basalt cone to right. Ortiz Mountains at 9:00. The extensive piedmont surface west of the mountain is the type Ortiz surface of Bryan and McCann (1938) and Ogilvie's (1905) conoplain landform. **0.5**

18.5 Overpass; Waldo interchange. Frontage road from rest area and Stop S21 rejoins 1-25 here. **0.5**

19.0 Milepost 267. Route ahead starts descent of La Bajada escarpment. **0.5**

19.5 Cuts ahead in basalt of Mesita de Juana Lopez. This unit is part of a flow sequence K-Ar dated at 2.8 ± 0.1 m.y. by Bachman and Mehnert (1978, no. 7). **0.3**

19.8 Contact of basalt on thin, reddish to brown sandy layer overlying a strong calcic paleosol formed in upper Santa Fe "pediment" deposits. The surface on which the flow rests and the underlying sandy to loamy alluvium (Ancha and Tuerto equivalent) are traceable to the southeast up the valley of Galisteo Creek. In that area the surface is at a level conforming to the level of the type Ortiz surface of Bryan and McCann (1938, p. 8, fig. 2) south of the Galisteo. **0.2**

20.0 Contact of thin upper Santa Fe beds on Mancos Shale (Upper Cretaceous). The Mancos is cut by a limburgite dike. **0.5**

20.5 Morrison sandstone and shale (Upper Jurassic) in cuts ahead. The Morrison is cut by a dark-reddish igneous dike. **0.1**

20.6 At west end of roadcut yellowish Morrison sandstones are in vertical (fault) contact with dark-gray Mancos Shale. In valley ahead on right, red beds of the Galisteo Formation (Eocene) are conformably overlain by greenish-gray fanglomerates and volcanic breccias of the Espinaso Formation (Oligocene). **0.1**

20.7 The Espinaso is exposed in roadcut ahead. **0.1**

20.8 *Prepare for right turn. CAUTION! Dangerous intersection ahead.* Roadcuts ahead in red to brown mudstones and conglomeratic sandstones of the Galisteo Formation. **0.3**

21.1 *Turn right on NM-22.* Continue northwest along base of La Bajada escarpment to **STOP S20, La Bajada escarpment,** opposite mouth of Cañada de la Santa Fe. See miles 217.3 to 220.5 entries in Socorro to Santa Fe tour guide. *After stop, return to this junction; continue southwest on I-25-US-85.* **0.1**

21.2 Dakota Sandstone (Cretaceous) caps ridges to left. The Dakota is thin in this region and rests on sandstone of the upper Morrison Formation. **0.3**

21.5 Crossing La Bajada fault (Rosario fault of Stearns, 1953a). Pinkish to brownish Santa Fe beds are downthrown to the west against the Galisteo Formation. Valley slopes ahead are mantled by reddish-brown alluvium derived mainly from Galisteo red beds exposed in La Bajada escarpment. **0.7**

22.2 At 9:00, beneath thin ledges of Dakota Sandstone, the Jurassic section includes uppermost rounded ridges of Morrison sandstone over lavender mudstone, light-colored Todilto limestone and gypsum, and thin reddish Entrada Sandstone. The base of the exposed section up Galisteo Creek is in Triassic red beds. **0.2**

22.4 Rosario gypsum plant to left. **0.1**

22.5 Overpass. Crossing transcontinental route of ATSF Railroad. Roadcuts ahead in Santa Fe conglomeratic sandstone with narrow strip of inset terrace deposits along Galisteo Creek. **0.4**

22.9 Crossing Galisteo Creek. Rosario gypsum quarry at 9:15 is developed in Todilto Formation (Jurassic). **0.3**

23.2 Galisteo Reservoir to left. Route ahead ascends to high-level surface complex (Ortiz-La Bajada). Alluvial slope and terrace deposits (Quaternary) form a discontinuous cover on Santa Fe beds. **2.9**

26.1 Crossing high-level erosion surface correlated by Kelley (1977) with the Ortiz surface of Bryan and McCann (1938). Thin alluvial veneers cap east-tilted upper Santa Fe beds. The gravel mantle on the type Ortiz surface has been designated the Tuerto gravel by Stearns (1953a). Bryan (1938) designated surfaces in this area as La Bajada (see discussions at Stops S19, S20, and mile 27.6).

Junction ahead; *prepare for left turn.* **0.9**

27.0 *Turn left on NM-22. Continue south* on graded road to **STOP S19, Hagan embayment.** See miles 208.0 to 209.8 in Socorro to Santa Fe tour guide. After stop, *return to this junction; continue southwest* on I-25US-85. **0.6**

27.6 Kearny Route historical marker on La Bajada-Ortiz surface: "General S. W. Kearny raised the American flag at Santa Fe on August 18, 1846, in a bloodless conquest of New Mexico. On September 25 he began his march to California. Here his route crosses U.S. 85."

Bryan (1938) correlated the high-level surfaces in this immediate area with his type La Bajada surface, which is located in northeastern Santo Domingo subbasin at the base of La Bajada escarpment (Stop S20). Unfortunately, the work in that area by Bryan and Upson has remained unpublished. Bryan believed that the La Bajada surface was the oldest part of the river-valley- border sequence and was thus an erosional inset below the Ortiz. Kelley and others (1976, p. 28) believe that "there is no La Bajada surface that is different and younger than the Ortiz." According to Kelley's (1952, 1977) interpretation discussed at Stops S19 and S20, differences in elevation and slope of these surfaces are due mainly to structural deformation including tilting as well as faulting. 0.8

28.4 The road descends dissected scarp of San Francisco fault. Erosion-surface veneers (pediment deposits), which cap east-tilted Santa Fe beds, are offset by the fault. These veneers are associated with Bryan's (1938) La Bajada surface and are correlated with gravels of the Ortiz surface by Kelley (1977). 1.5

29.9 Parking and optional stop area to right. The wagon wheel monument was erected by the Latter Day Saints to commemorate the Mormon Battalion explorations in 1846-1847 for a wagon route to the Pacific. The north tip of Espinaso ridge is about 1 mi to the south at 8:30-9:00. The ridge is formed on coarse, latitic to andesitic volcanic breccias and fanglomerates of the Espinaso Formation (Oligocene; Stearns 1953a, b). Along the western base of the ridge, eastward-dipping Espinaso beds conformably overlie the Galisteo Formation (Stearns, 1943). The Espinaso Formation is in turn overlain by basal Santa Fe beds (Abiquiu ? of Stearns, 1953a) correlated by Kelley with his Zia member of the Santa Fe Formation (chart 2). Dips of the section exposed along the ridge are all northeasterly at 10-25 degrees.

The Espinaso monocline is terminated on the northwest by the San Francisco fault, with the upper Santa Fe-Middle red member of Kelley (1977) downfaulted to the west against the Zia member and rocks of the underlying Espinaso-Galisteo-Mesozoic sequence. Diagonal cross faulting and left curving of the San Francisco fault suggest some left shift along this major boundary structure of the Rio Grande rift (Kelley and others, 1976; Kelley, 1977, p. 44; and this guidebook, Stop S18). The San Francisco fault crosses 1-25 about 1.5 mi northeast of this point (mile 28.4), and it extends about 6-10 mi (4-6 km) before dying out in basin fill. The fault displaces the high-level erosion surfaces, to the east and south, that are correlated by Kelley (1977) with the Ortiz. 0.5

30.4 Route descends into valley of Vega de los Tanos Arroyo. The valley skirts the northern end of Espinaso ridge and heads in the southern Santo Domingo subbasin (Hagan embayment area). The valley walls are cut in upper Santa Fe piedmont-alluvial facies (undivided Santa Fe Formation-Middle red member of Kelley, 1977). 1.1

31.5 Crossing Vega de los Tanos Arroyo. 1.0

32.5 Crest of divide between Vega de los Tanos and Tongue Arroyos. Roadcuts ahead in piedmont facies comprising sandy alluvium with conglomeratic sandstone lenses. This unit overlaps and appears to be gradational with a fluvial gravel-and-sand unit with volcanic ash beds. The piedmont facies is unconformably overlain by a very thin erosion-surface veneer that contains some boulders. 0.2

32.7 Bed of volcanic ash with some pumice clasts is exposed in arroyo and roadcut to left. This lenticular unit crops out at several places in the lower valley of Tongue Arroyo (Stearns, 1953a), where it is interbedded with axial river sand and gravel. The deposit probably includes air-fall facies as well as water-reworked facies; and it is derived from the Bandelier-Cerro Toledo series of eruptions from 1.4 to 1.1 m.y. ago. (Glenn Izett, U.S. Geological Survey, personal communication, December 1978). The ash postdates emplacement of the lower Bandelier unit (Guaje Pumice). 0.6

33.3 Crossing Tonque Arroyo. The Tongue (San Pedro Creek) watershed includes much of the eastern slope of the Sandia Mountains. 0.3

33.6 Roadcuts ahead for the next 1.2 mi are in crossbedded gravel and sand of the upper Santa Fe fluvial facies. 0.8

34.4 Large cut on right in fluvial gravel and sand stained with iron oxide. In exposures 0.5 mi to the southeast, similar Santa Fe beds are partly impregnated with manganese oxides. Note that beds in this area dip a few degrees to the northeast. 0.6

35.0 The low ridge area at 9:00-9:30, between San Francisco and Maria Chavez Arroyos, is part of a wide, northeast-dipping monocline that exposes nearly 3,000 ft of Middle red member of the Santa Fe (Kelley and others, 1976). About the upper 1,100 ft (335 m) of the section includes thick fanglomerates with clasts derived from most of the rocks now exposed in the Sandia uplift. According to Kelley (1977, p. 16), intertonguing mudstones in a zone 400-1,100 ft (120-335 m) below the top of the section thicken to the northwest at the expense of fanglomerate beds, and the unit grades into axial river deposits near 1-25. 0.5

35.5 San Felipe Pueblo to right; *continue straight* on I-25-US-85. The route is now on the Holocene alluvial slope bordering the Rio Grande floodplain. The Pueblo is located along the river at the narrows between the bluffs at 3:30. Two basalt layers (single flow downfaulted to the west) crop out in the eastern bluff. The basalt is the basal flow (upper Pliocene) from the San Felipe center on Santa Ana Mesa at 12:00-4:00 on the west side of the valley. The flow intertongues eastward with upper Santa Fe beds (Stearns, 1953a; Kelley, 1977; and Kelley and Kudo, 1978). Spiegel (1961) mapped the deposits with the faulted basalt tongue as the "axial river gravel" unit in his ."upper unnamed formation" of the Santa Fe Group. Smith and others (1971) include the deposits in a post-Santa Fe (Quaternary-Tertiary) "river gravel" unit that overlies the Cochiti Formation in this area. Kelley (1977; Kelley and Kudo, 1978) considers the beds as facies of his Middle red member in the Santa Fe Formation "main body." The 2.5-2.6 m.y. K-Ar age determinations on San Felipe basalts in the Jemez Dam-Canjilon Hill area (Stop S18; Armstrong and others, 1976; Kudo and others, 1977; and Bachman and Mehnert, 1978) indicate that these axial river deposits are in the uppermost part of the Santa Fe section. 0.2

35.7 Crossing Arroyo de San Francisco. 1.7

37.4 Plains Electric power plant on right. The view at 10:00 is along axis of east-tilted Sandia block and toward area of Stop S18. 1.5

38.9 Junction; *continue straight* on 1-25. NM-474 to Algodones and Angostura on right. **0.1**

39.0 Roadcuts in older valley fill (upper Pleistocene). Las Huertas Creek fan alluvium overlaps channel gravels of the ancestral Rio Grande. These deposits are inset against Santa Fe basin fill. 0.3

39.3 Crossing Las Huertas Creek. 0.6

39.9 Crossing older surface of Las Huertas Creek fan (late Pleistocene). This surface is graded to a valley base-level about 120 ft (36 m) above the present floodplain. The mouth of Jemez River is across the river valley at 3:00. Just south of this point the route crosses the Algodones fault, which merges southward with the Rincon frontal fault of the Sandia uplift (Stop S18). This fault extends north across the river and forms the eastern margin of San Felipe graben, at 3:00 on Santa Ana Mesa (Kelley, 1977, p. 49). 0.4

40.3 Descending into inner valley of the Rio Grande. Cuts ahead are in river channel gravel and overlapping fan deposits. These upper Quaternary units are unconformable on the Santa Fe Middle red member. This general sequence (discussed at mile 47.0) is exposed in the bluffs bordering the inner river valley from here to Albuquerque. 0.7

41.0 Milepost 245. Canjilon Hill diatreme (see Stop S18) forms irregular bluffs across river at 2:00-2:30. 0.6

41.6 Buffs to left are in Middle red member consisting of reddish sandstone and mudstone with fanglomerate tongues. Inset river-terrace gravel (Edith) and deposits or graded alluvial slopes cap the ridges. **1.4**

43.0 Milepost 243. *Prepare to take NM-44 (Cuba) exit ahead* for Stop S18 and connection with Jemez Mountain tour via Bernalillo and San Ysidro (Stops S22 and J1). **0.5**

43.5 *Take Cuba exit (NM-44). Keep right on exit ramp for westbound NM-44* to Bernalillo, San Ysidro, and Jemez Mountain tour (see connecting log and Stop S22). *Keep left on exit ramp for eastbound NM-44* to **STOP 518, Placitas overlook** (see miles 181.9-186.4 in Socorro to Santa Fe road log). After Stop S18 excursion, *return to this interchange and take 1-25 South (Albuquerque) approach ramp.* Road log from here to 1-25 Rio Grande bridge is adapted from northbound log by Lambert. **0.2**

43.7 Approach ramp from Placitas (NM-44) merges from right at underpass; *continue south on 1-25.* For the next 4 mi 1-25 is routed along the scarp bordering the east side of the Rio Grande floodplain. The scarp has been formed by downcutting and lateral migration of the Rio Grande and subsequent dissection by its west-flowing tributaries. Red sandstone and mudstone of the Santa Fe Group (Lower Santa Fe-red member of Spiegel, 1961; or Middle red member, Kelley and others, 1976) are exposed in the lower part of the scarp. Bailey and others (1969) correlated the "red member" with the Cochiti Formation (refer to logs of Bernalillo-San Ysidro and Jemez Mountain tours). The Santa Fe beds are overlain by a sequence of upper Pleistocene terrace and alluvial-fan deposits that are described in the next road log entries. **2.0**

45.7 Arroyo crossing. About 700 ft (215 m) east of 1-25, just east of the high-tension line, a small normal fault offsets the alluvium of Edith Boulevard (upper Pleistocene; see mile 47) and overlying alluvial-fan deposits (fig. S67). The fault is not visible from the highway, but it is well exposed in a small tributary on the south side of the arroyo and in arroyos to the south. The fault strikes N. 12° E. and dips about 80° NW. It can be traced across the arroyos and intervening ridges for a distance of about 950 ft (290 m). Dip separation, as measured on the base of the Edith overbank sediments, is 17 ft (5 m). Because it offsets an upper Pleistocene terrace deposit, this fault is one of the youngest known faults in the Albuquerque area (see discussion of County Dump fault, Stop S16). **1.3**

47.0 Milepost 239. The Bernalillo measured section of Lambert (1968, p. 267) is exposed in roadcuts just north of the milepost. The section extends from the base of the scarp west of the highway to the top of the roadcut east of the highway. The Middle red member crops out in the lower part of the scarp west of the highway. The alluvium of Edith Boulevard is exposed in the lower one-third of the roadcut east of the highway, a layer of orange alluvial-fan material in the middle one-third, and the alluvium of Menaul Boulevard in the upper one-third. East of the roadcut this alluvium is overlain by an unnamed alluvial-fan sand and gravel.

COMPILER'S NOTE-Lambert's (1968) alluviums of Edith and Menaul Boulevards are herein designated, respectively, the Edith unit and the Menaul unit, or simply the Edith and the Menaul.

The Edith unit is an upper Pleistocene Rio Grande terrace with an approximate thickness of 40-50 ft (12-15 m). It is composed of gray sandy gravel and light-colored overband mud and sand. The gravel is characterized by abundant, well-rounded pebbles and cobbles of metaquartzite. The Edith is exposed along the east side of the Rio Grande between Albuquerque and Bernalillo and occurs on both sides of the river in Albuquerque. It overlies rock units of several different ages and contains a Rancholabrean fauna (chart 1). The Edith is not an axial stream deposit within the Middle red member, in contradiction to a recent statement by Kelley and others (1976, p. 21) and Kelley (1977, p. 16).

The Menaul unit is a Rio Grande terrace deposit younger than the Edith and is composed of gray sandy-pebble gravel and overbank deposits. It is 10-25 ft (3-8 m) thick and overlies a wedge of alluvial fan sediment that rests on the Edith. Gravel in the Menaul contains less metaquartzite and more granite and intermediate volcanics than does gravel in the Edith unit. The Menaul crops out along the east side of the Rio Grande from a point 0.6 mi north of the Bernalillo measured section south to Albuquerque.

Hoge (1970, p. 75) has stated that the Edith is younger than the Menaul and inset into it, but exposures in this vicinity clearly indicate that the Menaul physically, as well as stratigraphically, overlies the Edith. The coarseness of the Edith and Menaul suggests that these units were deposited during a glacial interval when the Rio Grande probably had a much greater discharge than at present. The roadcuts between here and Bernalillo mainly expose these upper Pleistocene units. The Middle red member is generally visible only in the bottoms of the deeper arroyos. In many places overlying sediments have been eroded off of the more resistant gravels of the Edith and Menaul units leaving well-developed stripped-structural surfaces. 0.7

47.7 Bridge across Sandia Wash. Outcrop belt of alluviums of Edith Boulevard and Menaul Boulevard swings to east of 1-25. Road ahead is on Holocene alluvial-fan deposits. 0.5

48.2 Sandia Pueblo at 3:00. Sandia (1970 population: 198; area: 22,884 acres) was established around 1300 A.D. It was one of the pueblos visited by Coronado in 1540-1541 when he headquartered his troops in the nearby pueblo of Mohi Tiguex (Coronado State Monument, Bernalillo), now in ruins (U.S. Dept. of Commerce, 1974, p. 373). 0.5

48.7 The steep spur of the Sandia Mountains at 9:00 is Rincon Ridge. It is composed of Precambrian metamorphic rocks intruded by nearly vertical dikes of pegmatite. **0.4**

49.1 Roadcut at right in alluvial-fan deposits. Near here the outcrop belt of the alluviums of Edith Boulevard and Menaul Boulevard swings west of 1-25. Road ahead is on upper Pleistocene and Holocene alluvial-fan deposits. 0.9

50.0 Milepost 236. Roadcuts ahead in alluvial-fan deposits. Albuquerque volcanoes and Volcano Cliffs (basalt-capped mesa) at 2:00 across valley. The volcanoes consist of 10 small basaltic cinder cones arranged along an almost perfectly straight north-trending fissure 3 to 4 mi long. Basalt, perhaps derived largely from the fissure rather than from the present cones, flowed mainly east and covers an area of about 22 mil. A K-Ar age of 0.19 m.y. has been reported for one of the basalt flows (Bachman and others, 1975). 0.4

50.4 Sign-Tramway Road 11/4 mi. *Prepare to take Tramway Road exit.* 0.6

51.0 Milepost 235. Entering Bernalillo County. 0.8

51.8 *Take Exit 234* and *turn left at stop sign. Continue east on Tramway Road* to STOP S17, Tramway Road. See miles 169.3 to 171.3 in Socorro to Santa Fe road log. After Stop S17 excursion, *return to this interchange and take 1-25 South (Albuquerque) approach ramp.* 0.3

52.1 Approach ramp from Tramway Road merges from right; *continue south* on 1-25. 0.9

53.0 Milepost 233. Route is across a distal, Holocene portion of the Sandia piedmont plain known as the Llano de Sandia. Albuquerque volcanoes at 2:30. The high surface to the left and right of the volcanoes is the Llano de Albuquerque, a mid-Pleistocene basin surface into which the present Rio Grande Valley has been excavated (Lambert, 1969; Bachman and Mehnert, 1978). **1.0**

54.0 Milepost 232. Entering Albuquerque. See historical note at mile 118.2 in Socorro to Santa Fe log. 1.5

55.5 Overpass; San Mateo Boulevard. Route is across Llano de Sandia. 2.0

57.5 Underpass; Montgomery Boulevard and Montano Road. Route is approaching outcrop belt of alluviums of Edith Boulevard and Menaul Boulevard and scarp bordering east side of Rio Grande floodplain. The large flat areas to the west of 1-25 for the next mile are reclaimed gravel quarries in the alluvium of Edith Boulevard. 1.6

59.1 Underpass; Candelaria Road. *Keep to right and prepare to take 1-40 westbound* (Grants and Gallup). 0.5

59.6 *Bear right for 1-40 West. Continue west* across Rio Grande Valley to Llano de Albuquerque and STOP S15, **Ceja del Rio Puerco** and **STOP S16, Albuquerque overlook.** See miles 123.5-161.6 in Socorro to Santa Fe road log. After Stops S15 and S16 excursion, *return to this interchange and take 1-25 South (Belen-Socorro) approach ramp.* **0.6**

60.2 Approach ramp from 1-40 (west) merges from right; *continue south on 1-25.* For the next 3-4 mi, 1-25 is routed along the outcrop belt of the alluvium of Edith Boulevard. In most places the alluvium has been removed or covered by construction activities, but remnants of the alluvium and the terrace it holds up are visible in places along the route, especially west of 1-25. East of 1-25, the alluvium of Edith Boulevard is buried by arkosic alluvial fan sediments deposited by an ancestral Tijeras Creek. These pinkish-orange sediments are visible in bluffs east of 1-25. **1.4**

61.6 Overpass; Central Avenue. **1.4**

63.0 Overpass; Gibson Boulevard. **1.0**

64.0 Milepost 222. Road ahead is on a Holocene alluvial-fan apron built westward from high scarp east of 1-25. The southernmost exposures of the alluvium of Edith Boulevard on the east side of the Rio Grande are in this area. The belt of alluvium either turned southwest and was later removed by lateral migration of the Rio Grande, or the alluvium is buried beneath the sediment of the Holocene alluvial-fan apron. The high scarp east of 1-25 leads up to a remarkably flat and undissected surface that is a northward extension of the piedmont plain west of the Manzano Mountains. All but the upper few feet of the scarp are underlain by sediments of the Ceja Member. At the top of the scarp several feet of arkosic alluvial-fan sediment derived from the Sandia and Manzanita Mountains overlie a pedogenic caliche developed in the top of the Ceja. The Ceja Member in the Sunport-Tijeras Arroyo area is similar to the Ceja elsewhere except that it contains a greater proportion of lacustrine clay, mud, and sand, and a greater proportion of pebbles (silicic pumice, for example) derived from sources north of Albuquerque. In addition, sets of cross-strata dip mainly southeast to southwest. Locally, several relatively large bodies of clean channel sand and gravel are present within the member. These features suggest that the Ceja sediments in the Sunport-Tijeras Arroyo area accumulated in a basin-floor environment and probably represent a mixture of channel and overbank deposits of a south-flowing axial stream and distal deposits of its tributaries. **1.0**

65.0 Milepost 221. Hills ahead are underlain by Ceja Member. 0.5

65.5 Overpass over Rio Bravo Boulevard. Several relatively large bodies of clean channel sand and gravel are exposed in the Ceja Member in the hills east of 1-25 (Lambert, 1968, p. 103). 0.3

65.8 Large roadcut in Ceja Member. 0.4

66.2 Road begins descent into Tijeras Arroyo. Tijeras Arroyo drains an area of Precambrian, Paleozoic, and Mesozoic rocks within and east of the Sandia and Manzanita Mountains. Its course through the mountains is in a deep canyon that in places follows the Tijeras fault. **0.3**

66.5 Overpass; railroad spur. Hills bordering both sides of Tijeras Arroyo are underlain by Ceja Member. Early Pleistocene (late Blancan) vertebrate fossils (camel and horse) were collected from Ceja sediments near the top of the scarp on the south side of the arroyo at 9:00 (Lambert, 1968, p. 98; chart 1). **0.4**

66.9 Crossing Tijeras Arroyo. **0.8**

67.7 Roadcuts in Ceja Member. **0.8**

68.5 Road descends to Holocene alluvial-fan apron. Scarp east of 1-25 is underlain by Upper buff member. **0.5** 69.0 Milepost 217. Isleta volcano at 1:30. **1.6**

70.6 Underpass; South Broadway interchange. **0.5**

71.1 Crossing ATSF Railroad; Rio Grande floodplain ahead. Entering Isleta Indian Reservation. **0.4**

71.5 East bridge abutment; Rio Grande channel ahead. Road log from here to Rio Salado rest area adapted from northbound log by Hawley. **0.5**

72.0 Isleta volcano at 11:00 (Kelley and Kudo, 1978; Kelley and others, 1976) is a compound volcano with a cone buildup, 1-1.25 mi in diameter, of five basalt flows. The base of the 300-ft (90-m) high volcano is within an earlier maar crater that is almost completely buried except on the northeastern and eastern sides. Basal flow units rest on a maar accumulation of basalt tuffbreccia. There are also several outlying basalt flows with no exposed connection to the volcano. The lowermost flows of the volcano may have been part of a lava lake that erupted in the maar. The second flow above the maar has a K-Ar age of 2.78 m.y. (Kudo and others, 1977). The basalts of the Isleta center have alkali olivine affinities (Kelley and Kudo, 1978). See Renault (this guidebook) for discussion of rift basalts. **0.5**

72.5 Crossing Isleta Boulevard. Big roadcut ahead is through Black Mesa (of Isleta). Fluvial sand and gravelly sand of the upper Santa Fe Group is capped with beheaded basalt flow. The flow has no outcrop connection with Isleta volcano. A buried vent is suspected somewhere in nearby floodplain area to the south (Kelley and others, 1976; Kelley and Kudo, 1978). **0.3**

72.8 In roadcuts ahead fluvial sand and gravel of the ancestral Rio Grande interfinger westward with basaltic tuff emplaced during early development of Isleta maar (Kelley and Kudo, 1978). **0.7**

73.5 Crossing bridge over Coors Road. Basalt flow of Black Mesa overlies tuff unit in cuts ahead. The basalt of Black Mesa pinches out a short distanct to the west. **0.3**

73.8 End of basalt tongue, in tuffs of Isleta maar, is exposed in gullied slope to right. **0.2**

74.0 Milepost 212. Contact of basal basalt flow (lava lake unit) on tuffs of the maar ring exposed to right. Note intratuff unconformity with tuff and breccia of maar on truncated, flat-lying tuffs deposited outside the crater. For the next 0.4 mi thin Santa Fe beds mantle the basal flow. **1.1**

75.1 Cuts for next 0.3 mi in lower flow sequence over Isleta tuff (Kelley and Kudo, 1978). Site of Stop 1 of Kelley and others (1976, p. 7) is on left in gully having good exposures of the flow-maar contact. **0.6**

75.7 Outlying basalt mass in cut to right. **0.3**

76.0 Milepost 210. Underpass; Isleta Pueblo interchange. **0.1**

76.1 Panoramic view from east to west includes: Manzano Mountains from 8:00-11:00; Cerro de los Lunas volcanic center at 1:00; Mesa Lucero on skyline at 2:00-2:30; Cat Hills basalt flows and cinder cones at 2:30; and Wind Mesa basaltic andesites at 3:00. The volcanic features to the southwest are discussed at Stop S14.

The north-south trending break in slope from 8:00-10:00 midway up the Llano de Manzano is the scarp of the Hubbell Springs fault (Ojuelos fault of Reiche, 1949). The scarp marks the western edge of the JoyitaHubbell bench of Kelley (1977, fig. 19; fig. S55, section D, this guidebook). The upthrown structural bench on the east is formed on pre-rift, Permian, Triassic, and early Tertiary rocks. Basin-fill thickness increases abruptly west of the scarp. According to Kelley (1977; Stop S16, this guidebook) some movement along the 135-ft (40-m) high scarp has occurred in Holocene time.

Continue south on surface of an alluvial terrace complex that is tentatively correlated with the late Pleistocene Segundo Alto surface in west Albuquerque. **1.0**

77.1 Crossing transcontinental route of ATSF Railroad. **1.9**

79.0 Milepost 207. Flows in broad swale on plain to right are from Cat Hills center. As noted at Stop S14 the oldest flow (one of the two most extensive flows) has a K-Ar age of 0.140 ± 0.038 m.y. (Kudo and others, 1977). Thus, pre-Wisconsinan late Pleistocene is the youngest possible age of the surface on which the flow rests (chart 1). **1.0**

80.0 Milepost 206. The 16,346-ft (4,982-m) deep Shell Isleta Central oil test discussed at Stop S14 is located about 2 mi to the west. **2.0**

82.0 *Prepare to take next exit* for Stop S14 (optional). **0.5**

82.5 *Take Los Lunas exit; continue west on NM-6* to **STOP S14, Cerro de los Lunas** on the Llano de Albuquerque. Stop S14 is actually northwest of Cerro de los Lunas. See miles 92.8-96.9 in Socorro to Santa Fe road log. After Stop S14 excursion, *return to Los Lunas interchange* and *take 1-25 South (Belen) approach ramp.* **0.4**

82.9 Approach ramp from Los Lunas merges on right. **1.5**

84.4 Roadcut in pebbly-sand terrace alluvium. This deposit is possibly equivalent to the Los Duranes unit (upper Pleistocene) that forms the Segundo Alto terrace fill in west Albuquerque (miles 125.9-128.1). **0.8**

85.2 Note large landslide masses on south side of Los Lunas volcanic center to right. The route ahead descends from a dissected, late Pleistocene river terrace to a low-lying alluvial slope graded to near present floodplain level and underlain by valley fill of Holocene age. The route from here to the Rio Puerco-Rio Grande confluence is mainly on such low valley-border surfaces.

About 1 mi east of this point is the Harlan and others No.1 exploratory well. Kelley (1977, table 9) reports that the base of the Santa Fe in this 4,223-ft

(1,287-m) test hole is 2,835 ft (864 m) below the flood-plain surface. **0.8**

86.0 Milepost 200. E1 Cerro Tome across valley at 1:30 is a small andesitic volcanic center. Bachman and Mehnert (1978, no. 14) have K-Ar dated a plug from this center at 3.4 ± 0.4 m.y.

At 3:00-3:30 note high surface southwest of the central mass of Los Lunas volcanics. This surface truncates the thick west-tilted section of upper Santa Fe beds discussed at Stop S14. According to Bachman and Mehnert (1978, fig. 4) these beds in turn overlap outlying bodies of mafic lavas (dark, low-lying hills southwest of the central mass). They correlate the lavas with K-Ar-dated units (1.3 to 1.0 m.y., no. 13) sampled at three points on the central volcanic complex. Fig. S49 is a view from the southwest base of El Cerro de Los Lunas (about 2 mi west of here) past E1 Cerro Tome to the northern Manzano Mountains. Southeast-tilted Santa Fe beds shown in the foreground of the picture overlap and contain fragments of andesites that crop out on the lower left. **4.0**

90.0 Milepost 196. Overpass; north Belen interchange. From here to Bernardo (mile 110.8) the route skirts the base of the eastern Llano de Albuquerque escarpment. As discussed at Stops S14 and S15 the summit of this narrow, 65-mi (105-km) mesa is a remnant of the central plain of the Albuquerque Basin. The basic surface formed prior to the entrenchment of the Rio Grande and Rio Puerco Valleys. The original piedmont-slope and basin-floor components that made up this ancient plain have been faulted, dissected by erosion, and partly buried by local basalts as well as by eolian and local alluvial-colluvial deposits. All this considered, the broader summit areas of the Llano de Albuquerque, up to 8 mi (13 km) wide, are probably not aggraded or degraded significantly above or below the original (upper Santa Fe) constructional surface of the plain. The Llano is therefore similar in most respects to the extensive constructional plains of intermontane basins that will be seen south of Socorro. These plains comprise the Jornada I and La Mesa surfaces and their correlatives in the Hueco, Mesilla (Stops S1 and S2), Jornada (Stops S4 and S9), Palomas (Stop S6), and Engle (Stop S8) Basins. **1.8**

91.8 Cut on right in well-bedded sands to loams and clays of the upper Santa Fe Group (Formation). The entire 300-ft (90-m) section exposed from here to the top of the Llano escarpment is correlated by Machette (1978c) with the Sierra Ladrones Formation discussed at Stop S12. Kelley (1977) includes most of the exposed section from here to Bernardo (mile 110.8) in his undivided-Middle red member of the Santa Fe Formation. However, he separates out the surficial zone of soil-carbonate (caliche) accumulation and a thin layer of gravelly to sandy sediments that he interprets as being associated with an Ortiz pediment surface that truncates the upper Santa Fe sequence. **2.2**

94.0 Milepost 192. Water tank and Belen sanitary landfill on right. Titus (1963, p. 28-29) has described a 200-ft (60-m) section of upper Santa Fe beds that crop out in the escarpment badlands area at 3:00. The section is mainly sand and gravelly sand (including sandstone and conglomeratic sandstone lenses) with several prominent zones of interbedded clay, silt, and fine sand. Units are in upward-fining (channel sand and gravel to overbank silt-clay) sequences. A strong horizon of soil-carbonate accumulation engulfs the upper sedimentation unit. No angular unconformities are noted in the section. Preliminary studies of gravel character and sedimentary structures indicate that these units may have been deposited on the distal part of a broad piedmont alluvial plain sloping gently eastward toward the aggrading fluvial plain of the ancestral river. The log of a Belen city water well drilled near this base of the described section indicates that, for at least 500 ft (150 m), the gross lithologic character of the basin fill is similar to that of the bluff outcrop (Titus, 1963, tables 1 and 2). Well-sample studies are needed to determine whether axial river deposits are present in the subsurface section. Deep oil tests in the area west and north of Belen are discussed at Stop S14. **1.7**

95.7 Underpass. About 7 mi east of this point on the Llano de Manzano is the Grober 1 Fugua oil test, drilled between 1937 and 1946 (sheet 2 and Foster, this guidebook, hole v). This 6,300-ft (1,920-m) hole penetrated 4,550 ft (1,387 m) of Santa Fe Group over older fill tentatively correlated with the Baca Formation. An earlier interpretation of data from this hole (Reiche, 1949) indicated that it penetrated Cretaceous and Triassic rocks below the Santa Fe section. **2.4**

98.1 Spur of Sierra Ladrones-Santa Fe Formation extending out from escarpment on left. **0.9**

99.0 Crossing irrigation canal with drop structures to right. **2.0**

101.0 Milepost 185. Crossing small floodplain embayment. About 330 ft (100 m) of weakly to moderately indurated, pebbly sand to clay beds of the Sierra LadronesSanta Fe Formations are well exposed in high bluffs on right. **0.9**

101.9 Entering Socorro County. The route ahead enters San Acacia 15-minute quadrangle, first mapped by Denny (1940, 1941). The southwestern part of the quadrangle is the site of recent studies by Machette (1978b; Stop S12). **2.4**

104.3 Low roadcuts for the next 0.6 mi are in sandy fluvial facies of the Sierra Ladrones Formation (Machette, 1978b, c). **0.7**

105.0 Milepost 181. Abo Pass at 9:00 between Manzano and Los Pinos Mountains. **0.5**

105.5 About 0.75 mi west of this point the Llano de Albuquerque surface (with pedogenic caliche cap) is offset at least 50 ft (15 m) along a northwest-trending fault scarp. Underlying Sierra Ladrones beds are upthrown to the east; however, the amount of displacement of upper Santa Fe strata has not been determined. This high-angle normal fault was first mapped by Denny (1941, fig. 9) and is also shown on maps by Kelley (1977) and Machette (1978c; fig. S45, this guidebook). **0.5**

106.0 Milepost 180. In 1939 an oil test, Central New Mexico 1 Livingstone, was drilled from the Llano surface, elevation 5,074 ft (1,547 m), 1.7 mi west of this point. The 2,978-ft (908-m) hole penetrated an estimated 2,100 ft (640 m) of Santa Fe basin fill and bottomed in possible Cretaceous rocks (sheet 2 and Foster, this guidebook, hole u). 0.3

106.3 Roadcut to left in small knob of Sierra Ladrones fluvial facies, which is capped with pebbly sandstone underlain by interbedded reddish-brown clay and gray-brown sand to sandstone. 0.7

107.0 Milepost 179. Near this point the highway crosses the buried trace of the fault described at mile 105.5. 1.6

108.6 Roadcuts for 1.6 mi are in light-gray to brown sand and sandstone with lenses of pebble gravel and thin layers of reddish-brown clay to loam. The deposits are interpreted herein as fluvial tongues in the Sierra Ladrones Formation. **1.4**

110.0 Milepost 176. *Prepare to take next exit* for Stop S13 (optional). 0.9

110.9 *Take US-60 East exit; continue east* through Bernardo on US-60 to **STOP S13, Black Butte** (Turututu), on the Llano de Manzano. See miles 49.3-57.1 in Socorro to Santa Fe road log. After Stop S13 excursion, *return to Bernardo interchange and take 1-25 South (Socorro) approach ramp.* 0.2

111.1 Approach ramp from Bernardo merges on right; *continue south* on I-25-US-60 across Holocene fan of the Rio Puerco. 0.7

111.8 Crossing Rio Puerco, the longest tributary entering the Rio Grande in New Mexico. This river contributes a great deal of sediment to the Bernardo-San Acacia reach of the Rio Grande Valley (See mile 142.7, Socorro to Santa Fe log).

112.0 Milepost 174. Socorro Mountain at 11:45; Polvadera Mountain of Lemitar Mountains at 12:15; Magdalena Mountains on skyline at 12:30. 2.0

114.0 Milepost 172. The town of La Joya is on the east side of the river at 10:00-10:30. Bluffs above the town are capped with thin fan and terrace gravels of Arroyo de los Alamos and Salas Arroyo (lower Palo Duro Canyon). These surface gravels rest on sandy fluvial beds here interpreted as an older river-channel deposit inset against the Sierra Ladrones Formation. The well-preserved fan-terrace surface is graded to a level about 130 ft (40 m) above the present floodplain. Denny (1941) briefly describes the cut-and-fill terraces in the La Joya area. **1.0**

115.0 Milepost 171. Sierra Ladrones Formation (Machette, 1978b) exposed in high bluffs to right. **1.1**

116.1 Overpass; La Joya State Wildlife Refuge to left. Bluffs to right are cut mainly in distal piedmont slope to basin-floor facies of the Sierra Ladrones Formation, although sandy axial-river zones crop out near the base of the section. Machette (1978b), on the basis of pebble-imbrication studies, interprets alluvial paleotransport directions as being from southeast to northwest in the lower part of the section exposed in the badland area 1 mi ahead on right. A possible source area would be east of the present river valley near the Joyita Hills (at 10:30 just east of inner valley). The ancestral river during this interval would thus have been west of here, possibly in the Lorna Blanca-Sierra Ladrones belt (5-6 mi to the west; Stop S14) where the older fluvial facies is presently preserved. Kelley (1977) includes all exposed Santa Fe beds in this area in his undivided or Middle red member of the Santa Fe Formation, which may include axial river facies. **1.0**

117.1 Starting ascent from Rio Grande Valley to high-level surfaces bordering the lower valley of the Rio Salado. Cuts ahead in Sierra Ladrones piedmont facies. The high ridge to the right is capped with Machette's (1978b) alluvial unit G and is a remnant of the 220,000-year-old Qt, surface discussed at Stop S12. The surface projects about 210 ft (63 m) above the Rio Salado and is offset about 20 ft (6 m) by the Cliff fault. **0.9**

118.0 Milepost 168. Crossing surface of major cut-and-fill terrace of the Rio Salado, here covered with stabilized veneer of eolian sand. The terrace fill (alluvial unit E of Machette, 1978b) has a well-preserved constructional surface 105-112 ft (32-34 m) above the Rio Salado. This is the Qty surface discussed at Stop S12 that has an estimated age of 120,000 years. Denny (1941) maps this surface as a Cañada Mariana(?) pediment, but it may be equivalent to the 100-ft (30-m) cut-and-fill terrace he mapped along the Rio Salado several miles upstream. **1.0**

119.0 Milepost 167. Descending into valley of Rio Salado. *Prepare to take rest area exit.* **0.2**

119.2 *Take exit for rest area.* **0.1**

119.3 **STOP S12, Rio Salado rest area.** See mile 40.8 entry in Socorro to Santa Fe road log. Recommended observation points for viewing features discussed at this stop are on high sand hills north of the picnic areas on both sides of the interstate highway. After stop *continue south* on 1-25. **0.9**

120.2 Crossing Rio Salado. **0.8**

121.0 Milepost 165. The route crosses low valley-border surface of late Pleistocene (Wisconsinan) age, which is formed mainly on thin fan alluvium of the Rio Salado. These deposits bury an erosion surface cut on the lower piedmont facies of the Sierra Ladrones Formation. Denny (1941) mapped this surface as his Cañada Mariana pediment; he designated the slightly higher graded surface west of the highway as Valle de Parida. Surfaces and surficial deposits of the valley-border sequence are further discussed at Stop S10. **1.0**

122.0 Milepost 164. Crossing Rio Grande floodplain. Loma Blanca at 3:30 is a rounded hill formed on sandy fluvial beds of the Sierra Ladrones Formation. At 9:30 the San Acacia constriction of the Rio Grande is cut into basal, basin-floor facies of the Sierra Ladrones Formation capped by basaltic andesite (early Pliocene). **1.0**

123.0 Milepost 163 at San Acacia underpass. **1.0**

124.0 Milepost 162. Route ahead ascends from floodplain to low valley-border surface, here the Holocene alluvial fan of San Lorenzo Arroyo. Reddish-brown hills at 3:00 are Cerritos de las Minas. They are formed on 26- m.y.-old basaltic andesite correlated with the La Jara Peak andesite (Machette, 1978b). **1.0**

125.0 Milepost 161. Crossing San Lorenzo Arroyo. Light-reddish-brown hills at north end of Lemitar Mountains (1:30-2:30) are formed on Popotosa fanglomerates. Lower hills in foreground are dissected piedmont facies of the Sierra Ladrones Formation (upper Santa Fe) with thin caps of alluvial-terrace and alluvial-fan deposits. **1.0**

126.0 Milepost 160. The east slope of the Lemitar Mountains at 2:00 includes Precambrian granites, schists, pegmatites, and diabase dikes. Just below the high point of the range, Polvadera Mountain, Pennsylvanian (Madera) limestones are in fault contact with Precambrian rocks. Near the south end of the range Mississippian and Pennsylvanian rocks overlie the Precambrian. The peak is formed on Oligocene volcanic rocks (rhyolite ash-flow tuffs and andesite flows) that overlie the Pennsylvanian and in places the Precambrian. The southern and northern ends of the range are overlapped by Santa Fe beds, including fan-glomerate and playa mudstone facies of the Popotosa Formation (Miocene), and piedmont gravel and fluvial sand facies of the Sierra Ladrones Formation. 1.7

127.7 Gravel pits on left in Wisconsinan river-terrace deposits. Mastodon and horse teeth have been collected from one of the pits by R. H. Weber. 0.3

128.0 Milepost 158. Socorro Peak at 1:00; Strawberry Peak at 1:30. **1.0**

129.0 Milepost 157. Loma de las Cañas uplift east of river valley from 9:00 to 11:00. **0.8**

129.8 Overpass; Lemitar-Polvadera interchange. **1.5**

131.3 Crossing large arroyo. Route ascends from inner Rio Grande Valley floor onto remnants of older basin-and valley-fill alluvium. Erosion remnants of upper Santa Fe Group basin fill (Sierra Ladrones Formation of Machette, 1978b) are capped with discontinuous mantles of post-Santa Fe valley-fill units. Roadcuts and arroyo-valley exposures ahead show complex intertonguing of piedmont and axial river (fluvial) facies in both the Sierra Ladrones Formation and the post-Santa Fe units of middle to late Quaternary age. As is observed to the south, between Socorro and San Antonio (Stop S10), piedmont and valley-border surfaces in this area have *been* offset by faults as young as late Quaternary. **0.9**

132.2 Valley of Arroyo de la Parida east of the river at 9:00. Reddish fan gravels to fanglomerates (derived in part from Permian red beds in the Loma de las Cañas uplift) interfinger westward with finer grained distal-piedmont to basin-floor facies that include tongues of gray pebbly sands deposited by the ancestral river. The sequence comprises the eastern piedmont and fluvial facies of the Sierra Ladrones Formation; intertonguing relationships were first described by DeBrine and others (1963). Vertebrate fossils collected from fluvial sands in the south bluff of the arroyo valley are of Blancan provincial age (mid-Pliocene to early Pleistocene, chart 1). The sparse fauna was originally described by Needham (1936). According to Bachman and Mehnert (1978, p. 288), the basal fluvial sand zone in the Arroyo de la Parida exposures rises "85 m [280 ft] in altitude northward over a distance of about 11 km [7 mi] along the east side of the Rio Grande, representing a gradient of about 7.7 m/km [about 40 ft/mi], compared with the existing gradient of about 1.0 m/km [about 5 ft/mi]." This upwarped part of the upper Santa Fe sequence extends north almost to San Acacia and coincides with the area where the preliminary studies of railroad level-line data by Reilinger and Oliver (1976) indicate high (4-6 mm/yr) rates of present uplift. **0.6**

133.8 Escondida overpass. **0.2**

134.0 Milepost 152 at flood-control canal crossing. Route from here to south Socorro is on Rio Grande floodplain. **1.4**

135.4 North Socorro exit to right. *Continue on 1-25 South.* **1.3**

136.7 Historic downtown Socorro and old San Miguel Mission to right. **1.2**

137.9 *Take south Socorro exit.* Exit ramp loops to north. **0.5**

138.4 Entering Socorro on US-85 (Business 1-25). 0.2 138.6 Railroad crossing. *Prepare for left turn ahead.* **0.2** 138.8 Junction; US-85 and US-60 at Spring and California Streets. *Turn left on US-60* for **STOP S10, Socorro and STOP S11, La Jencia Basin.** See miles 00.0-20.8 in Socorro to Santa Fe road log. End of Santa Fe to Socorro road log.

BERNALILLO TO SOUTH OF SAN YSIDRO

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The following road log connects with the Jemez Mountain road log by Bailey and Smith (this guidebook). The first 6 mi of the route along NM-44 crosses the west slope of the Rio Grande Valley. West of Loma Barbon the highway descends to the inner valley of the lower Jemez River and parallels the river to near San Ysidro and Stop S22 (Stop J1).

The area traversed contains surface exposures of the major stratigraphic units deposited during the interval (Miocene-Pliocene) that encompassed rift development and partial filling of the resultant structural depressions (chart 2). Moreover, this area is underlain by a great thickness of basin fill (rift and pre-rift), some of which is probably not represented in the exposed Jemez Valley sections (Black and Hiss, 1974; Kelley, 1977; discussions at Stops S15, S17, and S18; Foster, this guidebook, hole dd).

Volcanic tablelands north of the Jemez Valley (including Santa Ana Mesa and the high Borrego and Chamisa Mesas) form the footslopes of the Jemez Mountains. Slopes south of the Jemez River ascend to a high-level erosion surface bordering the north end of the Llano de Albuquerque. The broad belt of steep dissected terrain forming the south rim of the lower Jemez Valley is called the Rincones de Zia. The western part of the Rincones joins the north-south Ceja del Rio Puerco seen at Stop S15.

The Rincones de Zia-northern Ceja del Rio Puerco area is particularly important to studies of the upper Cenozoic geology of the Albuquerque Basin because it was there that Bryan and McCann (1937) first subdivided the Santa Fe Formation into mapping units. Their three-fold subdivision of the Santa Fe into Lower gray, Middle red, and Upper buff members was based primarily on gross color of major units, but the separations also involved consideration of lithologic characteristics including texture and cementation (see Stop S22). Even this broad subdivision of the Santa Fe was found to be useful in making estimates of minimum throw on major (intrarift) fault zones displacing the Santa Fe, allowing Bryan and McCann (1937, p. 801) "to speculate on the amount of the depression of the basin as a result of this faulting."

Subsequent studies of basin-fill stratigraphy and structure have been made near the Jemez River by Spiegel (1961), Galusha (1966), Bailey and others (1969), Smith and others (1970), Black and Hiss (1974), Kelley (1977), and Manley (1978). Spiegel (1961) mapped this immediate area (northern Sandia piedmont to Santa Ana Mesa) and made the first attempt at setting up a system of Santa Fe mapping units that would be useful for making detailed structural and hydrogeologic interpretations. Spiegel in part utilized earlier mapping by Soister (1952) and Stearns (1953a).

Galusha (1966) mapped the type Lower gray and Middle red area in the Rincones de Zia, south of San Ysidro and Stop S22 (Stop J1). He made the first definitive studies of vertebrate faunas of the area and was able to place major parts of the basin-fill section (Eocene to Pliocene) in time-stratigraphic categories (land mammal provincial ages-chart 2). Galusha (1966) formally named the Zia Sand Formation and defined two members. He showed that the Zia Sand was equivalent to the type Lower gray member of Bryan and McCann (1937). Galusha and Blick (1971, p. 39-40, 70) demonstrated that the lower Middle red member of the Santa Fe in the western Rincones de Zia correlated with the upper part of the Tesuque Formation in the type Santa Fe area of the Española Basin.

Bailey and others (1969) and Smith and others (1970) defined formal rock-stratigraphic units for the Jemez volcanic sequence that extends into the Jemez River area from the north. They also participated in establishing radiometric and paleomagnetic time scales for the Jemez volcanics (Doell and others, 1968). Bailey and others (1969), in defining stratigraphic units of the Jemez Mountains area, accepted the rock-stratigraphic units set up by Galusha (1966) in the Jemez River area. Smith and others (1970) outlined the Zia Sand and Santa Fe Formations in a reconnaisssance fashion in the southwestern part of their map area west of Santa Ana Mesa and north of Jemez River.

Bailey and others (1969) also defined a "post-Santa Fe unit," the Cochiti Formation, which comprises piedmont clastic deposits derived from the southern Jemez and adjacent Nacimiento highlands. They mapped the Cochiti as far south as the Santa Ana Mesa area, including the border strip along the Jemez River and the Rio Grande (Smith and others, 1970).

The area traversed from here to San Ysidro is the site of recent mapping by Kelley (1977), Manley (1978), and Woodward and Ruetschilling (1976). The last work, in the area of Stop S22, deals with the western rift boundary area between the Colorado Plateau, the Nacimiento uplift (Southern Rocky Mountain prong), and the northwestern Albuquerque Basin.

Kelley (1977) also proposes a three-fold division of the Santa Fe Formation in the Albuquerque Basin. These are the newly defined Zia and Ceja members that are broadly correlative with the Lower gray and Upper buff members of Bryan and McCann (1937). Kelley (1977) retains the term Middle red for "the main body" (p. 14) of the Santa Fe Formation between the Zia and Ceja members. He does not recommend extending the Cochiti Formation "into central areas of the basin" (p. 11) as done by Smith and others (1970) in the Jemez River-Santa Ana Mesa area.

In the Bernalillo Northwest quadrangle (crossed between miles 7.0 and 17.6) Manley has mapped a redefined "upper" Zia Sand that includes the Santa Fe beds mapped by Smith and others (1970) west of Santa Ana Mesa. This "Zia Sand-upper part" is equivalent to the upper Tesuque subdivision of Galusha and Blick (1971, p. 39-40) discussed at Stop S22. Manley (1978) also has extended the Cochiti Formation into the northeastern part of the type Middle red-Upper buff area in the Rincones de Zia. She thus differs from Kelley (1977) on interpretation of the Cochiti Formation.

The Zia (Sand) units of Kelley (1977) and Manley (1978) are similar but not identical; however, their concepts on how the Zia unit should be defined differ markedly from views held by Galusha (1966), Galusha and Blick (1971), and Bailey and others (1969). Neither Manley nor Kelley feels that major rock-stratigraphic subdivisions can be differentiated in the dominantly sandy section that comprises the Lower gray to lower Middle red (Zia Sand-Santa Fe) sequences exposed in the Jemez River Valley from Rincones de Zia to Chamisa Mesa and Santa Ana Mesa.

Mapping-unit design and stratigraphic correlation is particularly difficult because basin-fill deposits commonly exhibit rapid facies changes (involving color, texture, and thickness shifts). Moreover, these changes occur in an area characterized by poor exposures and complex patterns of faulting and warping. Additional detailed studies should resolve many of these problems. Progress and problems in mapping the lower Jemez River area are illustrated en route to Stop S22. Details of the stratigraphy and structure along the western rift boundary are discussed at that stop.

0.0 *Take Exit 242 (Cuba exit) to right.* 0.3

0.3 Crossing ATSF Railroad; *continue west* on NM-44 across Rio Grande floodplain. 0.4

0.7 Stop sign; *continue straight ahead.* Bernalillo to left via US-85. 0.6

1.3 Crossing Rio Grande. 0.3

1.6 Coronado State Monument on right on low river terrace. Coronado's expeditionary force wintered nearby in 1541-42. During that winter Coronado fell from his horse and broke his leg. His leg healed very slowly, and the morale of his expedition deteriorated. The expedition returned to Mexico the following summer. **0.4**

2.0 Milepost 2. Junction ahead; *continue west* on NM-44. Road to right is to Jemez Canyon Dam and southern tip of San Felipe basalt field south of Santa Ana Mesa. Basalt sampled near the dam has been K-Ar dated at 2.6 m.y. (Armstrong and others, 1976) and 2.5 m.y. (Bachman and Mehnert, 1978). The San Felipe field is discussed at Stop S18. Good exposures of the Cochiti Formation (Smith and others, 1970) occur along the road to the dam. These reddish conglomeratic and arkosic sandstones are mapped as Middle red member by Kelley (1977). **0.4**

2.4 Junction; *continue straight* on NM-44. Rio Rancho Estates and Corrales to left via NM-528. The route for the next 4 mi crosses broad alluvial slopes forming the western border of the Rio Grande Valley. Surfaces are cut on Middle red (Cochiti) sandstones to mudstones that are partly conglomeratic and are thinly mantled with alluvial, colluvial, and eolian deposits of late Quaternary age. 0.3

2.7 Roadcuts ahead in upper Quaternary valley fill (eolian sand over older alluvium). 1.3

4.0 Milepost 4. Middle red (Cochiti) beds in dissected hill-slope area to right. **0.4**

4.4 Note fault in roadcut to right. Middle red (Cochiti) beds are downthrown to the east along a fault that extends to Santa Ana Mesa 6 mi (10 km) to the north and displaces Pliocene basalts of the San Felipe center (Kelley and others, 1976, mile 15.2). This is the Luce fault of Kelley (1977) and one of a number of north-south faults within the San Felipe graben (mile 195.1, Bernalillo to Santa Fe). **1.9**

6.3 Summit of grade on Loma Barbon. Roadcuts in east-dipping Middle red (Cochiti) sediments. Badland amphitheater is ahead on right with excellent exposures of the Middle red member (Cochiti Formation). The unit comprises sandstones to clays with local conglomeratic zones. **0.7**

7.0 Milepost 7. Starting long descent to inner valley of Jemez River. The area ahead and to west has been mapped by Manley (1978). Nacimiento Mountains at 1 1 : 00-1 2: 00 and Jemez Mountains at 1:00 on northern skyline. In the middle distance at 12:30 is Borrego Mesa, with the small outlying Chamisa Mesa (butte) at its southwestern tip. Santa Ana Mesa is on the opposite side of Jemez River at 1:00-1:30. The Rincones de Zia border a high erosion surface at 9:00-10:00 that is inset below the main Llano de Albuquerque summit located several miles to the south. This surface was cut by an ancestral Jemez River-Rio Salado system that may have headed west of the Rio Grande-Puerco divide (G. 0. Bachman, written communication, 1978).

Near this point the route crosses the trace of the north-trending Santa Ana fault, which is downthrown to the east. The fault forms the western boundary of the San Felipe graben (Kelley, 1977), and it cuts the east flank of the south-plunging Ziana anticline (Black and Hiss, 1974). In 1972 a Shell Oil Company test well (Shell 1 Santa Fe; sheet 2, hole dd) was drilled about 2.5 mi southwest of this point and just east of the north-south anticlinal axis. The well site is near the crest of a gravity high (Black and Hiss, 1974, p. 369). This 11,045-ft (3,365-m) hole penetrated 2,970 ft (905 m) of Santa Fe, 174 ft (53 m) of Galisteo Formation, and 7,811 ft (2,381 m) of Cretaceous to Pennsylvanian rocks; it finished in Precambrian rocks below 10,955 ft (3,339 m)-5,202 ft (1,586 m) below sea level (Foster, this guidebook, hole dd). The Paleozoic and Mesozoic section penetrated is described by Black and Hiss (1974, table 1). Note that Foster picks the top of the Cretaceous at 3,144 ft (958 m), in contrast to the 3,644-ft (1,111-m) figure given by Black and Hiss (1974). They estimate that the Galisteo Formation is 674 ft (205 m) thick, while the log interpretation by Foster given above indicates that the Galisteo is much thinner. **1.4**

8.4 Entering Santa Ana Indian Reservation. **0.1**

8.5 Roadcut exposures of gray sand with concretionary sandstone bodies. This unit is mapped by Kelley (1977) as "Zia member" of the Santa Fe Formation. Manley (1978) includes these beds in the upper part of her newly defined "Zia Sand" (lower Santa Fe Group). Manley's "Zia Sand" includes the type Zia Sand Formation (Lower Miocene) of Galusha (1966), as well as a middle to upper Miocene "upper part" (seen here) that is equivalent in general age and lithology to the Ojo Caliente Sandstone of the Tesuque Formation in Española Basin. Galusha and Blick (1971, p. 39-40, 70) discussed the problems involved in stratigraphic correlation in this particular area and the need for further detailed work on the rock units and associated vertebrate faunas. Galusha does not feel that Kelley (1977) and Manley (1978) were justified in expanding the Zia concept to include these beds. He believes that, for the present, this sand unit should be included in an unnamed subdivision of the Santa Fe Group that is equivalent (in general age) to units of the upper Tesuque Formation in the Española Basin (such as Pojoaque and Ojo Caliente members). 0.3

8.8 Roadcut exposures of gray sand with lenticular masses of calcareous, concretionary sandstone that stand out as resistant layers. This "upper part" of Manley's Zia Sand is near the top of the upper "Tesuque-equivalent" section. Between here and Loma Barbon these beds are overlain by the Cochiti-Middle red unit (Manley, 1978). **0.2**

9.0 Milepost 9. Note white ash layer that crops out in arroyo wall to right. Manley (1978) reports two such layers in the "Zia-upper part" section. **1.0**

10.0 Santa Ana Pueblo to right (1970 population, 376; area, 42,527 acres). This pueblo community was established about 1700. The native tongue (Keresan) and religion continue to play vital roles in Indian life (U.S. Dept. of Commerce, 1974, p. 383). Visits to this pueblo are usually not permitted. **2.0**

12.0 Milepost 12. Gray sand in "Zia-upper part" crop out at 1:00-3:30 on north side of Jemez River. These beds are exposed in the upthrown (western) block of Santa Ana fault and were originally mapped as Santa Fe by Smith and others (1970). They map Cochiti Formation in the downthrown block, as does Manley (1978). However, Kelley (1977) maps his Zia member on both sides of the fault. He shows the Middle red-Zia contact on the slopes east of the fault that ascend to Santa Ana Mesa. **1.0**

13.0 Milepost 13. The prominent butte at 1:30 is Chamisa Mesa, capped with the basal basalt unit of the Keres Group dated at 10.4 m.y. (Bailey and Smith, this guidebook, fig. J2). The basalt caps several hundred feet of sandy beds-correlated by Galusha (1966) with the Santa Fe-which in turn overlie the upper part of the type Zia Sand (Chamisa Mesa Member). Kelley (1977, p. 12) has discussed problems in defining mappable rock units in the Chamisa Mesa area. **4.3**

17.3 Arroyo Ojito ahead (Canyada de Zia of Galusha, 1966). The buried trace of Kelley's (1977) Zia fault, downthrown to the east, is mapped across Jemez Valley near here. About 2 mi to the south this fault appears to coincide with the Rincon fault of Galusha (1966) and Manley (1978). The entire exposed section east of the Rincon fault is believed by Galusha to comprise post-Zia units. These units are primarily the "upper Tesuque equivalent" and Cochiti Formations (see Stop S22). **0.3**

17.6 Zia Pueblo to right (1970 population, 464; area, 112,511 acres). This Keresan pueblo was established in about 1300 when pueblo Indians moved from a site farther up the river. They took part in the Pueblo Revolt in 1680. During reconquest, a bloody battle was fought in which 600 Indians died and 70 were taken into slavery. The old men were executed. The present mission structure built in 1692 is still in use (U.S. Dept. of Commerce, 1974, p. 394). The original pueblo is on the stream terrace north of the Jemez River. The Zia sun symbol is the design on the New Mexico State flag. *Continue west* on NM-44; leaving area mapped by Manley (1978). **1.3**

18.9 Entering San Ysidro quadrangle mapped by Woodward and Ruetschilling (1976). White Mesa at 12:00. Todilto gypsum (white cap) and limestone (gray ledge) rest on Entrada Sandstone (Jurassic), gray in upper part, red in lower slope. The Jemez fault trace trends northerly along the eastern base of White Mesa.

At 2:00 the Yeso Formation (Permian), bright-red sandstone and shale, is overlain by thin yellowish Glorieta Sandstone (Permian) and ragged yellowish ledges of the Agua Zarca Sandstone Member of the Chinle Formation (Upper Triassic) along the eastern limb of a south-plunging syncline. The Agua Zarca is exposed in the axial portion of the syncline. Ridge to left is formed on Zia Sand Formation (lower Miocene) of Galusha (1966). **1.1**

20.0 Milepost 20. *Park by barrier in abandoned highway segment ahead on right* for Stop S22. **0.3**

20.3 STOP S22, South of San Ysidro. This stop (fig. S76) is on a short segment of abandoned highway about 0.7 mi east of road to White Rock **gypsum** quarry and **coincides** with Stop **J1 of the Jemez Mountain** tour. Emphasis of discussions is on stratigraphic and structural relationships in the type areas of the Lower gray-Middle red-Upper buff members (Bryan and McCann, 1937) and the Zia Sand Formation (Galusha, 1966).

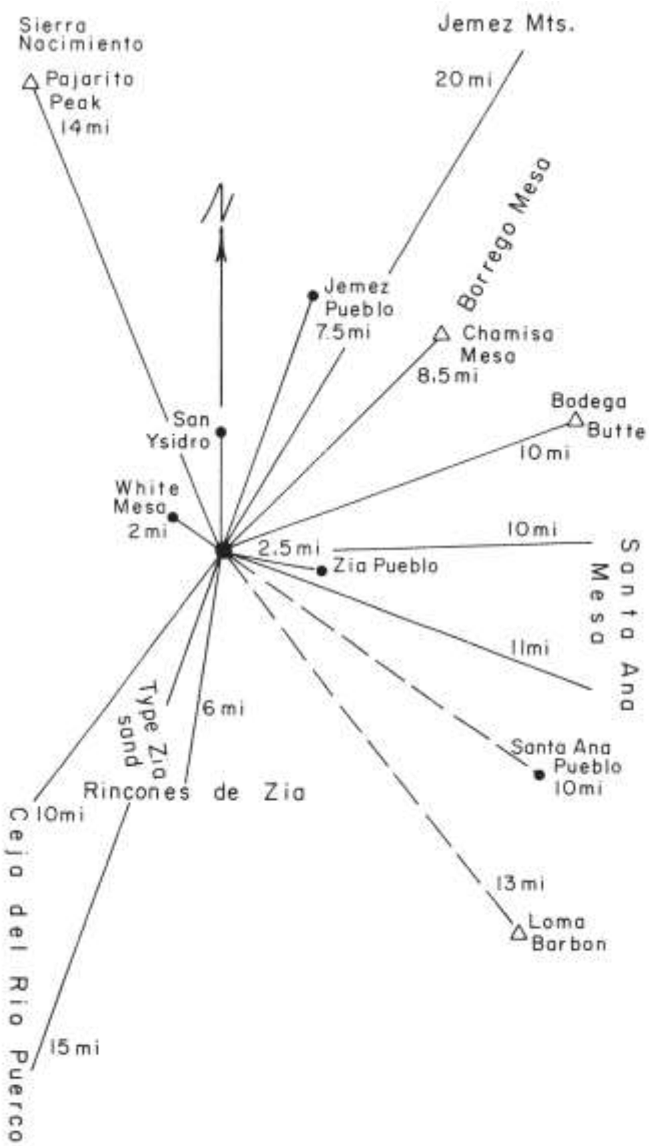

FIGURE S76—PANORAMIC INDEX OF FEATURES SEEN FROM STOP S22 (Stop J1), SOUTH OF SAN YSIDRO IN LOWER JEMEZ RIVER VALLEY.

According to Woodward and Ruetschilling (1976) and Kelley and others (1976, Stop 2), the western boundary of the Rio Grande rift is here formed by the San Ysidro fault at the eastern border of the Colorado Plateau. The trace of this north-trending fault (Sierrita fault of Galusha, 1966) is about 1 mi west of this stop along the east rim of White Mesa. Cretaceous rocks (Dakota-Mancos) in the eastern downthrown block are faulted against Jurassic rocks (EntradaTodilto-Morrison) of the White Mesa block. Strati-graphic separation along this fault is about 900 ft (275 m). To the north the western margin of the rift is complex, reflecting in part the approach to the Nacimiento uplift.

The Jemez fault (Galusha, 1966; Kelley, 1977) closely parallels the San Ysidro (Sierrita) fault on the east. The Jemez fault trace crosses NM-44 near the White Rock Quarry turnoff. Along this fault, about 2 mi to the southwest, the Zia Sand Formation is downthrown to the east against Mancos Shale. The valley ("canyada") of Arroyo Piedra Parada occupies much of the area between the Jemez and San Ysidro faults. The valley heads about 7 mi southwest of here in the upper Rincones de Zia. Slopes in the lower to middle valley segment are characterized by thin alluvial and eolian fills that form a discontinuous cover on Cretaceous (Mancos-Crevasse Canyon) and Eocene (Galisteo) formations. About 4 mi south-southwest of this stop, overlying deposits of the rift-depression sequence are unconformable on or in fault contact with the Eocene and Cretaceous rocks. These deposits make up the Santa Fe Formation of Bryan and McCann (1937) and Kelley (1977).

The northern part of the type area of the Lower gray-Middle red-Upper buff members (Bryan and McCann, 1937, fig. 4) is in the upper "Canyada" Piedra Parada basin southwest of this stop. The type area extends southward along Ceja del Rio Puerco to near the Sandoval-Bernalillo County line. Bryan and McCann (1937) characterized the Lower gray and Middle red units as having mainly sandy texture, with clay and gravel beds being locally present along with calcareous, concretionary sandstone masses. The main distinguishing feature used by Bryan and McCann (1937) was color: white to gray in the lower unit and common shades of red to buff in the middle unit. The presence of gravel and variable textures, as well as a generally buff color, were considered to be characteristic of the Upper buff unit. The basic Bryan and McCann units have been used (with some modifications) by a number of subsequent workers including Denny (1940), Wright (1946), Lambert (1968), and Kelley (1977) and are still commonly applied in general descriptions of basin-fill stratigraphy.

In 1966 Galusha discussed the geology and vertebrate paleontology of the Tertiary units exposed in the Rincones de Zia. He documented the presence of the Galisteo Formation (Eocene) in "Canyada" Piedra Parada between the Jemez and Sierrita (San Ysidro) faults, and he defined the overlying Zia Sand Formation (lower Miocene). This basal unit of the upper Tertiary basin-fill sequence is about 1,000 ft (300 m) thick in this area. The formation has been recognized as the general equivalent of the Lower gray member of Bryan and McCann (1937); however, Galusha excluded it from the Santa Fe because it was significantly older than dated beds in the Española Basin type area. Vertebrate faunas from the type Zia section have established that the formation covers a time span extending from latest Arikareen to late Hemingfordian provincial age. Present estimates of absolute age of these faunas, using the radiometric time scale of Berggren and van Couvering (1974, fig. 1), is from slightly older than 21 m.y. to between 17 and 18 m.y. (chart 2).

Galusha (1966, p. 11, fig. 3) also described red to gray sandy strata of the Santa Fe (Middle red) Formation that overlie the Zia both in the type area and in an area north of Jemez River between Jemez Pueblo and Chamisa Mesa. The Santa Fe-Middle red section described in the Rincones de Zia is about 500 ft (150 m) thick, and it unconformably overlies the Zia Sand. Fossils recovered from these Santa Fe beds are of Valentinian and Clarendonian provincial age and are not older than about 12 m.y. (chart 2). As already noted, the K-Ar age of basalt of Chamisa Mesa capping the Santa Fe section is 10.4 m.y. (Bailey and Smith, this guidebook).

Galusha and Blick (1971, p. 39-40) discussed problems in correlation of units in the lower Jemez River area with units of their type Santa Fe Group in the Española Basin. They informally correlated the post-Zia (post-Lower gray) Santa Fe beds of the Rincones de Zia and Chamisa Mesa sections with the upper Tesuque Formation of Valentinian-Clarendonian provincial age. These beds are the "Zia-upper part" unit of Manley (1978). Equivalent Tesuque members in Española Basin include Ojo Caliente Sandstone and the Pojoaque Member. However, Galusha and Blick (1971, p. 40) make this point: "On purely rock-stratigraphic criteria all the recognized subdivisions of the formations in the Jemez Creek [River], Ceja del Rio Puerco, and Lower Ceja del Rio Puerco should be described as separate formations and not correlated directly with the formations of the type locality of the Santa Fe Group."

Bailey and others (1969) and Smith and others (1970) defined the Cochiti Formation (see road log introduction), which overlies the Tesuque equivalent-Santa Fe beds of Galusha and Blick (1971) in the vicinity of Santa Ana Mesa. The Cochiti is partly equivalent to beds designated by others as upper Middle red and lower Upper buff. In its type area west and southwest of Cochiti Dam (mouth of White Rock Canyon), the Cochiti Formation is a thick-sequence volcanic gravel and sand derived from penecontemporaneous erosion of units of the Keres Group (with a K-Ar age range of 10.4-6.5 m.y.). Basalt of Chamisa Mesa forms the basal unit of this group. Angular clasts derived from granite and Paleozoic sedimentary rocks of the Nacimiento uplift become common constituents of the reddish to yellowish Cochiti exposures to the south and west of Santa Ana Mesa. The Cochiti appears to predate formation of the integrated Rio Grande system 4 to 5 m.y. ago (chart 2).

West of the Jemez fault at the head of "Canyada" Piedra Parada, Bachman (written communication, 1978) has recognized a distal piedmont facies of the Cochiti Formation that overlies the reddish Santa Fe-upper Tesuque equivalent unit. The Cochiti beds are yellowish in color and are equivalent to the Upper buff member mapped west of the Jemez fault by Bryan and McCann (1937). These beds are truncated by a major high-level erosion surface that is capped by Pleistocene gravels of the ancestral Jemez River-Rio Salado system.

East of the Jemez fault the exposed outcrop belts of units ranging from Zia Sand through lower Cochiti are offset to the north. The amount of stratigraphic displacement is at least 1,000 ft (300 m) and may be considerably greater. The studies in progress by Bachman (written communication, 1978) show that the Cochiti Formation thickens abruptly east of the fault and that this unit continues to thicken eastward across the Rincones de Zia (see Manley, 1978). This thickening of the Cochiti section results mainly from the decreasing amount of erosional truncation toward the central basin area east of the Jemez and Rincon faults. According to Bachman, past correlation problems have occurred because the color patterns in the Cochiti Formation also change to the east but not necessarily in accordance with textural or thickness changes. The yellowish facies, characteristic of the basal Cochiti unit preserved west of the Jemez fault, persists in the block to the east. However, in the area between the Jemez and Rincon faults the yellowish (color) facies grades upward and laterally (eastward) into a red facies. The latter color facies is typical of the Cochiti exposures in southern Bernalillo Northwest quadrangle (Manley, 1978) east of Rincon fault (Zia fault of Kelley, 1977). As noted at mile 17.3, east of the Rincon fault the lower Miocene-Zia Sand section is faulted below the surface and the exposed section consists entirely of the Santa Fe-Tesuque equivalent ("Zia-upper part" of Manley, 1978) and overlying Cochiti beds. The latter are mapped as the Middle red member of the Santa Fe Formation by Kelley (1977). Much past confusion has arisen because reddish zones in both the middle Miocene Tesuque equivalent and the upper Miocene Cochiti Formation have been correlated as the same Middle red unit.

Much remains to be accomplished in establishing mappable rock units that can in turn be used to correctly portray the late Cenozoic structural history of the area. The problems really revolve around the occurrence of subtle changes in color, texture, and thickness of alluvial and eolian deposits that are generally medium to fine grained and poorly indurated. The complex fault pattern, extensive areas of poor exposure, and local problems in access add to the difficulties in establishing mapping units that are suitable for detailed work. However, as noted by Hawley and others (1976), definitive answers can still result from continued efforts in modern techniques of tephrochronology, paleomagnetic stratigraphy, and paleopedology, along with the traditional methods in paleontology and detailed mapping (for example, physical tracing of key beds). Additional work along these lines in this immediate area is being planned by Galusha and others, in cooperation with the New Mexico Bureau of Mines and Mineral Resources.

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Guide to Jemez Mountains and Española Basin

VOLCANIC GEOLOGY OF THE JEMEZ MOUNTAINS, NEW MEXICO

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This log begins on NM-44 about 3 mi south of San Ysidro. The general route through the Jemez Mountains (fig. J1) is along NM-4 from San Ysidro northward up San Diego Canyon past Jemez Pueblo and Jemez Springs to La Cueva on the southwest edge of the Valles caldera. From this edge of the caldera a side trip of about 9 mi (round trip) on NM-126 may be taken to the west rim, where an excellent view of the caldera interior can be seen. From La Cueva, the main route continues eastward through the south moat of the caldera to the Valle Grande and then out of the caldera over the southeast rim. The route descends the east flank of the mountains, crosses the Pajarito Plateau, passing Bandelier National Monument and the town of White Rock, and finally descends to the Rio Grande at Otowi Bridge near Totavi. The log covers a total distance of about 90 mi; allowing one-half hour at each stop, the trip can be expected to take 9-10 hours.

The route northward from San Ysidro follows the Jemez River along the bottom of San Diego Canyon, whose lower walls expose mainly Permian red beds and whose upper walls expose rhyolite ash flows of the Bandelier Tuff. The route through the south moat of the caldera traverses mainly postcaldera rhyolite domes and flows that erupted from the ring-fracture zone between the south wall of the caldera and the central resurgent dome, whose summit, Redondo Peak, dominates the northern skyline. Continuing eastward through the Valle Grande, the route climbs out of the caldera, traversing quartz latites of the precaldera volcanic sequence, and descends to the surface of the Pajarito Plateau, which is underlain by Bandelier Tuff. From Bandelier National Monument northeastward to White Rock, the route passes distal exposures of Bandelier Tuff, which rest mainly on basaltic lavas of Cerros del Rio. North of White Rock the route turns eastward, descends the north side of Los Alamos Canyon, and traverses in descending order: Bandelier Tuff, basaltic lava and tuffs of Cerros del Rio, volcanic fanglomerate and lithic tuff of the Puye Formation, and finally arkosic sands of the Chamita Formation of Galusha and Blick (1971) and the Tesuque Formation, both of the Santa Fe Group.

A useful aid to this road log is the Geologic Map of the Jemez Mountains, New Mexico (Smith and others, 1970). Additional information on the geology of the Jemez Mountains may be found in Ross and others (1961), Smith and others (1961), Smith and Bailey (1966, 1968), and Bailey and others (1969). The stratigraphic nomenclature and general chronologic relations of the rock units in the Jemez Mountains are summarized in fig. J2. The K-Ar dates cited in fig. J2 and in the log are from Dalrymple and others (1967), Doell and others (1968), and Miles Silberman (personal communication, 1973).

The mileages indicated in the log are measured from the NM-44 overpass at the ATSF Railroad in Bernalillo.

20.3 **STOP J1, South of San Ysidro.** *Stop near barrier on right* at abandoned segment of NM-44. On the skyline to the north lie the Jemez Mountains, a volcanic complex ranging in age from about 10 to 0.1 m.y., covering about 5,000 km' and straddling the west edge of the Rio Grande rift.

To the north-northeast are Chamisa Mesa and Borrego Mesa (fig. J3), which are capped by basalt flows representing the earliest eruptions (about 10 m.y.) in the Jemez Mountains. These basalts lie mainly on arkosic sands of the Santa Fe Group. Chamisa Mesa is an antithetic fault block tilted eastward toward the Rio Grande rift. The southern Jemez Mountains, rising north of Chamisa Mesa, are composed mainly of andesitic rocks of the Paliza Canyon Formation, which range in age from 9 to 7 m.y.

Slightly northwest is the gently south-sloping surface of the Jemez Plateau, underlain by the Bandelier Tuff, an extensive accumulation of rhyolite ash-flow deposits that erupted from the central part of the Jemez Mountains, forming the Toledo and Valles calderas 1.4 and 1.1 m.y. ago, respectively (figs. J1 and J2).

Nearly due north beyond the Jemez Plateau rises the dome-shaped crest of Redondo Peak, the highest point on the postsubsidence resurgent dome within the Valles caldera. Redondo is underlain by intracaldera Bandelier Tuff that has been uplifted at least 3,250 ft (1,000 m) above the caldera rim by postcaldera magmatic pressure. **0.6**

20.9 Highway curves north. Entrance to White Mesa gypsum quarry on left. *Continue north* on NM-44.

The yellowish beds on the left are marine shale and sandy shale of the Mancos Formation (Cretaceous). The orange beds and prominent grey ledge forming the cuesta of White Mesa are Entrada Sandstone and Todilto Formation (both Jurassic), respectively. Between the Cretaceous and Jurassic formations passes the north-trending San Ysidro fault (Woodward and Ruetschilling, 1976), which, together with the Jemez fault to the northeast, forms the western edge of the Rio Grande rift in this area. Both are high-angle normal faults with downthrow to the east. The Jemez fault, continuing 22 mi north-northeastward to the Valles caldera rim, has a maximum displacement of at least 1,950 ft (600 m) and has been recurrently active from at least the Miocene (Wood and Northrop, 1946) through middle Pleistocene. **1.6**

22.5 Bridge over Rio Salado. **0.8**

23.3 Junction of NM-44 and NM-4 at San Ysidro. *Bear right on NM-4* toward Jemez Pueblo and Jemez Springs. **2.0**

25.3 Bridge over Jemez River. At right is Zia Sand (Miocene) (Galusha, 1966) overlain by Pleistocene terrace gravels. **2.6**

27.9 Jemez Pueblo Enterprises. **0.7**

28.6 Jemez Pueblo. **1.7**

30.3 Contact between Zia Sand and red beds of Yeso Formation (Permian). **2.4**

32.7 **STOP J2, North of Jemez Pueblo.** *Stop on wide shoulder at left. Walk west along fence line* to edge of juniper trees. Due north is Guadalupe Mesa (fig. J4)

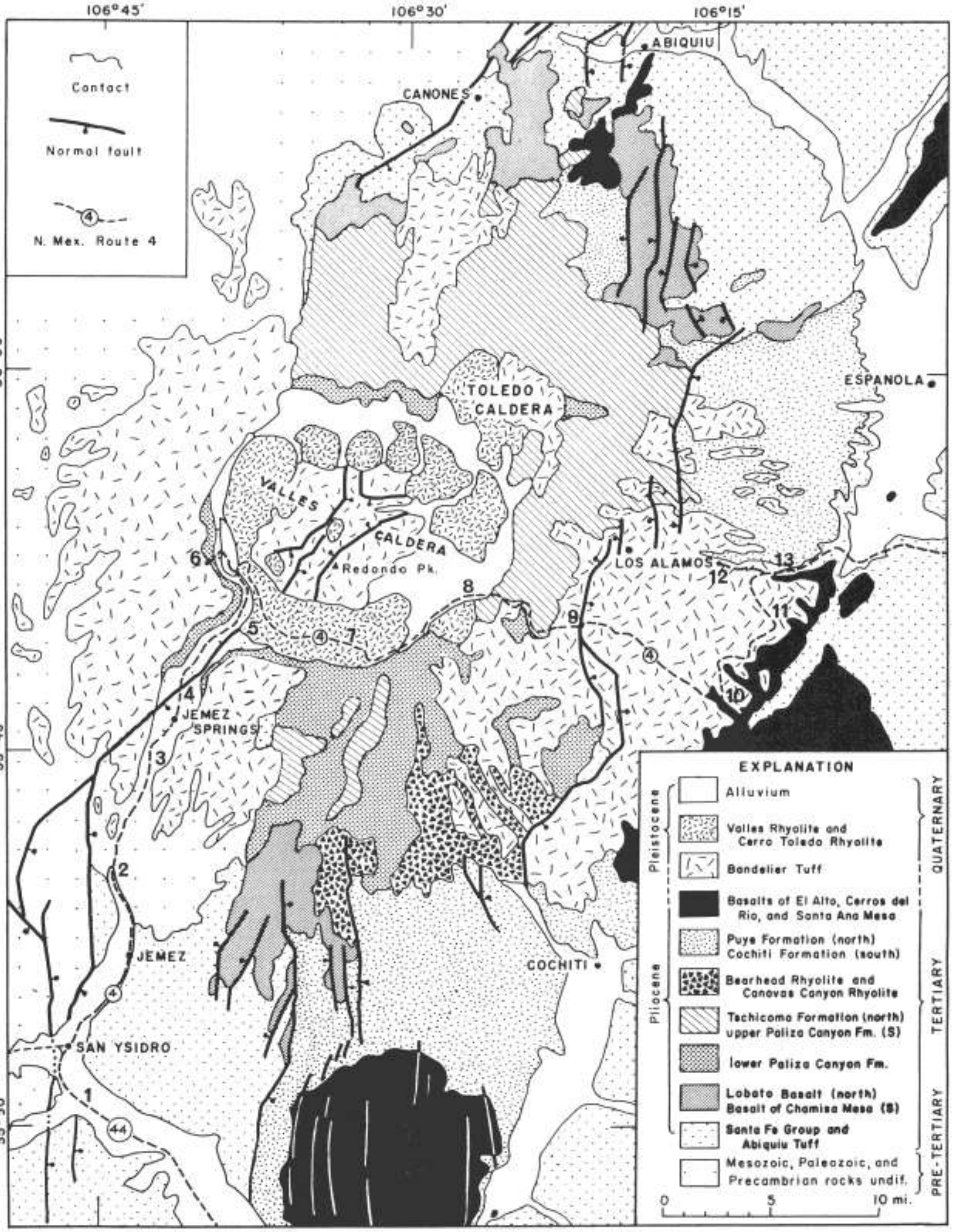

FIGURE J1—GENERALIZED GEOLOGIC MAP OF THE JEMEZ MOUNTAINS.

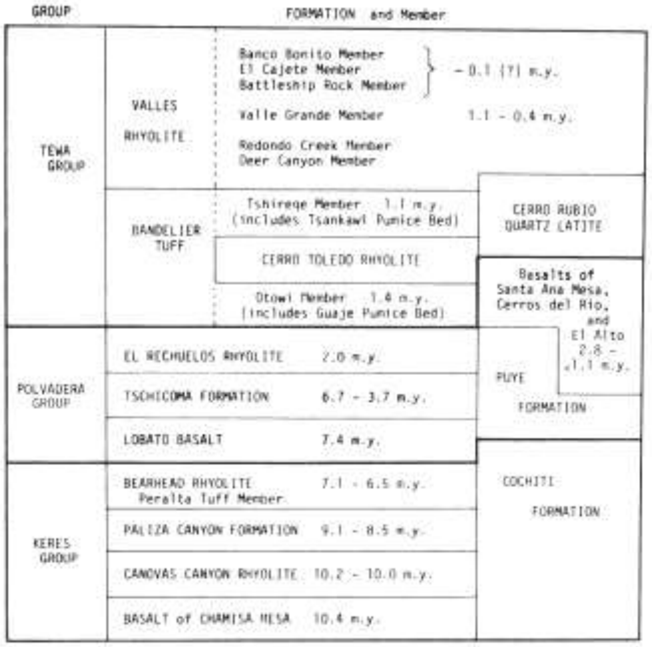

FIGURE J2—STRATIGRAPHIC NOMENCLATURE AND GENERAL CHRONOLOGIC RELATIONS OF VOLCANIC AND ASSOCIATED VOLCANICLASTIC ROCKS OF THE JEMEZ MOUNTAINS. Ages show range of K-Ar dates available and do not necessarily indicate maximum and minimum ages of formations.

underlain by the Bandelier Tuff, which in turn overlies Permian red beds of the Abo and Yeso Formations (Wood and Northrop, 1946). The Bandelier is composed of two members: the lower, Otowi Member, erupted 1.4 m.y. ago and caused the collapse of the Toledo caldera; the upper, Tshirege Member, erupted 1.1 m.y. ago and caused the collapse of the Valles caldera (figs. J1 and J2).

The lower tier of columnar cliffs at the south end of Guadalupe Mesa is in the Otowi Member; the upper ledges and the cliffs further north on both sides of the mesa are in the Tshirege Member. The contacts show that the Otowi Member here has been eroded into a mesa-like remnant during the 0.3-m.y. interval between its emplacement and subsequent burial by the Tshirege Member. 1.7

34.4 Cattle guard; entering San Diego Canyon. In general, the course of the Jemez River follows the trace of the Jemez fault, which intersects the caldera at its lowest point on the southwest rim. The river originated by overflow of an early caldera lake about 1.0 m.y. ago. Initially it flowed across the south-sloping surface of the Bandelier Tuff, but with the passage of time the river cut down through the Bandelier into the underlying Paleozoic sedimentary rocks.

For the next 12 mi Bandelier Tuff is continuously exposed in the upper canyon walls. Both members are present, including their respective basal air-fall deposits, the Guaje Pumice Bed, and the Tsankawi Pumice Bed (fig. J2). As noted at Guadalupe Mesa, the Otowi Member was considerably eroded before emplacement of the Tshirege Member, and the contact between the two at many points along the canyon walls is quite irregular; locally the Tshirege fills canyons cut into the Otowi, and steep erosional pinnacles of the Otowi project upward into the Tshirege (fig. J5). 2.8

37.2 **STOP J3, San Diego Canyon.** *Stop on right shoulder* opposite adobe shack on left. On the west wall of the canyon, Bandelier Tuff attains a maximum thickness of about 975 ft (300 m) (fig. J5). The contact between the Otowi and Tshirege Members is just below the orange-colored zone about 275 ft (85 m) above the base. The Otowi Member here is entirely vitric and, although columnar jointed, is only moderately welded. Most of the Tshirege Member is also moderately welded but has been devitrified by pervasive vapor-phase activity during cooling. The dark-grey unit at the top of the canyon wall is densely welded (less than 10 percent porosity) and is one of the more extensive units of the Tshirege Member. Although from a distance the dark-grey rock appears to be a single flow unit, it actually consists of at least three flow units at this point. Details of the internal flow contacts will be seen at closer hand in a similar densely welded unit at Stop J9. **3.8**

41.0 Jemez Springs. **1.7**

42.7 **STOP J4, Soda Dam.** This unusual travertine spring deposit has been built by carbonated waters issuing from a segment of the Jemez fault that crosses the canyon here and brings a structural horse of Precambrian granite up against Abo Formation (Permian) on the east and Madera Limestone (Pennsylvanian) on the west. Remnants of older travertine dams enclosing Pleistocene stream deposits occur as much as 975 ft (300 m) high on the canyon walls, indicating that the springs have been active for a long time during downcutting of the canyon. According to S. A. Northrop (in Kelley and others, 1961), 22 springs were issuing from the crest of the dam in 1902, but by 1912

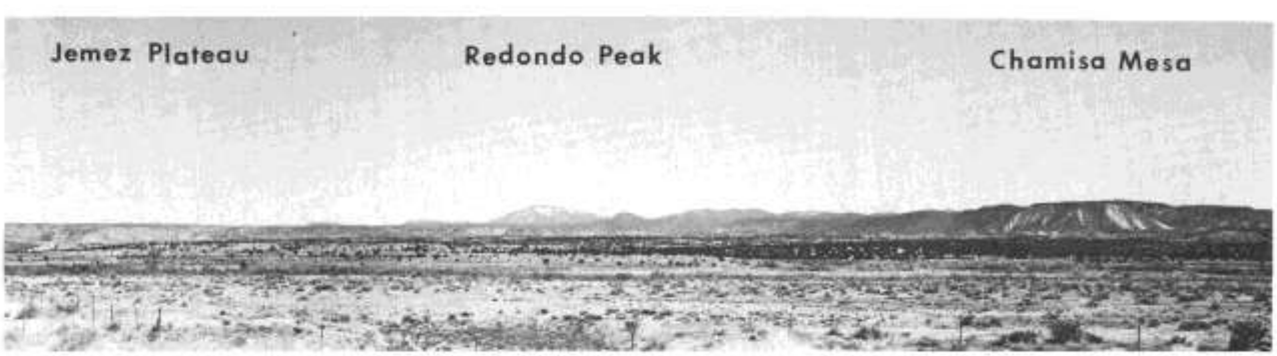

FIGURE J3—PANORAMIC VIEW FROM STOP J1, SOUTH OF SAN YSIDRO, looking north toward Jemez Mountains.

FIGURE J4—BANDELIER TUFF AT STOP J2, SOUTH END OF GUADALUPE MESA. Pa—Abo Formation; Py—Yeso Formation (Permian); Qbo—Otowi Member; Qbt—Tshirege Member (Pleistocene).

only 11 were active. During the 1950's spring waters were issuing from only three points near the east end of the dam, but highway reconstruction in the late 1960's cut off the water flow entirely, and the dam is no longer renewing itself.

Up-canyon from Soda Dam, pyroxene-andesite flow breccias of the Paliza Canyon Formation (fig. J2) can be seen between the Bandelier Tuff and the Permian red beds. The breccias gradually thicken to 800 ft (250 m) at the caldera rim. 3.2

45.9 The route passes a small solfatara (note strong H_2S odor) to the right below the highway. Like Soda Dam, this solfatara is on the Jemez fault and is one of the few solfataras outside the Valles caldera. **0.6**

46.5 **STOP J5, Battleship Rock.** Picnic Grounds at the junction of San Antonio Creek and the East Fork of the Jemez River. San Antonio Creek drains the north moat of the Valles caldera; the East Fork drains the south moat. Battleship Rock, a spectacular outcrop of columnar-jointed, rhyolite-welded tuff (fig. J6), was formed by a series of postcaldera small-volume ash flows that issued from a vent near E1 Cajete Crater about 0.1 m.y.(?) ago (figs. J7 and J8). Initially, these ash-flow deposits (the Battleship Rock Member of the Valles Rhyolite) extended a considerable distance down San Diego Canyon and filled it to a depth of about 325 ft (100 m), but subsequent erosion has removed all but the outcrops in the Battleship Rock area and one or two other small remnants down-canyon. Battleship Rock itself is the filling of a narrow vertical-walled gorge cut into Madera Limestone and Abo Formation, and the curved columnar jointing in the lower part of Battleship Rock is a consequence of cooling against the gorge walls. Subsequent erosion has removed the adjacent less resistant sedimentary rocks and has left the more resistant welded tuff standing as a promontory—an interesting example of inverted topography.

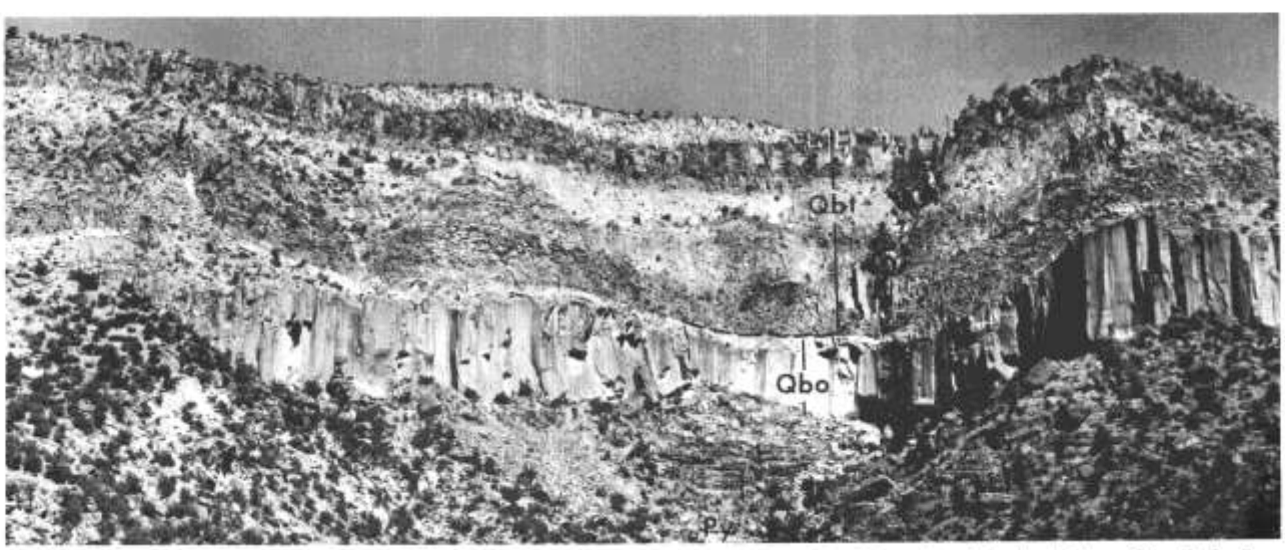

FIGURE J5—BANDELIER TUFF ON WEST WALL OF SAN DIEGO CANYON AT STOP J3. Py—Yeso Formation (Permian); Qbo—Otowi Member; Qbt—Tshirege Member. Note pinnacle of Otowi projecting up into Tshirege at left center (arrows).

FIGURE J6—OBLIQUE VIEW OF BATTLESHIP ROCK AT STOP J5 from west wall of San Diego Canyon.

The tuff at Battleship Rock is about 260 ft (80 m) thick and contains two main flow units that constitute a single cooling unit (Smith, 1960). The tuff is entirely vitric from bottom to top. The basal 50 ft (15 m) are composed of poorly consolidated pumiceous tuff breccia, which becomes increasingly compacted upward and grades into partly welded tuff having a minimum porosity of 15 percent at approximately 115 ft (35 m) above the base. The tuff becomes gradually less welded and passes again into unconsolidated pumiceous tuff breccia about 210 ft (65 m) above the base. Surprisingly, the contact between the two main flow units is in the middle of the most densely welded part, about 115 ft (35 m) from the base, indicating that the two units were emplaced in very rapid succession. This contact is marked by a 12-inch (30-cm) thick zone of large, flattened, vitrophyric pumice blocks that accumulated at the top of the lower flow unit as a result of their buoyant upward concentration during turbulent flowage. Two or three similar (but nonwelded) coarse pumice concentrations occur in the uppermost 50 ft (15 m) of unconsolidated tuff, suggesting the presence of two or three additional thin flow units near the top of the section. The Battleship Rock Member is well exposed up-canyon on the right (east) wall for a distance of 2 mi. **0.8**

47.3 On the left are large float blocks of pyroxene-andesite flow breccia of the Paliza Canyon Formation, which underlies the Bandelier Tuff high on the canyon wall. **1.0**

48.3 Spence Warm Spring, a popular bathing spot. The cliffs of black vitrophyre to the right and ahead are o•f the Banco Bonito Member of the Valles Rhyolite, a thick rhyolite glass flow that probably issued from the same vent as the Battleship Rock Member. In the canyon wall, the vertical contact between the glass flow and the older Battleship Rock Member is marked by a zone of steep flow banding. The tuff has been fused next to the flow banding, owing to heat and pressure from the flow. 1.2

49.5 La Cueva (The Cave), on the right side of San Antonio Creek, is formed in cliffs of welded tuff of the Battleship Rock Member. **0.3**

49.8 Junction of NM-4 and NM-126. *Turn left on NM-126.* **1.9**

51.7 Crossing San Antonio Creek. For the next mile the road climbs the west wall of the Valles caldera. Road-cuts expose in succession: Abo Formation, Abiquiu Tuff (Smith, 1938), basalt of Paliza Canyon Formation, quartz latite of Tschicoma Formation, and Bandelier Tuff, some of which are repeated by faulting and landsliding that accompanied caldera collapse. **2.5**

54.2 **STOP J6, West caldera overlook.** Top of grade; *turn left into unsurfaced turnaround.* Caldera overlook, elevation 8,500 ft (2,615 m). The high domical mountain due east is Redondo Peak, elevation 11,250 ft (3,460 m), summit of the resurgent structural dome occupying the center of the Valles caldera (fig. J9). The nearer and lower irregular-crested ridge to the left of Redondo Peak is Redondo Border, which forms the western half of the resurgent dome. The valley between the two is a northeast-trending medial graben separating the two halves of the dome. Except for local, thin patches of elevated caldera fill (sediments and breccias), the dome is underlain entirely by dense-

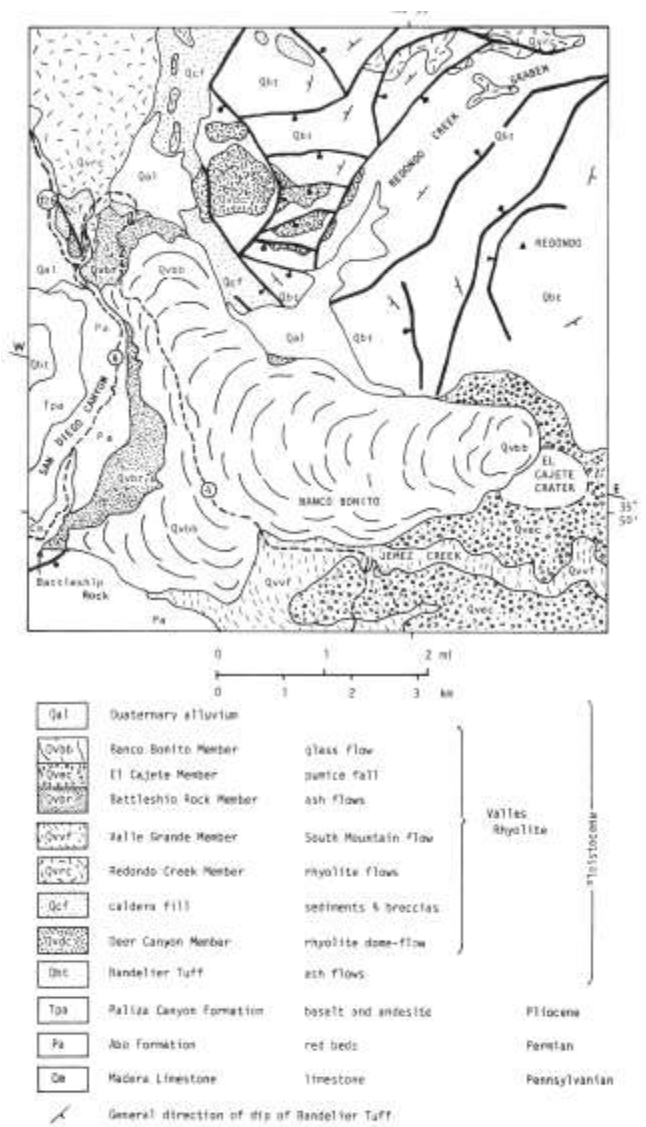

FIGURE J7—GEOLOGIC SKETCH MAP OF SOUTHWEST PART OF THE VALLES CALDERA.

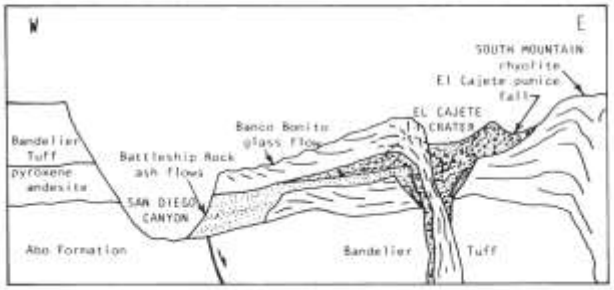

FIGURE J8—SCHEMATIC CROSS SECTION OF SOUTHWEST PART OF THE VALLES CALDERA, showing general relations between postcaldera rhyolite members. Approximate location of section is along line W-E in fig. 7 (section not drawn to scale).

ly welded Bandelier Tuff, which has been uplifted 3,250 ft (1,000 m) above the caldera rim and possibly as much as 1,500 m above its postcollapse position within the caldera. The tuff on Redondo Peak is tilted generally south to southeast; the tuff on Redondo Border, generally west to northwest (fig. J7). The high benches on the west face of Redondo are structural slices downthrown on the east side of the medial graben. At the south end of Redondo Border several subsidiary fault blocks tilted to the north and down-thrown to the south are distinguishable. The darker green slopes forested with conifers on these blocks are dip slopes, whereas the lighter brush-covered slopes are eroded fault scarps. The uplift of Redondo Peak occurred within 100,000 years after caldera collapse as a result of magma uprise. This renewed upwelling was probably related to isostatic readjustments within the subcauldron crustal column. These readjustments were caused by the loss of mass accompanying eruption of the 300 km' of magma represented by the Tshirege Member of the Bandelier Tuff (Bailey, 1976).

To the northeast in the middle distance are San Antonio Mountain and Cerro Seco, two post-resurgent rhyolite domes in the northwest caldera moat, 0.54 and 0.73 m.y. old, respectively. They are two of twelve ring domes that form the Valle Grande Member of the Valles Rhyolite. On the distant skyline to the northeast is Cerro de la Garita (on the northern rim of the caldera), formed of quartz latite of the Tschicoma Formation.

Just visible over the south shoulder of Redondo Peak is the top of South Mountain, a 0.49-m.y.-old postresurgent rhyolite dome in the south moat. On the skyline further to the southeast is the ragged crest of Los Griegos (on the south rim of the caldera), formed mainly of andesites of the Paliza Canyon Formation. In the foreground to the east-southeast is the west moat of the caldera. The southern part of this moat is occupied by the 0.1(?)-m.y.-old glass flow of the Banco Bonito Member of the Valles Rhyolite, and the central and northern parts are underlain by older rhyolite flow breccias of the Redondo Creek Member (fig. *J7). Return to junction of NM-126 and NM-4.* **4.5**

58.7 Junction of NM-126 and NM-4 at junction of San Antonio and Sulphur Creeks. *Turn left onto NM-4.* **0.6**

59.3 Road crosses approximate position of caldera ring-fracture zone, here concealed by postcaldera sediment and rhyolite. Outcrops on both sides of road are perlitic rhyolite of the Redondo Creek Member, Valles Rhyolite (fig. J7, Qvrc). These outcrops constitute the dissected toe of a flow; the vent of this flow is about 3 mi to the north in the west moat. Lake sediment (fig. J7, Qcf) associated with the flow margin indicates that a lake occupied the caldera moat when the flow erupted and that part of the flow may have been sub-lacustrine. **0.2**

59.5 Junction of Sulphur Creek and Redondo Creek. Side road on left leads to Sulphur Springs, the most active solfataric area in the caldera, and in former years the site of a small hotel that catered to visitors seeking health cures in the bubbling mudpots and hot springs. *Continue on NM-4.* **0.3**

59.8 Side road on left follows Redondo Creek to the medial graben of the resurgent dome, where the Baca Land and Cattle Company and the Union Oil Company have been drilling for geothermal steam since 1963. *Continue on NM-4.* **0.1**

59.9 In the roadcut on the left are deformed lake sediment and tuffaceous sand constituting postcaldera fill. **0.1**

60.0 Road climbs through poorly exposed, unconsolidated pumiceous tuff breccia of the Battleship Rock Member of the Valles Rhyolite. **0.3**

60.3 Road crosses contact between Battleship Rock and Banco Bonito Members (fig. J7, Qvbr and Qvbb) onto

FIGURE J9—VIEW OF REDONDO PEAK RESURGENT DOME, looking east from Stop J6, west rim of Valles caldera.

the hummocky surface of the Banco Bonito glass flow and traverses concentric flow ridges of black vitrophyre that project through the blocky, pumiceous carapace of the flow. 3.2

63.5 Road descends a 325-ft (100-m) scarp of the south margin of glass flow. Roadcut on left shows complex contact relations between glass flow and Battleship Rock Member. At the bottom of the scarp, the road continues on the surface of an older rhyolite flow (fig. J7, Qvvf) that issued from South Mountain, a prominent rhyolite dome to the east in the south moat. The dome's original hummocky surface has been subdued by a mantle of E1 Cajete Member pumice fall (fig. J7, Qvec), which lies between the Banco Bonito Member and the South Mountain flow at Stop J7. 0.7

64.2 STOP J7, E1 Cajete roadcut. *Park on right near top of grade; walk down road ahead.* Road descends north side of the gorge of East Fork of Jemez River. Exposed in downward succession in left roadcut are three members of the Valles Rhyolite: 1) vitrophyric blocks of the basal part of Banco Bonito Member glass flow, 2) well-bedded pumice and ash of E1 Cajete Member (fig. J10), and 3) South Mountain flow of Valle Grande Member.

Although most of the beds in this section of the E1 Cajete Member are air-fall deposits, in the lower part are two ash flows, each 6-10 ft (2-3 m) thick, with pinkish color due to high-temperature oxidation. Unlike the laterally persistent air-fall beds, they are limited in extent and fill a shallow swale, thickening in the center and thinning at their margins.

Charcoal found at the base of the uppermost fine, white ash bed in this El Cajete section gave an age of more than 42,000 years (Meyer Rubin, personal communication, 1967). On the basis of this determination and comparative morphology, the E1 Cajete Member and associated overlying Banco Bonito Member glass flow are thought to be about 0.1 m.y. old. The underlying South Mountain flow has a K-Ar age of 0.49 m.y. **0.4**

64.6 Bridge across East Fork of Jemez River. Roadcuts along the next 4 mi are in mantle-bedded rhyolite pumice and ash of the E1 Cajete Member, locally resting on rhyolite of the South Mountain flow. **4.0**

68.6 Entering upper valley of East Fork Jemez River. Prominent outcrops on the left are of South Mountain rhyolite flow (Valle Grande Member), abutting the south wall of the Valles caldera for the next 2 mi. The flow is here composed mainly of basaltic rocks of the Paliza Canyon Formation. The constriction caused by this flow dammed the south moat and formed a lake to the east in the Valle Grande. Overflow and downcutting through the South Mountain flow have since drained the lake. **0.6**

69.2 Los Conchas Picnic Ground 2.3

71.5 Entering the Valle Grande, largest of the intramontane valleys of the Valles caldera 2.7

74.2 **STOP J8, Valle Grande overlook** (fig. J11). The high flat-topped mountain to the west is Redondo Peak, summit of the resurgent dome. The high knob just to the north (Redondito) and the lower ridge extending northeast (Redondo Extension) also are structural elements of the resurgent dome. All are underlain by densely welded Bandelier Tuff, which dips generally southeast toward the observer. Postcaldera ring domes of Valle Grande Member that are peripheral to the resurgent dome include 0.49-m.y.-old South Mountain, just south of Redondo Peak; 0.50-m.y.-old

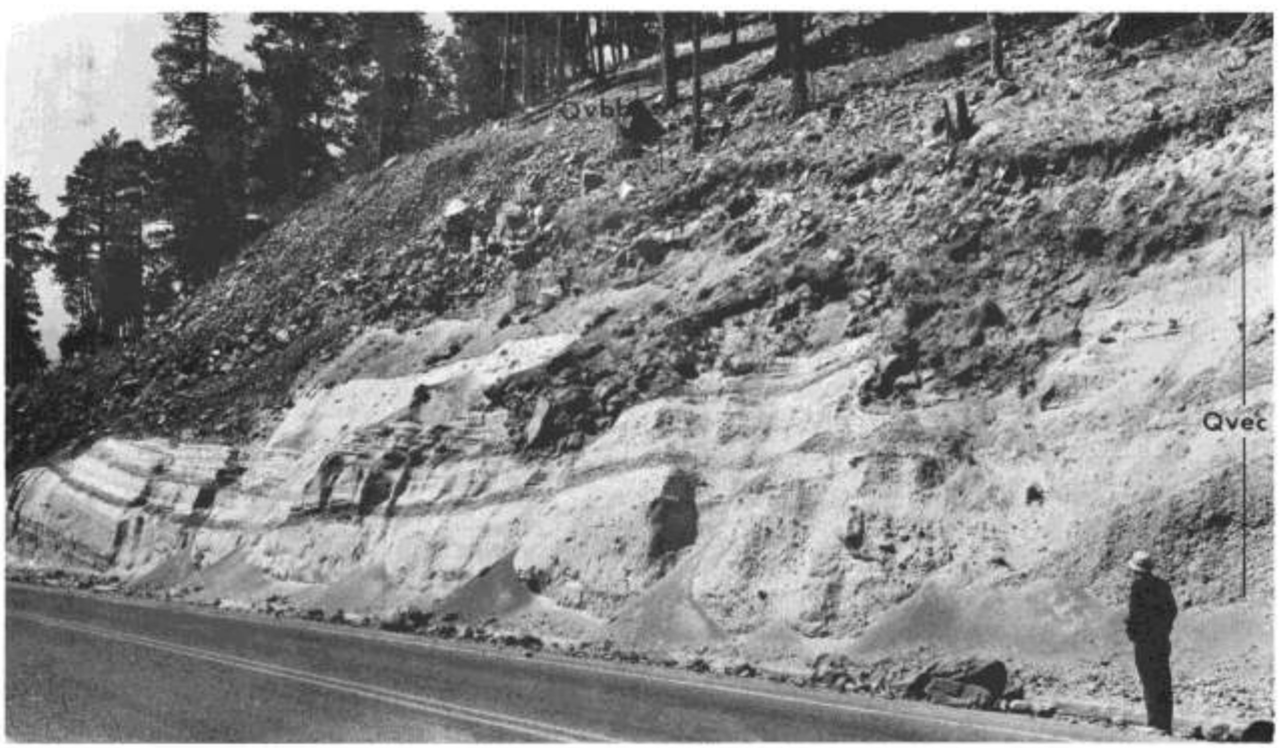

FIGURE J10—ROADCUT AT STOP J7, CROSSING OF JEMEZ CREEK, showing El Cajete Member (Qvec) and Banco Bonito Member (Qvbb) of the Valles Rhyolite.

FIGURE J11—VIEW WEST FROM STOP J8, VALLE GRANDE.

Cerro La Jara (the small treed knob immediately to its east); and the heavily logged mountains in the middle distance to the north; these mountains, from left to right, include 0.88-m.y.-old Cerro Santa Rosa, 0.89- m.y.-old Cerro del Abrigo, and 1.04 to 1.14-m.y.-old Cerro del Medio (fig. J12).

The rim of the Valles caldera begins at the far left (southwest), continues behind the observer, and extends to the grass-covered peaks of Cerro Grande and Pajarito Peak on the far right (fig. J12). The red-brown, talus-strewn peak of Cerro Rubio is on the east rim, at its junction with the south rim of the Toledo caldera. Tschicoma Peak, elevation 11,561 ft (3,557 m) just visible on the far northeast skyline, is on the north rim of the Toledo caldera. The Valles caldera rim continues northwest out of view behind the heavily logged rhyolite ring domes of Cerro del Medio, Cerros del Abrigo, and Cerro Santa Rosa. The rim is again visible on the far northern skyline, as is the grass-covered face of Cerro de la Garita 11 mi distant.

Rabbit Mountain on the south rim of the Valles caldera is a large rhyolite center temporally and chemically related to the Cerro Toledo Rhyolite, which erupted mainly within the Toledo caldera between 1.4 and 1.1-m.y.-ago (figs. J1 and J2). 0.3

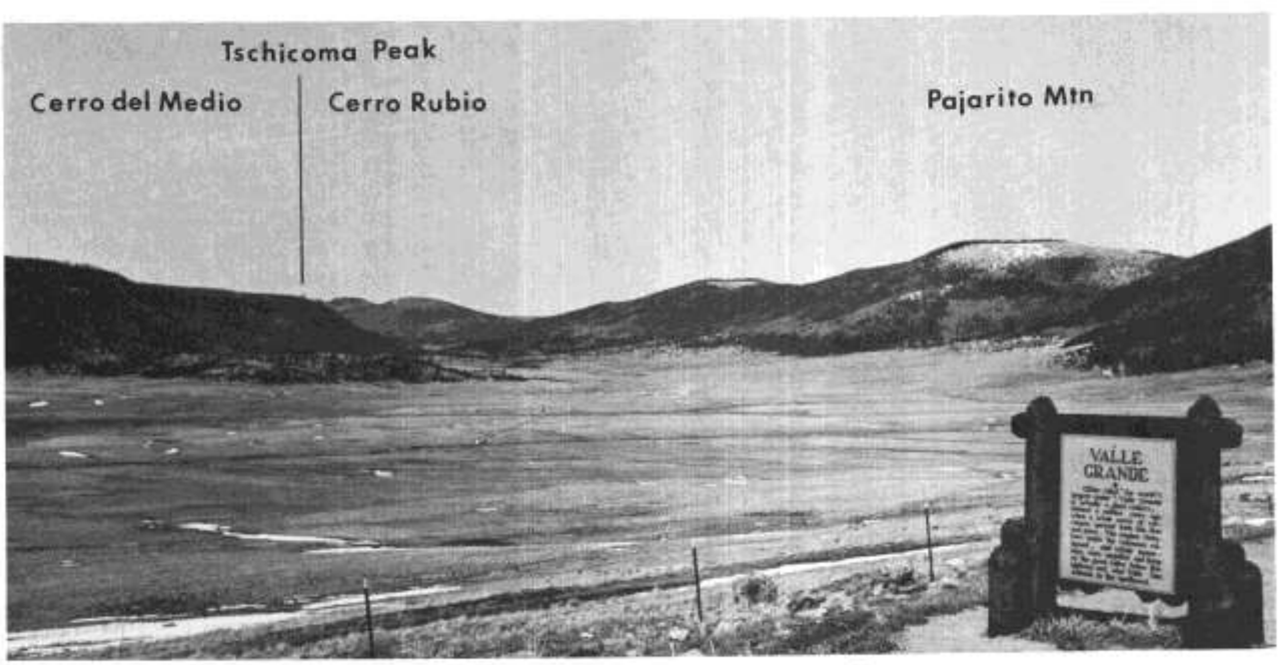

FIGURE J12—VIEW NORTHEAST FROM STOP J8, VALLE GRANDE.

74.5 Road ascends southeast wall of Valles caldera in hornblende quartz latite of Tschicoma Formation. **1.0**

75.5 Crest of Valles caldera rim. For the next mile road traverses surface of Bandelier Tuff. 1.5

77.0 Hairpin curve at head of Frijoles Canyon. Roadcuts are in densely welded Bandelier Tuff (Tshirege Member), containing lenticular lithophysal cavities and small fumarolic pipes. 1.6

78.6 On the right is Frijoles Canyon, cut more than 975 ft (300 m) into Bandelier Tuff. On the skyline to the west are the southern Jemez Mountains, composed mainly of andesitic rocks of the Paliza Canyon Formation and of Bearhead Rhyolite. Roadcuts on the left are quartz latite of the Tschicoma Formation. 0.5

79.1 Road curves left. To the south in the near distance is St. Peter's Dome (with fire tower), a structural outlier of Paliza Canyon Formation surrounded by Bandelier Tuff. On the distant skyline to the south is Sandia Mountain, east of Albuquerque, and to the left of Sandia Mountain, in succession, are South Mountain, San Pedro Mountains, and Ortiz Mountains, all early Tertiary intrusive-volcanic centers. Roadcuts for the next mile are in quartz latite of Tschicoma Formation. 1.9

81.0 Roadcuts on the left are in poorly welded, uppermost units of Tshirege Member, Bandelier Tuff. 0.4

81.4 On the left is a densely welded unit of the Tshirege Member that is similar to, but not precisely correlative with, that at the top of the Bandelier cliffs in San Diego Canyon seen from Stop J3. **0.3**

81.7 STOP J9, Pajarito Plateau overlook and fault scarp. Below the escarpment, at the sharp turn left in the road, spreads the gently eastward-sloping surface of the Pajarito Plateau, formed of ash-flow deposits of Bandelier Tuff (see Budding, this guidebook). In the near distance is White Rock Canyon, gorge of the Rio Grande, and just beyond are the Cerros del Rio, composed of Pliocene and Pleistocene basaltic rocks against which lap the distal ends of the Bandelier Tuff ash flows. On the distant skyline are the Sangre de Cristo Mountains, on the east side of the Rio Grande rift.

The escarpment at the turn in the road is the Pajarito fault, which extends 30 mi (50 km) along the east side of the Jemez Mountains and is one of the main displacements on the west side of the Rio Grande rift. The Pajarito fault has been intermittently active throughout Pleistocene time and has displaced 3- to 4-m.y.-old quartz latites of the Tschicoma Formation as much as 975 ft (300 m) and has displaced the Bandelier Tuff 325-500 ft (100-150 m). In the roadcuts on the left are several gouge zones between which large blocks of densely welded Bandelier Tuff have been steeply tilted eastward.

Careful examination of the more gently dipping Bandelier in outcrops 160-325 ft (50-100 m) west along the road will reveal two or three thin, sandy partings between densely welded flow units as well as a number of vertical fumarolic pipes containing concentrations of gas-entrained quartz and sanidine phenocrysts. The occurrence of these partings and pipes within such a densely welded unit indicates that both features formed within a very short time span during which the flows remained sufficiently hot to weld together. Each member of the Bandelier Tuff consists of numerous flow units that constitute a compound cooling unit (Smith, 1960); however, the multiple-flow character of the Tshirege Member is more conspicuous than that of the Otowi. Many of the Tshirege flow units are separated by minor disconformities marked by beds of crossbedded sand (sandy partings), up to 20 inches (50 cm) thick, consisting mainly of quartz and sanidine phenocrysts. These crystal concentrations appear to be wind-winnowed lag deposits formed by thermal winds, pyroclastic surge, or related ash-flow emplacement processes. These outcrops are especially interesting because they show the concentration of phenocrysts by two distinctly different processes: 1) fumarolic and 2) wind, surge, or emplacement processes. **0.6**

82.3 Junction of NM-4 and Alternate NM-4. *Proceed straight ahead on Alternate NM-4* toward Bandelier National Monument. **0.9**

83.2 Roadcuts on left are uppermost flow units of the Tshirege Member, Bandelier Tuff.

On the Pajarito Plateau, the Otowi Member of the Bandelier (fig. J13) consists of a 10-50 ft (3-15 m) thick basal pumice-fall deposit (Guaje Pumice Bed) and an overlying 245-ft (75-m) thick sequence of ash-flow deposits consisting mainly of poorly consolidated pumiceous tuff breccia. Southwest of the mountains the Otowi ash-flow sequence thickens, and on the Jemez Plateau this sequence attains a maximum of 650 ft (200 m) and is partly to densely welded. The Tshirege Member on the Pajarito Plateau consists of a basal pumice fall (Tsankawi Pumice Bed) 3 ft (1 m) thick and an overlying sequence of ash flows, locally about 800 ft (250 m) thick. Thus, the Tshirege tends to be thicker on the Pajarito Plateau, and the Otowi is thicker in the Jemez Plateau.

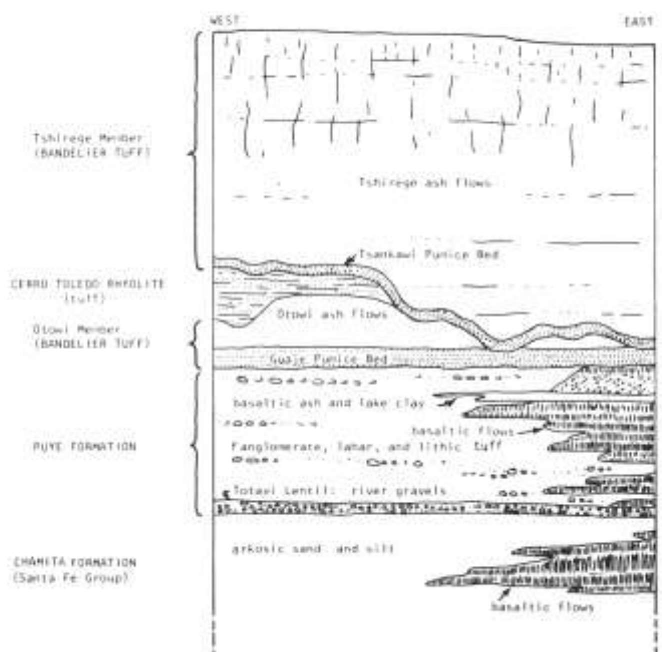

FIGURE J13—SCHEMATIC SECTION SHOWING STRATIGRAPHIC RELATIONS ACROSS THE PAJARITO PLATEAU.

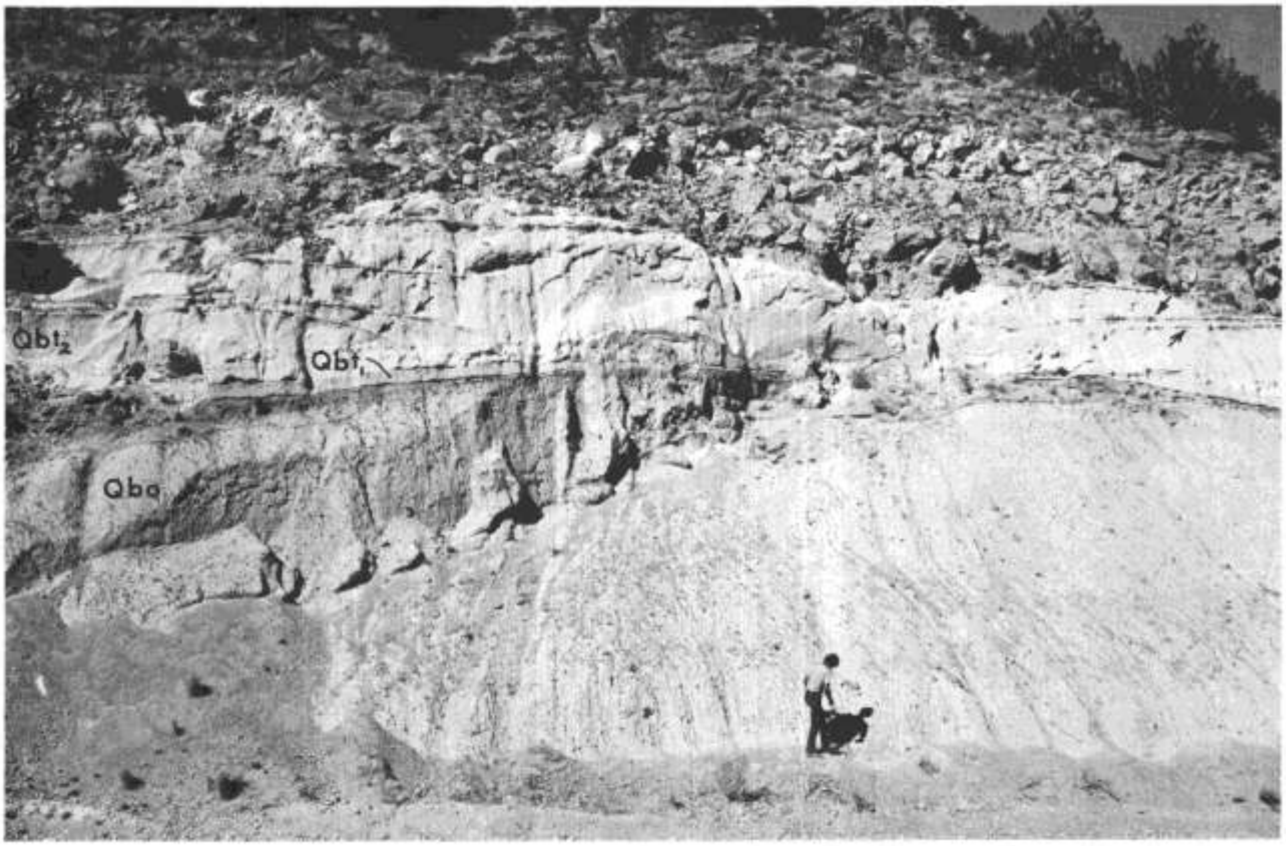

FIGURE J14—ZEOLITIZED FOSSIL GROUND-WATER TABLES (ARROWS) IN BANDELIER TUFF AT STOP J10, ANCHO CANYON. Qbo—Otowi Member ash-flow tuff; Qbt_1—Tsankawi Pumice Bed; Qbt_2—Tshirege Member ash-flow tuff.

Nonwelded parts of the Otowi and Tshirege ash-flow sequences are superficially similar in appearance, but Tshirege units can generally be distinguished by 1) fewer accidental inclusions (2-5 percent as compared to 10-15 percent in Otowi units), 2) the coarser texture of the pumice lapilli, and 3) the inclusion of distinctive grey pumice lapilli of hornblende-rich quartz latite.

The contact between the Tshirege and Otowi Members on the Pajarito Plateau, like that on the Jemez Plateau, is marked by an erosional unconformity, and locally the two members are also separated by a sequence of bedded rhyolite tuffs (Cerro Toledo Rhyolite), which erupted from within the Toledo caldera (figs. J2 and J13).

Budding (this guidebook) discusses the subsurface geology of the Pajarito Plateau in this area, emphasizing interpretations based on gravity surveys and test borings. **5.1**

88.3 Entrance to Bandelier National Monument on right. *Continue ahead* on Alternate NM-4. **1.4**

89.7 Road descends south wall of Ancho Canyon in Tshirege Member. **0.8**

90.5 Outcrops at left are poorly consolidated basal ash-flow tuff of the Tshirege Member. The thin, more indurated, horizontal ledges or apparent "beds" are zeolitized zones developed at former ground-water tables; they are essentially fossil water tables that record progressive lowering of ground-water levels in the area. **0.2**

90.7 **STOP J10, Ancho Canyon.** roadcut on left (fig. J14) exposes a small mound of buff, nonwelded ash-flow tuff (Otowi Member) overlain by a 3-ft (1-m) thick grey pumice fall (Tsankawi Pumice Bed) and white nonwelded ash-flow tuff (Tshirege Member). Near the crest of the Otowi mound, indurated zeolitized ground-water tables in the Tshirege ash-flow tuff curve downward forming cones of depression that mimic former piezometric surfaces drawn down by the more permeable Tsankawi Pumice Bed. Note that the cones of depression steepen in successively lower levels. Successive lowering of the water table in this area is related to the cutting of Ancho Canyon and to concomitant progressive headward migration of a waterfall upheld by a basalt flow exposed less than a mile (about 1 km) down-canyon. **1.6**

92.3 View left (northwest) is of east side of Jemez Mountains. High peaks are quartz latites of Tschicoma Formation on east rim of Valles caldera. **1.2**

93.5 At right, basalt of Cerros del Rio underlies Tshirege Member. **2.3**

95.8 Traffic light. On the left is Pajarito Canyon. About 0.3 mi up-canyon, atop the long low mesa on the north side, is Tshirege Ruin, after which the Tshirege Member of the Bandelier Tuff is named. **1.2**

97.0 White Rock. *Turn right at Chevron station on River Road.* **0.2**

97.2 *Turn left on Meadow Lane.* **0.8**

98.0 *Turn left on Overlook Road.* **0.7**

98.7 **STOP J11, White Rock Canyon overlook** (fig. J15). White Rock Canyon takes its name from the distant outcrop of Bandelier Tuff to the south on the east side of the canyon. To the north along the west side of the

FIGURE J15—VIEW NORTH-NORTHWEST FROM STOP J11, WHITE ROCK OVERLOOK.

canyon, the contact between Bandelier Tuff and underlying basalt of Cerros del Rio is visible. The basalt is underlain by Puye Formation, which is in turn underlain by buff arkosic sediments of the Santa Fe Group (fig. J13). To the north on the east side of the canyon is La Mesita, a complex basaltic center underlain by a thick sequence of basaltic tuffs. The small basaltic mesa to the north, in the Española Basin, is San Ildefonso Black Mesa, sacred to the Indians of nearby San Ildefonso Pueblo, who were besieged there by the Spaniards in 1690.

The course of the Rio Grande in this area has had a complex history; the river has been intermittently dammed and diverted, alternately east and west by the Puye Formation fanglomerates, the Cerros del Rio basalts, and the Bandelier Tuff. Aubele (this guidebook) discusses the geology of the Cerros del Rio field, with special emphasis on phreatomagmatic features of White Rock Canyon and other parts of the field. *Return to Alternate NM-4.* **1.7**

100.4 *Turn right on Alternate NM-4.* 2.2

102.6 Tsankawi Ruin on left, type locality of Tsankawi Pumice Bed, basal pumice fall of Tshirege Member of the Bandelier. 1.9

104.5 Junction of Alternate NM-4 with NM-4. *Turn left toward Los Alamos on NM-4.* **0.8**

105.3 In roadcut on left, Tsankawi Pumice Bed of the Tshirege Member overlies Otowi Member. **0.5**

105.8 **STOP J12, Pueblo Canyon overlook** at Clinton P. Anderson commemorative plaque (fig. J16). Canyon bottom is underlain mainly by Otowi Member non-welded ash-flow tuff. Otowi Ruin, for which the member is named, can be seen to the north in the open area on the far side of the main arroyo. The cliff-forming units are Tshirege Member ash-flow tuff. At the base of the cliffs, the basal pumice fall of the Tshirege Member (Tsankawi Pumice Bed) is visible, and below it in a few places are bedded tuffs of the Cerro Toledo Rhyolite, which have their source in the Toledo caldera 15 mi northwest.

Return to junction of NM-4 and Alternate NM-4. **1.3**

107.1 Junction of NM-4 and Alternate NM-4. *Proceed straight ahead on NM-4.* **0.9**

108.0 **STOP J13, Guaje Pumice roadcut.** Guaje Pumice Bed of the Otowi Member overlies 2.4-m.y.-old basalt in roadcut on left (fig. J17). Note soil developed on top of basalt. In the slopes and cliffs above the basalt, about 325 ft (100 m) of Bandelier Tuff is exposed. The Guaje Pumice Bed is about 23 ft (7 m) thick here, but the bed is commonly as much as 23 ft (10 m) thick on the east side of the mountains. Underlying the slopes and exposed in gullies to the base of the cliffs are about 160 ft (50 m) of nonwelded Otowi ash flows. At the base of the cliffs are 3 ft (1 m) of the Tsankawi Pumice Bed of the Tshirege Member, and above are 160 ft (50 m) of partly welded Tshirege ash flows. In the upper 100 ft (30 m) of columnar-jointed tuff, at least eight distinct flow units separated by sandy partings and pumice concentrations are discernible.

The basalt underlying the Bandelier at this locality erupted from a vent exposed in the gorge immediately south of the road. The flow grades downward into pillowed palagonite breccia, which displays, in the road below and in the cliffs on the south side of the canyon, remarkable foreset bedding—an indication that the flow spread eastward from the vent into a lake that probably formed by damming of the Rio Grande elsewhere in the vicinity. About 650 ft (200 m) down the highway and to the east, water-laid basaltic ash and lacustrine clays underlie the palagonite breccia; the ash and clays provide further evidence of eruption into a former lake (fig. J13). **0.2**

108.2 At left a tongue of basalt at the toe of the flow has injected basalt into sand and gravel beds, causing intense deformation of the sand and gravel. On the

FIGURE J16—BANDELIER TUFF IN PUEBLO CANYON AT STOP J12, overlook from NM-4 at Clinton P. Anderson commemorative plaque. Qbo—Otowi Member (Bandelier Tuff); Qct—Cerro Toledo Rhyolite tuff; Qbt—Tshirege Member (Bandelier Tuff).

north side of this tongue, the basalt was in steep contact with ripple-marked sediments that have since been stripped from the contact, exposing a cast of the ripplemarks in the basalt surface.

Down the highway 300-1,000 ft (100-300 m) to the left, lacustrine clays overlie coarse boulder beds of the Puye Formation (fig. J13). The Puye is composed mainly of volcaniclastic debris derived from the central and northern Jemez Mountains by rapid erosion of Tschicoma quartz latites and by reworking of associated pyroclastic deposits. Proximal facies of the formation consist largely of lithic pyroclastic and laharic deposits, whereas distal facies are mainly fluvial. The base of the formation contains beds consisting predominantly of well-rounded boulders of Precambrian granite and metamorphic rocks from

FIGURE J17—BANDELIER TUFF AT STOP J13, GUAJE PUMICE ROADCUT near Totavi. Tb—2.4-m.y.-old basalt; Qbo_1—Guaje Pumice Bed; Qbo_2—Otowi Member ash flows; Qbt_1—Tsankawi Pumice Bed; Qbt_2—Tshirege Member ash flows.

distant sources. This unit, the Totavi Lentil of the Puye Formation (Griggs, 1964), is a channel deposit of the ancestral Rio Grande, which was forced eastward by rapid growth of the huge volcaniclastic fan that forms the Puye Formation. **0.7**

108.9 Gravel pit on the left exposes Totavi Lentil of the Puye Formation. **0.4**

109.3 Buff to tan silt and sand exposed for the next few miles are arkosic sediments of the Chamita Formation of Galusha and Blick (1971). The upper 230 ft (70 m) of Chamita here contain lenses of well-rounded volcanic pebbles foreign to the Jemez Mountains. Their source is uncertain, but they probably were derived by reworking of Abiquiu Tuff of Smith (1938), which, although underlying the Santa Fe Group, was probably exposed to the north along the margin of the rift during Chamita time, just as it is now. **1.7**

111.0 Junction of NM-4 to Santa Fe and NM-30 to Española. NM-4 crosses the Rio Grande at Otowi Bridge, about 1 mi ahead.

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SUBSURFACE GEOLOGY OF THE PAJARITO PLATEAU: INTERPRETATION OF GRAVITY DATA

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The Pajarito Plateau is an eastward-sloping surface, ranging from 2,200-1,900 m above sea level. The plateau, which extends from the Jemez Mountains in the west to the Rio Grande in the east, is underlain by units of the Bandelier Tuff. The surface is cut by several, mostly ephemeral, tributaries of the Rio Grande, which itself has cut a 300-m-deep gorge near White Rock. The towns of Los Alamos and White Rock and a number of technical installations of the Los Alamos Scientific Laboratory are located on the plateau.

The Bouguer anomaly map, shown in fig. 1, is based on more than 200 gravity stations. All gravity measurements were indirectly tied to a gravity base station in Santa Fe. The average density of the Bandelier Tuff (2.20 g/cm^3) was used to calculate terrain corrections.

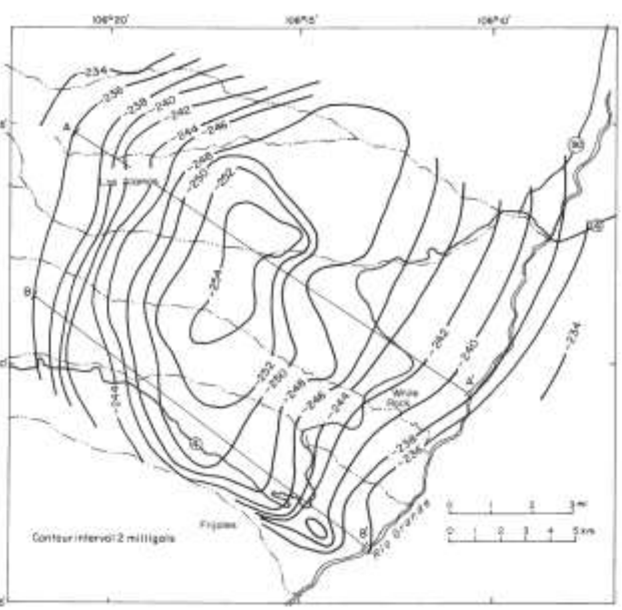

FIGURE 1—BOUGUER ANOMALY MAP OF PAJARITO PLATEAU.

The gravity map (fig. 1) shows a number of closed, or nearly closed, contours that outline a gravity low of -18 to -20 milligals, centered on a point 3 km southeast of Los Alamos. The Pajarito fault zone, which marks the western boundary of the Pajarito Plateau, coincides with the steep gravity gradient between the -238 and -240 milligal contours. This fault zone has had recurrent movement and was active before the deposition of the Bandelier Tuff. Budding and Purtymun (1976) estimate a downthrow of 120 m to the east based on the displacement of Bandelier Tuff unit, but the gravity data suggest a greater vertical displacement on beds older than the Bandelier.

The gravity low is the result of a north-northeast-trending graben, about 10 km long and 5 km wide, in which the less dense Santa Fe Group attains a large thickness. The mass deficiency, caused by the lighter sediments, is expressed as a negative gravity anomaly. This structural deepening of the Española Basin under the Pajarito Plateau is not noticeable, however, in the surface geology. In the geologic interpretation of the gravity map, data from boreholes and surface geologic information has been used. Fig. 3 shows columnar sections of six test holes drilled in the plateau, illustrating the intertonguing relationships and restricted distribution of several late Tertiary and Quaternary rock units. Section H-19 to L-4 clearly illustrates the thinning of the Bandelier Tuff from west to east. The basalts of Cerros del Rio, which underlie the Bandelier Tuff in part, are restricted mainly to the eastern part of the Pajarito Plateau. The thick section of basalts in test wells PM-1, PM-2, and PM-3 at relatively shallow depth is suspected to have caused the constriction of the gravity low near 106 °15 ' W. and 35 °52 ' N. (fig. 1).

With the exception of H-19, all test holes bottomed in Santa Fe Group rocks; the thickness of this formation is therefore undetermined. Some insight into the distribution and thickness of the Santa Fe Group under the Pajarito Plateau can be obtained from the work of Galusha and Blick (1971) in the Española Valley. Progressively younger members of the Santa Fe Group are exposed from east to west; this progression supports the idea that the deepest part of the Española Basin is along the west side.

Rocks older than the Santa Fe Group are not exposed within the boundaries of the Pajarito Plateau but crop out in adjacent areas. Early Tertiary rocks, which may be present below the Santa Fe Group sediments, include the Abiquiu for-

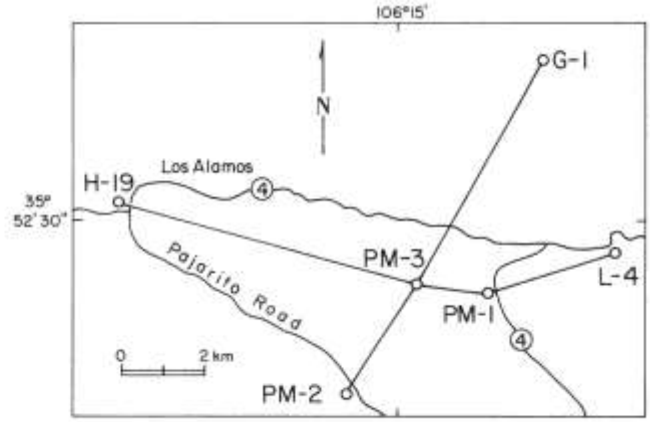

FIGURE 2—LOCATION MAP OF THE TEST WELLS used in constructing the cross sections.

mation and the E1 Rito/Galisteo Formations. The Abiquiu formation has been reported near Abiquiu and La Bajada and in the geothermal test wells drilled 32 km west of Los Alamos. A similar formation, probably equivalent to the Abiquiu, occurs near Peñasco. Where exposed, the thickness of the Abiquiu formation is between 100 to 400 m.

During the early Tertiary, in response to Laramide movements, clastic sediments were deposited in north-central New Mexico. The rocks are mostly sandstones and conglomerates stripped from the newly created uplifts; they have been named the El Rito Formation in northern New Mexico and the Galisteo Formation between Albuquerque and Santa Fe. Outcrops of the E1 Rito/Galisteo occur in several localities around the Pajarito Plateau and range in thickness from 60 to 1,430 m. From 350 to 400 m each of Abiquiu formation and E1 Rito/Galisteo Formation may be present under the plateau.

Rocks of late Paleozoic age are known to overlie the Precambrian in the Nacimiento-San Pedro Mountains to the west and the Sangre de Cristo Mountains to the east of the plateau, although they have been almost completely removed by erosion west of the Picuris-Pecos fault. Pennsylvanian rocks underlie the pre-Bandelier erosion surface in the western Jemez Mountains (Smith and others, 1970). Sections of Pennsylvanian rocks, 315 and 355 m thick, were encountered in the geothermal test wells west of Los Alamos (Purtymun, 1973; Purtymun and others, 1974). Rocks of probable Pennsylvanian age have been recognized in a test well east of Española.

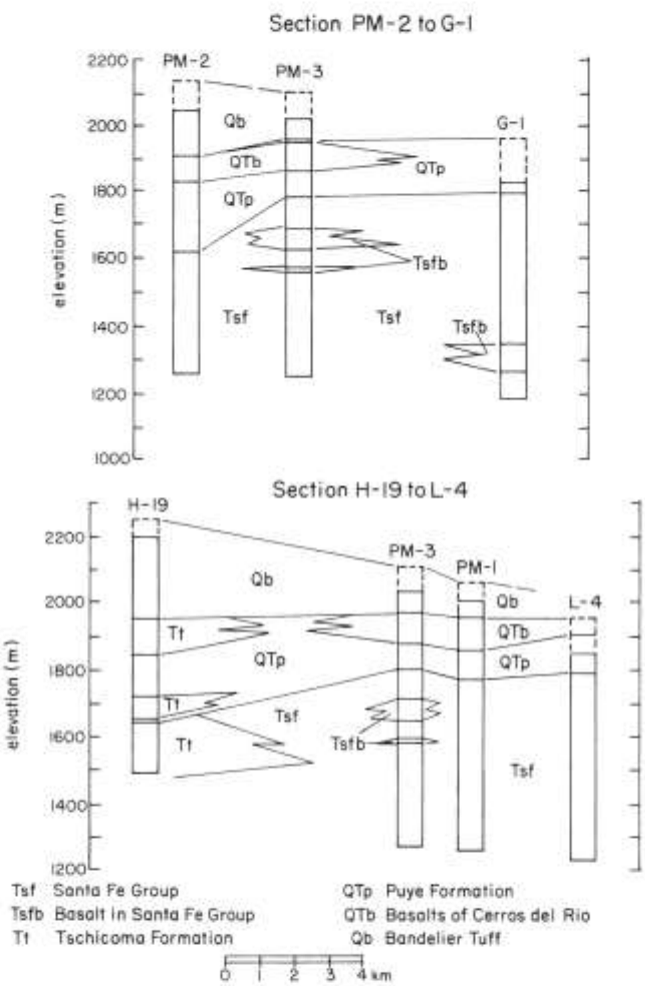

FIGURE 3—CORRELATION OF THE GEOLOGY OF THE TEST WELLS ON THE PAJARITO PLATEAU. An outcropping section in the vicinity of a well is shown by broken lines near the top of the column.

Late Paleozoic rocks, perhaps 250 m in thickness, may be present in the subsurface of the Pajarito Plateau. These rocks (predominantly limestone, sandstone, and shale) are similar in density to the Precambrian rocks; a uniformly thick layer of Pennsylvanian under the plateau will have little effect in interpreting gravity data.

Precambrian rocks of Proterozoic age are exposed in the surrounding uplifts, including the Nacimiento Mountains, 45 km to the west; the San Pedro Mountains, 55 km to the northwest; the Tusas Mountains, 55 km to the north; and the Sangre de Cristo Mountains, 30 km to the east. Granitic rocks predominate in these areas, except in the Tusas Mountains where metamorphic sedimentary and igneous rocks are common. Precambrian rocks of granitic composition were also found in the geothermal test wells west of Los Alamos, where the Precambrian surface was encountered at 1,919 m and 1,942 m above sea level.

For purposes of interpreting the gravity data, the geologic section was divided into three layers. The upper layer, consisting of Bandelier Tuff, Puye, and Tschicoma Formations, and intervening basalts, was assigned a density of 2.42 g/cm^3. This value is based on densities measured on a number of representative rock types in this layer, giving weight to their relative abundance in the upper layer. An underlying layer, composed of the Santa Fe Group and Abiquiu and E1 Rito/ Galisteo Formations was given a density of 2.32 g/cm^3. Thickness variations in this layer are mainly responsible for the Bouguer anomalies encountered on the plateau. The Precambrian basement and Paleozoic rocks make up the lowest layer, for which a density of 2.65 g/cm^3 has been assumed. The density contrast of 0.33 g/cm^3 between the basement rocks and the graben-filling sediments causes the gravity anomaly on the plateau. Where the lighter rocks have been downfaulted in the pre-Tertiary basement rocks, a mass deficiency occurs, giving rise to a negative gravity anomaly.

The shape of the basement configuration is shown in fig. 4 and is directly dependent on the density contrast. Cordell (1976) estimates that the density difference is between 0.3 and 0.4 g/cm^3.

Fig. 4 shows two cross sections in a northwest direction across the plateau, based on the assumed density difference and the geology. As much as 2,300 m of Santa Fe Group sediments may be present in the deepest part of the graben. This interpretation would confirm the opinion that the deepest part of the Española Basin is along the west side.

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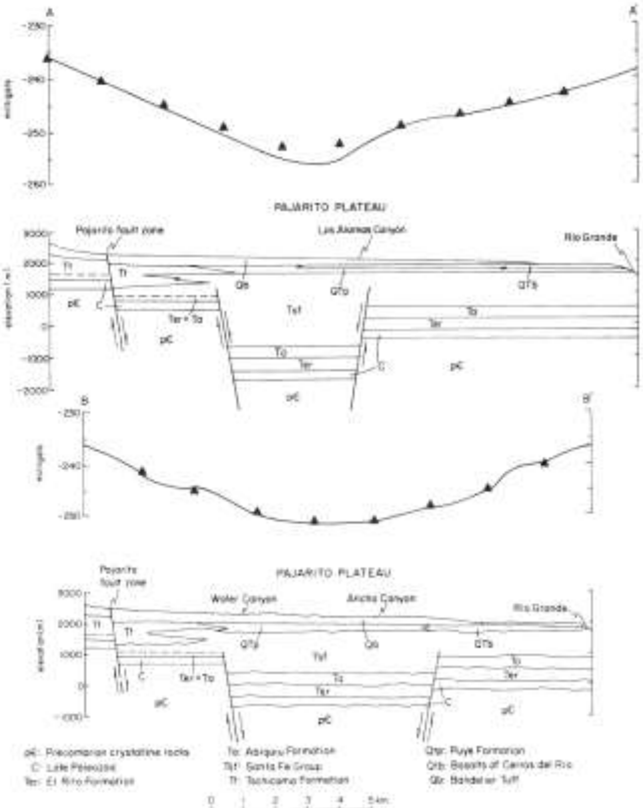

FIGURE 4—CROSS SECTIONS AA′ AND BB′ SHOWING THE GRAVITY PROFILE AND INTERPRETED GEOLOGY. Triangles indicate the calculated gravity anomaly based on mass distribution in the geologic profile.

GEOLOGY OF CERROS DEL R1O VOLCANIC FIELD

by Jayne C. Aubele
University of Arizona, Tucson, Arizona

Geologic setting

The Cerros del Rio field (fig. 1) is located on the La Bajada-Jemez constriction, which separates the Española and Santo Domingo Basins of the Rio Grande rift (Kelley, 1952; Kelley and others, 1976). At this point, the rift is laterally offset 19 mi (30 km) to the right. Elevations range from 7,471 ft to 5,358 ft (2,277 m to 1,633 m). Approximately 70 sq mi (180 sq km), including part of White Rock Canyon, have been mapped in detail (Aubele, 1978).

The early Pliocene to Pleistocene rocks of the Jemez Mountains partially cover the west boundary faults of the Española Basin. The upper Tshirege Member of the Bandelier Tuff, which erupted from the Valles caldera of the Jemez Mountains, overlies the distal northern edge of the Cerros del Rio flows (Bailey and others, 1969).

The Cerros del Rio field ends in an abrupt escarpment, on the southwest, 525 ft (160 m) above the fan deposits and stream gravels of the Santo Domingo Basin. To the east, the base of the Cerros flows is visible where it overlies the Pojoaque Member of the Tesuque Formation, Santa Fe Group (Galusha and Blick, 1971, fig. 38).

Stratigraphy

The activity of the Cerros del Rio field is younger than the deposition of the Santa Fe Group as defined by Galusha and Blick (1971). The volcanic activity is in part contemporaneous with the deposition of gravel conglomerate lenses, which are possibly equivalent to the Puye Formation (mid-Pliocene) (Bailey and others, 1969). The activity is also contemporaneous with the deposition of the Otowi Member of the Bandelier Tuff (Smith and others, 1970).

Approximately 60 vents have been identified within the Cerros del Rio volcanic field, and the majority of these are marked by cinder-spatter cone formation. The cones vary in size, shape, and state of degradation; however, all of them have the same general structure (Crumpler and Aubele, 1977). There were probably two stages of cinder-cone formation in the Cerros del Rio: 1) early-stage cinder cones predating the major flows and 2) late-stage cinder cones marking the final eruptive activity in the area. Early-stage cinder cones are now exposed by erosion, especially along the east edge of White Rock Canyon. A northeast-trending line of early cones occurs near the southern boundary of the Ceja del Rio Grant and is one of the few examples of possible fissure alignment of vents in the volcanic field. Late-stage cinder cones were erupted during the final activity of vents that had previously extruded lava flows.

Intrusions in the area include several plugs, dikes consistently trending to the northeast, and one sill exposed on the east side of White Rock Canyon.

The eruptive rocks of the Cerros del Rio field consist of alkali basalt (hawaiite), basaltic andesite, and andesite. Activity began with the extrusion of hawaiite, which forms extensive flows on the south and north margins of the area. The basal flow unit in the north has been dated at 2.6 ± 0.4 m.y. (Bachman and Mehnert, 1978, no. 2) and is exposed in White Rock Canyon. Cinder cones and phreatomagmatic eruptions occurred simultaneously, and remnants of these vents are ex-

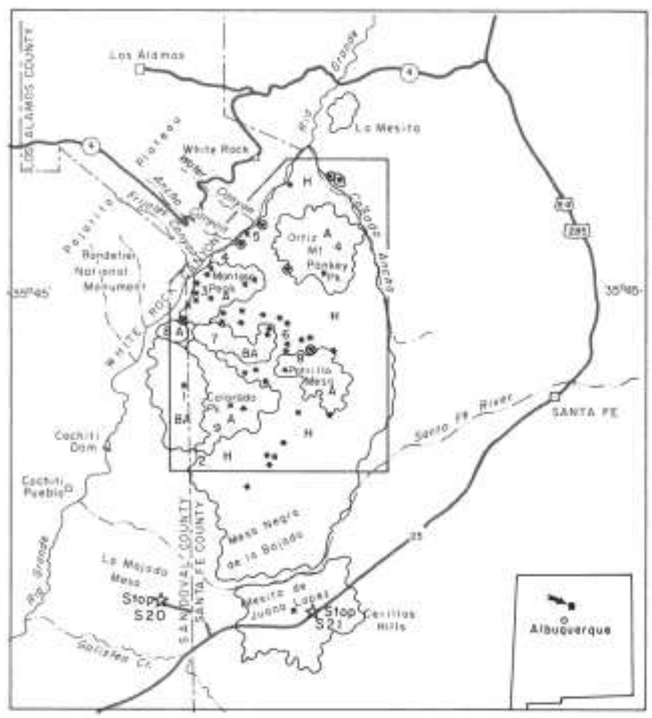

FIGURE 1—INDEX AND GEOLOGIC MAP OF THE CERROS DEL RIO VOLCANIC FIELD. Vents designated by asterisk; maars and tuff rings designated by circled asterisk; A—andesite; BA—basaltic andesite; H—hawaiite. Numbers refer to sample locations; see table 1. Rectangle outlines area mapped in detail.

posed in and near White Rock Canyon and in the southern part of the field. This activity was followed by eruptions of andesite flow-domes, first in the south and then in the north. Throughout these eruptions, less voluminous extrusions of hawaiite occurred along a zone of vents trending northwest-southeast in the center of the field. Following the andesitic eruptions, hawaiite activity continued along the central zone. One of the two stratigraphically youngest flows has been dated at 2.5 ± 0.2 m.y. (Bachman and Mehnert, 1978, no. 4).

Volcanic activity in the Cerros del Rio field had almost ceased before the formation of the Valles caldera in the Jemez Mountains. The upper member of the Bandelier Tuff, extruded from the caldera, overlies the hawaiite west of White Rock Canyon and is exposed in one location on the east side. Here an eroded valley in the hawaiite served as a channel for the tuff, which contacts the underlying basalt and ash unconformably. The tuff then appears to lap up on the east wall of the canyon as a wedge, and it thins rapidly to the east.

Extensive air-fall deposition of pumice from the Valles eruption must have covered the entire Cerros del Rio field. The pumice probably helped to preserve some of the original volcanic landforms (now being exhumed) and contributed to the development of Quaternary soils. In most cases the blanket of pumice has been eroded and redeposited as small surface deposits scattered throughout the field.

White Rock Canyon

White Rock Canyon, a 1,000-ft (300-m) gorge, was cut by the Rio Grande after the eruption of the Tshirege Member of the Bandelier Tuff (1.4 m.y.; Bailey and others, 1969). The present configuration of the canyon is the result of extensive toreva-block slumping, which has widened the canyon and repeated the stratigraphic section (fig. 2).

The cutting of the canyon has exposed an area of intercalated phreatomagmatic deposits and basalt flows. The yellow-tan phreatomagmatic deposits, designated as Santa Fe Group or stream-and-lake deposits by previous workers, are predominantly accidental materials of sedimentary origin. These materials include 1) thinly-layered sand and silt with basaltic ash; 2) palagonite; and 3) fragments of basalt, cinder, chert, quartzite, and Precambrian granitic and metamorphic rocks. The chert, quartzite, and granitic fragments are probably from early stream deposits underlying the phreatomagmatic deposits. In a few places the layered sand and silt grades into finely laminated clay, which also contains volcanic and Precambrian fragments and is interpreted as reworked tuff deposited in small lakes or ponds. The phreatomagmatic deposits vary in thickness from a meter to tens of meters. Bomb sags, cauliflower bombs, and crossbeds formed by base surge are common.

These deposits are clearly related to the activity of the Cerros del Rio field, because they are interbedded with hawaiite flows. The source of the deposits must have been a series of maar craters that paralleled the present White Rock Canyon. At least five of these vents are exposed in varying degrees of dissection in side canyons along the Rio Grande, including Montoso Arroyo and Frijoles Canyon.

North of Montoso Peak, a deeply dissected maar is exposed on the east edge of White Rock Canyon and has been informally named Montoso maar (fig. 3). This previously unknown maar has been described in preliminary reports by Aubele (1976) and Aubele and others (1976) and is the best exposed maar described to date in the literature (Lorenz, 1973; personal communication, 1977). Total relief is over 655 ft (200 m), and dissection has exposed several stratigraphic levels and a well-defined ring-fracture zone.

Several other phreatomagmatic vents identified as maars, tuff rings, and tuff cones have been discovered within the volcanic field south of White Rock Canyon, and explosive activity appears to have occurred throughout the eruptive history of the field.

FIGURE 2—TOREVA BLOCKS IN WHITE ROCK CANYON, NORTH OF ANCHO CANYON; view to the north. The Rio Grande is approximately 10 m wide here; the canyon rim is about 300 m above the river. Two old river terraces also visible.

FIGURE 3—AERIAL VIEW OF MONTOSO MAAR LOOKING SOUTH ACROSS THE RIO GRANDE; crater approximately 1 km in diameter.

Petrology and petrogenesis

Regional setting and geologic implications

No modern perennial streams flow through the Cerros del Rio volcanic plateau, although intermittent runoff toward the Rio Grande has cut deep arroyos in the pumiceous soil cover and in the interior of flows. Phreatomagmatic deposits in the vicinity of White Rock Canyon could be cited as evidence for a through-going stream in the area at the time of the eruptive activity of the Cerros. Additional evidence for a depression, probably a valley cut by a stream, is based on the thickness of the Cerros del Rio flows. To the east and southeast, the vol canic section thins to 100 ft (30 m) and 10 ft (3 m) respectively, while to the north and west, along White Rock Canyon, the exposed section is consistently 1,000 ft (300 m) thick. The thin western edge of the flows appears to be about 1 mi (1.5 to 2 km) west of the present Rio Grande (Kelley, 1948). This distribution pattern implies that the flows filled in a valley or depression in the vicinity of the modern White Rock Canyon. These flows were later eroded into valleys, which were filled by the distal edge of the Bandelier Tuff. Finally, White Rock Canyon was formed by continued stream incision.

The flows of the Cerros del Rio appear to have followed two distinct gradients. A northwest-trending line of vents in the center of the area appears to have acted as a divide for the two gradients. Flows from its south side flow west or south, while flows to the north consistently head north. These gradients may relate to the regional gradients caused by the Española Basin to the north and the Santo Domingo Basin to the southwest. If so, then the northwest-trending vents may be aligned along an extensional zone between the basins. The dominant volcanism along this trend is hawaiite, which is generally thought to represent relatively deep magma genera-

TABLE 1—CHEMICAL ANALYSES AND CALCULATED NORMS OF THE VOLCANIC ROCKS OF THE CERROS DEL RIO VOLCANIC FIELD, NEW MEXICO (analyses by J. C. Aubele). * Gravimetric analyses of SiO_2 performed by John Husler; † S.I. (solidification index) = (MgO × 100)/(MgO + FeO_T + Na_2O + K_2O); ‡ norms calculated with adjusted values of percent Fe_2O_3, such that percent Fe_2O_3 = percent TiO_2 + 1.5 (after Irving and Baragar, 1971).

	1	2	3	4	5	6	7	8	9	10
SiO_2*	60.16	49.11	59.24	60.09	50.18	47.52	56.44	59.73	60.95	48.63
TiO_2	.84	2.07	.70	.78	.93	1.58	1.14	.88	.73	1.92
Al_2O_3	15.93	17.41	15.91	16.92	15.61	16.30	17.03	16.04	15.73	16.29
Fe_2O_3	2.51	4.44	2.53	2.10	3.83	4.47	2.80	3.32	2.58	3.55
FeO	3.59	6.54	2.66	3.53	5.61	5.43	3.82	2.21	2.63	7.41
MgO	3.26	5.40	3.66	2.80	6.58	6.77	3.17	2.64	3.42	6.85
CaO	5.34	8.24	5.75	5.21	8.67	8.44	5.95	5.01	5.43	8.32
Na_2O	3.94	3.95	4.12	4.22	4.10	4.07	4.39	4.14	4.22	3.83
K_2O	2.53	1.69	2.44	2.60	1.72	2.22	2.40	3.17	2.34	1.27
MnO	.10	.16	.09	.09	.14	.16	.09	.09	.09	.15
H_2O^+	.92	.35	1.18	1.08	.004	1.25	.68	1.35	1.04	.04
H_2O^-	.09	.22	.16	.18	.07	.14	.24	.08	.12	.06
P_2O_5	.37	.86	.58	.45	.74	.96	.67	.72	.39	.72
BaO	.07	.05	.08	.08	.05	.08	.08	.09	.07	.04
SrO	.09	.11	.10	.09	.12	.13	.11	.13	.08	.10
Total	99.74	100.60	99.20	100.22	98.35	99.52	99.01	99.6	99.82	99.18
S.I.†	20.6	24.5	23.8	18.4	30.1	29.5	19.1	17.1	22.5	29.9
normative mineralogy‡										
q	10.84	.00	9.25	9.85	.00	.00	5.13	9.76	11.19	.00
or	15.14	9.98	14.65	15.48	10.23	13.22	14.40	19.06	13.95	7.54
ab	35.83	34.42	37.60	38.19	32.40	24.28	40.03	37.83	38.25	34.34
an	18.55	24.78	18.00	19.70	19.24	19.81	19.98	16.10	17.23	23.63
ne	.00	.62	.00	.00	2.80	7.54	.00	.00	.00	.14
di	4.97	8.69	6.05	3.02	15.69	13.26	4.80	3.94	6.19	10.78
hy	10.23	.00	9.89	9.32	.00	.00	9.82	8.00	8.99	.00
fo	.00	8.95	.00	.00	9.70	10.51	.00	.00	.00	11.35
fa	.00	4.15	.00	.00	4.51	3.90	.00	.00	.00	4.43
il	1.18	2.88	.99	1.09	1.30	2.21	1.61	1.24	1.02	2.68
ap	.78	1.79	1.23	.94	1.55	2.02	1.42	1.53	.82	1.51
mt	2.47	3.73	2.33	2.40	2.55	3.24	2.80	2.53	2.35	3.59

Rock type, specimen number and locality

1) Andesite (CD-1), vent 31 (QTa_2), south of Cochiti cone
2) Hawaiite (Me10a), southern hawaiite (QTb_1), near Cañada Tetilla
3) Andesite (MaM16), Montoso Peak (QTa_5), west of Montoso Peak
4) Andesite (WF505), Ortiz Mountain (QTa_1), north of Pankey Peak
5) Hawaiite (WE11L), early northern hawaiite (QTb_2), south of vent 48
6) Hawaiite (MB61), Cerro Rito (QTb_3), north of vent 5
7) Basaltic andesite (Mc26c), Cerro Micho ($QTba_1$), west of vent 11
8) Andesite (MDP21), Cerrito Portillo (QTa_1), west of Tor tuff ring (vent 41)
9) Andesite (ME12c), Colorado Peak (QTa_4), south of Colorado Peak
10) Hawaiite (AGF1), Twin Hills vent 7 (QTb_7), north of Portales Pond

tion and differentiation (Carmichael, 1974). Extensional fractures would serve as a logical conduit for the rapid rise of alkalic magma from deep sources.

Recently, the Rio Grande rift has been compared to other rifts, many of which are associated with the global tectonics of spreading ridges. Some of these comparisons are instructive; however, an examination of the volcanic petrochemical assemblages leads to the conclusion that the rocks of the Cerros del Rio are not completely analogous to volcanic rocks in other rifts.

In their chemical composition, the hawaiites of the Cerros del Rio strongly resemble the plateau alkali basalts from Ethiopia (Mohr, 1971). No correlation exists, however, between the andesite of the Cerros del Rio and the intermediate lavas of the African rift, which have alkalic rather than calc-alkalic affinities. The northern Mt. Taylor volcanic field, which has been recently mapped by Crumpler (1977, 1978, and work in progress), is the only volcanic field in the Rio Grande area that follows a complete alkalic trend similar to that dominating the African rift. In both Kenya and Ethiopia, basalts become tholeiitic, or at least less alkalic, within the rift (Baker and others, 1972). Lipman (1969) has found a similar correlation in the northern Rio Grande region. However, no tholeiites have been identified in the Cerros del Rio, although the field is located within the rift.

The presence of hawaiite without tholeiite in the Cerros del Rio may be attributed to its location at an extensional fracture zone between two basins. This is not inimical to comparisons between the Rio Grande rift and other tectonic rifts. However, the most appropriate comparison of the petrologic assemblage (hawaiite-basaltic andesite-andesite) of the Cerros del Rio volcanic field is not to the east African rift, but instead to other volcanic fields of the Basin and Range province in the western United States.

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CENOZOIC GEOLOGY OF ESPANOLA BASIN

by Kim Manley, *U.S. Geological Survey, Denver, Colorado*

The Española Basin is in a north-south alignment of Cenozoic basins that extends from central Colorado to southern New Mexico (Chapin, 1971; Chapin and Seager, 1975; Manley, 1978), known as the Rio Grande depression or rift. The Española Basin extends 25 mi north to south and 40 mi east to west.

The western half of the basin is filled with the volcanic rocks of the Jemez Mountains (fig. El); these mountains define the western edge of the topographic basin, which is only 20 mi wide. The topographic basin terminates near mesas capped by basalts of the Servilleta Formation to the north and Cerros del Rio volcanic field to the south. Tertiary sedimentary rocks are preserved in the central basin: Galisteo, E1 Rito (Smith, 1938), Abiquiu (Smith, 1938), and Picuris (Cabot, 1938) Formations and the Santa Fe Group; several Pliocene and Pleistocene alluvial deposits are also preserved in the central basin, including the Ancha and Puye Formations (Pliocene). The topographic boundary to the east is the Sangre de Cristo range. Structurally, the basin is separated from the Santo Domingo subbasin to the south by the northwest-trending La Bajada fault, downthrown to the southwest. The Española Basin is bounded on the north by the San Luis Valley. This boundary is difficult to pinpoint but is generally assumed to be along the northern flanks of the Picuris range and to extend westward to the Ojo Caliente area via an isolated Precambrian exposure known as Cerro Azul. On the west and east the Española Basin is bounded by Precambrian-cored uplifts-the Nacimiento uplift on the west and the Sangre de Cristo Mountains on the east.

The Tertiary rocks in the basin have been described in part by several authors, and the terminology of these rocks is confusing. As accepted presently by the U.S. Geological Survey, the Santa Fe Group (Miocene to Pleistocene) includes the Tesuque, Puye, and Ancha Formations. Galusha and Blick (1971) (fig. E2) propose that the Santa Fe Group be considered Miocene and Pliocene age and include the Tesuque and Chamita Formation, but not the Ancha or Puye Formations—both post-Chamita in age and equivalent to other post-Santa Fe Group deposits.

The route for this field trip begins in Santa Fe, near the southern margin of the basin, and leads northward through the Tertiary sedimentary rocks and across some late Pleistocene surfaces to the eastern edge of the sediments near Cundiyo. Here an alternate log follows NM-4 from Truchas to Peñasco across the late Pliocene to early Pleistocene surfaces of the northeast plateau and returns to Española across the Precambrian rocks of the Picuris range and through the towns of Embudo and Velarde. The structure of the late Pliocene Velarde graben is discussed. The two logs join north of Española and the route continues to the western boundary fault zone near Abiquiu. From the western side of the basin, the log returns to Española and continues toward Los Alamos to exposures of the Cerros del Rio basalt flows and the Bandelier Tuff.

Mileage

0.0 Intersection of St. Francis Drive and Alameda. *Go north on US-84-US-285 truck bypass.* **0.2**

0.2 Paseo de Peralta. **0.6**

0.8 Underpass. **0.2**

1.0 *Merge with US-84- US-285 North.* **1.7**

2.7 **STOP El, Divide north of Santa Fe.** Summit of the hill on the north edge of Santa Fe. This is the "divide surface" of Spiegel and Baldwin (1963), who describe it as the highest of three in the area. The surface is underlain by 5-10 ft (1-3 m) of gravel and merges westward with the surface of the lavas on the northeast side of the Cerros del Rio volcanic field. Flows in this area have K-Ar ages of 2.0 m.y. and 2.6 m.y. (Manley, 1976a), and 2.5 m.y., 2.6 m.y., and 2.8 m.y. (Bachman and Mehnert, 1978). The surface truncates the Ancha Formation, a sand-and-gravel deposit that unconformably overlies the Tesuque Formation (Spiegel and Baldwin, 1963). The Ancha Formation in its type area has radiometric age control; an ash from the formation has a zircon fission-track age of 2.7 m.y. (Manley and Naeser, 1977), and an overlying basalt is 2.0 m.y old (Manley, 1976a). **1.4**

4.1 Junction; *continue straight;* road right (north) to Tesuque. **1.8**

5.9 Junction; *continue straight;* road to left (west) to Santa Fe Opera. **1.0**

6.9 Bridge across the Rio Tesuque. Exposures are of the Nambe Member (Galusha and Blick, 1971), of the Tesuque Formation. **0.1**

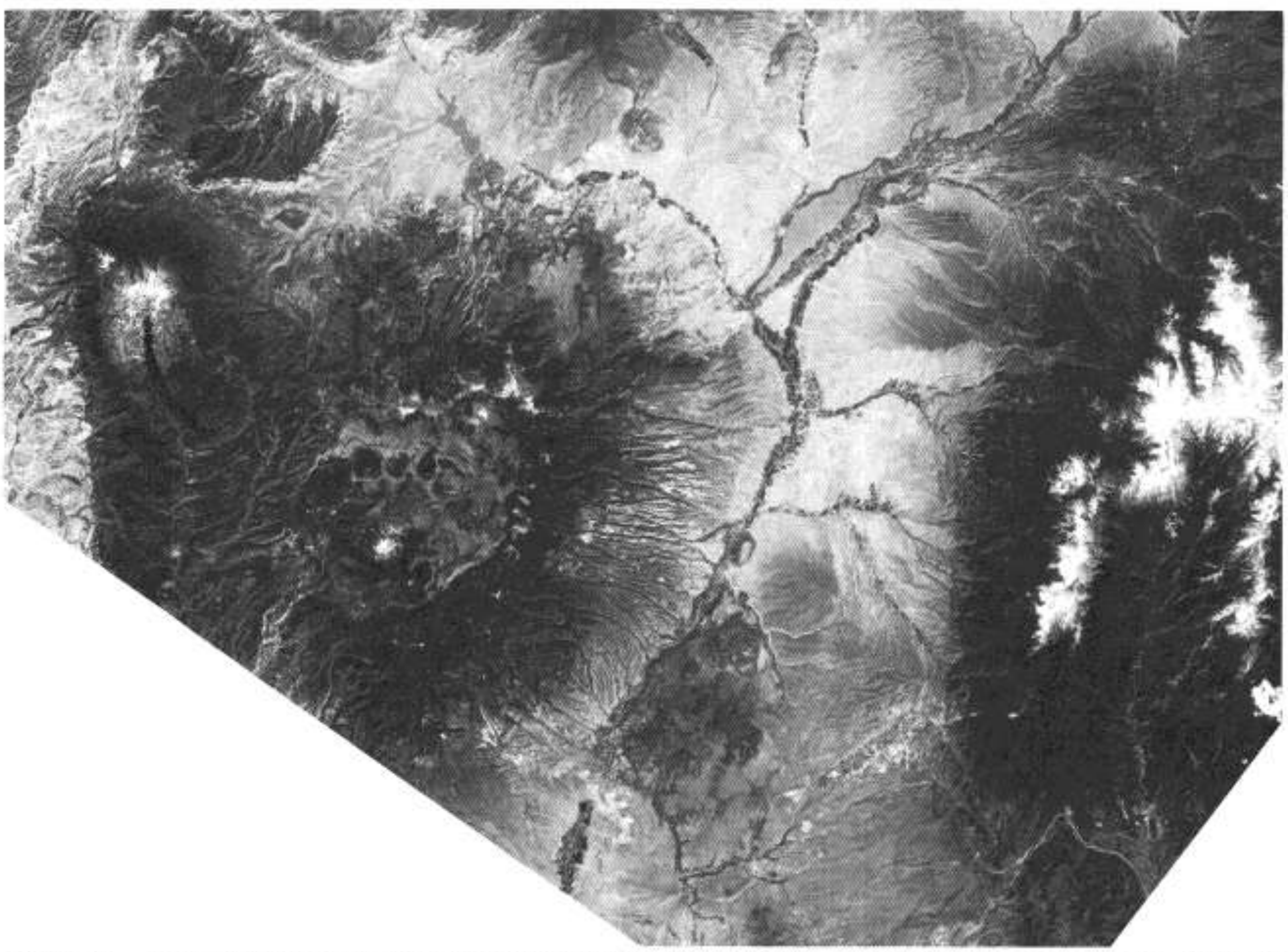


FIGURE E1—a) Skylab-2 photo and b) geologic map (at right) of Española Basin area, north-central New Mexico (photo SL2-10-020 courtesy of Technology Application Center, University of New Mexico; scale approximately 1:500,000).

7.0 Junction; *continue straight;* road to right (east) to Tesuque. **2.1**

9.1 Junction; *continue straight;* road to left (southwest) to the Tesuque Pueblo. **1.4**

10.5 **STOP E2, Camel Rock.** *Camel Rock picnic area* on the left side of the highway. Camel Rock is an erosional feature carved from the Skull Ridge Member (Galusha and Blick, 1971) of the Tesuque Formation. The Skull Ridge Member is composed of 650750 ft (200-230 m) of fine to medium-coarse sand and silt with interstratified beds of clay, conglomerate, and numerous volcanic ash beds; Barstovian ("late Miocene") fossils have been collected from the Skull Ridge Member (Galusha and Blick, 1971, p. 53 and 57). The prominent ash bed seen on the east side of the highway and in outcrops to the east-southeast is the base of the Skull Ridge Member. Below it are 1,500 ft (460 m) of conglomeratic sandstone and sand of the Nambe Member (Galusha and Blick, 1971, p. 31 and 45). A late Hemingfordian fauna (middle Miocene) has been recovered from the Nambe Member (Galusha and Blick, 1971, p. 53). **4.0**

14.5 *Enter Pojoaque.* **1.1**

15.6 Junction; *continue straight;* **NM-4 to left** (west) to Los Alamos. **0.2**

15.8 Junction; *continue straight;* **road to right (east) to Pojoaque** Pueblo. View ahead to cliffs of the Pojoaque Member (Galusha and Blick, 1971) of the Tesuque Formation. **0.3**

16.1 Bridge across Pojoaque River. **0.1**

16.2 Junction; *turn right onto NM-4* to Nambe. **1.9**

18.1 Nambe church on the right. 1.1

19.2 Junction; *continue straight;* road to right goes to Nambe Pueblo. Outcrops here and ahead are of the Nambe Member. To the left are cliffs of the Skull Ridge Member. **4.2**

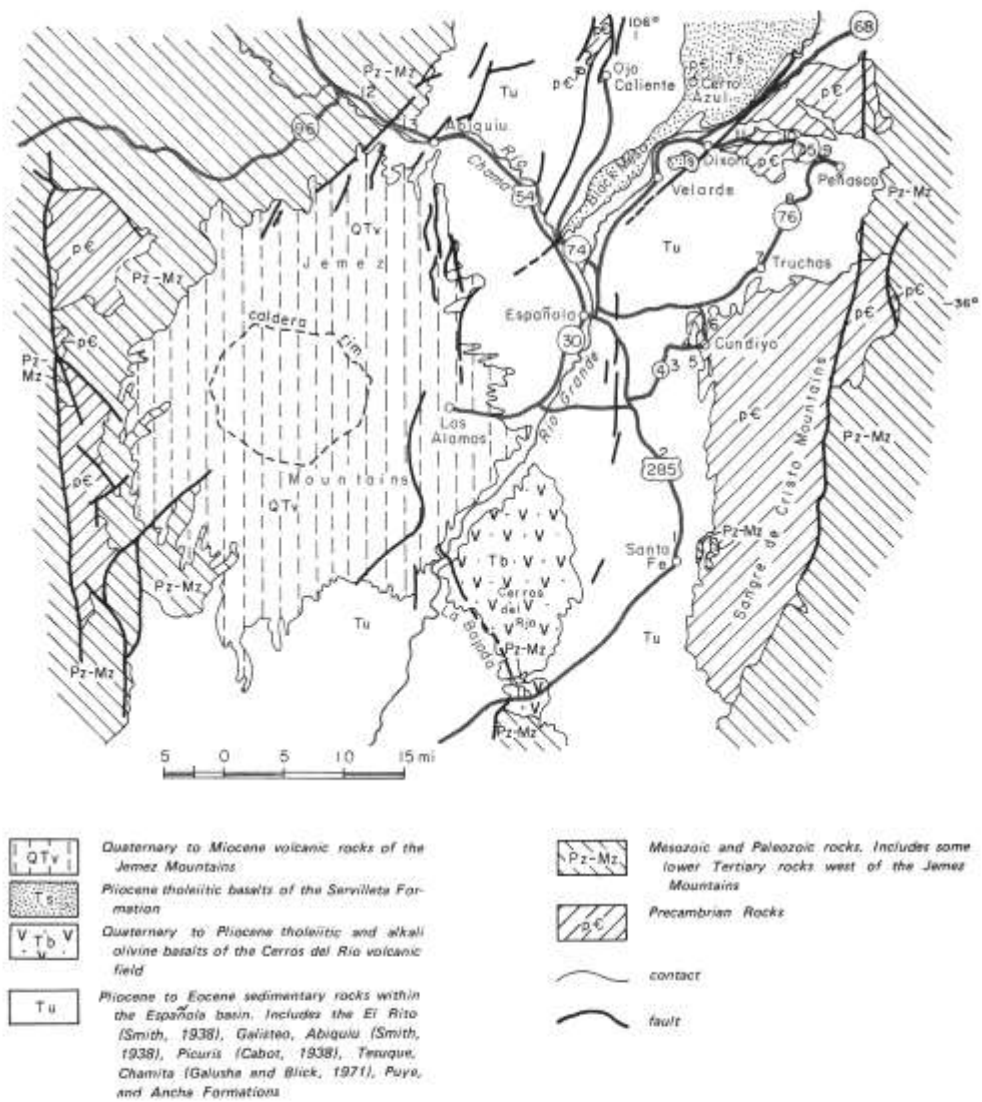
23.4 Normal fault in roadcut to the left. **0.2**

23.6 Junction; *turn right; continue on NM-4 to Cundiyo.* **0.5**

24.1 STOP E3, South of Chimayo. *Park to right of highway* for view of the Española Basin. Description of features indicated on fig. E3:

1) Sandia Mountains—A tilted fault block on the east side of the Albuquerque-Belen Basin

2) Cerros del Rio volcanic field—Predominantly



[New Mexico Bureau Mines & Mineral Resources, Circular 163, 1978]

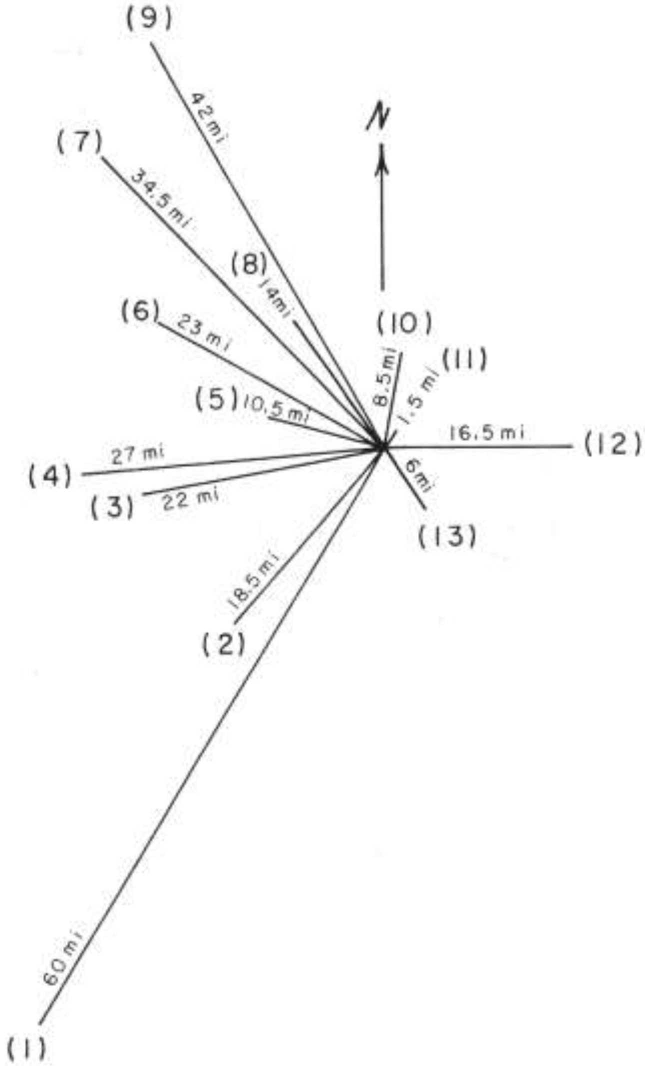


FIGURE E2—PANORAMIC INDEX OF FEATURES SEEN FROM STOP E4, SANTA CRUZ RESERVOIR OVERLOOK.

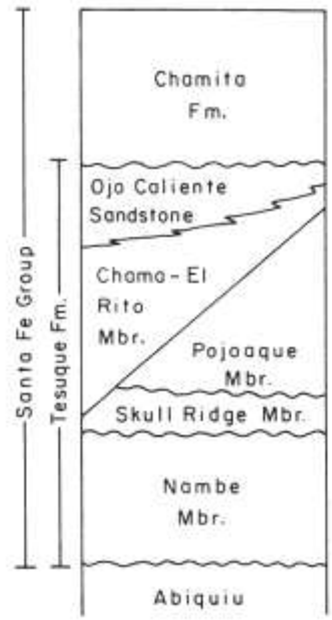


FIGURE E3—STRATIGRAPHIC NOMENCLATURE AND CORRELATION OF THE SANTA FE GROUP (adapted from Galusha and Blick, 1971).

basaltic cones and flows (see also Stop E1 and Aubele, this guidebook)

3) Pajarito Plateau—This plateau flanks the east side of the Jemez Mountains and is capped by either the Puye Formation or the Bandelier Tuff. In the middle distance is "small" Black Mesa of San Ildefonso, a volcanic neck and flow related to the Pliocene Cerros del Rio volcanic field.

4) Jemez Mountains—Skyline peaks include Pajarito Mountain, elevation 10,441 ft (3,212 m), to the south and Tschicoma Mountain, elevation 11,561 ft (3,557 m) to the north. This range represents the remnants of the eastern rim of the Valles caldera (Bailey and Smith, this guidebook).

5) Middle to upper Pleistocene alluvium—Three terrace levels of the Rio Grande and its western tributaries form an apron at the base of the Pajarito Plateau west and northwest of Española.

6) Basalt-capped mesas—High-level Miocene flows of the Lobato Basalt and lower (more northerly) Quaternary basalt of Mesa de Abiquiu. A sample of Lobato Basalt has a K-Ar age of 7.4 m.y. (Bailey and others, 1969).

7) Arroyo del Cobre—This canyon is a breached, faulted anticline at the western edge of the Rio Grande rift. The Cutler Formation (Permian) and Chinle Formation (Triassic) are exposed along the western side of Arroyo del Cobre. Copper mines in the Cutler Formation were worked by the Spaniards.

8) Black Mesa—"Large" Black Mesa is capped by an olivine tholeiite flow of the Servilleta Formation. This flow has a K-Ar age of 2.8 m.y. (Manley, 1976a). Gravels beneath the flow are multilithologic with extrabasin lithologies. They represent a deposit of either the ancestral Rio Grande or a major tributary. These gravels overlie the Chamita Formation (Galusha and Blick, 1971) of the Santa Fe Group with angular unconformity.

9) Magote Ridge, elevation 9,987 ft (3,072 m)—The ridge on the skyline is part of the Brazos uplift on the west side of the rift. The ridge is composed of Mesozoic rocks (Smith and others, 1961).

10) Northeast Plateau—The high surface seen on the skyline through the saddle of the road to Chimayo is the Truchas surface, one of three surfaces on the northeast plateau (Manley, 1976b). (See Stop E7 for further discussion.) The surface gravels unconformably overlie the Pojoaque Member of the Tesuque Formation as mapped by Galusha and Blick (1971). A zircon fission-track age of 12.7 m.y. (Manley and Naeser, 1977) was obtained from an ash bed 290 ft (88 m) below the surface. This age demonstrates that these sediments are probably the upper part of the Skull Ridge Member rather than the Pojoaque Member.

11) "Santa Cruz" surface—Middle foreground is the late Pleistocene "Santa Cruz" surface. Remnants of this surface are preserved both east and west of the Santa Cruz Reservoir. (See further discussions at Stops E5 and E6).

12) South Truchas Peak, elevation 13,101 ft (4,031

m)-This peak is composed of Precambrian rocks. There are several prominent cirques in the area.

13) Foothills-In the middle distance are foothills of Embudo Granite (Precambrian) (Montgomery, 1953). 0.3

24.4 Quaternary alluvium with a dark, 10-inch (25-cm) thick charcoal-rich zone 2 ft (0.6 m) below the surface. This zone is common in the Quaternary alluvium of the area. Two such layers can be found in some places; they probably represent extensive forest fires. No carbon-14 dating is available. **0.1**

24.5 To the left (north) side of road is a normal fault, downthrown to the east. **0.2**

24.7 To the left (north) are outcrops showing an increased thickness and number of conglomerate beds in the Nambe Member. Ahead left is a suite of normal faults, downthrown to the east. **0.1**

24.8 **STOP E4, Santa Cruz Reservoir overlook.** *Take graded road to left to Santa Cruz Reservoir overlook campground,* which is located 1 mi to the north on high-level terrace, capped by gravel of "Santa Cruz" surface (see Stop E6). The terrace gravels rest on an extensive valley erosion surface cut on west-tilted Tesuque beds. The reservoir overlook is closed in winter months. Use Stops E3 and E6 during that period.

Discussions at this stop stress structural relationships of the east margin of the topographic Española Basin. Refer to fig. 4 in Baltz (this guidebook) for geologic maps and a cross section of the area discussed. The pattern of faulting in the Santa Fe Group in this northeast portion of the basin is one of north-trending antithetic normal faults down-thrown to the east.

The contact between the Santa Fe Group and the Precambrian rocks is both fault and depositional. Where the contact is depositional, the Santa Fe Group sediments have filled valleys between, and eventually have buried, rounded hills of Precambrian rocks.

Many of the present drainages in this area have been superimposed onto Precambrian outcrops. Examples that will be seen enroute are the Santa Cruz River and Rio Quemado. *Return to junction with NM-4 at mileage 24.8; turn left (east); continue on main route.* **0.5**

25.3 **STOP E5, West of Cundiyo.** *Park in turnout* to the left (north) side of the road on a dirt road. This valley is formed along the contact of the Tesuque Formation with the Precambrian rocks. The Truchas surface can be seen in the distance to the north. To the northwest in the middle distance, is the "Santa Cruz" surface with about 100 ft (30 m) of upper Pleistocene gravels overlying with angular unconformity the Nambe Member of the Tesuque Formation. **0.7**

26.0 Precambrian rocks exposed on both sides of the road. **0.2**

26.2 View of the Cundiyo Valley. **0.5**

26.7 *Enter Cundiyo.* Left roadcut has about 10-15 ft (3-4 m) of coarse, moderately well-rounded, upper Pleistocene gravels. This surface is probably a remnant of a surface younger than the "Santa Cruz" surface. **0.1**

26.8 Contact of the surface gravel with the Tesuque Formation. **0.7**

27.5 Bridge over the confluence of the Rio Medio on the north and the Rio Frijoles on the south. **1.6**

29.1 To the west is a hill of Precambrian rocks. The "Santa Cruz" surface is in the foreground. The contact of the surface gravel with the Tesuque Formation can be seen here and also in the exposure to the north. **0.3**

29.4 Contact of gravel on the "Santa Cruz" surface with the Tesuque Formation (Nambe Member). Just beyond is a road junction. Road left (west) leads to Santa Cruz Reservoir. **0.1**

29.5 Junction; *continue straight;* road to right (east) to Borrego Mesa. **0.3**

29.8 **STOP E6, Rio Chiquito overlook.** *Park in turnout on the north side of the road.* View to the north is of the Truchas surface and underlying Tesuque Formation. An ash bed with a zircon fission-track age of 12.7 m.y. (Manley and Naeser, 1977) is visible in the prominent exposure at the eastern end of the surface. Walk down the road to the west to view an exposure of the gravel on the "Santa Cruz" surface with imbrication indicating transport direction to the west. The gravel is predominantly quartzite cobbles and small boulders (Manley, 1976b). **0.1**

29.9 Contact of gravel on the "Santa Cruz" surface with the underlying Tesuque Formation. **0.5**

30.4 *Enter the town of Rio Chiquito.* **0.1**

30.5 Bridge over the Rio Quemado. **0.3**

30.8 Junction of NM-4 and NM-76. *Turn right on NM-76* for continuation of log. See alternate log for route left (west) via NM-76 and NM-68 through Santa Cruz and Española to junction of NM-63 and NM-74 near San Juan Pueblo. **0.6**

31.4 Junction; *continue straight;* road to right (southeast) to Cordova. **0.7**

32.1 Road climbs up a sloping surface in this area. This surface was originally mapped by Miller and others (1963) as the Ancha Formation, but it is considerably younger than the type Ancha Formation near Santa Fe. This surface is probably late Pleistocene in age and may be a piedmont slope related to the "Santa Cruz" surface. **1.4**

33.5 Junction; *continue straight;* road to right (south) to Cordova. **2.1**

35.6 To the right (east) of the road is a small pumice pit. This pumice is the Guaje Pumice Bed of the Otowi Member, Bandelier Tuff (Manley, 1976b). The Otowi Member has a K-Ar age of 1.4 m.y. (Doell and others, 1968). The pumice is preserved at the head of a drainage cut into, and therefore younger than, the Truchas surface, which thus has a minimum age of 1.4 m.y. **0.4**

36.0 *Enter Truchas.* **0.3**

36.3 Junction; *turn left (north) and continue on NM-76* to Ojo Sarco. The road is now on the Truchas surface that has been cut across Precambrian and Santa Fe Group rocks. To the right (east) are gently rounded hills of Precambrian rocks that project slightly above the rest of the surface. 0.7

37.0 Roadcut on right (east) contains reworked volcanic ash thought to be Pleistocene Pearlette by Miller and others (1963). The ash is too contaminated to be identified, but shard shape is unlike the Bandelier Tuff ashes. **0.4**

37.4 In the roadcut to right (north) are three small exposures of ash. The high degree of alteration of glass to clay suggests these deposits are part of the Santa Fe Group. 0.3

37.7 **STOP E7, Truchas rest area.** *Park in rest area* on left. View of the Truchas surface and Española Basin (fig. E4). The Truchas surface is the youngest of three gently sloping surfaces comprising the northeast plateau. The surfaces extend northwestward from the Sangre de Cristo Mountains toward the Rio Grande at the northern margin of the Española Basin. The surfaces stairstep down from north to south with differences in altitude of approximately 90 ft (28 m). Each surface has been named (Manley, 1976b) for the drainage to the north of it: from oldest to youngest (north to south) they are the Oso, Entrañas, and Truchas. The surfaces are veneered with usually less than 9 ft (3 m) of gravel. The gravel is coarse (including boulders), moderately well rounded, and predominantly quartzitic (Manley, 1976b). The surfaces are late Pliocene to early Pleistocene in age. **0.8**

38.5 Road crossing the Entrañas surface. **1.6**

40.1 Road crossing a narrow saddle in the Oso surface. **1.6**

41.7 *Enter Ojo Sarco.* Tour stop ahead. **0.8**

42.5 **STOP E8, Ojo Sarco.** *Park in turnout to the left* (west) side of the road. Conglomerate outcrop across the road is similar in composition to the Cejita Member of the Tesuque Formation, although the rounding is poorer than in the type section (Manley, 1976b, 1977). The Cejita Member is well exposed in its type area at the northwestern end of the Oso surface, which is visible on the skyline to the southwest. This member consists of well-sorted and rounded coarse conglomerate and interbedded coarse- to fine-grained sand. The Cejita Member interfingers with the Pojoaque and Skull Ridge Members. **1.4**

43.9 *Enter Las Trampas.* This village was established in 1751 by 12 families from Santa Fe. The Church of San Jose de Garcia is one of the finest surviving 18th-century churches in New Mexico (from State Historic Marker). **0.4**

44.3 Exposures of Precambrian rocks on left (north) side of road. **0.9**

45.2 Junction; *continue straight;* road on right (east) to El Valle. **0.9**

46.1 Junction; *continue straight;* road on right (east) to Ojito. **0.5**

46.6 View ahead is of the Picuris Mountains (Precambrian rocks) on skyline and the "Chamisal" surface in middle distance. The gravel on this surface is about 10 ft (3 m) thick; clasts are predominantly Paleozoic sandstones with some basalt, quartzite, and Paleozoic limestone. This surface is younger than the Oso surface; its age is unknown but is probably late Pleistocene. **0.3**

46.9 *Enter Chamisal.* **2.1**

49.0 Coarse conglomerate outcrop (on right) is mapped as part of the Picuris Tuff by Miller and others (1963). This formation is considered equivalent to the Abiquiu Tuff on the west side of the basin. Both formations underlie the Santa Fe Group. See fig. E2. No paleontologic nor radiometric ages are available; however, the formations are thought to be Oligocene. **0.6**

49.6 **STOP E9, Rio Santa Barbara.** *Cross bridge and pull off road at north end of bridge,* right (east) side. East of here are two terrace levels that parallel the Rio Santa Barbara from the mountain front to the town of Penasco. The terrace on the northeast, the higher of the two, is approximately 160 ft (50 m) above the valley floor and is underlain by 80 ft (25 m) of gravel. The lower terrace, 80 ft (25 m) above present flood-plain, is underlain by 15 ft (5 m) of gravel. Both terrace deposits are predominantly well-rounded cobbles of Paleozoic rocks overlying the more quartzite-rich pebble gravels and sands of the Tesuque Formation.

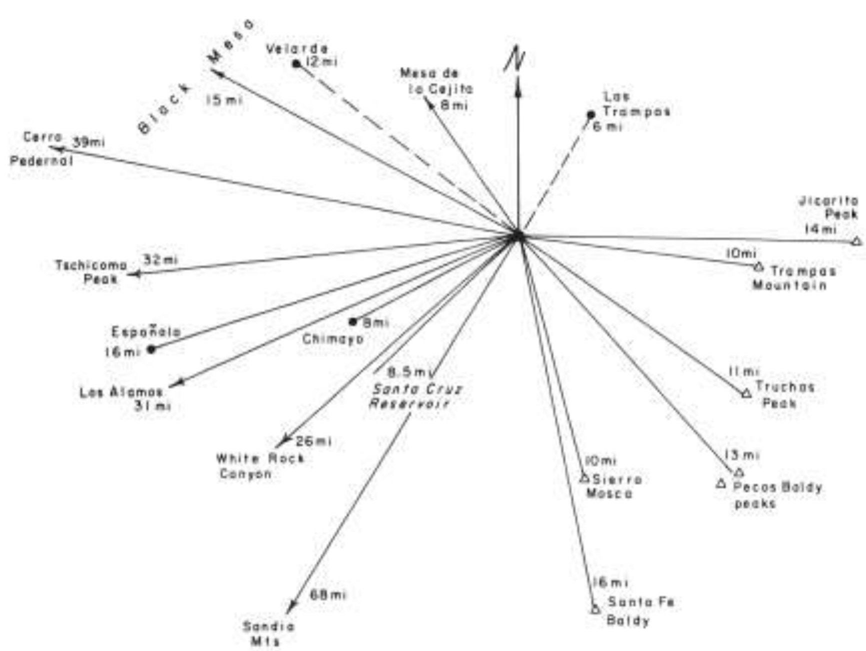


FIGURE E4—PANORAMIC INDEX OF FEATURES SEEN FROM STOP E7, TRUCHAS REST AREA.

These terraces are cut into the Tesuque Formation below the elevation of the Oso surface and have more gentle gradients than the Oso surface at equivalent distances from the mountain front (Manley, 1975b). They are probably outwash terraces of Wisconsin age. **0.2**

49.8 Junction; NM-76 joins NM-75. *Turn left (west) onto NM-75.* **0.6**

50.4 Junction; *continue straight;* road right (north) to Picuris Pueblo. **1.0**

51.4 Well-rounded, coarse upper Quaternary gravel in roadcut on right (north). View ahead on skyline is of a surface that was once the valley floor for the Rio Santa Barbara. The stream has been captured and now leaves the valley to the left in a canyon cut through Precambrian rocks. **0.5**

51.9 Junction; *continue straight;* road to right to Picuris Pueblo. Roadcuts ahead in Precambrian rocks of the Picuris uplift. **0.3**

52.2 View to the right is of Picuris Mountains on the skyline and of the white outcrops of the Picuris Tuff in the middle distance. **2.7**

54.9 **STOP E10, Southern Picuris Mountains.** *Park in large turnout to right;* walk to top of ridge south of highway for view of the Peñasco embayment area between the Picuris and Sangre de Cristo ranges (fig. E5). The Precambrian rocks of the Picuris Mountains include the older, dominantly metasedimentary Ortega Quartzite; the younger, dominantly meta-igneous Vadito Formation; and a variety of intrusive rocks (Montgomery, 1953; Miller and others, 1963). Long (1974) suggests that the Vadito Formation and the Ortega Quartzite be raised to group status, and he defines several formations within each. He also delineates four major sequential granitic units followed by a series of pegmatite dike intrusions. South of this stop is the Harding mine, developed in a pegmatite that contains large amounts of lepidolite, spodumene, tantalitecolumbite, and beryl (Jahns and Ewing, 1976). **0.3**

55.2 Harding mine road to left; *continue on NM-75* down steep grade into valley of Rio Embudo. **0.8**

56.0 Exposure on right of Precambrian metaconglomerate of the Vadito Formation and quartz dikes. **1.0**

57.0 Vertical faults in exposures of Precambrian rocks on the right, here and at mile 57.1. **0.6**

57.6 Precambrian phyllite of the Ortega Formation is exposed on the right. **0.6**

58.2 Santa Fe Group sedimentary rocks in contact with Precambrian rocks. **1.1**

59.3 **STOP E11, East of Dixon.** *Park in large turnout to left; walk to top of ridge north of highway.* View ahead of basalt-capped La Mesita. The basalt is part of a 2.8-m.y.-old flow in the Servilleta Formation and has apparently been displaced by movement along the fault that extends southward from the west end of the Picuris Mountains. To the left is the distal end of the Oso surface; the 300-ft (93-m) cliff faces are cut in the Cejita Member of the Tesuque Formation (Manley, 1977). The Cejita Member interfingers with deposits of the Tesuque Formation that contain an ash bed having a fission-track age of 10.8 m.y. (Manley and Naeser, 1977). **1.0**

60.3 Bridge across the Rio Embudo. Note prominent outwash terraces ahead on left. **0.3**

60.6 *Enter Dixon. 0.1*

60.7 View to the right is of three stream terrace levels along the Rio Embudo. **1.1**

61.8 A major fault zone that represents the eastern edge of the Velarde graben crosses the road. The graben formed between 5 and 3 m.y. ago and has been down-dropped as much as 1,000 ft (300 m) (Manley, 1978). **0.9**

62.7 Canyon cut in Precambrian rocks of the Ortega Formation. **0.3**

63.0 Contact of Ortega Formation (Precambrian) with Santa Fe Group. **0.6**

63.6 Junction; NM-75 joins NM-68. *Turn left onto NM-68* toward Española. On the right are hills of fine crossbedded sand. The relationship of these deposits to the Santa Fe Group has not been reassessed in light of the recent recognition of the Velarde graben. The sand is possibly of Pliocene age. This crossbedded sand unit has previously been mapped by Galusha and Blick (1971) as the Ojo Caliente Sandstone Member of the Tesuque Formation. **2.9**

66.5 Historical marker for the U.S. Geological Survey Rio Grande gaging station on right. Notes on history and geomorphology are contained in the Alamosa to Santa Fe road log that also covers the route from here to San Juan Pueblo. **3.1**

69.6 *Enter Velarde.* **0.9**

70.5 Outcrop at 11:00 on the skyline is a gravel cliff of the Cejita Member, Tesuque Formation. **2.4**

72.9 On the right (northwest) is Black Mesa. Underlain by the Chamita Formation (Galusha and Blick, 1971), it is capped by a basalt flow of the Servilleta Formation.

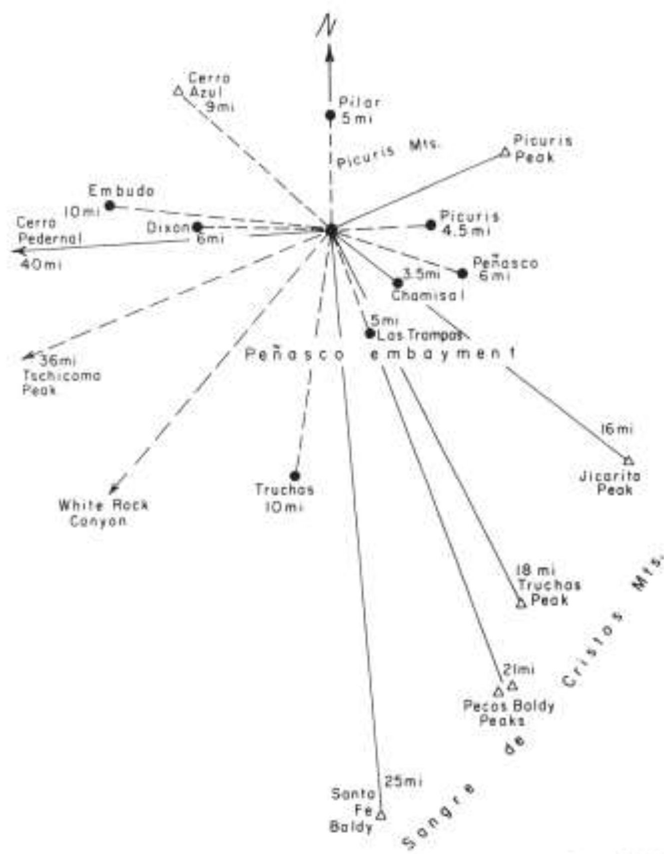


FIGURE E5—PANORAMIC INDEX OF FEATURES SEEN FROM STOP E10, SOUTHERN PICURIS RANGE.

The northwestern fault margin of the Velarde graben is beneath Black Mesa. Slump blocks on the east side of Black Mesa may reflect the graben structure as well as the effect of undercutting by the Rio Grande. 3.9

76.8 Junction of NM-389 and NM-68 opposite Alcalde. This is optional Stop N16 (mile 161.8) in AlamosaSanta Fe guide. View at 1:00 is of the Pajarito Plateau and the younger terraces seen at Stops E3 to E6. **1.0**

77.8 View to right is of the Chamita Formation in the middle distance. White areas are tuffaceous zones. (See discussion at miles 82.8-84.4). 2.3

80.1 Junction. *Turn right (west) onto NM-74* toward San Juan Pueblo. Alternate log joins main log here. **0.5**

Alternate route
Rio Chiquito to San Juan Pueblo

Mileage

0.0 Junction; NM-4 joins NM-76 just north of the town of Rio Chiquito at mile 30.8 on main log. *Turn left on NM-76* toward Española. Between here and Española the route passes through the Nambe, Skull Ridge, and Pojoaque Members (Galusha and Blick, 1971) of the Tesuque Formation. Numerous north-south faults have offset these members and make correlation of measured sections difficult. Near Española the route crosses the southern extension of the eastern margin of the Velarde graben (see also mile 61.8 on main log) and continues in the Chamita Formation (Galusha and Blick, 1971). The Chamita Formation consists of sand and gravel (predominantly quartzite) and two tuffaceous zones. (See further discussion, miles 82.8 to 84.4). **1.6**

1.6 Junction; *continue straight;* road left to Sanctuario. **8.4**

10.0 Junction; NM-76 joins NM-68 in Española. *Turn right (north) onto NM-68.* **0.8**

10.8 Junction; *continue straight;* road left (west) to new bridge across the Rio Grande. **2.6**

13.4 Junction; *turn left onto NM-74* to San Juan Pueblo. Alternate log joins main log here at mile 80.1.

Continuation of main log

80.6 *Enter San Juan Pueblo.* "This pueblo was named San Juan de los Caballeros in 1598 by the colonizer Oñate because of the kindness the Indians showed to the Spaniards. San Gabriel, the first Spanish colony in the western United States, was established by Oñate across the river from San Juan Pueblo" (State Highway Dept. Historical Marker). From here to about mile 89.7 the route is on the San Juan tribal reservation. *Do not leave the road* without permission of the Pueblo Governor. **0.4**

81.0 Junction; *turn left (west); continue on NM-74.* **0.6** 81.6 Bridge over the Rio Grande. **0.3**

81.9 Junction; *turn right (north) onto NM-291* toward Guique. **0.9**

82.8 To the left (west) are exposures of the type area of the Chamita Formation (Galusha and Blick, 1971). Behind the water tower is the lower tuffaceous zone, which has a zircon fission-track age of 5.2 m.y. (Manley and Naeser, 1977). **1.3**

84.1 To left (west) are exposures of the upper tuffaceous zone of the Chamita Formation. A zircon fission-track age from this zone is 5.6 m.y. (Manley and Naeser, 1977). The ages for the two tuffaceous zones, although stratigraphically inconsistent, are within one standard deviation of each other. Vertebrate fossils from here were assigned to the Hemphillian land-mammal age of Wood and others (1941) by Galusha and Blick (1971). **0.3**

84.4 Paved road to right (east). *Turn around for return to NM-74.* The Chamita Formation in this area has been preserved within the Velarde graben. The radiometric ages from these tuffaceous zones and Black Mesa bracket the period of major faulting between 5 and 3 m.y. **2.5**

86.9 Junction; *turn right (west) onto NM-74.* **1.7**

88.6 Junction; *turn left (southwest) onto US-285.* The west edge of the Velarde graben lies between this junction and the southern end of Black Mesa. **0.4**

89.0 Bridge over the Rio Chama. **0.7**

89.7 Junction; *turn right (northwest) on US-84.* **0.5**

90.2 View ahead is of the Ojo Caliente Sandstone Member of the Tesuque Formation cemented along a north-south-trending fault. **1.6**

91.8 Roadcut in basalt flow within the Ojo Caliente Sandstone Member. **1.1**

92.9 Bridge over the Rio del Oso. **4.3**

97.2 Junction; *continue straight;* road to right (north) to Medanales. **0.9**

98.1 On left are sand dunes of reworked Tesuque Formation. **3.5**

101.6 Terrace level in the middle foreground is underlain by the Chama-E1 Rito Member (Galusha and Blick, 1971) of the Tesuque Formation except at the western end where it is underlain by the Abiquiu Tuff. On Sierra Negra, the mountain to the right of the terrace, the pinkish-tan Chama-E1 Rito Member is in fault contact with the white Abiquiu Tuff. The basalt capping Sierra Negra is probably part of the Lobato Basalt of the northern Jemez Mountains (Bailey and others, 1969). **0.7**

102.3 Junction; *continue straight;* NM-96 to right (north) to E1 Rito. **1.4**

103.7 View at 12:00 is of Mesa de Abiquiu, capped by Quaternary basalt (middle foreground), and Tertiary flows capping Cañºnes Mesa (skyline), and Pedernal Peak (isolated on skyline). 2.3

106.0 Entering Abiquiu. "This town was established on the site of an abandoned pueblo in mid-eighteenth century. It became a settlement of genizaros, captives ransomed by the Spanish from the Comanche and Apache Indians. In 1830, the settlement became one of the stops on the Spanish trail which linked Santa Fe with Los Angeles" (State Highway Dept. Historical Marker). 0.3

106.3 Bridge over the Rio Chama. Well-cemented cliff of Tesuque Formation exposed both north and south of the road is in fault contact with the Abiquiu Tuff on the west. **1.7**

108.0 Exposure on right (north) of basalt dike intruded into the Abiquiu Tuff. This dike has a K-Ar age of 9.8 m.y. (Bachman and Mehnert, 1978) and therefore is probably related to the Lobato Basalt. Other dikes can be seen south of the Rio Chama. 2.0

110.0 Contact of the Abiquiu Tuff with the underlying E1 Rito Formation at the western edge of the Rio Grande rift. (See Stop E13 for further discussion). 0.8

110.8 Vertical fault, downthrown to the east, puts lower Chinle Formation (lower part of the Triassic) against the Cutler Formation (Permian). 0.3

111.1 Roadside rest area. To left (south) is Cañones Mesa. Note fault cutting the yellow and pink Entrada Sandstone (Jurassic) exposed at the end of the mesa. The Escalante expedition passed this way in 1776 attempting to find a northern route to Monterey, California. 0.5

111.6 Fault cuts the lower Chinle Formation. This fault is a continuation of the fault seen at the end of Cañones Mesa. **1.0**

112.6 STOP E12, North of Abiquiu Reservoir. NM-96 to left to Abiquiu Dam. *Pull off to right and turn around for return to Espanola.* Refer to fig. 7 in Baltz (this guidebook) for a geologic map and cross section of the area discussed at Stops E12 and E13. The prominent peak to the south is Cerro Pedernal, which is located west of the western margin of the rift. A Lobato Basalt flow caps this peak and is offset 960 ft (300 m) from Lobato flows on the east (Smith and others, 1970). Abiquiu Tuff and Santa Fe Group sediments are present beneath the basalt (Smith and others, 1970). A siliceous zone near the base of the Abiquiu Tuff was used as a quarry by Paleo-Indians for at least 10,000 years (Warren, 1974). The prominent cliffs rimming this basin are the Entrada Sandstone capped by the Todilto Formation (limestone and gypsum). Above these units are the Morrison Formation and Dakota Sandstone. *Resume route east to Espanola on US-84.* **1.5**

114.1 Rest area on left (north). **0.5**

114.6 STOP E13, West of Abiquiu. View to the right (south) is along a fault valley. Several faults intersect in this area. Together they are responsible for over 1,500 ft (450 m) of offset, effectively placing the Cutler Formation against the E1 Rito Formation (Eocene) and Abiquiu Tuff (Oligocene). Most of the faults in this zone cut the Abiquiu; many also offset the lower part of the Santa Fe Group; a few have displaced Lobato Basalt. The rifting was thus initiated no earlier than late Oligocene and continued in this area until at least late Miocene. View ahead and left (north) of road is of a cliff of Abiquiu Tuff overlying the red E1 Rito Formation. These two formations overlie a fault sliver of probable Entrada Sandstone. Colored clays on the valley floor are part of the Morrison Formation. **20.9**

135.5 Junction; *continue straight;* US-285 to the left (northeast). To the left (north) in the cliff face is the contact of the Cutler Formation with the overlying Chinle Formation. **3.5**

139.0 View to the left of the Sangre de Cristo Mountains, the northeast plateau, and the Picuris Mountains. The high peak behind the Picuris Mountains is Wheeler Peak, elevation 13,160 ft (4,049 m), highest point in New Mexico. **1.5**

140.5 Junction; traffic light at junction with new bridge across the Rio Grande. *Continue ahead.* **1.3**

141.8 Junction; *turn right (south) onto NM-30* toward Los Alamos. **1.5**

143.3 Santa Clara Pueblo on left (east). 0.8

144.1 View at 2:00 of the Puye Formation overlying the Chamita Formation with angular unconformity. At 11:00 is the Cerros del Rio volcanic field (Aubele, this guidebook) through which the Rio Grande exits from the basin via White Rock canyon. **1.5**

145.6 Junction; *continue straight;* NM-5 to right (west) to Puye Cliffs Ruin. Where this road crosses the basal Puye Formation, a pumice bed has provided a zircon fission-track age of 2.9 m.y (Manley and Naeser, 1977). The pumice overlies gravels of the ancestral Rio Grande (Totavi Lentil of Griggs, 1964), which are at the base of the Puye Formation. **1.4**

147.0 Volcanic neck and flow, "small' Black Mesa of San Ildefonso, to the left across the Rio Grande is probably related to the Cerros del Rio volcanic episode. **0.3**

147.3 To right is "Battleship Mesa" with exposures (in ascending order) of the Chamita Formation, the Puye Formation, and the Bandelier Tuff. **3.2**

150.5 Junction; *turn right (west) onto NM-4* toward Los Alamos. To the left (south) are exposures of the Chamita Formation, the Puye Formation, and a Pliocene flow from the Cerros del Rio volcanic field. **2.0**

152.5 Gravel pit on the right is in gravels of the ancestral Rio Grande that form the base of the Puye Formation here. **0.6**

153.1 The upper parts of the Puye Formation include coarse, laharic deposits derived from the Jemez Mountains and lake-clay deposits called the Culebra Lake Clay by Kelley (1952). **0.3**

153.4 Pillow basalts on right (west) were deposited in the Culebra lake. **0.4**

153.8 **STOP E14, Guaje Pumice roadcut.** *Park in large turnout to the left (south); turn around for return to Santa Fe.* This is also Stop J13 of the Jemez Mountain tour (Bailey and Smith, this guidebook). Exposure across the road to the north is of the Guaje Pumice Bed, an air-fall unit at the base of the Otowi Member of the Bandelier Tuff. The upper part of the Otowi Member (ash flows) is exposed in the tan cliffs above, along with the overlying Tshirege member of the Bandelier Tuff. Like the Otowi, the Tshirege consists of a basal air-fall unit (the Tsankawi Pumice Bed) and ash flows (Bailey and others, 1969). K-Ar ages for the members are, respectively, 1.4 and 1.1 m.y. (Doell and others, 1968). **0.4**

154.2 View ahead is of slump blocks of Bandelier Tuff on the Culebra Lake Clay. **2.8**

157.0 Junction; *continue straight* on NM-4 to Santa Fe. NM-30 to left (north) to Española. **0.3**

157.3 View ahead is of basalt capped "Buckman Mesa" with underlying striped cliffs of phraeatomagmatic deposits. **0.7**

158.0 Bridge over the Rio Grande. To the right (south) are the old highway bridge, Otowi Bridge, and the bridge abutments for the Denver and Rio Grande narrow gauge railroad, known as the "Chili Line," connecting Santa Fe to Denver from 1880 until 1941. Edith Warner lived and worked here as freight agent from 1928 until 1941 (Church, 1959). She was a long-time friend of the local pueblos and the Los Alamos scientists of the World War II Manhattan Project. **1.4**

159.4 Junction; *continue straight;* road left (north) to San Ildefonso Pueblo. 5.2

164.6 Bridge over Rio Tesuque. 0.4

165.0 Junction; *turn right (southeast) onto US-285; continue into Santa Fe.* **14.8**

179.8 Junction; *bear right onto US-84-285 truck bypass. 1.0*

180.8 End of road log at intersection of Alameda and St. Francis Drive.

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Invited papers

RESUME OF RIO GRANDE DEPRESSION IN NORTH-CENTRAL NEW MEXICO

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Overview

The Neogene Rio Grande depression in north-central New Mexico is a series of northerly elongate, tilted, sagged, and faulted blocks that are collapsed parts of a broad area of Laramide structural uplift between the Great Plains and the Colorado Plateau. The basins of the depression began to form in Miocene time; but they were defined in their present forms mainly in late Miocene and early Pliocene time, and subsequent modifications took place after the Neogene in Pleistocene time.

The northern part of the Albuquerque Basin and the Santo Domingo Basin are east-tilted blocks whose eastern boundaries are major faults with displacements downthrown to the west. The Española Basin is a sagged and faulted syncline. The western part of the basin has sagged along the Pajarito fault zone. The eastern margin of the basin is a faulted anticlinal bend, but the east limb of the basin and the western part of the Sangre de Cristo uplift probably constitute one west-tilted block. To the north, the San Luis Basin is an east-tilted block whose eastern margin is a large fault zone, downthrown to the west, at the base of the Sangre de Cristo uplift.

Precambrian basement rocks crop out at altitudes as high as 13,160 ft (4,011 m) in the Sangre de Cristo uplift east of the depression, and 10,000-11,000 ft (about 3,050-3,350 m) west of the depression. The top of these basement rocks lies at depths of perhaps more than 10,000 ft (3,000 m) below sea level in the Albuquerque Basin and perhaps 1,000-2,000 ft (about 300-600 m) below sea level in the Española Basin.

Precambrian basement rocks of the region include metasedimentary and metavolcanic rocks that total at least 20,800 ft (about 6,340 m) in thickness. These rocks were intruded by plutons whose ages range from about 1,870 m.y. to 1,400 m.y.

The oldest sedimentary rocks of the region are Mississippian, and at least parts of all succeeding systems are present. The preserved total thickness varies regionally because of Cenozoic tectonic activity and erosion and also because of Paleozoic and Mesozoic tectonic conditions. The maximum preserved section of rocks outside the depression is in the Raton Basin (Laramide), where Pennsylvanian through Eocene rocks are about 20,000 ft (about 6,100 m) thick. Within the depression, Pennsylvanian through Pleistocene rocks and sediments might be as thick as 23,000 ft (about 7,000 m) in the northern Albuquerque Basin, but they probably are thinner in the Espanola Basin. In much of the San Luis Basin, Tertiary sediments and volcanic rocks probably lie on Precambrian rocks. The total thickness of these sediments and rocks in the New Mexico part of the basin may be only 2,000-3,000 ft (600-900 m). However, these units are thicker in Colorado.

The Rio Grande depression in north-central New Mexico is geologically new. Although some individual structural elements are controlled locally by Precambrian and younger tectonic features, the Neogene deformation transected and disrupted an ancient and long-lived system of uplifts and basins that had maintained its general trends and identities from Pennsylvanian through early Tertiary time. The timing of formation of the depression coincides with late Miocene, Pliocene, and Pleistocene epeirogenic uplift of the Colorado Plateau, Southern Rocky Mountains, and western Great Plains. This writer suggests that regionally varying amounts of uplift in the eastern part of this region were important factors in producing the "rift," and extension in the northern basins was relatively small.

Introduction

The modern concepts of the Rio Grande "rift" stem mainly from the work of Kirk Bryan of Harvard and his students in the region from Socorro, New Mexico, to San Luis, Colorado. In this classic study area of the Rio Grande region, the interrelated natures of upper Tertiary and Quaternary sediments and volcanic rocks, geologic structure, and physiography were first defined and demonstrated.

Basic work by Galusha and Blick (1971) on the Santa Fe Group records vertebrate-faunal and stratigraphic data accumulated from 1924. Work on the volcanic rocks of the Jemez Mountains was begun in the 1920's by C. S. Ross and has provided the major references (Bailey and others, 1969; Smith and others, 1970) for this area. This work also has yielded some of the earliest radiometric dates for volcanic rocks of the region.

In recent years a renewed interest in the Rio Grande region has produced new geophysical as well as new geologic studies; Cordell (1978) summarized a variety of gravity, aeromagnetic, seismic-refraction, and heat-flow studies by many workers in the entire region from central Colorado to southern New Mexico.

In his classic summary report, Bryan (1938) described the chain of large physiographic and structural basins that contains the Rio Grande from southern Colorado to El Paso, Texas, as the Rio Grande "depression." This name is still the most definitive, because various recent workers who use the genetic classification "Rio Grande rift" do not always agree about which structural features should be included within the rift. A unifying feature of Bryan's original classification is that the present Rio Grande, as an integrated drainage system, appears to be relatively young (Pliocene inception); and evidence is accumulating that the courses of many segments were determined by Pliocene and Pleistocene tectonic events.

V. C. Kelley (1952) apparently was the first to apply the term Rio Grande "rift" to this region. He later pointed out (Kelley, 1977, p. 54) that he originally used the term because he believed in the possibility of significant longitudinal displacement in the "trough" or depressions. According to Kelley, "For better or worse the Rio Grande trough together with a considerable group of auxiliary troughs is becoming known as the Rio Grande rift." In this résumé, I will avoid the issue of what features should be included in the "rift." Instead, I will simply use the names of the physiographic and structural basins of Bryan's Rio Grande depression and the individual names of structural elements that bound the basins.

The résumé is a general introduction to the geology of the region in which Santa Fe, New Mexico, lies and where the technical sessions for the International Symposium were held. The résumé presents partial results of a seismotectonic-analysis project of the U.S. Geological Survey's earthquake-hazards reduction programs.

Regional tectonic setting

The Rio Grande depression in north-central New Mexico consists of large, northerly elongate, tilted, sagged, and faulted blocks that form structural and physiographic basins, which are mainly bordered by mountainous structural uplifts (fig. 1). The basins generally are arranged in a right-stepping echelon pattern, with each basin lying primarily east of its neighbor to the south. Although the basins are more or less distinct, they merge into one another at structural and physiographic constrictions and form a continuous structural depression (Bryan, 1938; Kelley, 1956). The bounding uplifts also are arranged in a right echelon pattern.

The concept of the Rio Grande depression is intimately associated with the stratigraphy and areas of occurrence of Miocene through Pleistocene terrestrial sediments and volcanic rocks that are generally referred to the Santa Fe Group (Spiegel and Baldwin, 1963). Except in a few places, sediments and rocks of the Santa Fe Group (or its equivalents) are at the surface and mask all the older rocks of the basins. The basins have undergone considerable evolutionary modification since they began to develop in early Miocene time. Bryan (1938, p. 205) observed that the older Santa Fe sediments are deformed and eroded everywhere along their margins and that the early basins once extended beyond the present limits of the older parts of the Santa Fe Group. However, the present distribution of the Santa Fe Group and other time-equivalent sediments and rocks reasonably delineates the present basins, which were formed mainly in late Miocene-early Pliocene and Pleistocene time (fig. 1).

The Albuquerque Basin is a large, complex feature that extends far south of the area of fig. 1. (See Kelley, 1977, for a detailed description of this basin.) Generally, the northern part of the basin is an east-tilted block that is internally warped and faulted. At the west, the basin merges into the Puerco fault zone where Cretaceous rocks are tilted gently east and are broken by a more-or-less echelon system of faults downthrown both east and west. The displacements on these faults are not large but may locally range up to 1 km (S1ack and Campbell, 1976, p. 48). The eastern boundary of the basin is a zone of large faults near the base of the Sandia uplift. These faults are downthrown to the west. Kelley (1977, p. 42) indicated that the vertical separation of Precambrian rocks along faults between the basin and the northern part of the Sandia uplift could be on the order of 21,000 ft (about 6,400 m). The northern boundary of the Albuquerque Basin is mainly concealed by the Jemez Mountains volcanic pile. However, this boundary seems to be a northeast-trending faulted sag along the southeast margin of the Nacimiento uplift.

The Santo Domingo Basin is an east-tilted block whose eastern parts are depressed along two major curved fault zones with displacement down to the west. At the south the amount of displacement on these faults is on the order of several thousand feet, but the faults die out to the north. The western part of the basin merges into a broad zone of north-trending faults downthrown both east and west. The

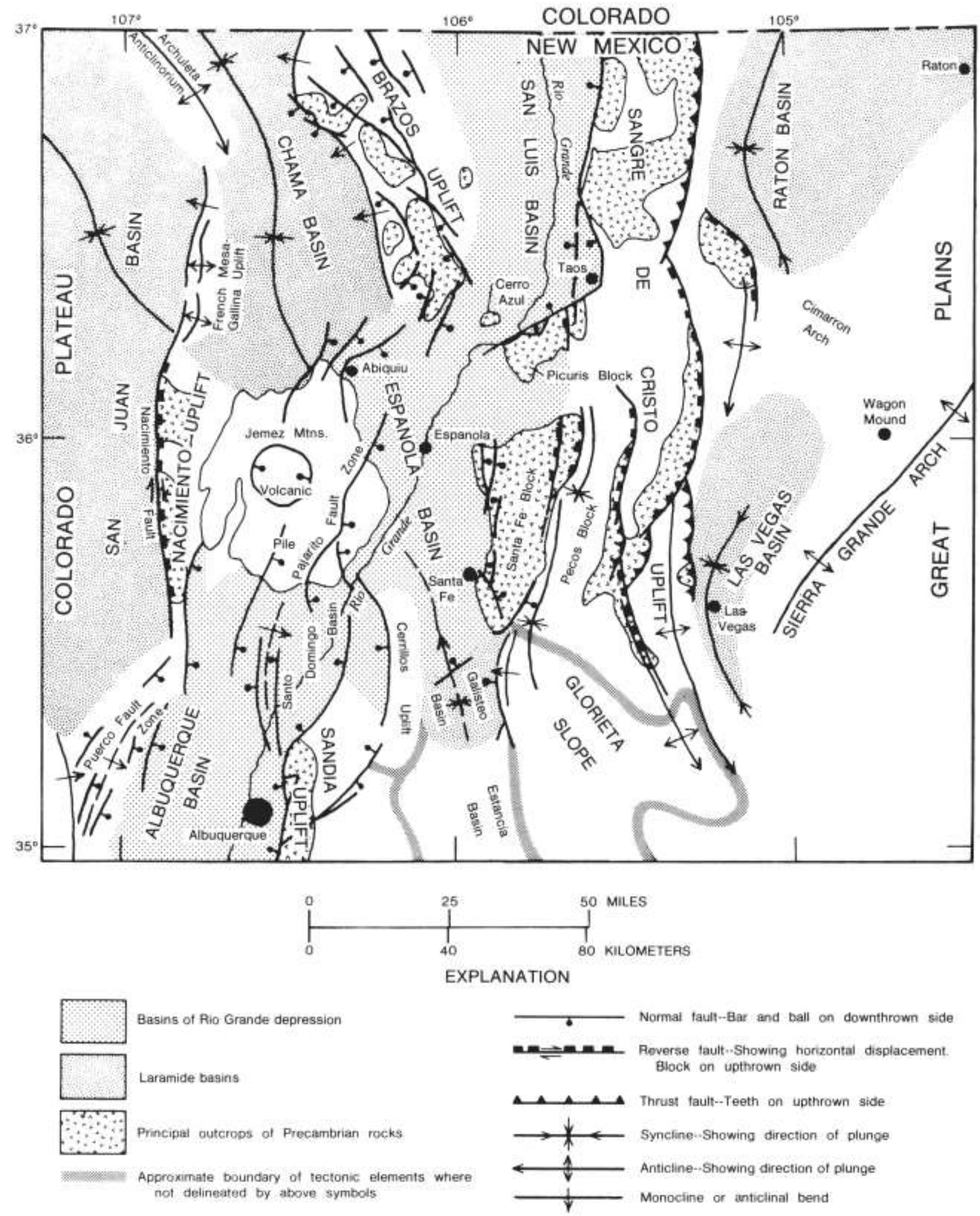

FIGURE 1—MAJOR TECTONIC ELEMENTS OF NORTH-CENTRAL NEW MEXICO.

displacements on these faults generally are in the range of a few tens of feet to several hundred feet, and they seem to represent "cracking" along a broad, east-facing anticlinal bend or hinge (the general area of the San Felipe graben of Kelley, 1977, fig. 19).

The Española Basin is a synclinal sag whose western limb is broken locally by the Pajarito fault zone and by other faults in the vicinity of Abiquiu that are downthrown to the east. The eastern limb of the basin mainly merges with the west-tilted Santa Fe block of the Sangre de Cristo uplift. The margin between uplift and basin is marked by a faulted, west-facing anticlinal bend. The faults are mainly downthrown to the east, although some are downthrown to the west and thereby delineate local horsts and grabens.

The area of maximum structural depression of the Española Basin is north of Española (Manley, 1978). Although the total thickness of the Santa Fe Group is not known with certainty in the area, the amount of depression of the basin probably is on the order of 7,000 ft (about 2,100 m) relative to the eastern and western edges of the Santa Fe Group in the uplifts on the margins of the basin. Except for the Velarde graben area in the northern part of the basin, the geometry of the depression seems to be mainly the result of the synclinal shape of the basin, rather than being primarily a result of downfaulting. However, displacements on the Pajarito fault zone may be several thousand feet where the Española and Santo Domingo Basins merge.

The San Luis Basin, from Cerro Azul northward in New Mexico, is an east-tilted block. Its eastern boundary is a series of down-to-the-west faults along which the basin has been depressed several thousand feet relative to the Sangre de Cristo uplift. At the west the basin merges into the east-tilted Brazos uplift. The western basin margin shown on fig. 1 is arbitrary and approximately represents the western outcrops of basin-fill sediments and basalts of the Taos Plateau. The southeast margin of the basin is a major, northeast-trending hinge fault. The amount of displacement on this fault increases from southwest to northeast, thereby geometrically accommodating the east tilt of the San Luis Basin block relative to the west-tilted Picuris block and eastern limb of the Española Basin.

West of the depression, Precambrian crystalline basement rocks in the Nacimiento uplift crop out at altitudes as great as 10,420 ft (3,176 m) and, in the Brazos uplift, as great as 11,400 ft (3,475 m). East of the depression the Precambrian in the Sandia uplift crops out at altitudes as great as 10,300 ft (3,139 m) and, in the Sangre de Cristo uplift, 13,160 ft (4,011 m). The present high altitudes of the basement rocks are only partly the results of Laramide uplifting. They are also the results of late Cenozoic local differential movements. For example, Laramide folds and faults occur in the Sandia uplift, but this tilted block rose to its present structural height mainly in late Tertiary time (Stearns, 1953, p. 482-484; Kelley and Northrop, 1975, p. 95-96).

The top of Precambrian basement rocks in the deeper parts of the Albuquerque and Santo Domingo Basins is interpreted from geophysical data to be perhaps 9,000-10,000 ft (about 2,700-3,000 m) below sea level (Cordell, 1976, fig. 8), and therefore deeper than it is in adjacent parts of the Colorado Plateau and Great Plains. However, the Precambrian basement in the Española Basin probably is not much below sea level and is not as deep as the basement in the axial part of the San Juan Basin (Colorado Plateau), where the top of the Precambrian may be 6,000-7,000 ft (about 1,800-2,100 m) below sea level. At the east, in the deepest part of the Las Vegas Basin (Great Plains), the top of the Precambrian may be as much as 5,000 ft (about 1,500 m) below sea level.

In the southern part of the San Luis Basin the Precambrian basement is relatively shallow, being at an altitude of 7,455 ft (2,271 m) at Cerro Azul; the basement is deeper to the north along the east margin of the basin, possibly about 5,000 ft (1,500 m) above sea level. In Colorado north of Alamosa, well data indicate that the top of the Precambrian is locally as deep as 2,260 ft (about 690 m) below sea level in the San Luis Basin. Possibly the Precambrian is deeper than this in the eastern part of the basin. To the east, in the axial part of the Raton Basin (Great Plains), the top of the Precambrian may be 6,000-8,000 ft (about 1,800-2,400 m) below sea level.

In regional perspective, the Española and San Luis Basins in north-central New Mexico and southern Colorado are sagged and collapsed parts of a broad area of general (Laramide) structural uplift between the Great Plains to the east and the Colorado Plateau to the west. Even the Chama Basin (Laramide), north of the Nacimiento uplift, is part of the area of general uplift, being a shallow synclinal bench or terrace that is structurally elevated above the adjacent San Juan Basin. However, this early history of uplift is only part of the picture; the entire region has undergone additional uplift since Laramide time. To give credence to this statement, the geological history of a much larger region than north-central New Mexico must be considered.

The post-Laramide epeirogenic uplift, warping, and tilting of the Colorado Plateau has long been postulated as the reason for the widespread erosion and deep incising of the Colorado River and its tributaries. Hunt (1969) discussed the history of the entire Colorado River system and concluded (p. 116, 120, 125) that some of the erosion and canyon formation is pre-middle Miocene and that regional uplift probably began in Oligocene time and continued into Quaternary time. Lucchitta (1972) synthesized data on the Colorado River near the mouth of the Grand Canyon and in the Basin and Range province to the south. He concluded that there was no Colorado River in that region prior to about 10.6 m.y. ago and that by about 3.3 m.y. ago the river had cut to within a few hundred feet of its present positon in the Lake Mead area. In studying the headwaters region of the Colorado River in the Plateau and Rocky Mountains of Colorado, Larson and others (1975) found that about 10 m.y. ago major tectonism occurred and initiated the present upper Colorado River system.

The history of the San Juan Basin sector of the Colorado Plateau in northwestern New Mexico since early Eocene time is not well known. Nevertheless, deep erosional stripping by the San Juan River and its tributaries undoubtedly took place, at least in Quaternary time, and probably earlier also. Oligocene and Miocene volcanic rocks, or their erosional detritus, must have extended southward at one time from the San Juan Mountains into the San Juan Basin (Steven, 1975, p. 80), but they have been completely removed by erosion, which has also stripped much of the Eocene San Jose Formation. The San Juan Mountains also must have been part of the Neogene epeirogenically uplifted region, as shown by their deep erosional dissection in Pliocene and Quaternary time (Steven, 1968, p. 13-14).

Scott (1975) summarized physiographic data for the Rocky Mountains in Colorado that show uplift of the mountains relative to the Great Plains. He indicated that a major episode of uplift in the mountains began in Miocene and continued through Pliocene time, disrupting the preceeding Laramide features.

In the Sangre de Cristo uplift and western Great Plains in New Mexico, studies are not as advanced as those described above (Pillmore and Scott, 1976). Nevertheless, existing knowledge indicates that Miocene through Pleistocene physiographic and structural changes accompanied broad regional uplift of the western Great Plains and various ranges east of the Rio Grande depression.

The Ogallala Formation of late Miocene and Pliocene age, which forms a thin, widespread blanket on part of the Great Plains in eastern New Mexico, contains sediments derived from the mountain ranges to the west (Frye, 1970). West of the outcrops of the Ogallala, the Las Vegas Plateau (the area of the Las Vegas and Raton Basins and the Sierra Grande Arch shown on fig. 1) has been dissected considerably; its margins have deep canyons and entrenched meanders. As was recognized by Fenneman (1931, p. 38, 45-46), much of this erosion has occurred since the time when a series of basalt flows was erupted on a high-level surface (possibly an ancient valley system) north and northeast of Raton, near the Colorado-New Mexico boundary. Levings (1951) described the late Cenozoic erosional history of this Raton Mesa region and correctly deduced that the high-level basalt flows and underlying gravels are Tertiary. The oldest of these basalts is now known to be about 7.2 m.y. old (Stormer, 1972) from radiometric dating.

Since the deposition of the Ogallala Formation, the Pecos River has worked its way headward (northward) in eastern New Mexico, truncating streams that formerly drained eastward (Hawley and others, 1976, fig. 3 and table 1). For its headwaters, the Pecos has captured a stream system that formerly drained eastward into the Canadian River and whose former valley seems to have been disrupted by uplift in the southern part of the Sangre de Cristos as well as by various stream-capture events.

Although much remains to be done to substantiate aspects of the geologic history of northern New Mexico, a safe working hypothesis seems to be that the Rio Grande depression is within and near the eastern margin of a very large region of epeirogenic uplift that occurred in late Miocene, Pliocene, and Pleistocene times. This uplifted region includes the western margin of the Great Plains, the Southern Rocky Mountains (and Rio Grande depression), and the Colorado Plateau.

Regional stratigraphic summary

BASEMENT ROCKS—Strongly folded Precambrian metasedimentary and metavolcanic rocks are exposed in all the major uplifts. The base of these rocks is not exposed. In the Sangre de Cristo uplift the composite thickness of the exposed metamorphic rocks is about 20,800 ft (about 6,340 m), according to Montgomery (1963, p. 9). In the uplifts, the metamorphic rocks have been intruded by plutons that are mainly granitic but which also include quartz monzonites and tonalites. Diabase dikes are common. Gresens (1976, p. 136) casts doubt on the intrusive origin of some granite in the Brazos uplift and indicates that it may be recrystallized metarhyolite. (For a summary of the literature of Precambrian rocks in this and other parts of New Mexico, see Robertson, 1976.)

Rubidium-strontium dates of quartz-monzonite plutons in the Sangre de Cristo uplift range from 1,673 ± 41 m.y. to about 1,400 m.y. (Long, 1974), with dates of pegmatites as young as about 1,300 m.y. Brookins (1974) summarized RbSr age determinations for north-central New Mexico and indicated that granodiorite and other granitic plutons in the Nacimiento uplift have ages of 1,870 ± 130 m.y. to 1,840 ± 170 m.y. and that gneiss and granite in the Sandia uplift have ages of 1,600 ± 60 m.y. and 1,504 ± 15 m.y.

SEDIMENTARY ROCKS—The oldest sedimentary rocks of the region are a thin but widespread sequence of marine rocks of Mississippian age. At least parts of all succeeding systems are present regionally. The ages, nomenclature, lithologies, and thicknesses of these rocks are summarized for the Santa Fe region in fig. 2, and for the region west of the Rio Grande depression in fig. 5.

The thickness of the sedimentary cover in north-central New Mexico varies not only because of Cenozoic tectonic activity and erosional stripping, but also because of Paleozoic and Mesozoic paleotectonic conditions. Probably the thickest preserved sedimentary section of the region outside the depression is in the northern part of the Raton Basin (Laramide) in Colorado, where sedimentary rocks ranging in age from Pennsylvanian to Eocene are preserved. These rocks have not been penetrated completely by drilling, but they may be as much as 20,000 ft (about 6,100 m) thick (Baltz, 1965, p. 2044). Pennsylvanian and Lower Permian rocks constitute probably 13,000-15,000 ft (about 3,960-4,570 m) of this thickness. These rocks were deposited in the Paleozoic central Colorado basin, part of which was in the position now occupied by the northern Sangre de Cristo uplift and the Raton Basin. A thick sequence of Pennsylvanian and Permian rocks was deposited also in the Paleozoic Rowe-Mora basin, which was in the position of the present southern part of the Sangre de Cristo uplift and Las Vegas Basin. Elsewhere, the Paleozoic rocks are relatively thin and are absent locally from several Paleozoic uplifts (see section on Late Paleozoic). Triassic rocks also are known to thin and lap out on some of the ancient uplifts.

The total thicknesses of sediments and rocks in the basins of the Rio Grande depression are poorly known. Most of the San Luis Basin appears to have formerly been a part of the Paleozoic Uncompahgre uplift that was rejuvenated in latest Cretaceous and early Tertiary time. Therefore, Paleozoic and Mesozoic rocks probably were mostly eroded from this region, and the Precambrian basement in the San Luis Basin may be overlain at most places by Tertiary volcanic rocks and sediments that are perhaps 8,000-10,000 ft (about 2,400-3,000 m) thick in Colorado. In the northern part of the Albuquerque Basin, drilling shows that Pennsylvanian through Cretaceous rocks are present beneath the Tertiary basin fill. The total thickness of Pennsylvanian through Quaternary sedimentary rocks and sediments here could be as much as 23,000 ft (about 7,000 m), according to Black and Hiss (1974, pl. 2), or about 17,000 ft (about 5,200 m), according to Kelley (1977, fig. 20, section B).

Espanola Basin

The Española Basin is somewhat asymmetric, and the structurally deepest part lies mainly west of the Rio Grande in an area extending from north of Española southwestward beneath the eastern part of the Jemez Mountains volcanic pile through the vicinity of Los Alamos. The northern part of this centrally depressed area, north of Española, has recently been described by Manley (1978, p. 233) as the Velarde graben. From the latitude of Española south, a complex system of young faults, the Pajarito fault zone, occurs in the western part of the basin. The overall trend of the Pajarito zone is north-northeast as a result of a right-echelon arrangement of northeast- and north-trending segments. The main displace-

Era	System	Series	Stratigraphic unit	Lithology	Thickness (meters): Espanola Basin	Sangre de Cristo Uplift: Santa Fe block	Sangre de Cristo Uplift: Pecos block	
Cenozoic	Quaternary	Holocene	Unnamed local sedimentary deposits	Alluvium in valleys and colluvial deposits on slopes	3-30	3-15	3-15	
Cenozoic	Quaternary	Pleistocene	Unnamed local sedimentary deposits	Glacial till and gravel in high valleys; gravel on low terraces	0-15	0-20	0-20	
Cenozoic	Quaternary	Pleistocene	Unnamed local sedimentary deposits	Stream gravel on high terraces	0-30	0-20	0-15	Rocks spatially associated with Rio Grande depression
Cenozoic	Quaternary	Pleistocene	Santa Fe Group: Basaltic rocks of Cerros del Rio	Airfall pumice and ash related to Bandelier Tuff	0-6			
Cenozoic	Quaternary or Tertiary	Pleistocene or Pliocene	Santa Fe Group: Basaltic rocks of Cerros del Rio	Piedmont-slope gravel and local fan breccia	0-25			
Cenozoic	Tertiary	Pliocene	Santa Fe Group: Ancha Formation	Piedmont-slope gravel, sand, and silt. Clasts mainly Precambrian rocks	0-100			
Cenozoic	Tertiary	Miocene	Santa Fe Group: Tesuque Formation	Partly consolidated sand, silt, and gravel; arkosic; pink to light reddish brown and tan. Contains pebble to cobble gravel of Precambrian metamorphic and igneous rocks and Paleozoic sedimentary rocks. Contains locally abundant layers of volcanic ash and some conglomerate of latite and andesite clasts. Local flows of olivine basalt are interbedded with sediments	0-1500 (maximum not known accurately)			
Cenozoic	Tertiary	Miocene and Oligocene	Espinaso Formation of Stearns, 1953	Partly consolidated sand, silt, and volcanic-pebble gravel and interbedded latite and andesite flows	0-160 (locally 600 at southwest)			
Cenozoic	Tertiary	Oligocene(?) and Eocene	Galisteo Formation at south and El Rito Formation of Galusha and Blick (1971) at north	Sandstone, siltstone, claystone, and pebble to cobble conglomerate. Clasts derived from Mesozoic, Paleozoic, and Precambrian rocks	0-15 (locally 900 at southwest)			Regionally extensive rocks older than Rio Grande depression
Mesozoic	Cretaceous, Jurassic, and Triassic		Mesozoic rocks are present around southern margin of Espanola Basin. Unknown in subsurface to north	Mainly sandstone and shale with minor units of limestone; marine and nonmarine. See Figure 5	Not known			
Paleozoic	Permian	Upper and Lower	Bernal Formation San Andres Limestone Glorieta Sandstone Yeso Formation	Sandstone, red to gray; gray limestone; gray sandstone; and red to gray sandstone, shale, and limestone. Mainly marine	Not known	0-120	60-120+	
Paleozoic	Permian	Lower	Sangre de Cristo Formation	Arkosic conglomerate, sandstone, and shale, mainly red; nonmarine	Not known	0-90	915	
Paleozoic	Pennsylvanian	Upper	Alamitos Formation of Miller and others, 1963; Madera Formation: Upper member	Shale, arkosic sandstone, and limestone; marine and nonmarine	Not known except on southeast margin of basin where thicknesses are similar to those of the Santa Fe block	0-250	360-390	
Paleozoic	Pennsylvanian	Middle	La Pasada Formation of Miller and others, 1963; Madera Formation: Lower member	Shale, limestone, and sandstone; marine		0-45	180-1300	
Paleozoic	Pennsylvanian	Middle and Lower	La Pasada Formation of Miller and others, 1963; Sandia Formation	Shale, sandstone, conglomerate, and thin limestone; marine and nonmarine		0-75	90-490	
Paleozoic	Mississippian	Upper	Tererro Formation	Limestone and limestone breccia; marine		0-10	0-25	
Paleozoic	Mississippian	Lower	Espiritu Santo Formation	Limestone and sandstone; marine		0-12	0-15	
Precambrian				Granite, granodiorite, gneiss, quartzite, and amphibole schist				

FIGURE 2—STRATIGRAPHIC UNITS EXPOSED IN SOUTHEASTERN ESPAÑOLA BASIN AND SOUTHWESTERN SANGRE DE CRISTO UPLIFT.

ment on this zone is down to the east, although faults downthrown to the west occur in the zone (Smith and others, 1970). Although displacements of the Bandelier Tuff (Pleistocene) by this fault zone range up to only 300-400 ft (90-120 m), the zone has had recurrent movements (Griggs, 1964, p. 73-74). Along the southern segment, the Santa Fe Group and underlying rocks might have been displaced several thousand feet (about 1,500 m) north of the area where the fault zone dies out into the east-tilted Santo Domingo Basin (Smith and others, 1970, structure section C-C').

The east limb of the Española Basin, east of the Rio Grande, is a gently west-tilted, warped structural slope surfaced almost entirely by Miocene sediments of the Tesuque Formation of the Santa Fe Group that dip generally 2 °-10 ° west. The dips become locally 25 °-30 ° near the margin of the Sangre de Cristo uplift. The Tesuque Formation on the eastern limb of the basin is broken by several zones of north-trending normal faults mapped by Galusha and Blick (1971). According to them, most of the faults are downthrown to the east. Most of the faults have dip slips of only a few feet and nearly all have less than 300 ft (90 m).

The boundary of the Española Basin and Sangre de Cristo uplift is conveniently defined to be the generally north-trending zone of tilted and faulted blocks of the Tesuque Formation and Precambrian crystalline rocks extending north and south from Santa Fe. Differences exist in the literature about the nature of this zone. All investigators have noted that the Tesuque Formation lies in sedimentary contact, from place to place, on Oligocene, Pennsylvanian, or Precambrian rocks, but that at many places the Tesuque is faulted against the Precambrian. However, the faults have been portrayed differently on maps by Cabot (1938), Denny (1940), Kelley (1954, 1956), Miller and others (1963), and Galusha and Blick (1971). Without belaboring the details of differing interpretations, the general interpretation has been that the eastern margin is largely a zone of faults downthrown to the west and that the Precambrian rocks of the Santa Fe block of the Sangre de Cristo uplift were the source terrain for much of the Tesuque Formation.

Reexamination of the border from south of Santa Fe to Chimayo and detailed mapping of parts of this area by the writer provide a somewhat different general interpretation (fig. 3). South of Santa Fe the eastern margin of the Española Basin merges with the slightly faulted west-tilted limb of the Sangre de Cristo uplift. This is essentially the structural picture indicated by Spiegel and Baldwin (1963), although several northwest-trending hypothetical faults shown on their plate 5 may not exist. Angular unconformities in this area offer convincing evidence that west tilting and erosion of the uplift, and deposition of sediments in the adjacent part of the basin, occurred in widely separated episodes during Eocene, Oligocene, and late Miocene or Pliocene time as previously reported (Stearns, 1953; Spiegel and Baldwin, 1963). Directly north of Santa Fe the border zone is a west-tilted block marked by small local grabens and horsts (Spiegel and Baldwin, 1963, pls. 1 and 5).

Farther north, the border zone is marked by tilted blocks that are bounded by faults downthrown primarily to the east but also to the west, delineating local grabens and horsts. The details of this kind of structure are well displayed in the vicinity of Cerro Piñon and near Santa Cruz Reservoir (fig. 4). As shown in fig. 4, the easternmost outcrops of the Tesuque Formation dip gently northwest. In the central part of the area of fig. 4, the Tesuque has been tilted along east-dipping faults in what may have been the axial part of an anticlinal bend. At the west, the Tesuque dips steeply on the west limb of the bend. West of the area of fig. 4, the dip of the Tesuque is gentle again, although still farther west other zones of steeper dips and associated faults occur.

Preliminary studies of this structural zone and physiographic surfaces in the Sangre de Cristo uplift lead me to tentatively conclude that the east limb of the Española Basin and the adjacent west limb of the Sangre de Cristo uplift are essentially parts of one major structural block tilted west. The border zone does not represent an eastern margin of a graben or the rift boundary, but instead is a broad west-facing faulted anticlinal bend in this block. The faulting and tilting of blocks appears to have occurred as the response to stretching in the structurally shallow part of the bend. The anticlinal bending probably occurred in late Miocene and Pliocene time during tilting and sagging of the part of the Española Basin that subsided along the Pajarito fault zone.

The basal part of the Tesuque Formation was clearly derived from underlying Precambrian rocks, probably during pedimentation of preexisting hills and perhaps during minor movement on preexisting faults. However, I concur with Denny's suggestion (1940, p. 690-691) that the Tesuque Formation once may have extended a considerable distance to the east, perhaps nearly to the present summits of the Sangre de Cristos. I concur also with Galusha and Blick (1971, p. 100101) who said, "It is not enough to interpret the original extent of the Santa Fe [Group] Basin, in which the beds of the type area were deposited, by the outlines of the post-Santa Fe Group deformation, which is now considered to mark the Rio Grande depression. An attempt must be made to separate the concepts of pre-Santa Fe and post-Santa Fe deformations. . . ." Most of the faulting along the eastern margin of the Española Basin is clearly post-Tesuque (at least its lower part), rather than pre-Tesuque as Galusha and Blick suggested (p. 100; 104), although some of the faults may be rejuvenated Laramide or older structures.

Although the events are still open to question, the sediments of the upper Tesuque may have been derived from Precambrian rocks of the Santa Fe block during Miocene episodic depression of the basin, pedimentation of the uplift, and eventual eastward onlap of sediments onto the worn-down western limb of the uplift. On the other hand, another likely source for at least part of the sediments may have been the area of the northern Sangre de Cristos and the Brazos uplift and the area now part of the southern San Luis Basin. The San Luis Basin was probably a region of residual volcanic highlands and hills of Precambrian rocks prior to late Miocene-early Pliocene tectonic events.

The northwest margin of the Española Basin (figs. 5 and 6) presents a structural situation somewhat similar to that at the northwest margin of the Albuquerque Basin. West of Abiquiu, the basin is bordered by a northeast-trending fault zone that separates it from the Colorado Plateau (Chama Basin) and from an easterly tilted Precambrian-cored uplift (Brazos uplift). Within this fault zone the displacements are down-thrown to both east and west, although the major displacements are mainly down to the east. As shown by Smith and others (1970), the faulting is all younger than the Santa Fe. Basaltic dikes intruded along a fault northwest of Abiquiu are dated (Bachman and Mehnert, 1978, p. 290) as 9.8 m.y. before present, thus indicating movement prior to late Miocene time. However, other faults cut the Tschicoma Formation (dated as 3.7-6.7 m.y. by Bailey and others, 1969) and the

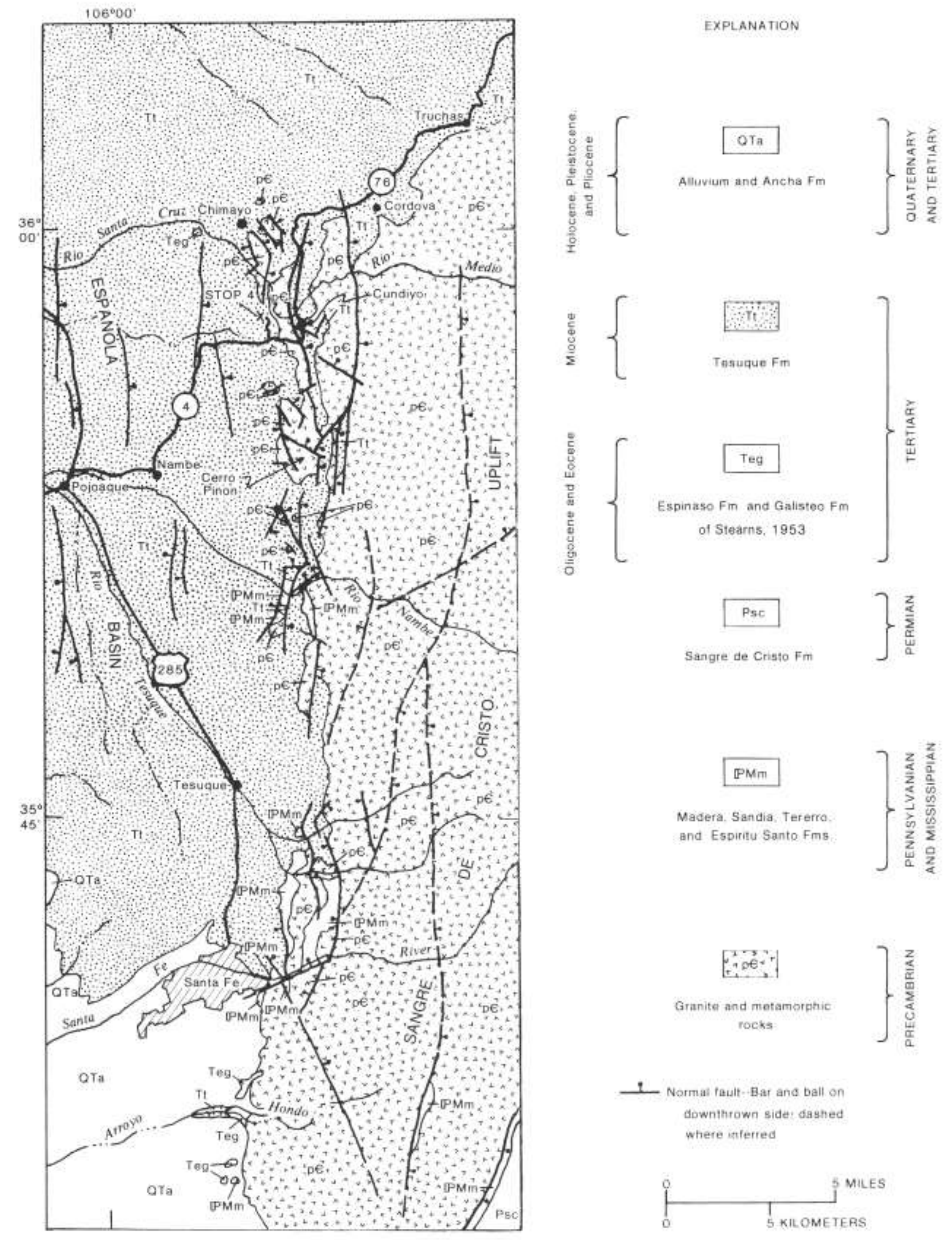

FIGURE 3—MAP OF SOUTHEASTERN ESPAÑOLA BASIN AND SOUTHWESTERN SANGRE DE CRISTO UPLIFT (compiled from maps of Denny [1940], Spiegel and Baldwin [1963], Miller and others [1963], Galusha and Blick [1971], and Budding [1972]; modified by mapping by E. H. Baltz in 1975).

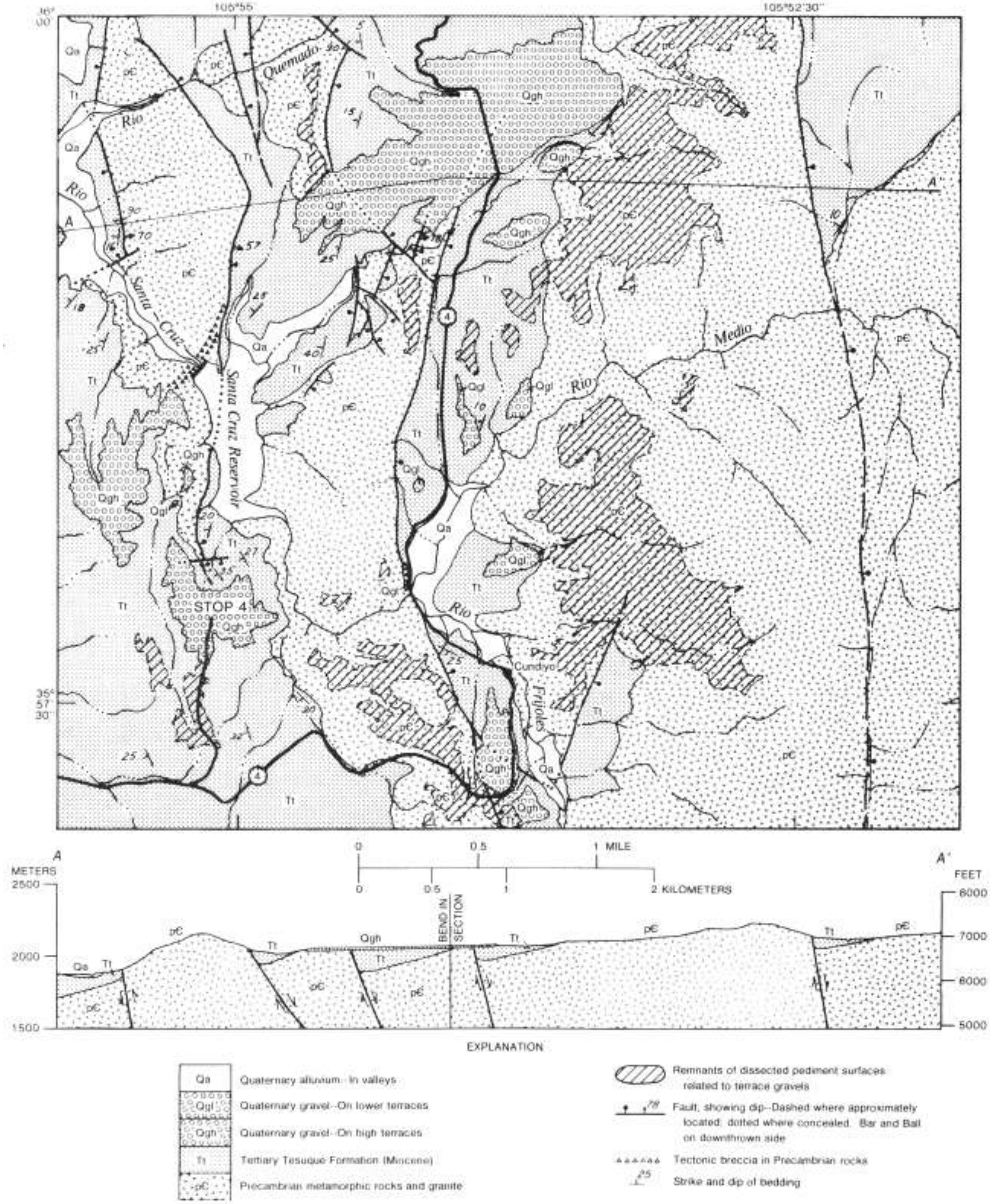

FIGURE 4—Reconnaissance map and cross section of Santa Cruz Reservoir area. For regional location see fig. 3; Stop 4 is discussed in road log of Española Basin by Manley (this guidebook; mapped by E. H. Baltz, 1975).

Era	System	Series	Stratigraphic unit	Lithology	Thickness (meters)		
					San Juan Basin	Nacimiento Uplift	
Cenozoic	Quaternary	Holocene	Unnamed local sedimentary deposits	Alluvium in valleys; stream gravel on low terraces; colluvium on slopes	3-30	3-15	
		Pleistocene		Stream gravel on high terraces; alluvium on high pediments	0-30	0-15	
			Bandelier Tuff	Welded and nonwelded rhyolite ash flows		0-150	Rocks spatially associated with Rio Grande depression
	Quaternary or Tertiary	Pleistocene or Pliocene	Unnamed local sedimentary deposits	Gravel on high-level pediment, west and northwest sides of Nacimiento Uplift		0-30	
	Tertiary	Pliocene	Puye Formation	Sand, volcanic gravel, tuffaceous beds, and river gravel		15-215	
		Pliocene and Miocene	Tschicoma Formation	Dacite, rhyodacite, and quartz latite of Jemez Mountains volcanic pile		0-900	
			Lobato Basalt	Olivine-augite basalt		0-180	
			Santa Fe Formation of Smith, Bailey, and Ross, 1970. Mainly equivalent to Miocene Tesuque Formation	Partly consolidated cross-bedded sand, arkosic sand, and volcanic-pebble gravel and sand; pinkish brown to buff		0-1200+	
		Miocene and Oligocene	Abiquiu Tuff of Smith, 1938	Tuffaceous sandstone, volcanic-pebble conglomerate and, at the base, conglomerate of Precambrian and Paleozoic clasts; light gray		0-360+	
		Oligocene(?) and Eocene	El Rito Formation of Smith, 1938	Sandstone, shale, and conglomerate of Precambrian clasts; red to brown; nonmarine		0-120	Regionally extensive rocks older than Rio Grande depression
		Eocene	San Jose Formation	Shale, sandstone, conglomerate; nonmarine	60-550		
		Paleocene	Nacimiento Formation	Shale, sandstone, conglomerate; nonmarine	160-530		
			Ojo Alamo Sandstone	Sandstone and conglomerate; nonmarine	20-60		
Mesozoic	Cretaceous	Upper	Kirtland Shale and Fruitland Formation	Shale and sandstone; nonmarine	30-135		
			Pictured Cliffs Sandstone	Sandstone; marine	0-70		
			Lewis Shale	Claystone, siltstone, and some thin limestone; marine	150-680		
			Mesaverde Group	Sandstone, shale, and some coal; marine and nonmarine	170-560		
			Mancos Shale	Claystone, siltstone, and some thin limestone; marine	700-760		
			Dakota Sandstone	Sandstone, some shale and conglomerate; marine and nonmarine	45-60	0-60	
	Jurassic	Upper	Morrison Formation	Sandstone and shale; nonmarine	100-180	0-180	
		Middle	Todilto Formation	Gypsum and underlying limestone; nonmarine	18-38	Present	
			Entrada Sandstone	Sandstone; nonmarine	70	0-70	
	Triassic	Upper	Chinle Formation	Claystone, siltstone, sandstone, and basal conglomeratic sandstone; red and brown; nonmarine	300-320	0-300	
Paleozoic	Permian	Lower	Cutler Formation	Sandstone, shale, and conglomerate; arkosic; red and brown; nonmarine	150-290	150-290	
	Pennsylvanian	Upper and Middle	Madera Formation	Limestone, shale, and arkosic sandstone; mainly marine	0-300	0-300	
		Lower	Sandia Formation	Sandstone, shale, and some limestone; marine and nonmarine	0-60	0-60	
	Mississippian	Upper and Lower	Arroyo Penasco Group	Limestone and thin basal sandstone; marine	Present	0-55	
Precambrian				Granite, tonalite, gneiss, schist, metavolcanic rocks, quartzite, and local mafic and ultramafic rocks			

FIGURE 5—Stratigraphic units exposed in San Juan Basin, Nacimiento uplift, and northwest margin of Española Basin. Thicknesses of the Oligocene(?) through Pliocene units in the Nacimiento uplift column are those from the uplift to the northwestern part of the Española Basin.

Puye Formation (dated at approximately 2.4 to 3 m.y. by Manley and Naeser, 1977).

Sediments of the upper part of the Santa Fe, which are probably equivalent to the Ojo Caliente Sandstone Member of the Tesuque Formation (Galusha and Blick, 1971), are preserved high on the north flanks of the Jemez Mountains west of the structural margin of the Española Basin; rocks of the Abiquiu Tuff (Oligocene and Miocene) of Smith (1938), which lap westward in the Nacimiento uplift across rocks ranging in age from Eocene to Precambrian, are also pre served high on the uplift. As portrayed by Wood and Northrop (1946) and Smith and others (1970, section A-A '), these relationships seem to indicate that the east part of the Nacimiento uplift merged into the west limb of the Espanola Basin prior to late Miocene and Pliocene faulting and volcanic activity. Both the Nacimiento uplift and Espanola Basin were probably coextensive with the southeast part of the Chama Basin (Laramide), as this broader precursor basin is defined by remnants of the E1 Rito Formation (Eocene) (Smith, 1938; fig. 7).

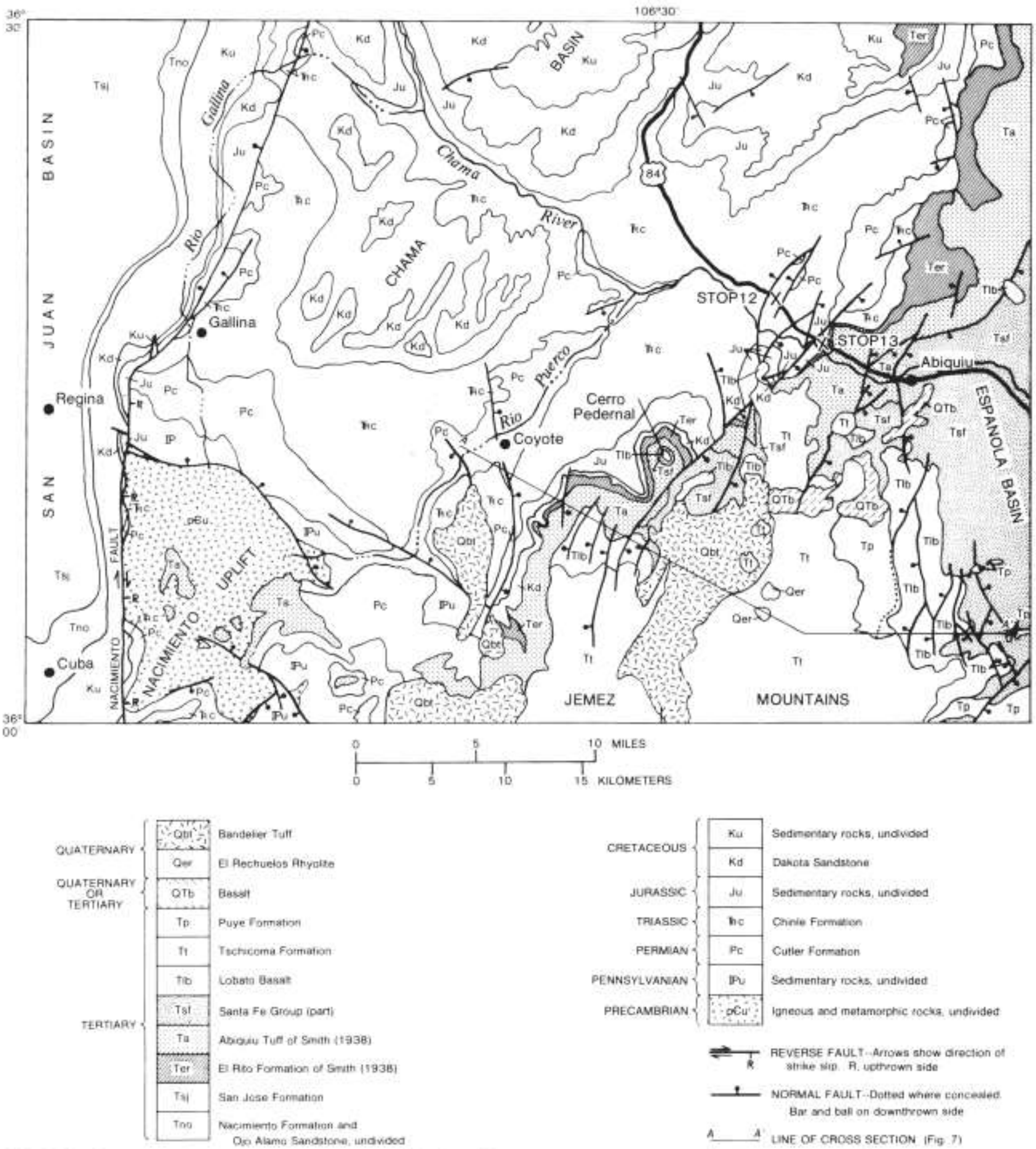

FIGURE 6—GENERALIZED MAP OF NORTHWEST PART OF ESPAÑOLA BASIN AND ADJACENT PARTS OF NACIMIENTO UPLIFT, CHAMA BASIN, AND SAN JUAN BASIN. Stops E12 and E13 are those in road log of Española Basin by Manley in this guidebook (adapted from Dane and Bachman, 1965, and Smith and others, 1970, with minor modifications adapted from Woodward and others, 1974).

San Luis Basin

The San Luis Basin extends northward from the vicinity of Taos for about 135 mi (217 km) into Colorado and is the northernmost basin of the Rio Grande depression. Other smaller graben structures farther north in Colorado have been considered parts of the Rio Grande rift by recent writers (Chapin, 1971; Chapin and Seager, 1975). The San Luis Basin, north of the Embudo constriction at Cerro Azul (fig. 1), is an east-tilted internally faulted block, downfaulted along its eastern and southeastern borders with the Sangre de Cristo uplift.

At the west, in New Mexico, the San Luis Basin merges into the Brazos uplift. As Butler points out (1971, p. 300), the southern part of the Brazos uplift is tilted gently east and is broken by northwest-trending normal faults, mainly downthrown to the southwest, on which the displacements are generally less than 1,200 ft (about 365 m). This fault zone may represent shallow cracking along a broad hinge at the west side of the major east-tilted block. This arrangement is similar to other basin-marginal areas to the south where faults are generally downthrown in the direction opposite to the direction of basin tilt. In Colorado the western part of the San Luis Basin merges into the east-tilted Del Norte structural sag (Atwood and Mather, 1932, p. 24 and pl. 2) on the eastern flank of the complex uplift upon which the San Juan Mountains volcanic field is situated. The western border of the San Luis Basin in Colorado appears to be faulted only locally (Tweto, 1977); therefore, the basin and uplifted areas to the west probably constitute mainly one northeast-tilted block. This block, however, is structurally complex beneath the upper Tertiary and Quaternary sediments in the basin. The basin in Colorado is segmented internally by several large faults (Upson, 1939; Baltz, 1965; Tweto, 1977), and gravity data suggest an intrabasinal horst.

Less is known about the San Luis Basin than about the basins to the south because the San Luis Basin has not yet been dissected by erosion to reveal its stratigraphic record. In most of the basin in New Mexico, the surface rocks are basaltic to andesitic flows of the Servilleta Formation (Pliocene), which includes some interflow sediments. Lambert (1966) described the series of shield volcanoes and cones that surmount the volcanic Taos Plateau and noted that they are not of the fissure type. The volcanoes in the central part of the plateau were sources of the Servilleta basalts; others, especially near the west side, are quartz latite and rhyolite (Butler, 1971).

Intermediate volcanic rocks of Oligocene or early Miocene age are exposed beneath the Servilleta basalts at places northwest of Taos. In the adjacent parts of the Brazos uplift and the Sangre de Cristo uplift, Precambrian rocks are overlain by thin, locally occurring patches of lower Tertiary red beds, in turn overlain by thick series of volcaniclastic conglomerates, tuffs, andesitic breccias, and latitic to rhyolitic flows and ash flows of the Conejos Formation (Oligocene). In the subsurface of the southern part of the basin, these rocks probably also lie on mainly Precambrian rocks, as is indicated not only by regional stratigraphic relations in the bounding uplifts but also by several deep wells in the Colorado portion. In the part of the basin north of Alamosa, Colorado, thick fill (Alamosa Formation) of Pliocene or Pleistocene age occurs underlain by sediments probably equivalent to some part of the Santa Fe Group (Powell, 1958; Baltz, 1965, p. 2072-2073).

The eastern boundary of the San Luis Basin is a zone of large faults downthrown to the west. Except for a few places, such as along the northeast-trending hinge fault southwest of Taos (Montgomery, 1953; Lambert, 1966), the boundary faults are masked by Quaternary fans derived from the Sangre de Cristo uplift; but the existence of the faults is not in doubt, because of the present sharp relief on the west front of the Sangre de Cristos, the relatively straight segments of the western front of the uplift, and several young fault scarps in sediments west of the front near the Colorado-New Mexico border (Upson, 1939). Lambert (1966, p. 47) described young fault scarps in basin fill near the mountain front east and south of Taos. The total stratigraphic separation on these faults is difficult to estimate, but it must be on the order of 3,000-5,000 ft (900-1,500 m) at places in the vicinity of Taos. McKinlay (1956) estimated as much as 7,000 ft (about 2,100 m) of throw on the faults north of Taos. The northern part of the basin in Colorado may have subsided as much as 15,000 ft (about 4,600 m) along eastern-boundary faults in late Tertiary time (Baltz, 1965).

A northerly trending zone of faults that cuts the basalts and sediments of the Servilleta Formation in the basin west of Taos was described by Lambert (1966, fig. 1, p. 47), who observed that these faults are downthrown to the west and have displacements of a few tens to a few hundreds of feet. Lambert noted that these faults more or less align with the Precambrian Pecos-Picuris fault farther south. Additional young faults in the eastern part of the basin north of Taos were discussed by Lambert; these faults are mainly downthrown to the northeast and have throws of less than 100 ft (30 m).

Paleotectonics

PRECAMBRIAN—In summarizing geophysical data for the Rio Grande region, the Colorado Plateau, and the Great Plains, Cordell (1978, p. 1076-1078) discussed regional magnetic-anomaly gradients that are thought to be representative of Precambrian basement structural grains. He stated that the aeromagnetic trends seem to indicate a change in

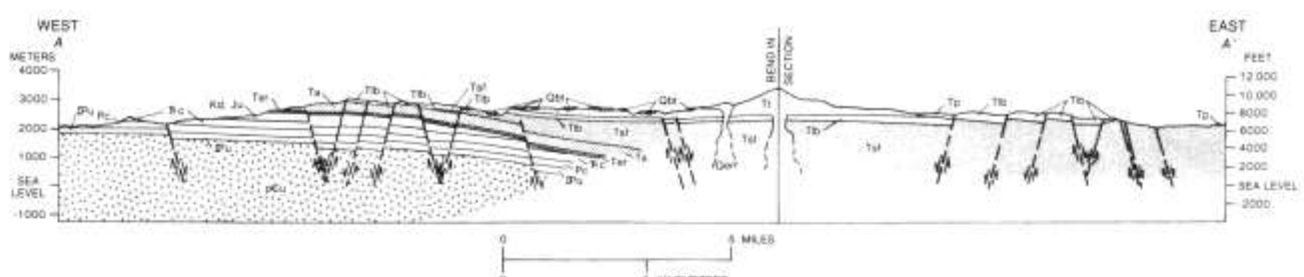

FIGURE 7—CROSS SECTION OF NORTHERN PART OF JEMEZ MOUNTAINS AND NORTHWEST PART OF ESPAÑOLA BASIN. For location and explanation of symbols see fig. 6 (adapted from cross section A-A' of Smith, Bailey, and Ross, 1970).

basement grain across the rift. He also postulated that a lack of parallelism between the grain in the Colorado Plateau and the grain in the Great Plains indicates that the Plateau was appended onto the craton (Great Plains) during Precambrian time, forming a basement suture "along the site of the future rift," although he noted that the evidence for a suture is circumstantial. Cordell (1978, p. 1080) also observed that, taken at face value, deep seismic refraction lines in the Colorado Plateau, Southern Rocky Mountains, and Great Plains indicate asymmetric crustal and upper mantle structure across the region.

The direct, geologic knowledge of the Precambrian structure of north-central New Mexico is meager and known only in broad outlines, mainly because Precambrian rocks are exposed only in the present uplifts. However, Just (1937) and Montgomery (1953) observed that Precambrian metasedimentary and metavolcanic rocks in the Brazos uplift are similar to, and at least partly correlative with, Precambrian rocks in the Picuris block of the Sangre de Cristo uplift south of Taos. In both areas the rocks are folded along westerly to northwesterly trending axes. These rocks are more than 1,600 m.y. old, on the basis of radiometric ages (Long, 1974) of the plutons that invade them in the Sangre de Cristo uplift. Montgomery (1963, p. 20) found that, in the Picuris block and along the eastern margin of the Santa Fe block, the easterly trending belt of folded metamorphic rocks and granitic plutons appears to have been offset horizontally about 23 mi in a right-lateral sense along the north-trending Precambrian Pecos-Picuris fault. East of the Pecos-Picuris fault in the southern Sangre de Cristo uplift, the easterly trending fold belt persists; but locally near the eastern margin of the uplift, the metamorphics bend into northeast-trending antiformal and synformal folds.

From all these relations, it seems that if suturing occurred between the Colorado Plateau and Great Plains it occurred in a time of great antiquity; otherwise the suture is not in the position of some parts of the present Rio Grande depression and adjacent uplifts in north-central New Mexico.

Segments of the Pecos-Picuris fault have had vertical displacements in Paleozoic and early. Cenozoic time, but the fault does not appear to have been active in Miocene time or later, except for local vertical movements on a few segments. However, the projected trend of the fault, north of the Picuris block and beneath Quaternary deposits, is near the eastern boundary of the Neogene San Luis Basin in New Mexico; therefore, the ancient fault might have controlled the position of the late Tertiary vertical displacements there.

Complex large plutons underlie much of the Sandia uplift, the Nacimiento uplift, and the Santa Fe block of the Sangre de Cristo uplift. In the Nacimiento uplift and the Santa Fe block, the areas of the plutons were uplifts in late Paleozoic as well as in Cenozoic time.

The problem of possible deep-seated basement control of post-Precambrian structural features remains an intriguing one. At places Laramide and Neogene structural features can be seen locally to follow Precambrian trends. At many other places, however, major Cenozoic structures cut across Precambrian trends with apparent disregard and break new ground.

EARLY PALEOZOIC—During much of Paleozoic time the region of north-central New Mexico was part of a broad, generally southwest-trending epeirogenic positive area. No Paleozoic rocks older than Mississippian are preserved on this positive area in northern New Mexico. Across southern New Mexico marine rocks of Cambrian, Ordovician, Silurian, and Devonian ages lap out northward onto the positive area. Similarly, in southern Colorado, lower Paleozoic marine rocks lap out southward onto the positive area. Thin marine-shelf carbonates of Mississippian age are widely distributed on this positive area, and nothing in their stratigraphy indicates that structural anomalies existed in the position of the present Rio Grande depression in Mississippian time.

LATE PALEOZOIC—In Pennsylvanian and Early Permian time a series of huge orogenic uplifts and basins was developed (fig. 8) in New Mexico and Colorado. These structures often are called the Ancestral Rockies because, in places, they correspond geographically to the Cenozoic Rocky Mountain uplifts. However, the correspondences are by no means one to one everywhere. The Pennsylvanian-Permian uplifts and basins in New Mexico extend far to the east and west of the Laramide and later uplifts and basins (Read and Wood, 1947). In New Mexico the Pennsylvanian and Permian uplifts and basins mainly trend north-northwest, and in Colorado they curve into the northwesterly trending Paleozoic Paradox basin, Uncompahgre uplift, central Colorado basin, and Wet Mountains-Apishapa uplift (Mallory, 1975).

The facies of Pennsylvanian and Permian sediments, and the timing of deformational events (both orogenic and epeirogenic), are similar in the adjacent parts of the Great Plains and Colorado Plateau; this similarity indicates that no influential structural boundary existed between them in the position of the present Rio Grande depression.

As shown on fig. 8A, the position of the eastern boundary of the Paleozoic Uncompahgre uplift in the southern San Luis Basin (Neogene) is not known. East of Taos a very thick section of Pennsylvanian rocks of the ancient Rowe-Mora basin is tilted west and disappears beneath Quaternary fans of the San Luis Basin. These rocks are possibly preserved in the subsurface of the eastern part of the San Luis Basin; or they may have been present in this area in Pennsylvanian time but were removed by erosion during Late Pennsylvanian, Permian, or Laramide orogeny. Sutherland (1963, p. 40) suggested that the Precambrian Pecos-Picuris fault, as projected beneath the San Luis Basin (Neogene), was the eastern margin of the Paleozoic Uncompahgre uplift. This suggestion awaits confirmation by deep drilling.

MESOZOIC—By the end of Triassic time most of the Paleozoic structures were blotted out by erosion and sedimentation, although locally some of the uplifts contributed some sediment. The Uncompahgre uplift maintained its generally positive character as shown by angular unconformities along its southwestern margin between Permian, Triassic, Jurassic, and Cretaceous rocks, in both New Mexico and Colorado. Again, as in the Paleozoic, the facies of various Mesozoic rock units indicate a similar—in some respects nearly identical—history of the eastern Colorado Plateau and western Great Plains in north-central New Mexico. Onlap and thinning of various Mesozoic rock units show that the ancient uplifts maintained their relative positive characters, but the regional tectonic activity appears to have been primarily very gentle epeirogenic warping.

LATE CRETACEOUS AND EARLY TERTIARY—Beginning near the end of Cretaceous time and culminating in late Eocene time, the Laramide orogeny produced the first generation of the Rocky Mountains and their complementary basins (fig. 8B). Other uplifts and sedimentary basins and fold systems in central and southern New Mexico were also produced at this time in the Colorado Plateau, the Great Plains (Black, 1976),

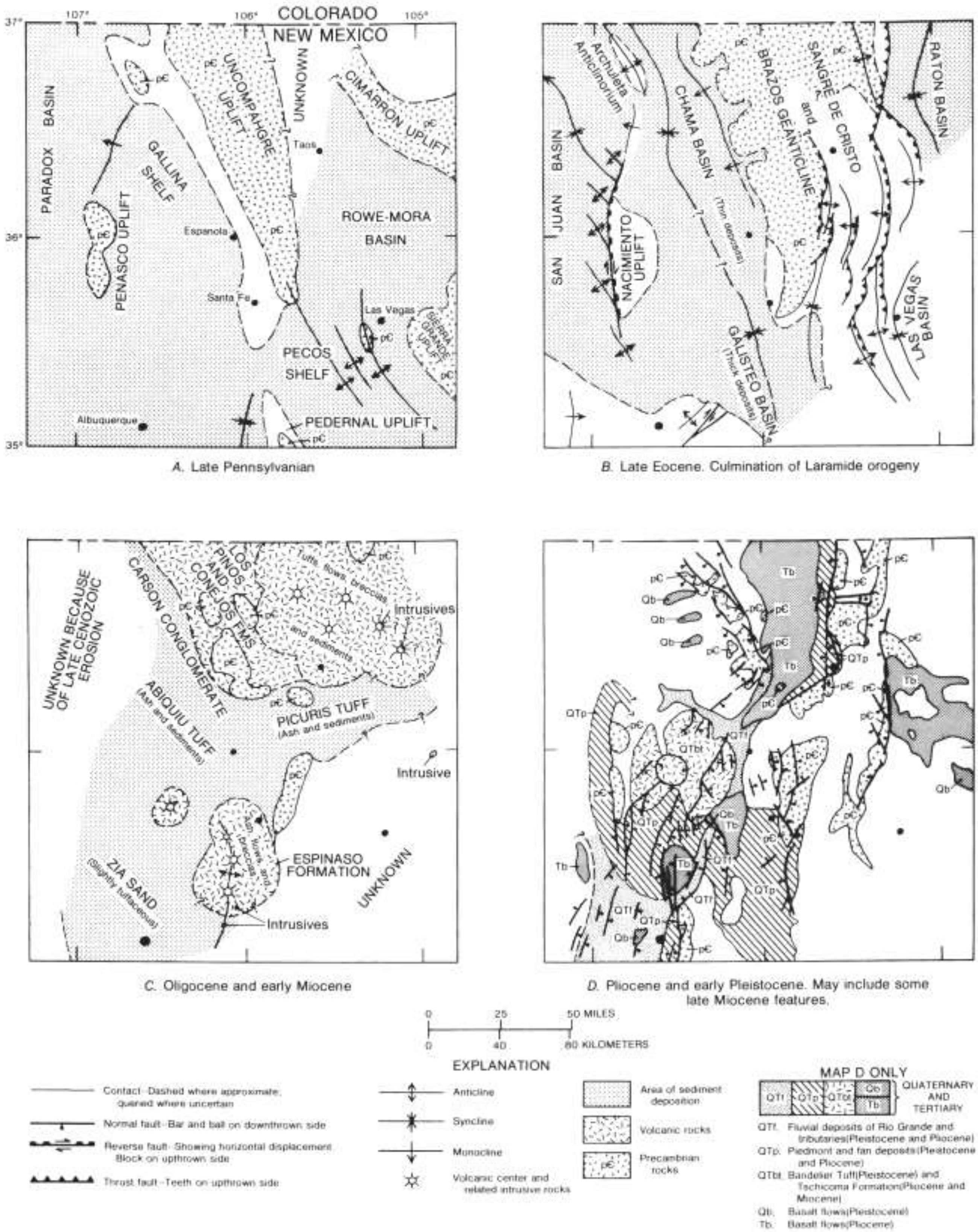

FIGURE 8—PALEOTECTONIC DIAGRAMS OF NORTH-CENTRAL NEW MEXICO.

and the area now part of the Rio Grande depression (Kelley and Silver, 1952; Wilpolt and others, 1946). The margins of the Rocky Mountain uplifts generally are characterized by sharp folding, reverse faults and thrusts, and locally, right-lateral wrench faults. These structures were probably formed by regional compression.

A regionally arcuate arrangement (concave to the southwest) of various Laramide uplifts and basins around the northern and eastern margins of the Colorado Plateau in Utah, Colorado, and New Mexico suggests that a crustal segment—including the area of the present Plateau but extending east of the present Rio Grande depression—was shifted north-northeast relative to the Great Plains (Kelley, 1955, p. 68), crumpling the margins (by folding and upthrusting) and wrinkling the interior (Baltz, 1967, p. 85). In New Mexico the horizontal shortening accomplished during Laramide compression was not large, and the amount of uplift in the major deformed zones was about the same as the amount of horizontal deformation. For example, in the southeastern Sangre de Cristo uplift northwest of Las Vegas, the total horizontal shortening across several zones of thrusts is a little less than 2 mi (about 3 km), and the vertical structural relief relative to the Las Vegas Basin is about the same (Baltz, 1972).

The Laramide history of north-central New Mexico is fairly well known from detailed studies of early Tertiary stratigraphy in the Galisteo Basin region (Stearns, 1953), the Raton Basin (Johnson and Wood, 1956), and the San Juan Basin (Baltz, 1967). During the northeastward retreat of the late Cretaceous sea, a geanticlinal area began to rise in the area of the present Brazos and Sangre de Cristo uplifts. Some volcanic activity, probably in the region of the present San Juan Mountains, attended these events and left a slight record as bentonitic clay and andesitic pebbles at places in the Kirtland Shale of the San Juan Basin.

By latest Cretaceous time and in Paleocene time, Precambrian detritus as well as volcanic detritus was being eroded from parts of this geanticline in Colorado and deposited as the Animas Formation in the northern San Juan Basin. Precambrian detritus (but no reported volcanics) was deposited as the Poison Canyon Formation in the Raton Basin in Late Cretaceous and Paleocene time. The Nacimiento uplift probably did not exist in Paleocene time, although right-lateral shift along the Nacimiento fault began in Paleocene time (Baltz, 1967). Cretaceous rocks in the southern part of the San Juan Basin, and probably in the area of the present Sandia uplift, Galisteo Basin, and southern Sangre de Cristo uplift, were being eroded in Paleocene time and may have been the sources of reworked Cretaceous sediments that constitute much of the Nacimiento Formation (Paleocene) of the San Juan Basin.

By middle Eocene time the structural elements shown on fig. 8B were defined, and the basins were filled with sediments (San Jose Formation in the San Juan Basin; Cuchara Formation in the Raton Basin; lower part of the Galisteo Formation in the Galisteo Basin). By the end of Eocene time, the physiographic relief of the whole region probably was low, and sediments had lapped back onto the worn-down source areas. A shallow structural basin containing thin deposits of the E1 Rito and Galisteo Formations probably extended from the Chama Basin across the area of the present Española Basin to the Galisteo Basin; this probability is indicated by small outcrops of these rocks east of Española and in the southeastern Jemez Mountains (Galusha and Blick, 1971, p. 34-35). Thus, by the end of Eocene time, the general area of structural uplift between the Great Plains and Colorado Plateau in north-central New Mexico and southern Colorado was formed; but the region was characterized by low-hill and alluvial-plain physiography.

MIDDLE TERTIARY—In Oligocene time and continuing into Miocene time (fig. 8C), large-scale volcanic activity began in the San Juan Mountains in Colorado; flows, tuffs and volcaniclastic sediments extended south onto the Brazos uplift in New Mexico (Muehlberger, 1967; Butler, 1971). Eruptive centers, flows, breccias, and welded tuffs, as well as large intrusive bodies, are present in the Sangre de Cristo uplift (McKinlay, 1956; Clark and Read, 1972; Robinson and others, 1964). Lower Miocene volcanics also are exposed at a few places beneath Pliocene basalts northwest of Taos. The Espinaso Formation of Stearns (1953) and associated intrusives in the Cerrillos area are Oligocene to early Miocene (Weber, 1971; Bachman and Mehnert, 1978). Intrusives, probably of the same general ages, are exposed in the Turkey Mountain dome (Hayes, 1957) and Temple and Capulin domes in the Great Plains (Wood, Northrop, and Griggs, 1953). The Oligocene and lower Miocene volcanics are generally intermediate in composition, including andesite, latite, dacite, and some rhyolite.

The volcanic activity was preceded by an orogenic pulse as shown by coarse conglomerates at the base of some of the volcanics in the Sangre de Cristo uplift (Clark and Read, 1972) and by interbedded tuff and clastics in the Brazos uplift (Barker, 1958, p. 37-43). To the south, the eruptive rocks are bordered by aprons of tuffaceous volcaniclastic rocks of the Carson Conglomerate of Just (1937), Picuris Tuff of Cabot (1938), and Abiquiu Tuff of Smith (1938). These units have basal conglomerates of Precambrian and, locally, Paleozoic clasts and contain interbedded conglomerates of Precambrian clasts as well as of volcanic clasts. Additionally, the Abiquiu lies with local angular unconformity on the Eocene and Oligocene(?) E1 Rito Formation; flows of the Espinaso overlap tilted Galisteo beds to rest on Precambrian rocks south of Santa Fe; and the Zia Sand (lower Miocene) lies with angular unconformity on the Galisteo Formation to the south (Galusha, 1966). The details of stratal equivalence of the Oligocene-lower Miocene sedimentary units are not yet established; nevertheless, the units all belong within the same general time interval, and their geographic distribution suggests that they are parts of a sedimentary apron spread southward from volcanic highlands in northern New Mexico and southern Colorado, much in the manner suggested by Stearns (1953, fig. 8). At the south, the Zia Sand (as defined by Galusha, 1966) consists mainly of nonvolcanic sediments, but it also contains tuffaceous material and clasts of volcanic rocks.

The nature and size of the basins in which the Oligocene-lower Miocene sediments were deposited are not well known. However, the basins of the Rio Grande depression did not yet exist, as shown by the fact that the Abiquiu is preserved high on the present Nacimiento uplift and the Picuris is preserved in fault slices high in the Sangre de Cristos east and southeast of Taos. Tuffs and other units extended from the Brazos uplift to the Sangre de Cristo uplift, and the San Luis Basin, at least in New Mexico, did not exist in its present form.

About 20 million years ago, the basins began to form in which the Tesuque Formation of the Santa Fe Group and its equivalents were deposited. These basins were more extensive than the present basins of the Rio Grande depression. Despite a traditional belief that the Miocene basins were downfaulted and so indicate the beginning of rifting, evidence that such was the case in north-central New Mexico is difficult to find. Instead, the faults that bound parts of the present basins appear younger than the Tesuque, which has been tilted as well as faulted.

Some faulting in the vicinity of Abiquiu is shown to be Miocene, because a dike intruded along the fault is radiometrically dated as about 9.8 m.y. (Bachman and Mehnert, 1978, p. 290). However, Smith and others (1970) have shown that other major faults in this area cut the Santa Fe Group and also cut rocks as young as the Tschicoma Formation (age 6.7-3.7 m.y.); there is no reported evidence of fans or angular unconformities in Miocene rocks near the faults to indicate that they were active during deposition of the Santa Fe.

The basin in which the type Tesuque was deposited (partly the area of the present Española Basin) was probably broad and relatively shallow, perhaps similar to the late Eocene Chama-Galisteo structural basin (fig. 8B); and this Miocene basin was probably mainly warped down rather than subsiding along faults. The Cochiti Formation of Miocene and Pliocene age in the northern Albuquerque Basin is at least partly equivalent to the Pojoaque Member (Galusha and Blick, 1971) of the Tesuque. The Cochiti was derived from Paleozoic and Precambrian rocks of the Nacimiento uplift and from erosion of volcanic rocks of the Keres Group (Miocene), which were erupted in the southern part of the Jemez Mountains about 8.5-9 m.y. ago (Bailey and others, 1969, p. P-4 and P-5). The Cochiti sediments indicate that some warping and east tilting occurred in the NacimientoJemez uplift in late Miocene time. Indirect evidence suggests that the southern part of the Sangre de Cristo uplift was domed and tilted slightly west in Miocene time. At the northwest, the Tesuque may be partly equivalent to the upper part of the Abiquiu Tuff (Smith and others, 1970); and the upper part of the Tesuque in this region may have been derived from and eventually lapped back across old highlands in the southeastern part of the Brazos uplift, as suggested by Galusha and Buick (1971, p. 66, 88). To the south, the Cerrillos uplift is remarkably devoid of the Tesuque; this absence suggests a margin of the basin. However, it is also possible that the Tesuque was deposited there but removed in Pliocene time. The understanding of this area and the contiguous part of the Santo Domingo Basin awaits some further unraveling of the stratigraphy of Miocene-Pleistocene sediments in this area and at the north end of the Sandia uplift.

Lipman and Mehnert (1975, p. 128-130) indicated, on the basis of radiometric dates, that the Los Pinos Formation in the San Luis Basin spans an interval from 28.2 m.y. to perhaps 5 m.y. B.P. Therefore, the age of the Los Pinos spans the age of the Tesuque, some older rocks, and some younger sediments. According to Lipman and Mehnert, the strati-graphic relations of the Los Pinos and the basalts of the Hinsdale Formation indicate that the Los Pinos began to accumulate within the subsiding Rio Grande depression in early Miocene time as a result of extension and block faulting. Recently, however, Tweto (1976) has classified sediments east of the San Luis Bain as the Santa Fe Formation. These sediments are in faulted blocks in the Culebra reentrant (Upson, 1939) of the San Luis Basin in Colorado and on the flank of the Sangre de Cristo uplift in northernmost New Mexico. The existence of these sediments at considerably higher elevations than equivalent sediments within the main San Luis Basin suggests that the Miocene basin was both larger than and different from the present basin, which has been downfaulted at the east side since late Miocene.

LATE TERTIARY AND QUATERNARY—In late Miocene and early Pliocene time the present structural basins of the depression in north-central New Mexico began to be defined (fig. 8D). Basalts, intermediate volcanics, and some rhyolite (Keres and Polvadera Groups) of the Jemez Mountains volcanic pile were erupted near the boundary between the Nacimiento uplift and the Española Basin in the interval about 10 m.y. to 3 m.y. B.P. (Bailey and others, 1969). Abundant regional evidence exists to show that the later part of this volcanic episode was attended by a collapse of the former central part of the Laramide uplifted area and the Tesuque-age basins. This collapse involved sagging, tilting, and faulting.

At the south end of the San Luis Basin, a sharp angular unconformity can be seen between Santa Fe Group sediments and the overlying gravels and basalts of the Servilleta Formation near the basin-bounding hinge fault southwest of Taos (Montgomery, 1953). In places the Servilleta lies unbroken across the fault; therefore, the main faulting episode occurred prior to the period of eruption of the tholeiitic basalts (dated as 3.6 to 4.5 m.y. by Ozima and others, 1967).

In the northern part of the Española Basin near Velarde, the youngest of the Servilleta basalts has been dated as 2.78 ± 0.44 m.y. (Manley, 1976a). The basalts are underlain unconformably by beds equivalent to the Cejita Member of the Tesuque Formation (Manley, 1977); the Cejita is dated middle Miocene by Manley (1976b) on the basis of fission-track dates of volcanic ash. North of Española the basalts are underlain by the Chamita Formation (upper Miocene to Pliocene) of Galusha and Blick (1971, p. 71), who noted that the Chamita is unconformable with the underlying Tesuque Formation and that the lithology of the Chamita ". . . marks a profound change in the sedimentary regimen of the type area of the Santa Fe Group" and the introduction of clasts from different source areas. Manley and Naeser (1977) dated zircons from ash beds in the Chamita as being 5.2-5.6 m.y. B.P. The Servilleta basalts themselves have been warped and locally faulted, and west and north of Taos they have been tilted gently east; the tilting indicates further subsidence along eastern boundary faults in late Pliocene or Pleistocene.

Farther south, the western limb of the Sangre de Cristo uplift is tilted west and broken by faults. The contiguous west-tilted limb of the Española Basin has sagged more than the uplift; and the youngest part of the Tesuque Formation, where last seen in the basin west of the Rio Grande, dips west beneath a slightly angular unconformity at the base of river gravels of the Puye Formation (Pliocene). Ash beds of the Puye, just above the river gravels, were dated as about 3 m.y. by Manley and Naeser (1977). The Pajarito fault zone probably marks the west edge of this sagged, west-tilted part of the Española Basin. The Pajarito zone also displaces the Bandelier Tuff (early Pleistocene) and thus indicates recurrent movements.

From the Santa Fe area to the south and west, piedmont and fan deposits of the Ancha Formation (upper part dated as 2.7 m.y. by Manley and Naeser, 1977) are generally equivalent to the Puye and lie with angular unconformity on the southward-bevelled Tesuque Formation (Spiegel and Baldwin, 1963); the deposits eventually lie on the Espiñaso Formation (Oligocene and Miocene) and older rocks near the Cerrillos uplift (Disbrow and Stoll, 1957; Bachman, 1975).

The Rio Grande apparently began to be an integrated drainage system during the late Miocene-early Pliocene tectonic events described. Bachman and Mehnert (1978) have discussed the geomorphic history of the central Rio Grande region in the light of new radiometric dates. They discussed the concepts and extent of the Ortiz surface, a widespread compound erosional and constructional surface of Pliocene age that was postulated by Bryan and McCann (1937). This surface developed during a period of regional tectonic stability after the late Miocene-early Pliocene tectonic activity. The Ortiz surface is deformed by Pleistocene east-tilting and faulting in the northern Albuquerque Basin and the Santo Domingo Basin and by movements downthrown to the east on the Pajarito fault zone after eruption of the Bandelier Tuff (Pleistocene).

Recent work by the writer and J. M. O'Neill in the eastern part of the Sangre de Cristo uplift indicates that late Pliocene or Pleistocene down-to-the-west normal faulting, totaling as much as 700 ft (213 m), locally was superimposed along Laramide thrust faults. These relations indicate that the Pliocene and Pleistocene "shattering" of older tectonic elements extended east of the Rio Grande depression in north-central New Mexico just as it did in Colorado and farther south in New Mexico.

Conclusions

The Rio Grande depression in north-central New Mexico is geologically new. Undoubtedly, parts of some structural elements are controlled locally by renewed action of Precambrian and younger structural features; however, late Miocene-Pliocene and Pleistocene deformation transected some Precambrian trends and early Paleozoic trends. This deformation also disrupted an ancient and long-lived system of north-northwesterly trending uplifts and basins that was established in Pennsylvanian and Permian time. This ancient system maintained its general trends and identities through the Mesozoic Era and into early or middle Tertiary time. For example, part of the region of the San Luis Basin (Neogene) previously stood as a sediment-shedding highland (the Uncompahgre uplift) in late Paleozoic and parts of Mesozoic time and was part of an uplifted "backbone" of the Laramide Sangre de Cristo orogenic belt (Baltz, 1965). However, this long-lived positive area foundered and became a deep basin in late Miocene-Pliocene time as did other parts of the generally uplifted (Laramide) area between the Great Plains and Colorado Plateau.

A concept of east-west regional extension and possible mantle upwelling is favored by recent writers for the Neogene origin of the Rio Grande rift (Chapin, 1971; Chapin and Seager, 1975; Lipman, 1969; Lipman and Mehnert, 1975; Bridwell, 1976). Kelley (1977, p. 50-55) discussed various ideas and evidence concerning the origin and development of the rift and reasoned that some evidence exists for transcurrent faulting and left-lateral movements.

Surface geologic data do not suggest that much Neogene extension has occurred in north-central New Mexico other than the amount that would be geometrically necessary to accommodate dip slips on a few large normal-fault zones. The amount of extension is possibly about the same as the amount of shortening that was caused by the preceding Laramide compressional phase. This amount of deformation might be only several kilometers regionally from the San Juan Basin to the Raton Basin, a point on which I concur generally with the suggestion by Cordell (1978, p. 1085-1086). In this respect, the northern basins of the Rio Grande depression may differ somewhat from those farther south in New Mexico.

Interpretations of the origin of the Rio Grande rift seem to depend partly on one's view of what constitutes the rift. If the rift is viewed as relatively discrete (that is, viewed as comprising the basins of the Rio Grande depression), one might believe that its position and origin were predestined because of an ancient deep crustal discontinuity, a crustal spreading center, or an evolutionary consequence of a subduction zone. All of these ideas have been postulated recently.

On the other hand, one might envision the rift as a regionally broad and pervasive "system" of Neogene faults, such as the Rio Grande rift system of Tweto (1977) in Colorado and the rift in southern New Mexico as portrayed by Chapin and Seager (1975, fig. 1) and Woodward and others (1975). In this case, one might interpret the rift as the eastern vagaries of slight intraplate shifting, of stretching because of vertical crustal movements, and of shattering of large areas during regionally varying amounts of the Neogene epeirogenic uplift of a large region of the southwestern United States. Such an impression is heightened because basalts of late Miocene, Pliocene, and Pleistocene ages were erupted not only in the Rio Grande depression, but also in the Colorado Plateau and Great Plains outside the area considered to be the Rio Grande rift. Tholeiitic basalts were formerly thought to be restricted to the northern part of the Rio Grande depression, but they are now known to occur also in the eastern Colorado Plateau and in the western Great Plains east of the Sangre de Cristo uplift (Aoki and Kudo, 1976, p. 87).

With regard to local structural origins of basins of the Rio Grande depression, an idea of long standing is that the Albuquerque Basin might be the collapsed axial portion of a broad arch between the Colorado Plateau and the east-tilted Sandia uplift (Herrick, 1904; Hunt, 1938, p. 78; Eardley, 1962, p. 401). Darton (1928, p. 98-101) suggested a faulted anticlinal structure for the northern Sandias and the eastern part of the basin. Kelley and Northrop (1975, p. 93) and Kelley (1977, p. 54) briefly mention this idea and consider it doubtful. Data from deep wells, although scanty, indicate that Cretaceous and older rocks underlie the Santa Fe Group; therefore, there is little indication from missing stratigraphic units that a former large structural high existed in the area of the Albuquerque Basin.

Cordell (1978, p. 1085-1086) illustrated several sections across the region from the Colorado Plateau to the Great Plains by means of gravity and topographic-altitude profiles. From these and other data, he reasoned that structural vaults occur across the region and that the Rio Grande depression basins seem to be collapsed parts of these vaults. As Cordell pointed out, altitude is only a crude structural datum. The topographic profiles themselves are not structural datums; they are the measures of late Cenozoic erosion across a variety of structural features that range in age from Laramide through Pleistocene.

The geologic history of the northern basins of the depression does indicate, nevertheless, that formerly structurally high areas, such as part of the Laramide Sangre de Cristo-Brazos geanticlinal area, have been depressed in Neogene time. However, in the present state of knowledge, local Neogene doming in this region has not been substantiated or discounted.

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PHYSICAL BEHAVIOR OF UPPER MANTLE BENEATH NORTHERN RIO GRANDE RIFT

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This discussion will briefly review geophysical data relevant to geometry and behavior of crust and upper mantle beneath the Española Basin, a rift valley in the northern Rio Grande rift. Seismic refraction, surface heat flow, and Bouguer gravity pertain to the geometry of the upper mantle. Surface heat flow and estimates of mantle shear stresses from natural xenoliths pertain to the temperatures and viscosity of the upper mantle. Taken together these geophysical signatures have been interpreted to represent a mantle diapir beneath the northern rift (Bridwell, 1976; in press).

Seismic refraction data on the Colorado Plateau at 107° 10′ W. (Toppozada and Sanford, 1976), in the Rio Grande rift at 106° 15′ W. (Olsen and others, 1977), and on the Great Plains at 103° 8′ W. (Stewart and Pakiser, 1962) suggest a marked change in crustal thickness from ~40 km (Pn ~7.9 km) to ~33 km (Pn ~7.7 km/s; Olsen and others, 1977) to more than 50 km (Pn ~8.2 km/s) at respective longitudes. There is a clear lateral inhomogeneity between the Colorado Plateau and the Great Plains, with a marked variation in crust and mantle seismic velocities and thinning of the crust beneath the rift.

Two general differential equations govern heat flow and stress calculations. The heat flow equation is

$$Q = K \frac{\delta T}{\delta Z} \tag{1}$$

where Q is heat flux, K is thermal conductivity (1 TCU = mW/m°C), and $\delta T/\delta Z$ is the geothermal gradient (°C/km). The shear stress is calculated knowing the temperature distribution when (1) is solved for a two-dimensional fit to the surface heat flow. The shear-stress equation is

$$\dot{\varepsilon} = Ae^{(-E/RT)}\tau^{n} \tag{2}$$

where $\dot{\varepsilon}$ is strain rate (S^{-1}), A is a physical constant (kb^{-n}), E is activation energy (kcal/mole), R is universal gas constant (cal/°C/mole), τ is shear stress, and n is an experimentally determined exponent ranging from 2 to 4 in typical mantle rocks. The effective viscosity is

$$\eta = \frac{\tau}{3\dot{\varepsilon}} \tag{3}$$

Regional surface heat flow ranges from ~62.8 mW/m² (41.87 mW/m² = μcal/cm²s = 1 HFU) west of 107° W. in the San Juan Basin to more than 105 mW/m² on the west flank of the rift at ~106° 30′ W. to ~59 mW/m² in the Great Plains at ~103° 30′ W. at latitude 36° N. These data were collected by Reiter and others (1975). When the surface heat flow and heat generation are modeled by steady-state thermal models, the depth of the melting isotherm can be estimated. Experimental petrology suggests that the melting temperature for dry dunite, a typical mantle material, is ~1200° C. Fig. 1 is a two-dimensional fit to the surface heat flow, with resulting isotherms above the melt temperature labeled as partial melt zone (PMZ). If the melt isotherm represents the boundary between plastically flowing crust or mantle material and partially molten material below, this time-dependent boundary is a natural mechanical discontinuity, which represents the thermal base of the lithosphere. Clearly, the lithosphere is deep beneath the Colorado Plateau and Great Plains, and it is shallow beneath the Rio Grande rift. The principal cause of high surface heat flow beneath the rift is a relatively high temperature at shallow depths.

Bouguer gravity data have a significant variation in the broad negative trends across the northern rift (Woollard and Joesting, 1964). Bridwell (1975) modeled these data as a ~-70 mgal residual caused by upper-mantle material, with $\Delta\varrho$ ~-0.1 g/cm³ overlain by several lower crustal materials with positive density contrast of $\Delta\varrho$ ~+0.2. Allowing for natural ambiguities of gravity models, which include an assumed depth to the level of isostatic compensation, the principal result of the gravity model is a strong indication of a negative density contrast in the upper mantle; this would create gravitational instability and subsequent uplift of the hot, less dense, upper mantle beneath the Rio Grande rift.

The physical behavior of the crust and upper mantle is

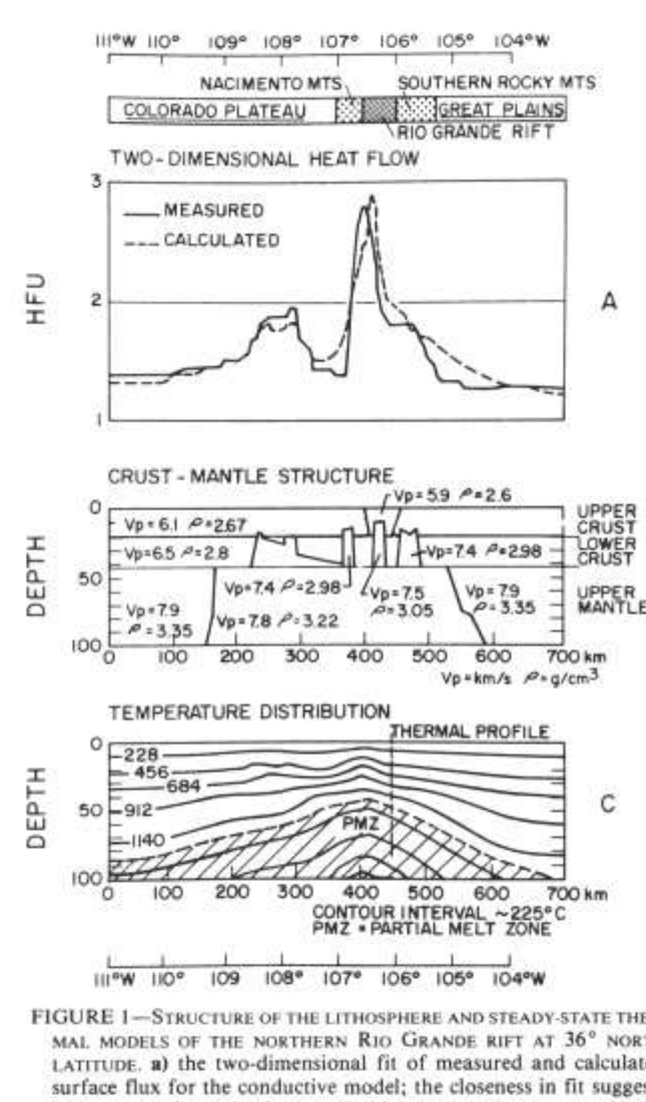

FIGURE 1—STRUCTURE OF THE LITHOSPHERE AND STEADY-STATE THERMAL MODELS OF THE NORTHERN RIO GRANDE RIFT AT 36° NORTH LATITUDE. **a)** the two-dimensional fit of measured and calculated surface flux for the conductive model; the closeness in fit suggests an energy balance in the calculated heat transfer process; **b)** the crust-mantle structure using long wavelength negative Bouguer gravity residuals deduced from the data of Woollard and Joesting (1964); **c)** the steady-state thermal model, shown to be a solution to the surface heat flow in the top portion of the fig. (from Bridwell, 1976).

basically determined by the pressure, temperature, and viscosity of the crust and mantle. The pressure can be considered as the sum of lithostatic or confining pressure and associated tectonic shear stresses, which cause deformation. Shear stress is strongly affected by the thermal gradient; temperatures near the melting point of upper-mantle materials strongly attenuate magnitudes of shear stress. Since effective viscosity is a function of shear stress and strain rate, the thermal gradient strongly controls the viscosity. Fig. 2 is a combined model of temperature, shear stresses, and effective viscosity of the lithosphere and asthenosphere beneath the rift. Increased shear stress gradients clearly occur beneath the rift. Reduced gradients occur beneath the Colorado Plateau and Great Plains. Such shear-stress concentrations would increase mechanical deformation in the crust and upper mantle beneath the rift. Bridwell (in press) contrasted calculated shear stresses with estimates from xenoliths of Kilbourne Hole and Mt. Taylor in New Mexico; the determinations show good correlation and predict shear stresses of less than 100 bars at depths of 40-80 km. The temperature control on the effective viscosity indicates a reduced viscosity beneath the rift.

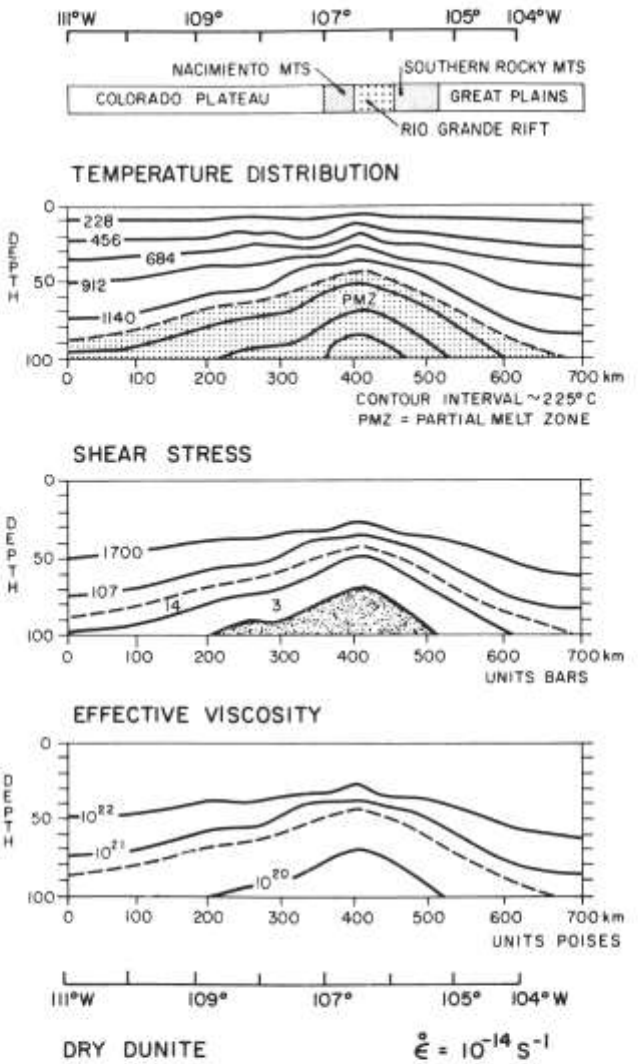

FIGURE 2—VARIATIONS OF SHEAR STRESS AND EFFECTIVE VISCOSITY ASSOCIATED WITH THINNING OF THE LITHOSPHERE BENEATH THE NORTHERN RIO GRANDE RIFT AT 36° NORTH LATITUDE. The temperature distribution has a dominant effect on variations of shear stress and effective viscosity. Shear stresses range from 1,700 to 3 bars through the plastically flowing lowermost crust and upper mantle. Viscosities vary two orders of magnitude with a pronounced low viscosity beneath the rift (from Bridwell, 1978).

The combined implications of refraction, heat flow, Bouguer gravity, shear stress, and effective viscosity beneath the Rio Grande rift are: lateral variations in the geometry of the Moho, lateral variation in seismic velocities of lower crust and upper mantle, high temperatures beneath the rift, less dense materials in the upper mantle, shear stress concentrations that cause enhanced deformation beneath the rift, and low viscosities at shallow depths. As one progresses laterally from the rift, each of these characteristics diminishes in magnitude and increases with depth. Each aids in creating a gravitational instability in the upper mantle beneath the rift. The hot, low-density, low-viscosity mass, which can be considered a mantle diapir or possibly the uppermost features of a convection cell, would reduce the instability by moving upward.

A preferred genetic sequence outlining physical processes of rifting consists of: 1) initiation of a thermal pulse in the asthenosphere, which convects mass and heat upward, creating magma chambers in the plastic upper mantle, 2) buoyant uplift of the overlying lithosphere to form broad arches, 3) thinning of the elastic crust owing to enhanced shear stress gradients, 4) initiation of extensional normal faulting along a "keystone" crest, 5) magmatic injection and extrusion of volcanics along fault zones, 6) accelerated uplift as a response to reduction of strength during both faulting and increased temperature, and 7) development of deep, elongate, clastic-filled rifts whose graben bottoms are moving downward relative to adjacent arches but whose total motion is probably upward relative to convecting masses below (Bridwell, in press).

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OVERVIEW OF RIO GRANDE BASALTS WITH SPECIAL REFERENCE TO TiO_2 VARIATION

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Cenozoic basaltic rocks are abundant along the Rio Grande rift from Colorado south to the international border; within the last few years, much information has emerged concerning the role of these rocks in the tectonic framework of the rift. Recently, chemical data generated by Aoki, Kudo, Lipman, and Renault have been summarized by Aoki and Kudo (1976). Warren (1978) presents numerous analyses of the Engle basalts, and new analyses for the diverse basaltic rocks of the Isleta volcanic field are presented in this paper. Chapin (personal communication, 1978) has compiled a large number of radiometric dates pertinent to the tectonics of the Rio Grande rift, and Bachman and Mehnert (1978) have recently published many new radiometric dates of the basalts of the central Rio Grande region.

The eruptive styles of the Rio Grande basaltic rocks include fissure eruptions with abundant terminal pyroclastic activity (West Potrillo, Cat Hills, Albuquerque volcanoes, San Felipe, and Cerros del Rio), highly fluid lava eruptions from isolated vents (Carrizozo and Jornada), large outpourings of highly fluid lavas without conspicuous vents (Taos area); and shield volcanoes (Wind Mesa and Aden crater). Kilbourne and Hunt's Holes have long been recognized as maars; recently, Aubele and others (1976) have drawn attention to numerous other maars along the Rio Grande.

Among the basaltic rocks of the Rio Grande, compositions vary from basaltic andesite at Cerro de los Lunas to basanite in the West Potrillo field. Volumetrically, tholeiite is probably the most abundant by virtue of the large thickness of the Servilleta basalts in the Taos area. Basaltic andesites are the least common but are conspicuous landforms at Cerros de los Lunas, Wind Mesa, and Cerro de Tome.

Cinder cones are abundant along the Rio Grande and are well developed in the Potrillo, Isleta (Cat Hills), Albuquerque, San Felipe, and Cerros del Rio fields. The cone-like land-form at Black Butte (Turututu) is a basalt fault block (Stop S13).

Generally the volumes of basaltic lava erupted are small. Allen (1951) estimated that the Carrizozo vent erupted about a cubic mile of lava. Usually the period of volcanism is relatively short lived; we usually see no extensive stacking of flows with soil horizons developed between them. The Servilleta tholeiites, with their 500-ft sequence of flow, are important exceptions.

Sheets 1 and 2 show the distribution of basaltic rocks along the Rio Grande rift for which chemical data is available. Map symbols, ages and data sources are given in table 1. Fig. 1 summarizes the compositional data in an AFM diagram. Included in these rocks are the basaltic andesites at Uvas, Cerro de los Lunas, and Wind Mesa. The compositions lie broadly on the calc-alkaline trend with considerable scatter in the MgO/FeO ratio. With the exception of the rocks from the Wind Mesa shield volcano, the basaltic rocks from a particular volcanic field are so uniform in composition that it is difficult to identify igneous differentiation patterns from the major-element chemistry. The 20-percent spread of MgO in the AFM diagram implies a considerable departure from the "primitive" magma—MgO = 40—of Kuno (1968). The West Potrillo basalts may be taken as typical of compositional variation in a consanguinous series of lavas along the Rio Grande. Here the coefficients of variation for the major elements in a mean of 14 samples are as follows: K_2O (.19), Na_2O (.12), MgO (.08), TiO2 (.06), CaO (.05), FeO (.04), $A1_20$, (.03), and SiO_2 (.02).

Although the classical differentiation trends are difficult to demonstrate, differentiation has occurred on a small scale

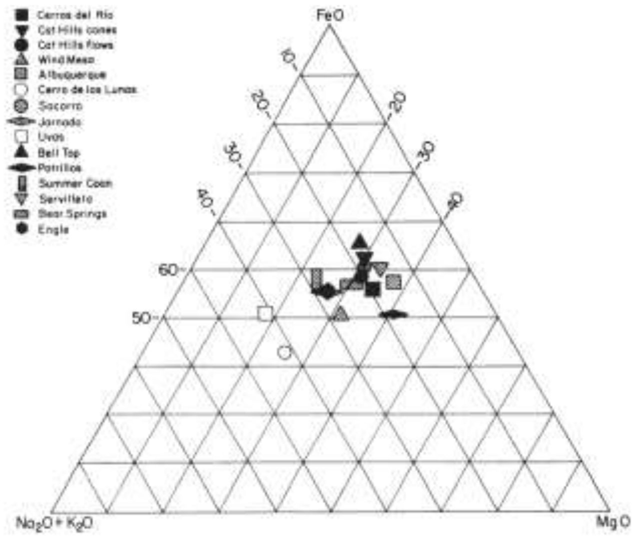

FIGURE 1—AFM DIAGRAM SHOWING COMPOSITIONAL VARIATION OF RIO GRANDE BASALTS AND BASALTIC ANDESITES. SiO_2 concentration is <50 percent in rocks with closed symbols, 50-55 percent in rocks with hachured symbols, and >55 percent in rocks with open symbols. See table 1 for sources of data.

within closely related rocks. Table 2 shows the mean compositions of 23 samples of the Cat Hills cones and 45 samples of the Cat Hills flows (Isleta volcanic field). Only Alumina shows no compositional overlap at the 95-percent confidence level. Lime and magnesia have relatively small overlaps. The greater concentration of magnesia in the cones suggests that in this volcanic field, at least, plagioclase was more concentrated in the earlier phases of eruption and that olivine and other ferromagnesian minerals were more concentrated in the lavas of the terminal pyroclastic period. This interpretation is consistent with an olivine-settling hypothesis, but the effect of differentiation is small. Warren (1978) presents evidence for a small amount of differentiation in the Engle basalts, but differentiation trends are difficult to see in the data of Aoki (1967) on the chemistry of the Servilleta basalts.

The brief duration of much of the basaltic volcanic activity in any one volcanic field along the Rio Grande rift, the relatively small volumes of lava produced, and the minor amount of igneous differentiation that has occurred suggest that small magma chambers are involved, and that their contents were transported to the surface very quickly without ex-

TABLE 1—AGES OF RIO GRANDE BASALTS.

Volcanic field	Map symbol	Age (m.y.)	Age source	Chemistry source
Carrizozo	CAR	≪0.1	Weber (1964)	Renault (1970)
Potrillo	POT	.1	Renault (1970)	
Albuquerque	ABQ	.19	Bachman & Mehnert (1978)	Aoki & Kudo (1976)
Cat Hills	CAT	.2 (?)		Renault (this paper)
Jornado del Muerto	JOR	.76	Bachman & Mehnert (1978)	Renault (unpub.)
Wind Mesa	WDM	<1 (?)		Renault (this paper)
Cerro de los Lunas	CLL	1.01	Bachman & Mehnert (1978)	Renault (this paper)
Engle	ENG	2.0	Bachman & Mehnert (1978)	Warren (1978)
Cerros del Rio (Cienega)	CDR	2.6	Bachman & Mehnert (1978)	Sun & Baldwin (1958) Aoki & Kudo (1976)
San Felipe	SFP	2.9	Bachman & Mehnert (1978)	Aoki & Kudo (1976)
Socorro	SOC	4.0	Bachman & Mehnert (1978)	Aoki & Kudo (1976)
Servilleta	SER	4.1	Ozima and others (1967)	Aoki (1967)
Uvas	UVA	26	Seager & Clemons (1975)	Seager & Clemons (1975)
Bell Top	BLT	33-39	Seager & Clemons (1975)	Seager & Clemons (1975)

TABLE 2—MEAN COMPOSITIONS OF BASALTS AND BASALTIC ANDESITES FROM THE ISLETA VOLCANIC FIELD. Values in parentheses are the number of samples in the mean. Errors are at 95 percent or greater confidence. All concentrations are determined by x-ray fluorescence spectrometry except FeO, Fe_2O_3, and water in the Cerro de los Lunas volcano. Lynn Brandvold, chemist, New Mexico Bureau of Mines & Mineral Resources, determined these components by titration and difference. *Total iron represented as FeO.

	Cat Hills		Wind Mesa	Cerro de los Lunas
	cones (23)	flows (45)	(25)	(13)
SiO_2	49.78 ± .26	49.97 ± .26	51.65 ± .24	55.29 ± .36
TiO_2	1.91 ± .05	1.84 ± .03	1.51 ± .05	1.04 ± .03
Al_2O_3	15.47 ± .39	16.32 ± .30	16.28 ± .30	16.00 ± .40
Fe_2O_3				5.75 ± .40
FeO	10.15 ± .18*	10.15 ± .26*	8.06 ± .20*	0.36 ± .30
MgO	7.20 ± .37	6.76 ± .22	6.43 ± .27	4.36 ± .14
CaO	9.17 ± .18	9.33 ± .19	8.30 ± .24	6.41 ± .45
MnO	.16 ± .01	.17 ± .01	.15 ± .01	.16 ± .01
Na_2O	3.38 ± .27	3.33 ± .22	3.97 ± .36	4.76 ± .34
K_2O	1.06 ± .06	1.03 ± .06	1.59 ± .05	2.49 ± .08
P_2O_5	.60 ± .02	.61 ± .02	.57 ± .01	.47 ± .03
S	.19 ± .10	.15 ± .06	.08 ± .03	.19 ± .17
H_2O^+				1.29 ± .46
H_2O^-				.25 ± .10
Total	99.07	99.66	98.59	100.13

periencing conspicuous compositional changes. Consequently the small basalt flows (and perhaps the more mafic basaltic andesites as well) probably provide mantle samples that have been influenced predominantly by the processes of partial melting at their sources.

Yoder (1976) gives cogent arguments attributing the uniformity of basalt compositions to their origin from univariant liquids. He shows that the variations observed in major-element concentrations are controlled by the pressure at which partial melting occurs in the mantle and by crystal fractionation between the source and the surface. In the absence of important differentiation within the consanguinous suites of basalts of the Rio Grande rift, regional variation in major-element concentration is probably the result of variations in the depth of partial melting.

In 1969, Lipman observed systematic compositional differences in basalts from west to east across the Rio Grande in Colorado and northern New Mexico and attributed them to tectonic control. More recently, Aoki and Kudo (1976) concluded that the basalts of the northern Rio Grande tend to be tholeiitic and those of the southern Rio Grande tend to be alkali basalts. They concluded from their limited sampling that the middle Rio Grande basalts are transitional between these two groups.

In 1970, I suggested that TiO_2 in Rio Grande basaltic rocks is sensitive to structural setting. A systematic regional variation in TiO_2 now seems to exist along the axis of the Rio Grande rift. Fig. 2 illustrates this trend. Here the ratio (TiO_2 x 100)/(TiO_2 + MgO + SiO2) is plotted against distance along the Rio Grande south from Salida, Colorado. The values of the ratios are roughly double the actual weight percents. Forming this ratio has a smoothing effect on the data and relates to pressure as discussed below. In general, Ti and Mg concentrations are inversely proportional to silica concentration; as silica accentuates the differences in TiO2, magnesia variation dampens them.

The variation in titania along the rift might be attributed to some kind of fundamental tectonic control, because MacGreggor (1969) has shown that, during partial melting in the system SiO_2-MgO-TiO_2, titania is fractionated into the liquid phase in proportion to the pressure on the system. It can be inferred from fig. 2, then, that in the upper mantle, the locus of partial melting giving rise to the basalts that we see on the surface systematically increases in depth from north to south.

Basalt rises to the surface mainly because of lithostatic pressure. Therefore, in the upper mantle, the shallowest magma chamber that can support a continuous filament of magma to the surface must be deeper beneath thick crust than beneath thin if the mean density of rock above it is to be greater than the density of the rising lava. A simple calculation will show that the depth to the shallowest magma chamber beneath a 50-km crust is about 60 km and beneath a 35-km crust is about 42 km. Because the crust in the southern Rio Grande is thinner than the crust in the northern Rio Grande (Toppozada, 1974), the pressure effect on TiO2 concentrations must be occurring at depths greater than the shallowest magma chamber. Evans (Evans and Nash, 1978, and personal communication) observed this effect in the

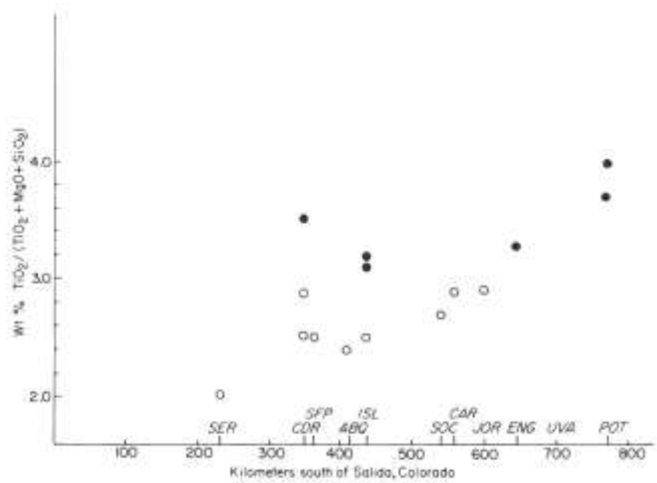

FIGURE 2—TITANIUM VARIATION IN PLIOCENE-HOLOCENE BASALTS OF THE RIO GRANDE RIFT. Open symbols are for basalts with SiO_2 >50 percent; closed symbols are for basalts with SiO_2 <50 percent. The middle value for the CDR basalts is from Sun and Baldwin (1958). The upper two values for the ISL basalts are from the Cat Hills; the uppermost is from the flows, and the other is from the cones. See table 1 for sources of data.

basalts of the San Bernardino Valley, southeast Arizona, where depths to partial melting are about 90 km, but the thickness of the crust is only about 30 km.

The minimum depth to melting in the upper mantle is controlled by the slope of the geothermal gradient and the point at which it intersects a basalt solidus curve. If geothermal gradients decrease from north to south, the depth to melting would increase southward. Unfortunately, although the Potrillo field seems to have a lower heat flow than volcanic areas northward along the rift (Reiter, personal communication, 1978), the resolution of the heat-flow data is not good enough to support or reject this hypothesis.

The data presented in fig. 2 are for Pliocene and younger basalts. Older basalts, such as the Bell Top, Bear Springs, and Summer Coon basalts that are marginal to the rift, are consistent with the younger basalts but degrade the correlation somewhat. Data are not yet available for the 24-m.y. Turututu basalt east of Bernardo.

Fig. 2 shows that there is a lower boundary to the correlation with distance. Furthermore, the basalts along this boundary are more siliceous than those above it. This relationship is consistent with the notion that alkali basalt liquids equilibrate at greater depths than tholeiite liquids and conforms to Lipman's interpretation of tectonic control over basalt compositions in the northern Rio Grande (Lipman, 1969). The sharp lower boundary to the TiO_2-distance correlation implies that, although melting occurs over a substantial depth zone, the minimum depth is tightly controlled on a regional scale. Southward diminishing geothermal gradients along the Rio Grande rift seem to be the best explanation for systematically increasing the depth of partial melting.

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Special maps and tables

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HEAT-FLOW DATA AND MAJOR GEOLOGIC FEATURES ALONG THE RIO GRANDE RIFT IN NEW MEXICO

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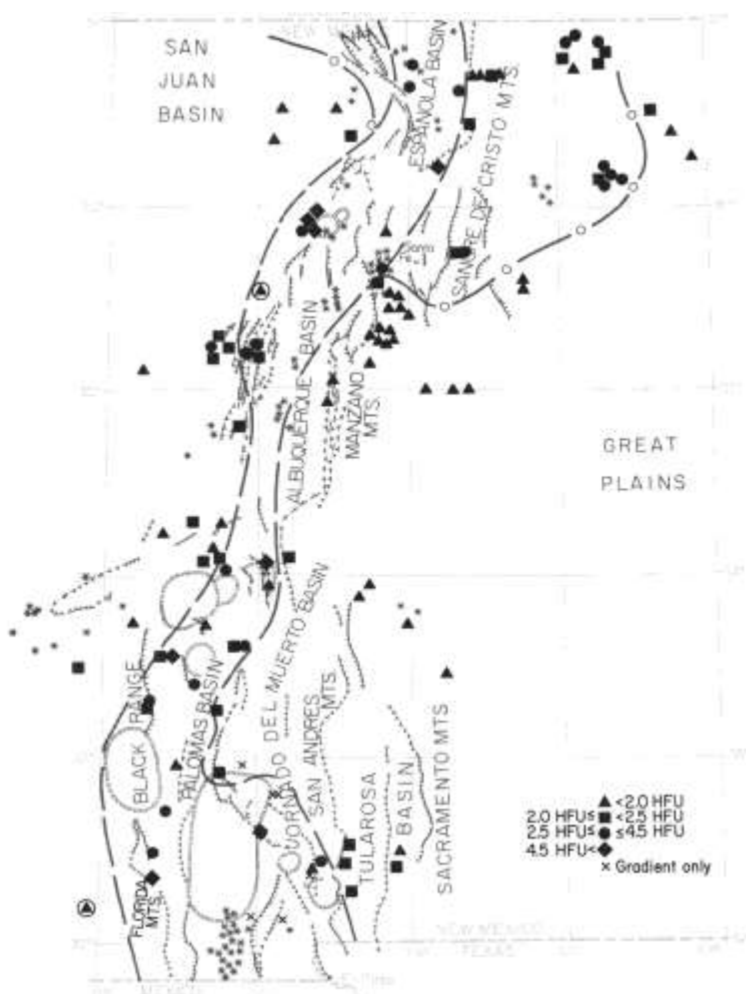
Abstract

Heat-flow data suggest that there are regions along the Rio Grande rift where crustal temperatures exceed those in adjacent areas. Magma bodies at depths of 15-30 km (predicted by several investigators) seem to provide reasonable sources of heat that could increase heat-flow values from 1.8 to about 2.5 HFU and somewhat higher. However, heat-flow values of 6.0 to 16.0 HFU occur at four locations along the Rio Grande rift; these values occur within geologic environments such as recent volcanic centers and the intersections of cauldron boundaries with large normal faults where upward heat transport by magmatic and/or ground-water movement is plausible. Test drillings of several kilometers are necessary to confirm the continuity of these very high geothermal gradients at depth and to relate them to possible sources in the upper crust (adapted from Reiter and others, 1978).



HEAT-FLOW DATA AND GEOLOGIC FEATURES ALONG THE RIO GRANDE RIFT, NEW MEXICO. Hachured lines indicate normal faults, hachures on downthrown side; asterisks indicate volcanic centers; double broken lines encircle cauldron boundaries; heavy broken lines indicate the high heat-flow envelope believed to be associated with the Rio Grande rift; dashed/dotted lines denote the Southern Rocky Mountains complex thermal anomaly; circled data points along the western edge of the Rio Grande rift in New Mexico indicate data sites in preparation. Heat-flow sites from Edwards and others 1978, Reiter and others 1975, Reiter and others 1976, Reiter and others 1978, and Reiter and Smith 1977. Geologic features along the Rio Grande rift after Woodward and others 1975, Socorro Peak cauldron boundary by Chapin and Chamberlin 1976 (adapted from fig. 1, Reiter and others, 1978).

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HEAT-FLOW DATA AND MAJOR GEOLOGIC FEATURES IN CENTRAL COLORADO

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Abstract

The high heat-flow zone associated with the Rio Grande rift in New Mexico appears to extend into Colorado, perhaps to north of Vail. High heat flows (>2.5 HFU) are observed in the San Luis Valley and between Leadville and Vail within a major fracture zone. The east-west extent of this apparent high heat-flow zone is complicated by regions of high heat flow to the west (the San Juan volcanic field) and to the east just beyond the Sangre de Cristo Mountains (the Raton Basin). Heat-flow data in the Front Range average about 2.0-2.2 HFU with relatively little scatter.

HEAT-FLOW DATA AND MAJOR GEOLOGIC FEATURES IN CENTRAL COLORADO. Hachured lines indicate normal faults, hachures on downthrown side; double broken lines encircle cauldron boundaries; heavy broken lines indicate the high heat-flow envelope believed to be associated with the Rio Grande rift; dashed/dotted lines denote the Southern Rocky Mountains complex thermal anomaly; circled data points in northern Colorado and southern Wyoming indicate data sites in preparation. Heat-flow sites from Birch 1950, Decker and Birch 1974, Edwards and others 1978, Monroe and Sass 1974, Reiter and others 1975, and Roy and others 1968. Geologic features after Tweto 1977 and 1978.

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SELECTED DATA FOR DEEP DRILL HOLES ALONG RIO GRANDE RIFT IN NEW MEXICO

by Roy W. Foster
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	hole/location/county	spud/complete	elev.: ft(m)/TD/unit	formation	depth: ft(m)	elev.: ft(m)	thickness: ft(m)
a)	Texaco 1 Weaver 660S, 660W, 35-26S-1E Dona Ana	10-29-65 1-6-66	KB4,172 (1,272) 6,620 (2,018) Tertiary volcanics	Santa Fe volcanics	surface 2,420 (738)	4,162 (1,269) 1,742 (531)	2,420 (738) 4,200+ (1,280)
b)	Grimm 1 Mobil 1315N, 1315W, 32-25S-1E Dona Ana	10-2-72 10-12-73	GL4,220 (1,286) 21,759 (6,632) Ordovician, El Paso?	Santa Fe volcanics lower Tertiary Cretaceous+ Precambrian (est.) Lit. # *	surface 1,940 (591) 5,880 (1,792) 12,300 (3,749) 22,380 (6,821)	4,220 (1,286) 2,280 (695) -1,660 (-506) -8,080 (-2,463) -18,160 (-5,535)	1,940 (591) 3,940 (1,201) 6,420 (1,957) 9,459+ (2,883)
c)	Clary 1 State 106N, 41W, 36-23S-2E Dona Ana	10-30-48 11-1-49	Est.4,240 (1,292) 2,584 (788) Pennsylvanian	Precambrian (est.) #	7,494 (2,284)	-3,254 (-992)	
d)	Sinclair 1 Dona Ana[1] 660N, 660W, 27-22S-1W Dona Ana	3-2-62 4-7-62	GL4,684 (1,428) 6,510 (1,984) Tertiary intrusive	Santa Fe volcanics Pennsylvanian*	surface 280 (85) 2,850 (869)	4,684 (1,428) 4,404 (1,342) 1,834 (559)	280 (85) 2,570+? (783) intrusives
e)	Cities Service 1 Corralitos 1980N, 1980W, 6-22S-2W Dona Ana	6-17-71 7-25-71	GL4,776 (1,456) 5,129 (1,563)	Precambrian (est.) #	5,160 (1,573)	-384 (-117)	
f)	Corps of Engineers, WSMR, T-14 NE, NW, NE, 15-22S-5E Dona Ana	7-22-67	GL3,950 (1,204) 6,005 (1,830) Santa Fe	Qal/upper Santa Fe Santa Fe *	surface 200 (61)	3,950 (1,204) 3,750 (1,143)	200 (61) 5,805+ (1,769)
g)	Western 2 Guame 1980S, 1980W, 21-16S-2E Sierra	8-11-52 12-28-52	3,507 (1,067) Topo. 5,115 (1,559)	Precambrian (est.) Lit.	7,645 (2,330)	-2,530 (-771)	
h)	Sunray Mid-Continent 1 New Mexico 660S, 660E, 23-15S-2W Sierra	1-16-59 4-18-59	KB4,690 (1,430) 9,765 (2,976) Ordovician, El Paso	McRae Cretaceous-Paleozoic Precambrian (est.) *	surface 954 (291) 9,905 (3,019)	4,677 (1,426) 3,736 (1,139) -5,215 (-1,590)	941 (287) 8,951 (2,728)
i)	Beard 4 Jornada del Muerto 744N, 2390W, 2-15S-1E Sierra	3-8-76 4-28-76	DF5,304 (1,617) 2,015 (614) Permian, San Andres	Precambrian (est.) #	8,783 (2,677)	-3,479 (-1,060)	
j)	Beard 1 Jornada del Muerto 1980S, 660E, 17-14S-1W Sierra	2-22-73 4-16-73	DF4,805 (1,465) 9,800 (2,987) Pennsylvanian	Qal Precambrian (est.) #	surface 11,880 (3,621)	4,792 (1,461) -7,075 (-2,156)	?
k)	Exxon 1 Beard 1980S, 1980E, 5-14S-1E Sierra	1-4-74 3-4-74	KB5,179 (1,579) 8,850 (2,697) Precambrian	Qal/upper Santa Fe Cretaceous-Paleozoic Precambrian L	surface 95 (29) 8,742 (2,665)	5,163 (1,574) 5,084 (1,550) -3,563 (-1,086)	79 (24) 8,647 (2,636)
l)	Beard 5 Jornada del Muerto 1897N, 2066W, 13-14S-1E Sierra	4-22-77 6-1-77	GL5,562 (1,695) 830 (253) Permian, San Andres	Precambrian (est.) #	7,375 (2,248)	-1,813 (-553)	
m)	Beard 3 Jornada del Muerto 827S, 2197W, 22-13S-1E Sierra	3-4-75 3-15-75	Topo 5,290 (1,612) 2,320 (707) Permian, Glorieta	Precambrian (est.) #	7,905 (2,409)	-2,615 (-797)	
n)	Shell 1 Leeman 1980N, 660E, 17-13S-1E Sierra	12-30-64 3-13-65	DF5,261 (1,604) 7,346 (2,239) Ordovician, Montoya	Qal/upper Santa Fe Cretaceous-Paleozoic Precambrian (est.) *	surface 163 (50) 7,770 (2,368)	5,250 (1,600) 5,098 (1,554) -2,509 (-765)	152 (46) 7,607 (2,319)
o)	Gulf 1 Sierra 1980N, 660E, 35-12S-1W Sierra	6-24-70 8-10-70	KB5,123 (1,561) 7,860 Ordovician (Montoya)	Qal/upper Santa Fe Cretaceous-Paleozoic Precambrian (est.) *	surface 62 (19) 8,335 (2,541)	5,111 (1,558) 5,061 (1,543) -3,212 (-979)	50 (15) 8,273 (2,522)
p)	Summit 1 Mims 1980S, 660W, 2-13S-4W Sierra	6-11-50 (9-21-53) 10-3-51 (3-1-54)	GL4,570 (1,393) 6,195 (1,888) Pennsylvanian	Santa Fe Cretaceous-Paleozoic Precambrian (est.) **	surface 1,986 (605) 7,985 (2,433)	4,570 (1,393) 2,584 (788) -3,415 (-1,041)	1,986 (605) 5,999 (1,828)
q)	Gartland 1 Brister 2010S, 1988E, 8-12S-4W Sierra	1-21-51 10-3-75 (9-20-55)	DF4,860 (1,481) 8,585 (2,617) Pennsylvanian	Upper Santa Fe lower Santa Fe McRae? Cretaceous-Paleozoic Precambrian (est.) **	surface 580 (177) 1,450 (442) 1,540 (469) 8,805 (2,684)	est.4,850 (1,478) 4,270 (1,302) 3,400 (1,036) 3,310 (1,009) -3,955 (-1,205)	580 (177) 870 (265) 90 (27) 7,265 (2,214)

hole/location/county	spud/complete	elev.: ft(m)/TD/unit	formation	depth: ft(m)	elev.: ft(m)	thickness: ft(m)
r) Gartland 1 Garner 660S, 1980E, 11-12S-5W Sierra	10-11-50 12-21-50	GL4,920 (1,500) 6,524 (1,989) Santa Fe	Santa Fe **	surface	4,920 (1,500)	6,524+ (1,988)
s) Sun 1 Victoria 660S, 1980W, 25-10S-1W Sierra	10-16-51 1-25-52	GL4,809 (1,466) 6,053 (1,845) Precambrian	Qal/upper Santa Fe Cretaceous-Paleozoic Precambrian *	surface 100 (30) 6,000 (1,829)	4,809 (1,466) 4,709 (1,435) -1,191 (-363)	100 (30) 5,900 (1,798)
t) Sun 2 Victoria 1980N, 660E, 27-10S-1W Sierra	2-1-52 5-5-52	GL4,786 (1,459) 6,352 (1,936) Cambrian-Ordovician, Bliss	Qal/upper Santa Fe Cretaceous-Paleozoic Precambrian (est.) *	surface 120 (37) 6,380 (1,945)	4,786 (1,459) 4,666 (1,422) -1,594 (-486)	120 (37) 6,260 (1,908)
u) Central New Mex. 1 Livingston Ctr. SE, NW, 16-3N-1E Socorro	8-37 11-28-39	GL5,000 (1,524) 2,978 (908)	Santa Fe Cretaceous? DL	surface 2,100? (640)	5,000 (1,524) 2,900? (884)	2,100? (640)
v) Grober 1 Fuqua NE, NE, 19-5N-3E Valencia	2-25-37 4-46	Topo 5,022 (1,531) 6,300? (1,920) Tertiary, Baca?	Qal/Santa Fe Tertiary, Baca? **	surface 4,550? (1,387)	5,022 (1,531) 372?(113)	4,550? (1,387) 1,750+ (533)
w) Humble 1 Santa Fe 660S, 660E, 18-6N-1W Valencia	1-29-53 11-18-53	GL5,092 (1,552) 12,691 (3,868) Cretaceous	Santa Fe Baca Cretaceous-Paleozoic Precambrian (est.)	surface 6,145 (1,873) 9,905 (3,019) 19,300 (5,883)	5,092 (1,552) -1,053 (-321) -4,813 (-1,467) -14,208 (-4,331)	6,145 (1,873) 3,760 (1,146) 9,395 (2,864)
x) Shell 2 Santa Fe 1650S, 660W, 29-6N-1W Valencia	3-29-74 9-29-74	GL5,194 (1,583) 14,305 (4,360) Triassic, Chinle	Santa Fe Baca Cretaceous-Paleozoic Precambrian (est.) L	surface 7,780 (2,371) 11,010 (3,356) 20,200 (6,157)	5,194 (1,583) -2,586 (-788) -5,816 (-1,773) -15,006 (-4,574)	7,780 (2,371) 3,230 (984) 9,190 (2,801)
y) Long 1 Dalies[2] 660N, 660E, 32-7N-1E Valencia	4-11-52 8-3-53	GL5,316 (1,620) 8,495 (2,589) Santa Fe	Santa Fe **	surface	5,316 (1,620)	8,495+ (2,589)
z) Shell 1 Isleta 810N, 640W, 7-7N-2E Valencia	10-24-74 7-18-75	KB5,066 (1,544) 16,346 (4,982)	Qal/Santa Fe Cretaceous-Paleozoic L	surface 12,040 (3,670) 18,410 (5,665)	5,044 (1,537) -6,974 (-2,126) -13,344 (-4,067)	12,040 (3,670) 6,370 (1,942)
aa) Norins 1 Pajarito Grant 279N, 2284E, 22-9N-1E Bernalillo	8-19-31 6-5-33	Topo 5,630 (1,716) 5,104 (1,556) Santa Fe	Santa Fe DL	surface	5,630 (1,716)	5,104+ (1,556)
bb) Shell 1 Laguna Wilson 2090N, 1780W, 8-9N-1W Bernalillo	9-21-72 12-25-72	KB5,415 (1,650) 11,115 (3,388) Precambrian	Cretaceous-Paleozoic Precambrian L	surface 11,102 (3,384)	5,394 (1,644) -5,687 (-1,733)	11,102 (3,384)
cc) Carpenter 1 Atrisco 660S, 660E, 28-10N-1E Bernalillo	8-16-48 9-29-48	GL5,793? (1,766) 6,652 (2,028) Santa Fe	eolian sand/Santa Fe **	surface	5,793 (1,766)	6,652+ (2,028)
dd) Shell 1 Santa Fe 1500S, 1070W, 18-13N-3E Sandoval	6-19-72 8-28-72	KB5,753 (1,754) 11,045 (3,367) Precambrian	Santa Fe Galisteo Cretaceous-Pennsylvanian Precambrian L	surface 2,970 (905) 3,144 (958) 10,955 (3,339)	5,733 (1,742) 2,783 (848) 2,609 (795) -5,202 (-1,586)	2,970 (905) 174 (53) 7,811 (2,381)
ee) Shell 3 Santa Fe 1652S, 2310E, 28-13N-1E Sandoval	4-19-76 6-28-76	Topo 6,290 (1,917) 10,276 (3,132)	Santa Fe Cretaceous Lit	surface 4,185 (1,276)	6,290 (1,917)	4,185 (1,276)

[1]Remarks: Tertiary intrusive at total depth, but in lower part Cambrian-Ordovician Bliss Formation; thus Precambrian at near total depth. Tertiary-Pennsylvanian contact probable fault.

[2]Remarks: Includes interbedded basalt flows and pumiceous tuffs.

Abbreviations:

* = samples and logs
** = samples
\# = scout tops
L = logs

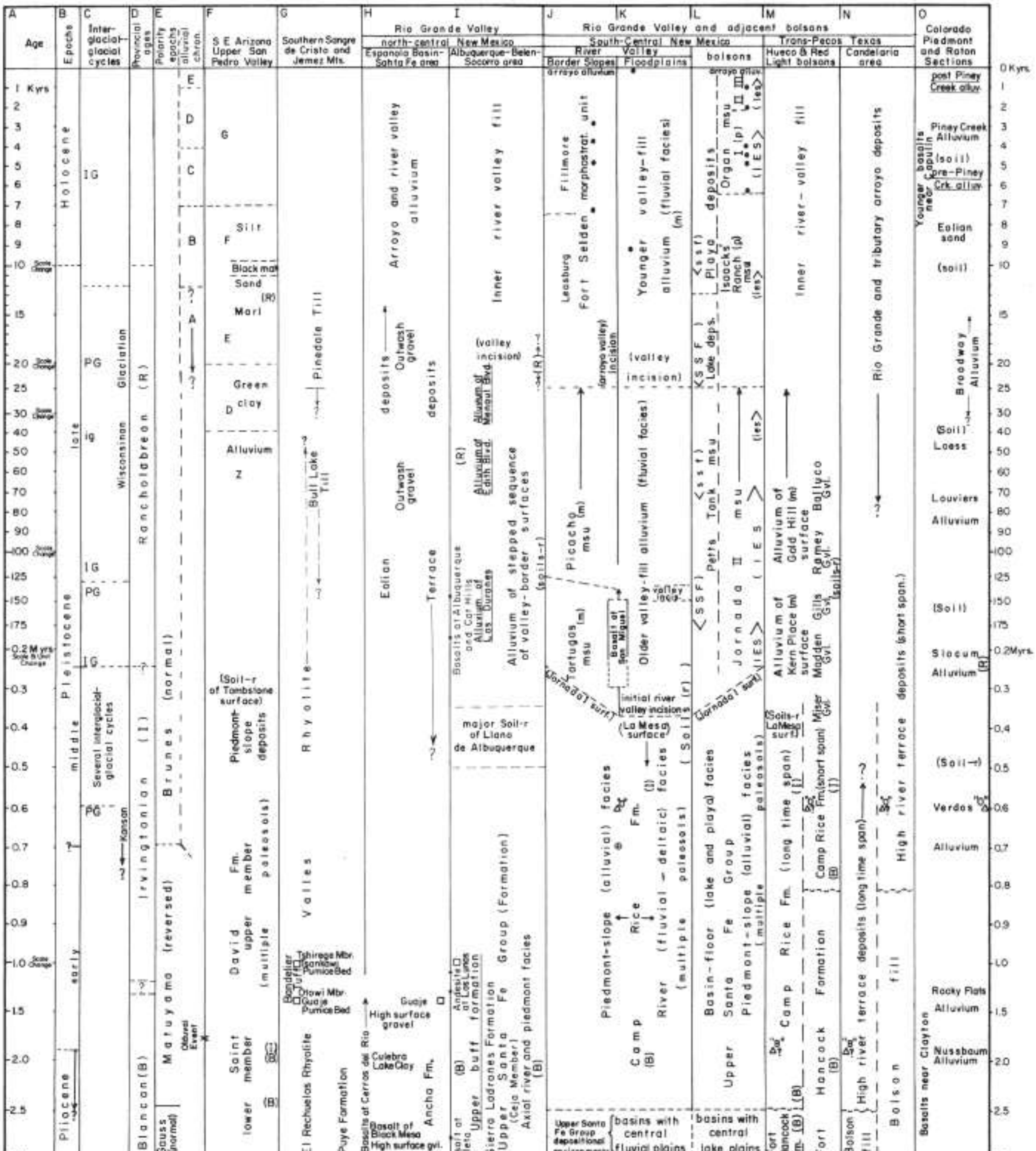
Lit = literature
DL = driller's log
Topo = topographic map
GL = ground level

KB = Kelly bushing
DF = drilling floor
est = estimate
Qal = Quaternary alluvium
TD = total depth

CORRELATION CHART 1—MAJOR QUATERNARY STRATIGRAPHIC AND GEOMORPHIC UNITS IN RIO GRANDE RIFT REGION

by J. W. Hawley

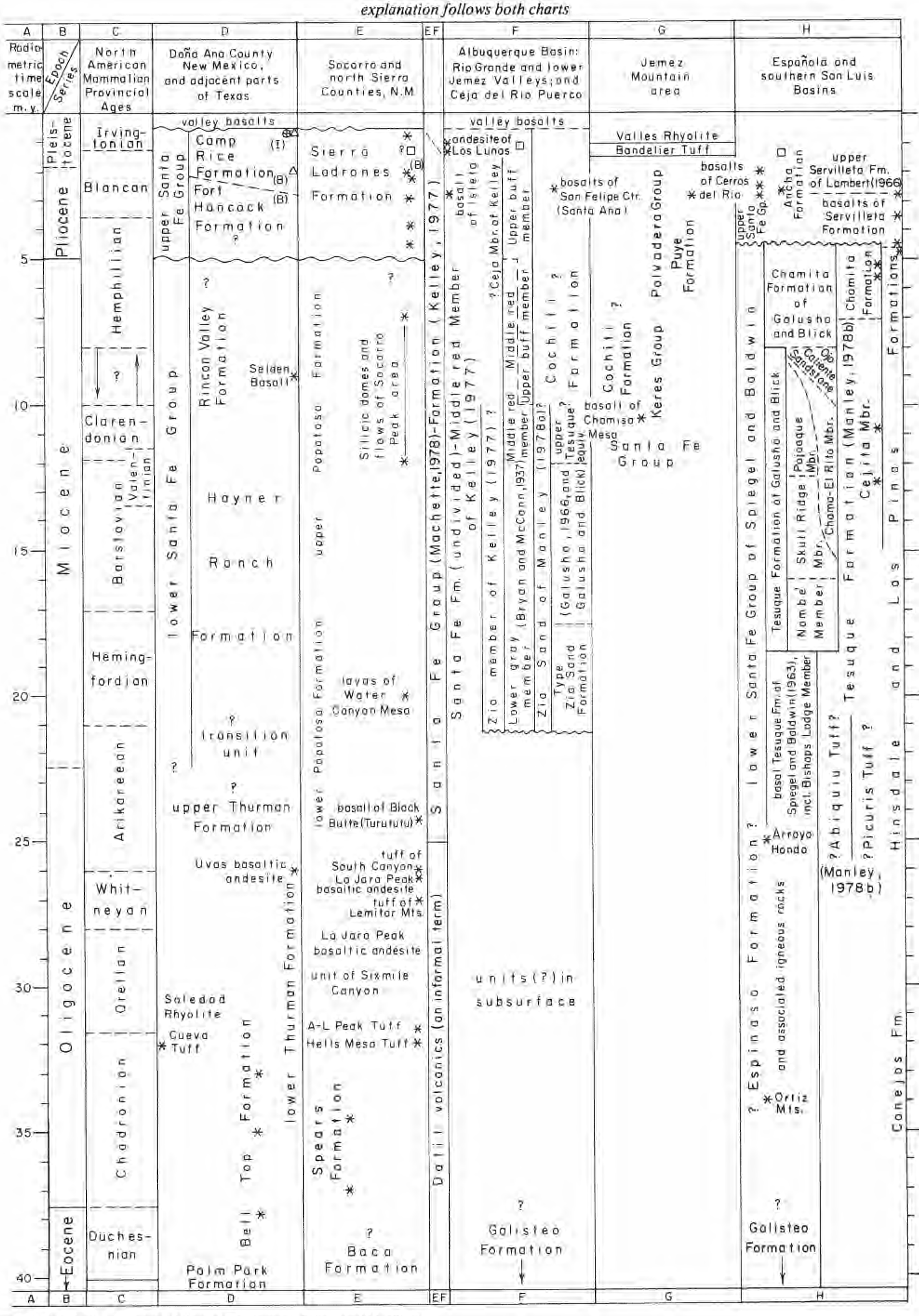
explanation follows both charts



CORRELATION CHART 2—MIDDLE TO UPPER CENOZOIC STRATIGRAPHIC UNITS IN SELECTED AREAS OF THE RIO GRANDE RIFT IN NEW MEXICO

by J. W. Hawley

explanation follows both charts



[New Mexico Bureau Mines & Mineral Resources, Circular 163, 1978]

Explanation – Chart 1

Chart adapted from Hawley (1975, table 2) and Hawley and others (1976, table 3)

Column C: Interglacial-glacial cycles
PG–full glacial IG–interglacial ig–interstadial

Columns D, I-K, M, O: North American mammalian provincial ages
(B)–Blancan (I)–Irvingtonian (R)–Rancholabrean

Column E: Alluvial chronology, southwestern United States
A to E–depositional units of Haynes (1968a)

Column F: Upper San Pedro Valley, Arizona
D to G, Z–valley-fill units of Haynes (1968b)

Columns F, I-K, M-O: Soils
(soil-r)–relict surface soil

Columns G-K, M-O: Volcanic ashes
□–Bandelier (Jemez) △–Pearlette (Yellowstone)
⊕–Bishop? (Long Valley, California)

Columns J-L:
●–Carbon-14 age of charcoal msu–morphostratigraphic unit
(m)–molluscan fauna (p)–pollen record

Column L: Dominant surface-geomorphic processes
(IES>, (ies>–instability, erosion-sedimentation
<SSF)–stability and soil formation >–decreasing process-intensity direction

Reference key – Chart 1

Column C: Kukla and others (1972)

Column D: Berggren and Van Couvering (1974), Birkeland and others (1971), Izett (1977)

Columns E, F: Birkeland and others (1971), Gray (1967), Haynes (1968a,b), Johnson and others (1975)

Column G: Bailey and others (1969), Clark and Read (1972), Doell and others (1968), Richmond (1963), Smith and others (1970)

Column H: Manley (1976), Manley and Naesser (1977)

Column I: Bachman and Mehnert (1978), Kudo and others (1977), Lambert (1968)

Columns J-L: Hawley (1975), Hawley and others (1976)

Column M: Albritton and Smith (1965), Hawley (1975), Kottlowski (1958), Strain (1966)

Column N: Groat (1972), Hawley (1975)

Column O: Birkeland and others (1971), Scott (1975), Stormer (1972)

Explanation – Chart 2

Chart compiled from entries in this guidebook and cited references

Columns D, E: North American mammalian provincial ages
(B)–Blancan (I)–Irvingtonian

Columns D-H: Volcanic ashes and radiometric dates
□–Bandelier (Jemez) △–Pearlette (Yellowstone)
⊕–Bishop? (Long Valley, California) ✱–K-Ar and fission-track (zircon) ages

Reference key – Chart 2

Columns B, C: Berggren and VanCouvering (1974), Galusha (1974), Izett (1977)

Column D: Chapin and Seager (1975), Clemons (1976), Hawley (1975), Seager (1973, 1975)

Column E: Bachman and Mehnert (1978), Chapin and Seager (1975), Chapin and others (1978), Machette (1978)

Column F: Bachman and Mehnert (1978), Bryan and McCann (1937), Galusha (1966), Galusha and Blick (1971), Kelley (1977), Kudo and others (1977), Lambert (1968), Manley (1978a)

Column G: Bailey and others (1969), Doell and others (1968), Smith and others (1970)

Column H: Bachman and Mehnert (1978), Galusha (1974), Galusha and Blick (1971), Lambert (1966), Lipman and Mehnert (1975), Lipman and others (1978), Manley (1978b), Manley and Naesser (1977), Ozima and others (1967), Spiegel and Baldwin (1963)

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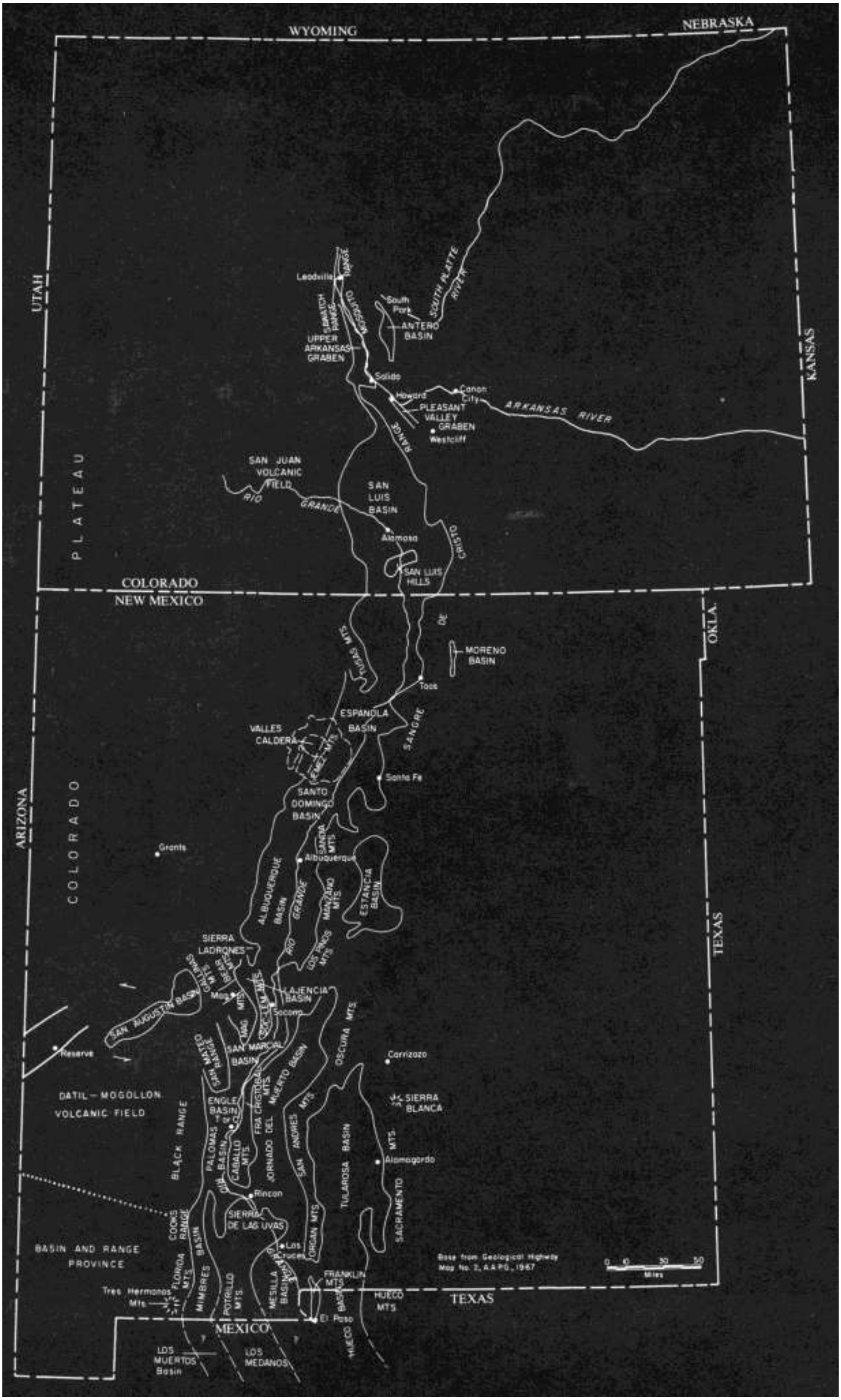
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