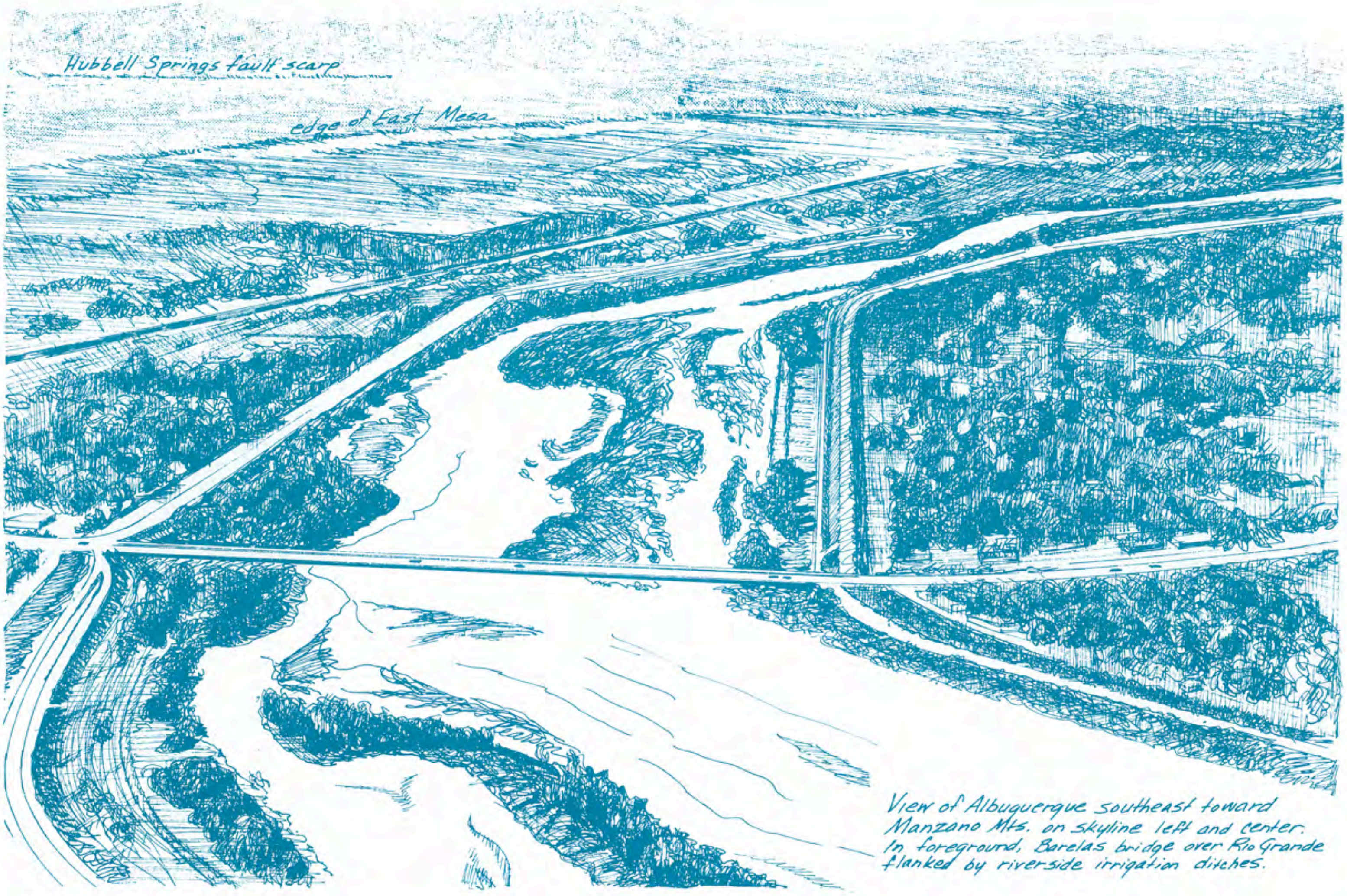
Geology of Albuquerque Basin, New Mexico

by VINCENT C. KELLEY



View of Albuquerque southeast toward Manzano Mts. on skyline left and center. In foreground, Barelas bridge over Rio Grande flanked by riverside irrigation ditches.

MEMOIR 33 New Mexico Bureau of Mines & Mineral Resources 1977

A DIVISION OF
NEW MEXICO INSTITUTE OF MINING & TECHNOLOGY

Memoir 33

New Mexico Bureau of Mines & Mineral Resources

A DIVISION OF
NEW MEXICO INSTITUTE OF MINING & TECHNOLOGY

Geology of Albuquerque Basin, New Mexico

by Vincent C. Kelley

SOCORRO 1977

NEW MEXICO INSTITUTE OF MINING & TECHNOLOGY
KENNETH W. FORD, *President*

NEW MEXICO BUREAU OF MINES & MINERAL RESOURCES
FRANK E. Kornowsiti, *Director*
GEORGE S. AUSTIN, *Deputy* Director

BOARD OF REGENTS
Ex Officio
Jerry Apodaca, *Governor of New Mexico*
Leonard DeLayo, *Superintendent of Public Instruction*

Appointed
William G. Abbott, 1961-1979, *Hobbs*
John M. Kelly, Treasurer, 1975-1981, *Roswell*
Owen Lopez, 1977-1983, *Santa Fe*
Dave Rice, Secretary, 1972-1977, *Carlsbad*
Steve Torres, President, 1967-1979, *Socorro*

BUREAU STAFF

Full Time

WILLIAM E. ARNOLD, *Scientific Illustrator*
ROBERT A. BIEBERMAN, *Senior Petrol. Geologist*
KATHRYN BRADLEY, *Secretary*
LYNN A. BRANDVOLD, *Chemist*
CORALE BRIERLEY, *Chemical Microbiologist*
CHARLES E. CHAPIN, Senior *Geologist*
RICHARD R. CHAVEZ, *Laboratory Technician IV*
RUBEN A. CRESPIN, *Laboratory Technician I*
Lois M. DEVLIN, *Office Manager*
Jim P. DoosoN, *Laboratory Technician I*
ROUSSEAU H. FLOWER, *Senior Paleontologist*
ROY W. FOSTER, *Senior Petrol. Geologist*
STEPHEN J. FROST, *Field Geologist*
JOHN W. HAWLEY, *Environmental Geologist*
STEPHEN C. HOOK, *Paleontologist*
BRADLEY B. HOUSE, *Metallurgical Technician I*
TERRI R. JARAMILLO, *Receptionist*
ROBERT W. KELLEY, *Editor & Geologist*
ARTHUR J. MANSURE, *Geophysicist*
NORMA J. MEEKS, *Secretary I*
CANDAcE H. MERILLAT, *Assistant Editor*
NANCY H. MIZELL, *Geologist*
KAREN D. PATTERSON, Secretary
NEILA M. PEARSON, *Scientific Illustrator*
JOAN PENDLETON, *Editorial Assistant*
JUDY PERALTA, *Executive Secretary*
CHRISTOPHER RAUTMAN, *Economic Geologist*
MARSHALL A. REITER, *Geophysicist*
JACQUES R. RENAULT, *Geologist*
JAmEs M. ROBERTSON, *Mining Geologist*
ROBERT SHANTZ, *Metallurgist*
W. TERRY SIEMERS, *Indust. Minerals Geologist*
JACKIE H. SMITH, *Laboratory* Technician *IV*
WILLIAM J. STONE, *HydrOgeOlOgiSi*
DAVID E. TABET, *Geologist*
JOSEPH E. TAGGART, JR., *Mineralogist*
SAMUEL THOMPSON III, *Petroleum Geologist*
ROBERT H. WEBER, *Senior Geologist*
DAVID L. WHITE, *Geochemist*
MICHAEL R. Wxy-rt, *Field Geologist*
MICHAEL W. WOOLDRIDGE, *Scientific Illustrator*
JULIE ZEPEDA, *Receptionist* (on leave)

Part Time

CHRISTINA L. BALK, *Geologist*
CHARLES B. HUNT, *Environmental Geologist*
JACK B. PEARCE, *Director, Information Services*
JOHN REICHE, *Instrument Manager*
ALLAN R. SANFORD, *Geophysicist*
THOMAS E. ZIMMERMAN, Chief *Security Officer*

Graduate Students

JULIE ATKINSON
SAM BOWING
ROBERT BROD
JO ANNE CIMA
DAVID MEYERSON
GLENN R. OSBURN
BRIAN K. PETERSON
DAVID PETTY
JUDY RUSSELL
CHARLES SHEARER

Plus about 25 undergraduate assistants

First printing, 1977

Available from New Mexico Bureau of Mines & Mineral Resources,
Socorro, NM 87801

Published by Authority of State of New Mexico, NMSA 1953 Sec. 63-1-4
Printed by University of New Mexico Printing Plant, October 1977

Price $9.50

Preface

In many ways, this work is the culmination of a career of studying the geology of New Mexico and adjoining parts of the Colorado Plateau and the Colorado Rockies. Very early in my career, I began work on uplifts adjoining the Albuquerque Basin, in particular the Sandia, Manzanita, Lucero, and Ladron uplifts. This work was done with both the U.S. Geological Survey and students at the University of New Mexico. Tectonic aspects of this work were expressed in the "Tectonic map of a part of the upper Rio Grande area, New Mexico" (Kelley, 1954). I continued my interest by writing several New Mexico Geological Society guidebook articles on the depression (Kelley, 1952), "Geology of the Caballo Mountains" with Caswell Silver (Kelley and Silver, 1952), and "Regional tectonics of the Colorado Plateau and relationship to the origin and distribution of uranium" (Kelley, 1955). However, current impetus for the work came mostly from a recent publication with Stuart A. Northrop entitled *Geology of Sandia Mountains and vicinity, New Mexico* (Kelley and Northrop, 1975). The unusual and well-displayed basin-border relationships between the Sandia uplift and the Albuquerque Basin allowed the logical and natural return to the Rio Grande depression (my own backyard) in the summer of 1974. In this work emphasis is on the basin—its internal stratigraphy, structure, and erosional history.

One can hardly overemphasize the importance of the works of Kirk Bryan, his students, and co-workers in laying the groundwork for our current understanding of geology of the middle part of the Rio Grande depression. Their early recognition of several depositional facies and informal stratigraphic members has been an important guide. Equally important were the recognition and naming of several erosional surfaces. Kirk Bryan, a product of the area because of his early training at the University of New Mexico, contributed greatly through an outstanding career devoted in large part to the Rio Grande depression (Bryan, 1938, p. 199).

During my work along the rift zone the following geologists, some professional and some students, helped in molding the concepts that are presented in this report: Charles B. Read, Gordon H. Wood, Jr., Charles B. Hunt, Walter H. Bucher, R. W. Duschatko, Earl P. Harrison, Phillip T. Hayes, Tom A. Fitzgerald, Charles B. Reynolds, Paul E. Soister, Alan E. Disbrow, Jerome E. Anderson, Edward C. Beaumont, Leon T. Silver, Paul W. Lambert, Bruce A. Black, Ned A. Noble, Brewster Baldwin, Zane Spiegel, Jock A. Campbell, Lee A. Woodward, A. M. Kudo, and Jon Callender. Special appreciation is extended to Russell E. Clemons who critically reviewed the manuscript. Curtis J. Little helped with data on recent deep wells drilled in the basin.

Dave Love, Barry Winters, and my son, Robert B. Kelley, helped at times in the field. Many ranchers allowed entry through their properties. Particular assistance was given by Fred and Jack Hunting, Weldon Burris, and Donald King of Estancia, Dwayne Luce of Bosque Farms, Orville Moore of Socorro, Alfred Baca of Bernalillo, Phillip Lauriano of Sandia Pueblo, and Sam Armijo of Santa Ana Pueblo.

Hassen Tinnen of U.S. Fish and Wildlife Service arranged entrance to the large La Joya land grant. Leroy Hacker of U.S. Bureau of Land Management provided airphotographs. William Hale, Walter Mourant, and Francis Koopman of the U.S. Geological Survey assisted with numerous problems.

Financial assistance was given by the New Mexico Bureau of Mines and Mineral Resources. In particular the author wishes to thank Frank Kottlowski and Robert Bieberman.

Vincent C. Kelley
Professor Emeritus
University of New Mexico

Albuquerque
May 12, 1977


Nacimiento Mts.
Valles caldera
Mt. Taylor
Rio Grande
Sandia Mts.
Albuquerque
Rio
Rio Puerco
Sierra Lucero
Manzano Mts.
N

Contents

TABLES

FIGURES

Frontispiece: facing page.
NASA LANDSAT 1, COLOR COMPOSITE BANDS 4, 5, AND 7. Scale: 1 inch to approximately 10 miles.
(courtesy Technical Application Center, University of New Mexico).

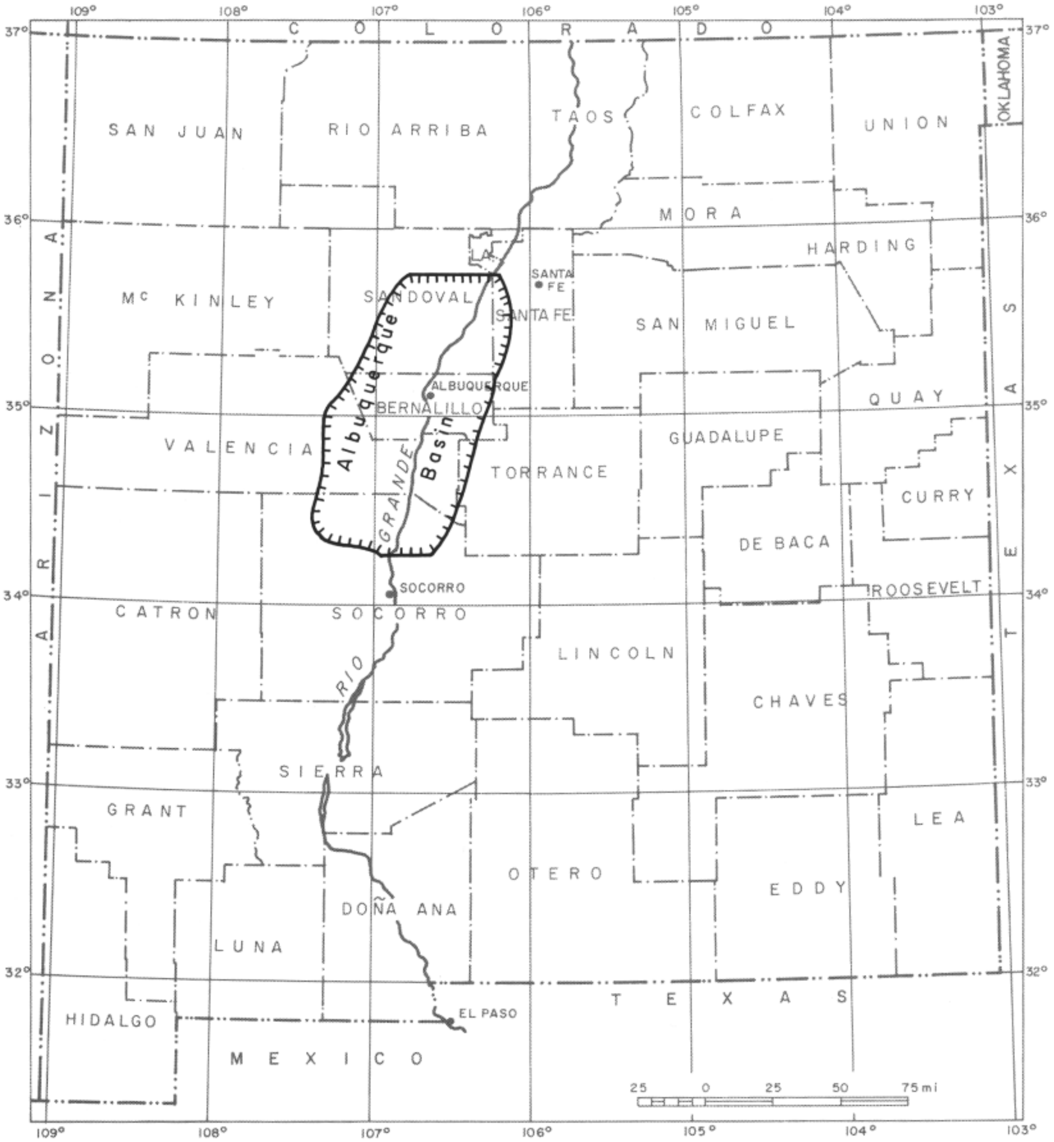


FIGURE 1—Location of Albuquerque Basin in New Mexico.

Abstract

The Albuquerque Basin of central New Mexico is about 102 mi long (north-south) and 25-40 mi wide (east-west). The Rio Grande, rising in Colorado and emptying into the Gulf of Mexico, flows southward through the basin which is surrounded by diverse Laramide and late Cenozoic uplifts. Several structural benches are delineated within the basin; fault scarps face the trough in most places. Ends of the basin are formed by convergence of side boundaries toward narrower structural and depositional channels that connect with basins north and south. The basin fill consists of up to 12,000 ft of sandstone, mudstone, and gravel of the Santa Fe Formation or Group (Miocene-Pliocene). In the northern part the fill is divided into the units of Bryan and McCann (1937) named in this report Zia, Middle red, and Ceja members. Elsewhere the fill generally is not divisible but may include equivalents of Zia and Ceja. Several facies of Santa Fe such as fanglomerates, playa, and river deposits and dunes are present. Late Pliocene deformation widened the basin, elevated the uplifts, and locally faulted and folded the Santa Fe. The deformation was followed by widespread pedimentation producing the Ortiz surface (probably early Pleistocene). Pleistocene and Holocene rejuvenation, deformation, and widespread dissection destroyed most of the surface. New correlations of Ortiz remnants are presented and the surface reconstructed. Numerous new faults are mapped and classified by relative ages, and several new folds and warpings of erosion surfaces are identified.

Introduction

The Albuquerque Basin is the middle part of the long Rio Grande valley which extends northward through the length of New Mexico (fig. 1). The area covered is 4,300 sq mi and extends from near the junction of the Rio Salado on the south to La Bajada escarpment and the White Rock gorge of the Rio Grande on the north. The map area, including strips of the bordering uplifts, averages about 42 mi wide and 102 mi long (fig. 1). The basin proper between adjacent uplifts is 25 to 40 mi wide. The ends of the basin open through narrow valleys and structural bedrock constrictions into the San Marcial Basin to the south and Espanola Basin to the north (Kelley, 1952, p. 92). Albuquerque Basin as used in this report includes the Albuquerque-Belen Basin of Bryan (1938, p. 213) and the Santo Domingo subbasin as delineated by Kelley (1952, p. 92).

The Albuquerque Basin is one of a long line of basins or troughs which were designated by Bryan (1938) as the Rio Grande depression. This depression was so named because the Rio Grande drainage system followed the intermontane basins through most of their known extent. Kirk Bryan clearly indicated the fault trough nature of the basins. Although he did not specifically so state, apparently he intended the Rio Grande depression to include only those basins and their borders along the drainage system. In 1952 I suggested the term Rio Grande rift belt (Kelley, 1952, p. 102) for the tectonics of the depression and indicated it to include the main alignment of grabens and adjoining uplifts that are an extension of the Rockies. Perhaps suggestion of the rift terminology was a mistake because many consider the term genetic (Willis and Willis, 1929, p. 81-82; Shand, 1938, p. 104-110). Rift trough or valley indicates an origin by extension and ramp trough by compression. Certainly not in 1952, and perhaps not even now, has there been enough thorough mapping and study to establish a conclusion that tends to close the door on other possibilities of origin. In retrospect, use of the term was motivated in part by evidence of strike-slip along the margins and the suggestion that rotational compressive stresses may have existed during the faulting.

The Albuquerque Basin is drained by two principal longitudinal streams, the Rio Puerco in the western part and the Rio Grande in the eastern part. Both streams are entrenched to several hundred feet into a former high level of basin filling still preserved in the long, narrow Ceja Mesa divide between the two streams. Remnants of this formerly widespread surface are preserved in the marginal strips of mesas to the east and west of the two longitudinal valleys. The Rio Grande, which follows the length of the basin, descends from about 5,320 ft at the bounding La Bajada fault in White Rock gorge to 4,700 ft at the Rio Salado junction, an airline gradient of 5.9 ft/mi. The principal uplift crests, along the eastern side of the basin, reach 10,678 ft at Sandia Crest. Altitudes and relief along the western side are much subdued by comparison, reaching 9,260 ft at one peak in the Ladron Mountains and 200-1,000 ft along the Lucero uplift. In a long stretch west of Albuquerque, there is no physiographic relief or rise at the structural edge of the basin. Absence of physiographic relief exists also locally along the eastern side of the basin north of the Sandia uplift.

Emphasis in this study is distributed into three principal aspects of the geology: 1) stratigraphy and sedimentational history of the basin deposits, 2) structure and regional tectonics, and 3) geomorphology. These aspects are considerably interrelated and description and analysis of each is contributory to the understanding of the others. Mapping was done on Army Map Service 1954 airphotos (scale 1:54,000) and reduced to the Socorro and Albuquerque 2-degree Army Map Service topographic bases that had been enlarged to a scale of 1:125,000. Geology of the border areas around the basin proper was taken from all available sources, commonly with modification or new mapping to fit the scale, needs, and purposes of the present work. The Precambrian terrane has been generalized everywhere into only two units, plutonic and metamorphic. Paleozoic and Mesozoic stratigraphy has been generalized into systems and/or groups (in a few instances).

The principal contribution is in the late Cenozoic basin and postbasin units as shown on the geologic map (in pocket) and described in the stratigraphy section. Another emphasis in this work has been on the predominantly andesitic to basaltic eruptions (intruded and extruded) within the basin. Results of this study form the basis for a separate publication by Kelley and Kudo (in press). Extensive new faulting and warping within the basin are mapped, described, and chronologically identified in many instances. Several stratigraphic sections of the larger, more nearly complete basin sections have been identified and measured.

Stratigraphy

Rocks of the Albuquerque Basin area are Precambrian to Holocene. Prebasin Precambrian, Paleozoic, and Mesozoic outcrops are almost entirely confined to the bordering rims of the basin or in small marginal embayments, benches, or minor inliers. Deposits directly related to basin subsidence and sharp marginal uplifts are probably all Miocene or younger. However, these sediments are not confined to the basin, and conversely the older rocks of the borders are also probably present in the basement of the basin or rift valley.

PREBASIN BEDS

Precambrian rocks have been widely exposed by border uplifting around the basin. Principal exposures are in the Sandia, Manzanita, Manzano, and Los Pinos Mountains (east of the trough) and in the Ladron Mountains (at the southwest corner of the basin). Lesser outcrops occur at the northern end of the Socorro constricti6n, which bounds the basin on the south, and very locally at the eastern base of the Lucero uplift. The principal Precambrian rocks are gneiss, schist, greenstone, and quartzite. Plutonic granitic rocks are present in large terranes of the Sandia, Manzano, Los Pinos, and Ladron Mountains. Representatives of these rock types are present either directly beneath basin fill or the oldest Paleozoic formations.

Paleozoic formations in the Albuquerque Basin are Mississippian to Permian and estimated original basin thicknesses are given in table 1.

Sediments are equally marine and nonmarine in origin. Aggregate thickness is not great originating from shelf and floodplain deposits.

Mesozoic formations range from Upper Triassic to Upper Cretaceous, and the character of the three systems contrasts distinctly in lithology and depositional types. Formations and estimated original basin thicknesses are given in table 2.

TABLE 1—Estimated original thicknesses (in feet) of Paleozoic formations in Albuquerque Basin.

	NW part of basin	NE part of basin	SE part of basin	SW part of basin
Permian:				
Bernal (sandstone, limestone, gypsum)	––––	0-100	100	100
San Andres (limestone, sandstone)	200	200	200	500
Glorieta (sandstone)	200	200	0-100	0-200
Yeso (sandstone, mudstone, gypsum)	200-500	500	1,200	1,100
Abo (red sandstone & mudstone)	650	900	800	850
Pennsylvanian:				
Madera (limestone, shale, sandstone)	0-700	800-1,200	1,200	1,700
Sandia (sandstone, shale, limestone, conglomerate)	0-200	200	250	300-400
Mississippian: (limestone, shale)	0-100	0	0-50	0-400
Totals:	1,250-2,550	2,800-3,300	3,750-3,900	4,550-5,250

TABLE 2—ESTIMATED ORIGINAL THICKNESSES (IN FEET) OF MESOZOIC FORMATIONS IN ALBUQUERQUE BASIN.

	NW part of basin	NE part of basin	Central basin	SE part of basin	SW part of basin
Cretaceous:					
Mesaverde	1,000-1,500	3,500	2,000	3,000	3,000
Mancos	1,200-1,400	1,500	900	1,000±	500
Dakota	100	100±	100	100±	100±
Jurassic:					
Morrison	900	500-800	500	200-300	500-1,000
Todilto	100	200	0-100	0-100	0
Entrada	200	200	0-100	100	100
Triassic:					
Chinle	1,500	1,500	1,000	500-1,000	0-500
Santa Rosa	200	200	150	100	0-100
Totals:	5,200-5,900	7,700-8,000	4,650-4,850	5,000-5,700	4,200-5,300

Triassic deposits are dominantly floodplain and playa. Jurassic deposits (also continental) consist of eolian sandstone, evaporitic gypsum and limestone, and the Morrison playa, floodplain, and eolian deposits. Cretaceous beds are marine and nonmarine floodplain deposits.

The principal early Cenozoic deposit of the area is the Galisteo Formation (Eocene) consisting of sandstone, variegated mudstone, and conglomerate as much as 3,000 ft thick in and bordering the northern part of the basin. The Galisteo is present in the Hagan embayment, along La Bajada escarpment, west of Placitas, south of the Zia Pueblo, and locally near the eastern base of the Jemez uplift.

In the southern part of the basin is the Baca Formation (probably also Eocene). Thin outcrops occur in the Socorro constriction, locally east and north of the Ladron Mountains, and locally at the base of the Manzano uplift west of Osha Peak. Similar beds might underlie the southern third of the basin. The beds in the dissected pediment at the base of the Manzanos are salmon-colored conglomerate, sandstone, and mudstone several hundred feet thick. Lithology is predominantly nonvolcanic and tannish-brown sandstone fragments (Permian). Limestone and Precambrian clasts are absent suggesting either an early or pre-Santa Fe unit.

Several post-Eocene to prebasin units are also present and include:

1) Datil Formation (tuff, tephra, and intermediate to felsitic breccias, and flows); several thousands of feet of bedded material in the Socorro constriction and the Popotosa Formation at the eastern base of the Ladron uplift; and tuff at the base of the Manzanos west of Osha Peak.
2) Espinaso Formation (intermediate bedded tephra or volcanic fanglomerate) in the Hagan embayment and La Bajada constriction.
3) Early Jemez volcanics and intrusions (basalt, andesite, and dacite) in the Bland mining district locally in the southeastern part of the Jemez uplift.

Variations in the thickness of formations are in part original, but greater differences in thickness are caused by erosional truncation. The first of these occurred in late Pennsylvanian and Permian as described by Read and Wood (1947). Typical warping along northerly-trending axes began in middle Pennsylvanian. Uplifted axes probably received less sediment (or possibly none) and subsequently onlapped or overlapped with thinner deposits. Alternately some uplifting was rapid or sufficient enough to cause removal of early deposits. Read and Wood identified two uplift axes with thin or thinned sequences of Pennsylvanian beds. One of these, Pefiasco, roughly coincided with the southern end of the Nacimiento uplift (Laramide) where it impinges the northwestern edge of the Albuquerque Basin. The other, Joyita axis, was identified at the southern end of the basin in the eastern side of the Socorro constriction. A line between these two roughly follows the length of the Albuquerque Basin, and along this line the subcrop of the Pennsylvanian is inferred to be thinned or absent.

The second disturbance, which may considerably influence existing thickness in prebasin rocks, took the form of an east-west hinge line lying approximately at the latitude of Isleta. South of this axis the crust was upwarped broadly across the state in Late Jurassic through Early Cretaceous. Accompanying subsidence, north of the hinge line, allowed Middle to Late Cretaceous transgression to bevel the southern area thus truncating or removing most of the Jurassic and possibly some of the Triassic beds in the southern part of the Albuquerque Basin.

The existence of Laramide deformation, the last disturbance reducing thickness of prebasin beds, and

TABLE 3—TOTAL ESTIMATED AND AVERAGE THICKNESSES (IN FEET) OF PALEOZOIC AND MESOZOIC FORMATIONS.

	NW part of basin	NE part of basin	Central basin	SE part of basin	SW part of basin
Total	6,400-8,450	10,500-11,300	–	8,750-9,600	8,750-10,500
Average	7,425	10,900	–	9,175	9,625

accompanying erosion in the area is well documented along the Rio Grande rift zone (Stark, 1956; Kelley and Silver, 1952; Jacobs, 1956; Kelley and Reynolds, 1954). Much evidence is based on the presence of deformation such as overthrusts, high-angle thrusts, diagonal folds, and wrench faults that are not compatible with horsts and grabens. Some evidence is based upon stratigraphic relationships such as Eocene beds lying unconformably upon Cretaceous beds (Black and Hiss, 1974, p. 368; Disbrow, 1956; Kelley and Northrop, 1975, p. 91; Black, 1964). Specific places of direct evidence in the basin are south of San Ysidro where Galisteo Formation is unconformable on Mancos and Mesaverde Formations and near Placitas where Galisteo Formation truncates Mesaverde Formation, which in turn is truncated by early basin-filling sediments.

Apparently much more evidence exists in the basin subcrop. Much of the subcrop is expected to be late Laramide with earliest basin deposits lying unconformably on prebasin deposits including terranes as old as Precambrian. Furthermore, considerable early basin (Oligocene to Early Miocene) deformation and erosion may have resulted in upper basin (especially Pliocene) deposits lying unconformably on early basin deposits or earlier deposits. As explorations of the subcrop progress, more complexity of prebasin structure will be seen. More on these concepts is presented in the chapter on structure.

SANTA FE AND OTHER BEDS

Basin deposits are of two types: 1) bulk of the sediment that has filled the subsiding trough and does not have a direct relationship to late Pleistocene and Holocene landforms, and 2) floodplain deposits, terraces, dunes, alluvial fans and cones, spring deposits, caliche blankets, landslides, and some pediments—all directly expressing present landforms. The latter group of deposits represents processes of erosion and deposition which may have prevailed throughout subsidence and filling of the basin. The Santa Fe Formation, which represents the great bulk of the basin fill, undoubtedly contains many of the kinds of sediment of the second type. However, the Pleistocene Ortiz and all younger deposits are not included as part of the Santa Fe because of the expression of their unconformable and local occurrences as in present landforms.

The name Santa Fe marls was given by Hayden (1869, p. 60, 69) to beds exposed north of Santa Fe. The term was intended for the thick sequence in the Tesuque and Espanola valleys. Johnson credited Hayden for the name Santa Fe marl group and applied it to the late Tertiary gravel beds in the Cerrillos Hills area including gravel on the Ortiz surface of planation (Johnson, 1903, p. 313, 472). Johnson (1903, p. 313-332) reviewed at length the early literature on the Santa Fe marl group in the Cerrillos area and concluded that its age ranged from Loup Fork (Miocene, Pliocene, and Pleistocene?) to the present time. Johnson's early recognition of a community of depositional and provenance environments is important in our current efforts on stratigraphic status. Some 20 years of terminology mellowing followed Johnson's critical considerations, and by 1922 (Darton, p. 187) the oneness of the depositional environment (despite a variety of lithologies) was so recognized as to result in the first use of the term Santa Fe Formation.

In 1938 after much regional study of the basin-fill sediments Bryan (1938, p. 205) observed that "The main body of sedimentary deposits of the Rio Grande depression, from the north end of the San Luis Valley, Colorado to and beyond El Paso, is considered to be of the same general age and to belong to the Santa Fe Formation." This term was extended widely to deposits along the Rio Grande valley, and also out of the valley (especially in southern New Mexico) to similar deposits and to some deposits in the Rio Puerco, Estancia, and Jornada Del Muerto valleys (fig. 2). Recognizing the commonness of tectonic setting and depositional environments, together with the potential for mapping subdivisions and correlation over wide areas, Kelley (1952, p. 102) suggested usage of group status for the Santa Fe to all the trough-filling beds including pedimentary and alluvial fan beds. Subsequently, I have come to believe that the term group should not be used until the succession can be better and more consistently divided. In the present work the named and

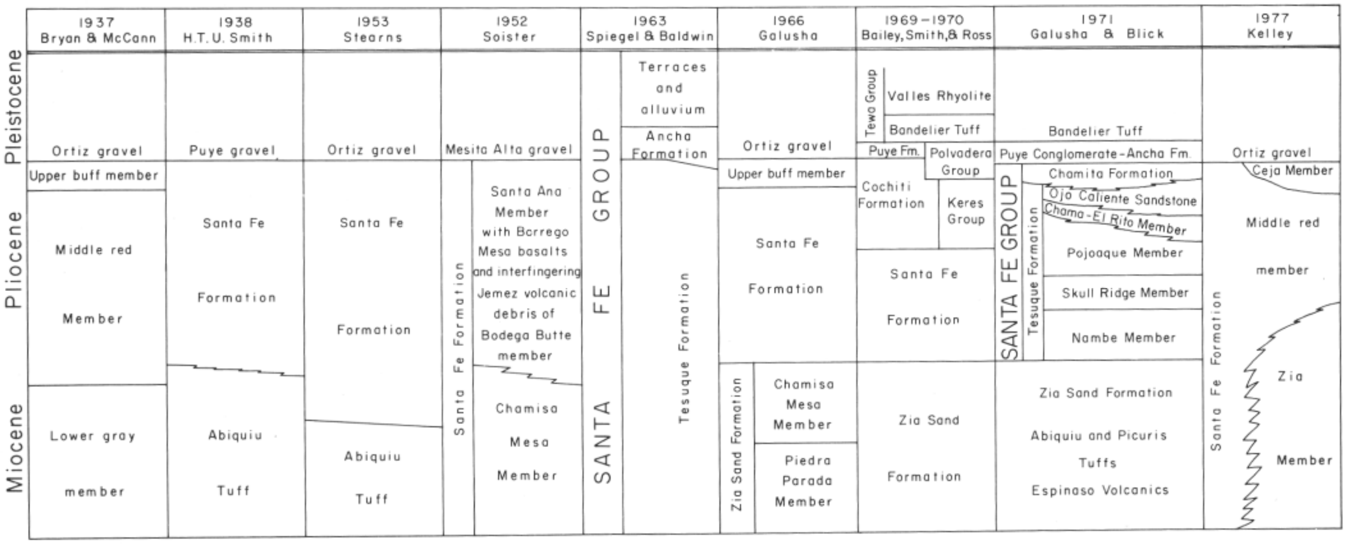


FIGURE 2—NOMENCLATURE CHART OF SANTA FE BEDS IN THE ALBUQUERQUE AND ESPAÑOLA BASINS.

mapped units are not distinctive enough to warrant more than member status. Spiegel and Baldwin (1963, p. 37-39) used the term Santa Fe Group for Quaternary terrace and pediment gravels as well as Tertiary beds and volcanic flows in the Rio Grande trough and adjacent areas. They also proposed extending the name in a group status to include the Abiquiu formation of Smith (1938, p. 301) and Stearns (1953a, p.477, pl. 1).

In Sandoval County, Galusha (1966, p. 4-7) defined and delineated the Zia sand formation (current U.S. Geological Survey usage) to beds previously referred to as the Lower gray member of the Santa Fe (Bryan and McCann, 1937) and retained the term Santa Fe Formation for most of the overlying beds. Hoge (1970, fig. 6) included the Zia with the Santa Fe by employing the term Tesuque Formation used in the Espanola Basin by Baldwin (1956, p. 115-116) for the main body of the Santa Fe exclusive of Quaternary insets and terraces related to the present Rio Grande inner valley. Hoge recommended substitution of Zia sand formation for Abiquiu formation as extended into the Santo Domingo Basin area by Stearns (1953a, pl. 1).

More recently Galusha and Blick (1971, p. 30) suggested restricting the term, Santa Fe Group, to occurrences in the Espanola Basin and described it as consisting of two formations: the thick and extensive Tesuque below and the lesser Chamita at the top. The base of the Tesuque and the Santa Fe Group as defined by Galusha and Blick (1971, p.37-48) would lie on such trough units as Abiquiu, Picuris, and possibly Espinaso. Galusha and Blick (1971, p. 39) recommended against extending the type Santa Fe term outside the Espanola Basin but at the same time applied Tesuque Formation to the Middle red unit of Bryan and McCann (1937) in the Jemez Creek area. By volume and occurrence the Tesuque is so nearly identical with the type Santa Fe as to possibly cause abandonment of the long accepted and well-known Santa Fe term in favor of Tesuque. However, whether the term Santa Fe be used as a group or formation depends upon the need for mappable subdivisions; group status might be desirable in the Santa Fe and Espanola areas but not in the Albuquerque Basin. I differ from Spiegel and Baldwin (1963, p. 38-39) by excluding the Ortiz gravels from the Santa Fe in the Albuquerque Basin. In the Albuquerque Basin subdivisions are so variable and exposure is so incomplete as to make group usage unnecessary.

I subscribe strongly to Bryan and McCann's (1937, p. 807) conclusion that the term Santa Fe Formation may be properly extended to the Albuquerque-Belen Basin "on two lines of evidence: 1) fossil evidence of equivalent age, and 2) continuity of slightly dissimilar and deformed alluvial deposits extending from the city of Santa Fe southwestward to the area." Retention of the term Santa Fe and the inadvisability of extending the term Tesuque to the Santo Domingo or Albuquerque areas was discussed by Kelley and Northrop (1975, p. 68).

In the Albuquerque Basin south of the Jemez Mountains, Soister (1952, fig. 4) divided the Santa Fe into three members from the three informal terms proposed by Bryan and McCann (1937, p. 816-817) for the middle Rio Puerco valley area. In the Santo Domingo area Anderson (1960, p. 20-36) divided the Santa Fe Formation into (ascending order): the Tano, Domingo, and Cochiti members. His Tano overlaid a unit, which he identified as Bishops Lodge Member (Kottlowski, 1953, p. 148; Spiegel and Baldwin, 1963, p. 43) but which roughly corresponds to beds of Zia or possibly Abiquiu (Smith, 1938; Stearns, 1953, p. 469). In 1969 Bailey, Smith, and Ross (p. 8-9) described and named the Cochiti Formation as lying above the Santa Fe Formation in the southern and southeastern part of the Jemez Mountains. They recognized that the Cochiti beds graded into red sandstone and mudstone of the Santa Fe along the western side of Santa Ana Mesa. These red beds are indeed the Middle red member of Bryan and McCann as shown on the geologic map (in pocket) and by Spiegel (1961). They are the heart of the Santa Fe, and therefore the Cochiti member is at best only a facies of the Santa Fe Formation. As early as the late forties there was recognition of the intertonguing and gradation of Jemez volcanics with the Santa Fe in the southeast quadrant of the Jemez area (Kelley, 1952, p. 94). Bailey, Smith, and Ross (1969) made a fine contribution in showing the identity of this part of the Santa Fe with K-Ar dates of 8.5 to 9.1 m.y. on dacites. However, mapping the unit well into central areas of the basin (Smith, Bailey, and Ross, 1970) was a mistake, especially without experience in the larger basin stratigraphy.

During the present work, the Santa Fe was at first mapped as a single unit hoping that divisions might be found that could be mapped with some persistence. Much of the problem lies in the great differences of thicknesses and the exposure of only the upper part of the formation in most of the basin. Considerable portions of the whole formation are exposed in only about four places: 1) Gabaldon badlands just east of Lucero uplift, 2) east of Ladron Mountains, 3) Maria Chavez Arroyo north of Sandia Mountains, and 4) around the northern end of Ceja Mesa. The Gabaldon section is the thickest and best exposed, but the lower part of the subsurface might be two or three times as thick as the surface exposure, but this is doubtful. The east Ladron exposures are considerably faulted, and their relationship to the underlying Popotosa Formation needs further study to determine whether the Popotosa is in part or entirely a facies of the Santa Fe. At the only unfaulted contact in the type area of Popotosa Creek, southward-dipping Santa Fe sandstone and mudstone appear to overlie Popotosa fanglomerate in near conformity (geologic map, sec. 35, T. 2 N., R. 2 W.). The Maria Chavez section, although beautifully exposed, cannot be well analyzed to a position above the base of the Santa Fe. The most complete exposures are those of the northern Ceja area, but they are thin compared to most of the basin. This is the area where Bryan and McCann made their three-fold subdivision, although they mapped them only locally and generally. Findings during the present work show that these divisions are the only ones traced in any extent. Poor exposures, faulting, and considerable lateral lithologic change cause problems in extending these divisions. Bryan and McCann made the following informal member designations: Lower gray, Middle red, and Upper buff. Soister (1952) found and mapped the lower two along the south side of the Jemez Mountains. His equivalent names, Chamisa Mesa and Santa Ana, are not adopted in this memoir chiefly because Galusha has more formally introduced the name Zia sand formation (which essentially matches the Lower gray). The Upper buff is mapped as far as it can reasonably be extended and is named the Ceja Member in this report. Inasmuch as the Middle red unit is the only unit of the three that is widespread in the basin, to give this unit a separate formal name is unwise as it would be essentially identical with Santa Fe in areas with no Ceja or Zia beds. Therefore, in this report, the unit is simply designated as the main body of the Santa Fe Formation or in places Middle red member.

Since all the members of the Santa Fe in the Albuquerque Basin that have been identified or mapped contain lithic facies of one another, and numerous occurrences of lateral stratigraphic change are present, having vertical subdivisions in the Santa Fe Formation probably is not needed. Perhaps the greatest differences are those of color and composition that apparently result from different source materials. Thus, in the main body of the Santa Fe, alternations of reddish brown and light greenish gray are very common. Many of the fine sands and muds appear to have been derived from Cretaceous or Morrison shales, mudstones, and sandstones. These characteristics are most prevalent in the Zia or Lower gray member. Reddish-brown or purplish-brown and buff mudstone and sandstone are prevalent in the Middle red or main body member; these may have come from Permian and Triassic terranes. Another source facies, which occurs marginal to the Jemez volcanic area, commonly consists of white, gray, buff, or brown tuff or tephra that grade and interfinger with volcanic fanglomerate.

One facies deposited by rivers, such as the present Rio Grande, along the longitudinal axis of the basin has long been recognized (Bryan, 1938, p. 206-207). These deposits are typically rounded gravels with fragments different from the rocks found in the adjacent borders. Such river facies also contain floodplain silts, muds, and sands wtih little or no gravel.

Another facies is fanglomerate derived from the nearby mountain sources. These deposits are found in upturned Santa Fe beds next to the Sandia and Lucero uplifts and locally around the Jemez uplift. Some of these fanglomerates show further compositional facies that consist of volcanics, granites, or limestone (caused by clasts). In general, the gravelly facies, regardless of composition, occur mostly in the upper part of the Santa Fe. However, in the Zia Reservation south of Jemez River pebbly gravel occurs in the upper part of the Zia (Lower gray) member, in the Middle red, and in the Ceja (Upper buff) Member.

Another facies consists of buff to reddish-brown, fine-grained to very fine grained sandstone and gray to reddish-brown mudstone apparently representing extensive playas. These are best seen in the tilted thick sequence of the Gabaldon badlands east of the Lucero uplift.

A final facies is eolian and may be widespread in the basin, but is most typically illustrated by the Zia member. This is especially true at its type locality and northward in the Jemez Pueblo area.

ZIA MEMBER

The term Zia is taken from Galusha's (1966) unit Zia sand formation. The use of "sand" is hardly necessary as he describes the unit as consisting of sandstones. Zia Sandstone (current U.S. Geological Survey usage) might be more appropriate as the unit is predominantly sandstone, even in adjoining areas where it contains mud and gravel. In the township east of the Zia-type locality, a contact between Bryan and McCann's Lower gray and Middle red members (fig. 2) has been traced into the top of the Zia at the type area. In the Zia badlands and north of Jemez River valley, Zia-type lithology is intercalated and interfingered with the Middle red Santa Fe beds. Likewise south of the type locality in the Rio Puerco drainage, the Zia grades into typical Santa Fe red beds (Middle red) lithologies. The Middle red above the Zia at Galusha's type section is much less red and more sandy than in areas east and south. Thus, the type area continued to deposit Zia-type sand after Zia time.

Generally it is not correct or possible to map formations or members on the basis of fossils alone, especially scattered remains of vertebrates. The vertebrate paleontologists may identify a fossil find as Miocene, Hemingfordian, or some other age but this identification is not sufficient to assign the beds to a certain formation or member. Such things as the mappability through cover, dip changes, and faults make it tenable. Mapping Galusha's upper (Chamisa) member of the Zia away from the area where he named it (along Pueblo Arroyo, east of Jemez Pueblo) is impossible. Galusha could not have traced the bed back to the member at the type locality because he mapped (Galusha, 1966) most of the Zia badlands east of the type locality erroneously as Upper buff. Galusha (1966) further states that lithic as well as faunal evidence are entirely lacking for correlation of the Lower gray with the Santa Fe. With regard to lithology, Galusha is mistaken as numerous reddish fine-grained sandstones, mudstones, and even gravel typical of Santa Fe occur (especially in the upper part) and white or light-gray, Zia-type sandstones occur in the Middle red. Soister (1952, fig. 4) mapped all the beds in the flanks of Chamisa and Borrego Mesas as Zia rocks, although he used the term Chamisa Mesa formation. On the other hand, Smith, Bailey, and Ross (1970) mapped nearly 1,000 ft of Santa Fe beneath the basalt cap of Chamisa Mesa, and this would embrace at least a part of Galusha's Zia sand formation. It includes a number of salmon-pink sandstones and some thin mudstones in the part measured by Galusha as Zia. Additionally, pinkish sandstone ledges, similar if not identical to those above the type measured section, are present in the upper part of the Zia-type formation. Galusha also noted that many of the fossils collected in the Rio Puerco drainage are equivalent to those from the uppermost beds west of Chamisa Mesa section. Evaluation of this comparison is difficult because the location or positions in the Rio Puerco area are not identified. The Rio Puerco exposures are in several separate, usually faulted and incomplete sections; outcrop continuity with the type area does not exist.

Mapping and measurement of sections along the Rio Puerco suggest that the much thinner, typical Zia sandstones are equivalent to the lower ones at the Zia-type section. The high Zia beds at the type area appear to grade into salmon-pink sandstones and interfinger with reddish-brown mudstone typical of the Middle red or main body of the Santa Fe. These introductory remarks show that the Zia is Santa Fe just as the Lower gray was defined to be by Bryan and McCann (1937). The same is true of the Upper buff (named Ceja Member in this report).

From surface exposures and the limited samples and descriptions from wells, the Zia member in its type facies is restricted to the northern part of the basin. The southernmost occurrences lie west of the Rio Puerco a short distance north of 1-40. These outcrops were first described by Wright (1946, p. 402-403) and were later mapped and described by Campbell (1967, p. 36-38). Wright measured the Zia thickness to be 250 ft, and Campbell,)35 ft.

Typical' Zia Sandstone is light gray, medium gray, light buff, or light pink. The light-pink and salmon-pink sandstone commonly appear much redder when wet or damp. The Zia may be thin bedded to thick bedded or massively bedded; thick crossbedded units are common. Texture is medium to coarse, but some of the higher beds are fine grained. Grains are typically subrounded and consist of clear quartz, red, black, and gray chert grains. Mica and feldspar are rare to absent. Much of the sandstone is poorly cemented and friable, but it commonly forms steep slopes and local cliffs. One of the more distinguishing aspects is local concretionary cementation forms. Some of these are along the bedding, whereas others take tubular, roll, or ball forms. Larger masses commonly resemble man-made masonry forms such as gutters or curbs. Pellet and marble sized concretionary masses are common, and locally calcite sand crystal aggregates are present. Although calcite is the common cement, local silicification of thin beds is present. As stated in the introductory remarks, buff to light-pink sandstone, reddish-brown mudstones, and pebbly conglomerate occur in the Zia, especially to the east and northeast of the type locality.

The largest area of outcrop lies in the Zia, Jemez, and Santa Ana Indian lands along, and north and south of, the Jemez River. In much of this area, outcrops are poor to absent. Much eolian, Holocene sand (derived from the Zia) covers the formation; some of these sand blankets have been stabilized and slightly indurated to the point where they may be mistaken for Zia outcrops. Exposures are very poor and quite spotty in the large Zia terrane north and east of Zia Pueblo. In this area local exposures of red rocks could easily be termed Santa Fe. Attempts to map Middle red type Santa Fe apparently fail, partly for lack of outcrops; but the main reason may be that they are part of the Zia member. The efforts of Smith, Bailey, and Ross (1970) to separate Santa Fe from Zia in the Indian reservations north of Jemez valley does not hold well. Much of the area mapped as Santa Fe has far more white Zia type sandstone than the local pinkish sandstone used as the basis for separation south of Chamisa Mesa; the sandstone on the downthrown sides of the faulted Mancos Shale inliers is Zia. Furthermore, in the area mapped as Zia, reddish Santa Fe-like sandstone and mudstone may be found. Additionally the south-running swath of Santa Fe, which was mapped either side and especially west of Arenoso Arroyo, has much exposure of typical Zia Sandstone; if the swath is projected south across the Jemez River, it conflicts with the main belt of type Zia. Soister (1952, fig. 4) better mapped all this as Zia although he termed it Chamisa Mesa member. In addition Smith, Bailey, and Ross separated another part of the Santa Fe which they designated Cochiti Formation which overlies Santa Fe Formation. The Cochiti is mapped and described as interfingering with several parts of the Keres Group (Pliocene). The Keres Group consists of flows, tuffs, and breccias ranging from rhyolite to basalt. This formation is considered by Smith, Bailey, and Ross to be older than the Tschicoma Formation (Pliocene) (Smith, 1938). They also mapped their Cochiti in a wide southward-extending swath east of their Santa Fe, but everywhere separated from it by the Santa Ana fault. As mapped in this swath, the Cochiti along the west face of Santa Ana Mesa includes a large thickness of typical Middle red Santa Fe beds. The Cochiti Formation (Bailey, Smith, and Ross, 1969, p. 8-9) is formally defined as a thick sequence of volcanic gravel and sand consisting of basalt, andesite, dacite, and rhyolite detritus. The Cochiti beds are simply a volcanic-bearing facies of the Santa Fe, mostly of the Middle red member, but possibly also some of the Zia in the upper part. Again Soister (1952, fig. 4) more correctly represented this Jemez volcanic facies as his Bodega Butte member of the Santa Fe. Being a facies derived from volcanic and other older rocks (some granitic) in the Jemez, its characterizing beds grade and thin into the more regular Santa Fe beds south and southeasterly in the basin. Boulders and cobbles may be seen to give way gradually to pebbles, granules, and coarse sand southward, especially along upper Borrego Canyon and in the many arroyos along the Santa Ana reservation road leading north from the Pueblo. This facies, like all facies in flat-lying beds, is essentially impossible to map rigorously because its lithologies intertongue up and down sections as well as laterally and longitudinally with respect to the direction of transport. Volcanic gravels occur west of the limits used by both Soister and Smith and others. These problems have caused me, after much field effort, not to map separate units of the Santa Fe Formation north of the Jemez or west of the Rio Grande (north of its junction with the Jemez).

At the type locality, Galusha measured about 1,000 ft of Zia. A bar line on the geologic map shows the approximate line of his section. The section crosses a fault where it underlies a small pediment-capped mesa. Movement on this fault may have decreased the thickness by about 100 ft. Thickness of the Zia decreases south-southwesterly in outcrops along the Rio Puerco valley. In a small isolated occurrence between the Navajo and Garcia faults 7 mi to the southwest of the type section thickness is 600-700 ft. About 6 mi farther south the thickness is about 245 ft with about 83 ft of reddish-brown mudstone at its top and Cretaceous unconformably beneath. The next exposure, on the Benevidez ranch about 3.5 mi to the southwest, is similar as shown in table 4.

TABLE 4—Benevidez Ranch section (sec. 34, T. 12 N., R. 1 W.).

Unit	Description	Thickness (ft)
	Top of second hogback (total thickness)	249
12	Sandstone: gray to light-tan, thin-bedded, medium-grained to coarse-grained; strong gray caliche in upper few inches; top of second hogback; overlain down dip slope by pinkish and gray mudstone of Santa Fe	3
11	Sandstone: light-tan and buff, medium-bedded to thick-bedded, fine-grained, friable, slope-forming	9
10	Sandstone: pinkish-tan, medium-bedded, medium-grained; much replacement by cement-gray caliche; pulverant; soily, limy soil intercalated	5
9	Claystone: olive-drab, shaly; bentonitic with floating medium quartz grains	1
8	Sandstone: tan to salmon-pink, medium-bedded to massive-bedded; fine-grained with widely spaced, well-cemented, thin, coarser sandstone beds and lenses; cementation usually finely nodular; cliff-forming	148
7	Mudstone: light-reddish-brown; massive with widely intercalated thin beds of medium-grained sandstone; calcareous cement; top of mudstone	38
6	Covered: alluvial valley bottom; at head mudstone like unit 7	45
	Top of Zia and first hogback (total thickness)	240
5	Sandstone: light-buff to salmon-pink, thin-bedded, very fine grained; 0.5-ft to 1-ft layers of caliche and silicified lenses; top of first hogback	15
4	Sandstone: light-buff, thin-bedded to thick-bedded, fine-grained to medium-grained; local thin nodular silicified beds; cliff-forming	77
3	Sandstone: medium-gray with light-pinkish cast, massive-bedded, medium-grained with local coarse-grained thin layers, subrounded to angular, very friable; top is base of first cliff	86
2	Sandstone: light-gray, thick-bedded and crossbedded, coarse-grained to medium-grained; clear quartz and red, black, and gray chert grains; no mica and little or no feldspar	12
1	Covered: with local to light-gray to white sandstone like unit 2 in upper part; top of Cretaceous estimated to be at base of interval	50

Units 6 and 7, which are 83 ft thick, are one mudstone unit occurring in the valley and dip slope between the two hogbacks. The sandstone of the second hogback might be equivalent to some of the beds of the upper part of the type section, but owing to lithology and color they are at this locality mapped as Middle red.

West of the Rio Puerco, mostly in T. 10 N., R. 2 W., are several separate exposures of Zia. In sec. 1, Wright (1946, p. 402) found a thickness of about 250 ft. Campbell (1967, p. 37-38) found a thickness of 335 ft in sec. 1, T. 10 N., R. 2 W. Zia is absent south of 1-40 where locally Middle red appears to lie directly on Cretaceous beds.

East of the type locality Shell Oil Company drilled its No. 1 Santa Fe well in 1972 (total depth of 11,045 ft). The well was spudded in the Zia member in NWV4SW1/4 sec. 18, T. 13 N., R. 3 E. at an elevation of 5,753 ft KB (kelly bushing) and bottomed in Santa Fe on Galisteo beds at a depth of 2,970 ft. This indicates a Santa Fe thickness of nearly 3,200 ft, which is more than twice that measurable near the western edge of the basin. The spud in the Zia member suggests that the Zia may have trebled its thickness in the 9 mi basinward from the type locality. There is a strong possibility of another unit of Santa Fe, possibly a Middle red or some other lithology that underlies the Zia member. No measured section of Zia north of the Jemez River is obtainable due to faulting and poor exposure. However, if one takes the highest elevation of exposed Zia and subtracts the elevation along the Jemez River, to the south the difference is about 2,000 ft, which might approximate a possible thickness because of the generally low dip. Possibility of another unit of Santa Fe beneath Zia beds still exists. Black and Hiss (1974, pl. 2) showed in structure section the Lower gray *(Tsf1)*, Zia equivalent, increasing to as much as 6,500 ft east of the No, 1 Santa Fe well. It is unlikely that so much of this increasing thickness would all be Zia-type beds. The basal aspect of the Zia in the outcrop is probably the result of onlapping of the western border of the basin. If this is the case then the Zia might occupy a middle or even upper part of the total Santa Fe Formation.

Three areas of Zia-type beds occur east of the Rio Grande, one in the Hagan Basin east of Espinaso Ridge, a second in La Bajada escarpment east of the village of La Bajada, and a third west of La Bajada fault in the western part of T. 14 N., R. 7 E. The Hagan beds lie in a belt 5 mi long, south of their termination at the San Francisco fault. The beds dip 10 to 40 degrees east and consist typically of massive, grayish-white but with some pinkish to tan sandstone. The basal part is locally pebbly and has some of the volcanic detritus of the underlying Espinaso Volcanics. In the northern one-third of the belt there are variegated mudstone beds in the lower part of the member. Stearns (1953a, p. 469) first described the belt and termed them Abiquiu(?) Formation. He measured the thickness as about 1,400 ft.

The Zia of La Bajada escarpment has not been examined in this work, but Stearns (1953a, p. 470) described it as consisting of siltstone and limestone in the lower one-third and sandstone and gray-white tuff in the upper two-thirds. The Zia is locally gravelly in the lower part, with an estimated total thickness of about 1,000 ft.

MIDDLE RED MEMBER AND MAIN BODY

The Middle red member epitomizes the Santa Fe Formation of the Albuquerque Basin. This member is the main body, and for most of the basin where Zia or Ceja beds are not present, it is the Santa Fe Formation. The pinkish, reddish, and purplish colors of the Middle red are most distinctive above or interfingering with the Zia in the northern Ceja Mesa and Jemez Valley areas. Distinction by color and contrasting lithologies is less evident toward the south. Even in the thick Gabaldon and Maria Chavez Arroyo sections recognition of more than tongues, local facies, or distinctive bed units is difficult. In all but the northwestern Ceja Mesa area, surface exposures represent only a fraction of the total formation. Even in the northern Ceja area, where there is no deposition of Ceja Member, there is some possibility that either pre-Ceja Member or pre-Ortiz erosion may have thinned the section. In the Gabaldon area two deep wells penetrated nearly 10,000 ft of Santa Fe beds. Principally in the Middle red member, fanglomerate and axial gravel, sand, and mud facies are developed. Where seen, these facies are mostly in the upper part of the unit. However, this does not mean that such facies are not present in the lower part.

The most continuous good exposures are along the slopes of Ceja Mesa. These exposures are especially good along the western slope from about Benevidez Arroyo to the southern tip of Ceja Mesa, a distance of approximately 60 mi. The east-slope exposures from about Belen southward are also very striking and easily seen, but they are only about 200 ft thick. Unusually fine exposures occur high on the northern slope of Ceja Mesa in the Zia and Santa Ana Reservation badlands, but there are very few and poor roads to this area. Unfortunately all these exposures are relatively thin even in the possibly complete sections. Table 5 is a section measured along the west limb of the Ziana anticline.

TABLE 5—ZIANA SECTION (secs. 1, 2, T. 13 N., R. 2 E.).

Unit	Description	Thickness (ft)
	Total thickness	952
7	Sandstone: tan-brown to buff, thin-grained to medium-grained, friable; Ceja Member gravel above	20
6	Mudstone: reddish-brown, medium-bedded; clays have quartz grain impurities	12
5	Sandstone and mudstone: sandstone is light buff, thin bedded to medium bedded, fine grained; mudstone is reddish brown and buff	85
4	Mudstone: reddish-brown, medium-bedded to thick-bedded	258
3	Mudstone and sandstone: mudstone is reddish brown; sandstone is tan brown to buff, thin to medium bedded, fine grained	111
2	Sandstone: buff, medium-bedded, fine-grained to medium-grained; several 0.5-ft to 5-ft pebbly beds with local channels of cobbles and boulders	83
1	Mudstone and sandstone: mudstone is reddish brown, medium bedded to thick bedded; sandstone is tan brown, thin bedded to thick bedded, fine grained to medium grained; rests on light-gray to white Zia Sandstone	383

The Middle red member is well exposed in the southwestern corner of Santa Ana Mesa beneath the San Felipe basalt flows. The section is typically light reddish brown and consists principally of sandstone and mudstone with lesser gravel beds. It has not been measured or studied in detail, but the very low dip allows a rough thickness approximation of 900 ft from the topographic map.

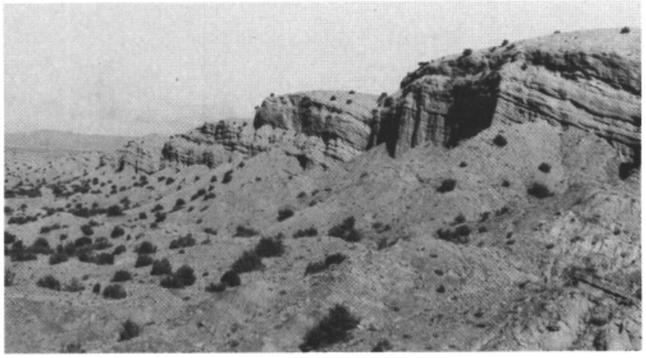


FIGURE 3—VIEW OF FANGLOMERATE CLIFFS IN SANTA FE BEDS ALONG MARIA CHAVEZ ARROYO. View northwest from about 6 mi north of Placitas.

Two good tilted sections of the upper part of the Santa Fe, the Maria Chavez Arroyo section (table 6) north of the Sandia Mountains (fig. 3) and the Gabaldon badlands section east of the Lucero uplift, expose thicknesses of 3,000 ft or more.

TABLE 6—MARIA CHAVEZ ARROYO SECTION (secs. 4, 8, T. 13 N., R. 5 E.).

Unit	Description	Thickness (ft)
	Total thickness	2,656
49	Fanglomerate: gray, angular, pebbly to cobbly; fragments include limestone, sandstone, chert, quartz, quartzite, gneiss, schist, porphyry	40
48	Mudstone: reddish-brown with some intercalations of fine-grained sandstone	40
47	Fanglomerate: gray, angular, pebbly to cobbly; fragments like unit 49	48
46	Sandstone: gray, medium-grained	9
45	Fanglomerate: gray, thick-bedded, pebbly to cobbly; fragments like unit 49	20
44	Sandstone: buff, thick-bedded, fine-grained to medium-grained	16
43	Mudstone: reddish-brown to tan-brown	101
42	Fanglomerate: tannish-gray pebbly to cobbly with a few boulders; fragments like unit 49	10
41	Mudstone: reddish-brown to tan-brown; a few thin intercalated, tan, fine-grained sandstones	71
40	Fanglomerate: gray, thin-bedded; several thin intercalations of fine-grained to medium-grained sandstone beds	28
39	Mudstone: tan-brown	30
38	Fanglomerate and mudstone: gray and light-tan; some intercalations of fine-grained sandstone	76
37	Mudstone: tan-brown	8
36	Sandstone: gray to light-tannish-brown; several thin mudstone and fanglomerate beds	23
35	Fanglomerate: gray, medium-bedded with minor crossbedding; pebbles to cobbles dominate but with some boulders and blocks	137
34	Mudstone: tan-brown	17
33	Fanglomerate: thin-bedded; like unit 35	8
32	Mudstone: tan-brown; at main ridge crest	30
31	Fanglomerate: gray, medium-bedded; pebbles to cobbles dominate but some boulders and blocks	190
30	Mudstone: reddish-brown; several intercalated 2-inch to 4-inch, coarse-grained, gray sandstone beds	52
29	Fanglomerate: gray, medium-bedded; minor thin crossbeds and shallow channels; pebbles to cobbles with scattered boulders and blocks; subangular; fragments include limestone, red sandstone, buff and white sandstone, quartz, quartzite, gneiss, schist, greenstone, minor gray felsites and rare porphyry, no basalt or andesite	152
28	Sandstone and mudstone: tan-brown, medium-bedded to thick-bedded; upper third contains several 6-inch to 20-inch fanglomerate beds	240
27	Mudstone and sandstone: reddish-brown to light-tan, medium-bedded to thick-bedded, sandstone is fine grained	413
26	Covered: by alluvium of arroyo, along strike several hundred feet away, beds are mudstone	87
25	Sandstone and mudstone: tannish-brown; sandstone is fine grained; contains several intercalations of 4 to 8 inches gray and light-tan, cemented, coarse-grained sandstone	154
24	Fanglomerate: gray, pebbly to cobbly	8
23	Sandstone and mudstone: tan-brown; fine-grained sandstone	4
22	Sandstone: tannish-gray, conglomeratic	3
21	Sandstone and mudstone: tannish-gray	4
20	Sandstone: tannish-gray, conglomeratic	2

(Continued on next page)

TABLE 6—MARIA CHAVEZ ARROYO SECTION (secs. 4, 8, T. 13 N., R. 5 E.). (Continued from previous page)

Unit	Description	Thickness (ft)
19	Sandstone and mudstone: light-tan, sandstone is fine grained but several intercalations of 4-inch to 6-inch tan, cemented, coarse-grained sandstone	37
18	Sandstone: tannish-gray, conglomeratic	2
17	Sandstone and mudstone: tan-brown; sandstone is fine grained	48
16	Fanglomerate: pebbly to cobbly with some boulders; much white-spotted, reddish-brown Abo sandstone	6
15	Sandstone and mudstone: mostly covered by alluvium of Maria Chavez Arroyo	120
14	Fanglomerate: gray, pebbly to cobbly	10
13	Sandstone and mudstone: tan-brown; sandstone is fine grained	62
12	Fanglomerate: gray, pebbly to cobbly	5
11	Sandstone and mudstone: tan-brown, medium-bedded to thick-bedded; sandstone is fine grained	66
10	Fanglomerate: gray, pebbly to cobbly	2
9	Sandstone and mudstone: light-tan to reddish-brown, thick-bedded; sandstone is fine grained	34
8	Fanglomerate: gray, pebbly to cobbly	7
7	Sandstone: light-tan, medium-grained to coarse-grained	2
6	Sandstone and mudstone: red-brown; sandstone is fine grained	21
5	Sandstone and mudstone: light-tan; sandstone is fine grained	53
4	Fanglomerate: gray, pebbly to cobbly with some boulders	8
3	Sandstone and mudstone: light-tan, buff, red-brown; sandstone is fine grained	57
2	Fanglomerate: gray, thin-bedded, pebbly to cobbly	6
1	Sandstone and mudstone: buff, tan and red-brown, thick-bedded; fragments include chert, porphyry, red sandstone, buff sandstone, pebbly to cobbly	89

The outstanding aspect of this section is the alluvial fan facies represented by unit 29 but continuing through unit 38 with alternating mudstone and sandstone, for a total thickness of 683 ft. These fan beds, dipping moderately along the Chavez monocline, grade into more mudstone northwestward and into axial river gravels near 1-25. To the south the fanglomerate continues to Placitas, but in poor exposures; and the nature and composition west of Placitas have been described by Kelley and Northrop (1975, p. 68). In the Chavez section the base is at the anticlinal bend of the monocline where relationships with flat-lying red beds of the Santa Fe southward are obscured beneath a local pediment. Thus, the position of the fanglomerate tongue in the whole Santa Fe is unknown, but it is probably rather high. There may be several thousand feet of Santa Fe at depth especially west of the Ranchos and Valley View faults; these faults are the western boundary of the Sandia structural ramp.

The long section of northeasterly dipping fanglomerate in the fault block west of the Montezuma salient, if not repeated by unseen strike faults, could be about 4,500 ft thick. Its full relationship to the narrow band of fanglomerate in the measured Maria Chavez section (table 6) is unclear. On the west, flat-lying red beds of the Santa Fe are faulted down on the Escala fault, and the throw opposite the southern part of the tilted fanglomerate beds should be large.

The finest exposure of Santa Fe in the basin is undoubtedly that of the Gabaldon badlands (table 7) about 4-5 mi east of Lucero uplift (fig. 4).

TABLE 7—GABALDON BADLANDS SECTION (secs. 34-36, T. 6 N., R. 2 W., and sec. 3, T. 5 N., R. 2 W.).

Unit	Description	Thickness (ft)
	Ortiz pediment gravel	
	Santa Fe Formation (total exposed thickness)	3,098
40	Sandstone: salmon-pink, poorly exposed, fine-grained; 3° dip	18
39	Gravel and sand: gray, thin-bedded to thick-bedded, pebbly, subrounded to angular; fragments include chert, rhyodacites, quartzite, gneiss, greenstone; 3° dip	22
38	Sandstone: salmon-pink, medium-bedded, fine-grained to medium-grained, friable; 3° dip	30
37	Gravel and sand: light-gray, thin-bedded to thick-bedded, pebbly, subrounded to angular, fragments include chert, silicic volcanics, quartzite, gneiss, greenstone; 5° dip	28
36	Sandstone: grayish-white, thin-bedded to thick-bedded, fine-grained and medium-grained, 5° dip	84
35	Sandstone and mudstone: sandstone is buff, thin bedded, and locally with pebbly (angular) fragments; mudstone is buff to pale lavender, medium bedded, contains suspended fine sand grains; locally covered by pediment gravel; 10° dip	278
34	Mudstone: red-brown, purplish-brown, thin-bedded to thick-bedded; a few 1-ft to 2-ft, fine-grained to coarse-grained, gray and tan sandstone beds, locally conglomeratic; 15° dip	119
33	Mudstone: reddish-brown, medium-bedded; several 1.5-ft to 2-ft sandstone beds; gray to tan-brown and locally conglomeratic; 0.5-ft gray calcareous sandstone at top; 15° dip	68
32	Sandstone: gray, thin-bedded; locally conglomeratic; several thin, buff to tan-brown mudstone; 15° dip	48
31	Sandstone and mudstone: sandstone in 1-ft beds at top and bottom; mudstone is reddish brown in middle; caps high ridge; 12° dip	8
30	Mudstone: purplish-brown and grayish-brown; contains a few thin, lenticular fine-grained sandstone beds; 12° dip	92
29	Sandstone and fanglomerate: sandstone is gray to buff, thin bedded, and fine grained to coarse grained; fanglomerate is gray and pebbly to cobbly; contains rhyolitic to basaltic fragments, also chert; 15° dip	28
28	Mudstone: buff to purplish-brown; 15° dip	58
27	Fanglomerate: gray, medium-bedded, angular and subrounded, pebbly to cobbly; 24° dip	11
26	Mudstone: brown, poorly exposed; 24° dip	22
25	Fanglomerate: gray, thin-bedded to medium-bedded, pebbly; fragments include chert, silicic to intermediate volcanics and sandstone; 24° dip	15
24	Mudstone: reddish-brown, massive, impure with floating sand grains; 24° dip	12
23	Sandstone: gray to light-gray, thin-bedded to medium-bedded, fine-grained to coarse-grained; locally conglomeratic in pebble sizes; a few thin mudstone beds, gray to buff; calcareous thin sandstone at top; 24° dip	49
22	Sandstone: gray, fine-grained to coarse-grained; locally conglomeratic in granule to pebble sizes; 33° dip	2
21	Mudstone: buff to purplish-brown, thin-bedded to thick-bedded; contains 2 to 3 thin, gray, pebbly medium-grained to coarse-grained sandstone; 33° dip	21
20	Sandstone: buff and yellowish-gray, thin-bedded, fine-grained, pebbles vary locally; 33° dip	47
19	Mudstone and sandstone: mudstone is gray and reddish brown; sandstones about 30% of intervals and mostly in upper part; gray to brown, thin-bedded; minor thin, white dense limestone lenses; 18° dip	115
18	Mudstone: purplish to reddish-brown, massive; 18° dip	10
17	Mudstone and sandstone: mudstone is gray and reddish brown; sandstone is fine grained, white to buff, thin to thick bedded; mudstone:sandstone ratio about 60:40; 18° dip	136
16	Limestone: gray, fine-grained, laminated	1

Unit	Description	Thickness (ft)
15	Sandstone: light-gray to buff, thin-bedded; minor mudstone is light buff; 12° dip	13
14	Mudstone: purplish-brown, thin-bedded; contains floating sand grains and a few thin, fine-grained, lenticular sandstone; 12° dip	7
13	Sandstone: white and yellowish-white, thin-bedded to medium-bedded, fine-grained; some thin beds are well cemented; two or three thin reddish-brown claystone beds; 12° dip	41
12	Limestone and sandstone: yellowish-brown, gray and yellowish-gray, thin-bedded; sandstone is medium grained; 10° dip	2
11	Sandstone and mudstone: sandstone is light greenish gray and buff, thin bedded to thick bedded with some beds laminated; fine grained; very locally granulitic to pebbly; mudstones are medium bedded and reddish brown, and constitute about 30% of the unit; 10° dip	174
10	Sandstone: light-greenish-gray and buff, thin-bedded to thick-bedded; local crossbedding; some beds are dish-laminated, fine grained; red-brown mudstones constitute about 15%; 10° dip	65
9	Mudstone: red and purplish-brown, thin-bedded; sand grains float in most mudstone; very local thin cream sandstone beds; 12° dip	93
8	Mudstone: buff and tan-brown, thin-bedded to thick-bedded; sand grains in mudstone and a few thin lenticular fine-grained sandstones; 12° dip	120
7	Mudstone and sandstone: mudstone is buff to reddish brown, thin bedded and sandy; sandstone is buff to tan brown, thin bedded to medium bedded, lenticular, and locally well cemented; sandstone constitutes about 40% of interval recurring at 20-ft to 30-ft intervals; locally ripple-marked; also quite local coarse-grained lenses of 1-inch to 3-inch pebbly conglomerate with chert, quartzite, and rhyolitic fragments; 12° dip	255
6	Mudstone: buff and tan-brown, thin-bedded to thick-bedded; floating sand grains; widely dispersed, thin, lenticular, well-cemented, fine-grained sandstone ledges; local aragonite sand crystals; 12° dip	127
5	Mudstone and sandstone: mudstone is buff, thin bedded to thick bedded and contains floating sand grains; sandstone is light gray and buff, thin bedded to medium bedded and locally well cemented; constitutes about 40%; 12° dip	59
4	Mudstone and sandstone: mudstone is gray, buff, and reddish brown with floating sand grains, thin bedded to thick bedded; sandstones are gray to buff, thin bedded to medium bedded and fine grained; sandstone alternates rather regularly with the mudstone and constitutes about 33% of the interval; 14° dip	658
3	Sandstone: buff to light-tannish-brown, thin to thick parallel bedding, fine-grained; argillaceous in many beds; several zones of large flat concretionary lenses; some scattered ironstone concretion zones; 15° dip	146
2	Mudstone: buff and reddish-brown, thick-bedded	12
1	Sandstone: buff, massive, fine-grained, argillaceous and friable	4
	Base not exposed	

The playa aspect of this section is reflected in the mudstones and fine grain size of the sand in the lower 2,000 ft. Above unit 19 medium and coarse sand along with granulitic and pebbly lenses and beds appear. Note first fanglomerate bed, unit 25, and considerable gravel above 3,000 ft, unit 37. A small additional section occurs to the west beneath Ortiz pediment and much more in the subsurface west of Gabaldon fault, whose trace is only a short distance east of the base of the section. Northwesterly from this section more gravel appears in the outcrops, especially in the upper part as noted by Wright (1946, p. 407-409), but the gravel actually interfingers from the west. In secs. 32 and 33, T. 6 N., R. 2 W. considerable cobbly and bouldery outcrops are present. Also in the A.T. & S.F. railroad cut in sec. 8, T. 7. N., R. 2 W., 100-150 ft of pebbly gravel is uptilted along the Santa Fe fault. The position of this gravel to the Gabaldon exposures is not clear. Detritus in the gravels consists of chert, silicic volcanics, quartzite, gneiss, and limestone, but there is no basalt as is present in the overlying Ortiz gravel. Therefore, if derived from the Lucero uplift, it must have been prior to eruption of the Lucero basalts.

East of the Ladron Mountains considerable thicknesses of Santa Fe and Popotosa Formations are exposed in tilted and considerably faulted sections. The Popotosa consists of andesite flows, andesite conglomerate, and fanglomerate. The volcanic sequence, located

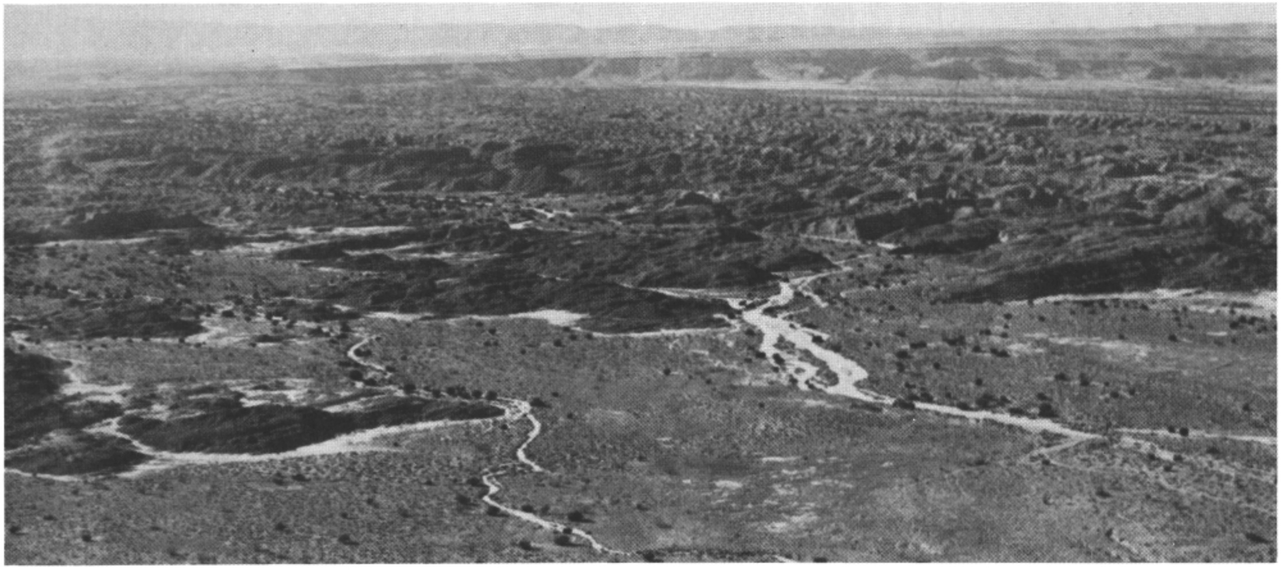


FIGURE 4—Airview of tilted Santa Fe beds in Gabaldon badlands.

next to the Cerro Colorado fault on the west, consists largely of andesitic conglomerate. The sequence contains some flows that lie next to the fault. Since such flows are considered to be a source of the conglomerate, their position on top of the conglomerates is odd. This leads to the possibility that the volcanic conglomerates, which dip steeply toward the Cerro Colorado fault, are overturned. However, there may be a fault between the flows and the conglomerates. To the east of the andesitic conglomerates, especially along Popotosa Canyon, is a thick sequence of fanglomerate consisting of a mix of granitic and volcanic rocks. These fanglomerates also dip primarily to the west, although southwest of the lower end of Popotosa Creek they dip south and are locally overlain in near conformity by typical reddish to salmon-pink Santa Fe sandstone and mudstone beds. If the west dipping Popotosa granitic-bearing beds were younger than the volcanic conglomerates west of Silver Creek fault, the throw on the fault would be quite large. To the east, along the Bell fault, (geologic map, in pocket) the Santa Fe is faulted down to the basin against the Popotosa fanglomerates. About a mile farther east the Santa Fe is again faulted down to the basin on the Pelado fault. The Santa Fe is disturbed and much covered by pediment gravel and colluvium; however, low westward dips continue a short distance even east of the Pelado fault.

The scale of the map and the regional scope of this work is quite inadequate to properly study the basin stratigraphy east of the Ladron Mountains. Unfortunately there is only the Riley topographic quadrangle (1:62,500) as a map base for further work that should be done in this area. Denny (1940, p. 80) has estimated the thickness of the Popotosa to be 3,000 to 5,000 ft and the Santa Fe (Denny, 1940, p. 93) to be at least 2,000 ft in surface exposures. The Santa Fe structure sections in the basin east of the Pelado fault may be as much as 6,000 ft thick. I have not seen a playa facies of the Popotosa in the Ladron area as suggested by Bruning (1973); rather, his playa map units appear to be Santa Fe either resting on Popotosa or faulted down against it.

Although the Popotosa occurs in a number of places outside the Rio Grande trough proper, it could well be a basin deposit, especially the granitic fanglomerate. This fanglomerate may indicate an early sharp rise and exposure of the Ladron Precambrian rocks. If the Popotosa can be shown to fill a fault valley of extensional origin and not just outwash fans from volcanic terranes, it could logically be placed in the Santa Fe. However, including or excluding the Ladron exposures of the Popotosa from the Santa Fe is not important.

CEJA MEMBER

As named and described here the Ceja Member is roughly the equivalent of Bryan and McCann's Upper buff member (1938, p. 815). The lithology of the Ceja Member is more variable than the Middle red, and the gravel is the principal characterizing aspect. Bryan and McCann marked the base by "beds of gray and brown silt and clay whose general appearance is buff." It is doubtful that those beds persist, and unless rather thick they would be a very poor unit on which to map. I have mostly mapped the base of the Ceja above such beds at the base of gravel deposits. If the silt and clay beds are included, then commonly there are other gravel beds beneath, and the contact soon becomes useless for mapping. In the Sand Hill area Bryan and McCann found a thickness of 286 ft which includes more than I have mapped. Around Doval triangulation point in the northern reaches of Ceja Mesa, T. 13 and 14 N., R. 2 E. well-developed gravelly Ceja beds are nearly 200 ft thick.

Bryan and McCann (1938, p. 817) state that in places this member is much thicker, estimating "from 1,000 to 1,500 feet." They observed that thin sections in some areas were due to erosion of the Ortiz pediment, the surface of most of Ceja Mesa. There is rather meager evidence from which to estimate so much stripping. It is difficult to see how Bryan and McCann estimated original thicknesses of as much as 1,500 ft unless they included gravel present in the Middle red. In places there are typical Middle red mudstones above the Ceja gravel unit; most notable is under the Ortiz surface in the western part of T. 12 N., R. 2 E. and in T. 9 N., R. 4 E., along Tijeras Arroyo. Some red beds that may be above Ceja gravel also appear along the walls of the Hell Canyon Arroyo about 5 mi into the arroyo.

Southward along Ceja Mesa the Ceja gravel thins out and appears to essentially end in T. 8 N., R. 1 W. The thinning is due in part to truncation by the Ortiz erosion surface and gravel. Ceja gravel does not occur beneath the Cat Hills basalt flow in sec. 9, T. 7 S., R. 1 E., but there is an isolated patch of gravel about 0.5 mi northwest of Los Lunas volcano in sec. 23, T. 7 S., R. 1 E., which might be an outlier of Ceja. Axial gravel facies in the bluffs complicate determining the Ceja gravel termination south of Tijeras Arroyo. Wright (1946, p. 416) correlated a thin gravel several tens of ft below the top of the Santa Fe in sec. 8, T. 7 N., R. 1 W. with Ceja beds farther north. Depiction of Ceja beds in Wright's measured-sections panel suggests interfingering with regular Santa Fe to the south. This indicates that some Santa Fe sandstone and mudstone high in the section in the southern part of the basin might be equivalent to the Ceja of the northern part. However, I do not believe the gravel of his cross section 29 is the same as that of his cross section 28.

Lambert (1968, fig. 1) was first to map the Upper buff beds in the Rio Grande valley. He mapped the beds along both sides of the inner valley in the Albuquerque area, and in the slopes west of the airport they may be at least 300 ft thick. From examination of well data Lambert estimated (1968, p. 74) that the Ceja is about 400 ft thick near the western edge of Ceja Mesa near 1-40, as much as 600 to 800 ft thick beneath the eastern edge of the mesa, and 100 to 150 ft thick beneath the Rio Grande. He, like Bryan and McCann, included finer sediments in the lower part of his measured section; he did not try to map the base because it was outside his map area. In general it is not difficult to map the base of the Ceja using the relatively more resistant gray gravels as a criterion. However, since gravel beds are usually lenticular, the base may be irregular by reason of interfingering with sandstone. Wright (1946, p. 405) found this to be true in his measured-sections panel constructed from sections along the western escarpment of Ceja Mesa. Another problem and misunderstanding by some workers is the nature of the Middle red member which is not everywhere reddish or even buff, and the color will vary within a single section. White, gray, and light-olive-drab beds commonly occur along with the characterizing reddish beds and frequently this member will have gravel beds. Wright (1946, p. 447, pl. 10) believed that gravel on numerous spurs leading toward the Rio Puerco valley from the dissected escarpment were remnants of earlier alluvial slopes or fans. With poor exposures it is easy to be deluded into assuming that some of these are the Ceja Member resulting in greater thickness.

Near the Rio Grande where gravels and sands of the axial facies occur recognition of the base of the Ceja Member is also difficult. Along both sides of the Rio Grande, gravel interbeds of cobbles and pebbles occur in the Middle red member west and south of Bernalillo. Similar beds continue along the valley sides toward Albuquerque where Lambert (1967, fig. 1) has mapped cobble and pebble gravels, termed Edith and Menaul, and in places these lie on beds that may be Ceja. He concluded that these gravels are younger insets of inner valley terrace fills (Lambert, 1967, fig. 2). On the west side of the valley he mapped similar (Edith) gravels resting on a lower part of a much larger and deeper inset of sands and muds termed Los Duranes. The difference in lithology of Los Duranes, which he designated a formation within Santa Fe Group, is the principal reason for separating this gravel from the Ceja Member. Lambert described Los Duranes as overbank river beds and hence axial in facies. On the geologic map (in pocket) Los Duranes is not mapped because of scale limitations and the possibility of its being part of the Primer Alto and Segundo Alto terraces (Bryan and McCann, 1938, p. 14). However, both Edith high-energy gravels and Los Duranes low-energy beds could be axial facies of the lower part of the Ceja Member. If Lambert's concepts prove correct, including the units in the Santa Fe is inadvisable primarily because of the considerable erosional unconformity which is implied, especially for Los Duranes beds. Calling such local units formations is also inadvisable; if such designations were further followed, numerous terrace gravels, the Ceja caliche beds, and large eolian sand fields would then be given formation status, a cluttering procedure for organized stratigraphy. The Ortiz pediment gravel of the Albuquerque area could logically be included in the Santa Fe, but it is excluded in this report for reasons similar to those given for Edith and Los Duranes beds; in several places the Ortiz pediment gravels rest with considerable angular unconformity on Santa Fe beds.

Lambert (1967, p. 72-113) made an in-depth study of the Ceja Member (his Upper buff formation) and gave much lithologic description and systematic analysis of its gravel and sand. He also collected numerous mollusk and vertebrate fossils from his upper part of the Ceja, mostly from Tij eras Arroyo and near the Public Service Company's Persons power station. Based on these finds he concluded (Lambert, 1967, p. 108):

"The association of *Equus, Plesippus* (late Pliocene to early Pleistocene) and *Camelops* (Pleistocene) in the upper part of the Upper buff formation suggests that that part of the formation is early Pleistocene (late Blancan) in age. The lower part may be either early Pleistocene or late Pliocene."

Bryan and McCann (1938, p. 815-816) briefly described the Ceja gravel as consisting of angular or little worn fragments of andesite and other volcanic rocks but with more abundant quartzite, chert, and agate. Wright (1946, p. 404) described the gravel similarly but noted "granite" and the nonbasaltic volcanic fragments. Lambert (1967, p. 74) described the upper part of the Ceja as being "dominantly yellowish to grayish sandy pebble gravel and pebbly sand with lesser amounts of interbedded clay, mud, and sand." In describing the minerals of the sand and fine-gravel fraction, Lambert (1967, p. 80-83) found volcanic as well as nonvolcanic quartz, some of the volcanic grains being high-temperature dipyramids. The lesser feldspar also included volcanic and nonvolcanic types. In 5 samples of subangular to subrounded pebbles, Lambert found fragments of Precambrian granite, gneiss, quartzite, and quartz ranging from 18 to 42 percent; fragments of sandstone, limestone, and chert ranging from 4 to 48 percent; and Cenozoic silicic to mafic igneous rocks ranging from 20 to 54 percent. Of the volcanic types, vesicular basalt pebbles were 2 percent or less in all samples. Two of the samples came from El Rincon west of Ceja Mesa, 2 from near the Public Service Company's Persons power station, and 1 from the east side of Ceja Mesa about 3 mi south of 1-40. Little can be reliably determined from the samples on the basis of geography except that the beds from the Rio Grande area appear to have slightly more Precambrian and slightly fewer sedimentary pebbles. As Lambert points out, more sampling would have to be done to draw significant conclusions. Lambert believed that the source of the western part of the member was west but that the eastern deposits probably had northern sources, especially certain beds containing pumice from the Jemez Mountains. The low content of basalt fragments in Lambert's samples is significant; this holds also for the gravel in the upper part of the Gabaldon section just east of Lucero uplift. The absence of basalt fragments is in strong contrast to the overlying Ortiz gravel, which has numerous large blocks of vesicular basalt. In the I-40-Rio Bravo roadcuts, a few scattered angular vesicular basalt fragments 2-3 inches can be found in local beds. On the other hand, usually vesicular basalt is abundant in the Ceja Member northern outcrops (T. 13 and 14 N., R. 1 and 2 E). Boulders and blocks with 3 to 4 ft diameters are common not only strewn on the surface but also in certain beds lower in the member, especially along the northern divide of the Ceja Mesa in sec. 2, T. 13 N., R. 2 E. Similarly large boulders of buff sandstone are also present in some beds, and smaller fragments of pink gneiss are locally abundant enough to give a pinkish cast to the beds. Locally, in the more fanglomeratic beds, northward-dipping imbricate texture indicates origin from northerly sources. Apparently from examination of numerous exposures of Ceja Member gravels along the western edge of Ceja Mesa, the volcanic fraction increases northward with respect to other fractions.

In formally naming the Ceja Member (table 8) a type locality is chosen along the south side of El Rincon in NEV4SE1/4 sec. 19, T. 10 N., R. 1 E. as shown on the geologic map (in pocket).

TABLE 8—CEJA MEMBER SECTION (NE¼SE¼ sec. 19, T. 10 N., R. 1 E.).

Unit	Description	Thickness (ft)
	Soil and dune sand of mesa surface (total)	211
8	Sandstone: buff, thin-bedded to medium-bedded, medium-grained to coarse-grained, subangular; conglomeratic	50
7	Conglomerate: buff to gray, thick-bedded; pebbles to boulders of chert, pink gneiss, sandstone, porphyry and various volcanics including some angular basalt blocks up to 3 to 4 ft; excellent northerly dipping imbricate texture	17
6	Sandstone and mudstone: sandstone is buff, thin bedded, medium grained to coarse grained; mudstone is reddish brown	34
5	Conglomerate: gray, thick-bedded; cobbles to boulders of compositions like unit 7	18
4	Sandstone: buff, medium-bedded, coarse-grained	15
3	Conglomerate: buff, cobbly with conglomeratic sandstone; cobbles to boulders of compositions like unit 7	30
2	Sandstone and mudstone: like unit 6	23
1	Sandstone and conglomerate: sandstone is buff, thin bedded, and medium grained to coarse grained; conglomerate is pebbly and gray; also contains thin reddish-brown mudstone and some conglomeratic sandstone; Santa Fe red beds below.	24

POST-SANTA FE SEDIMENTS

The oldest of post-Santa Fe sediments is the relatively thin alluvial pediment gravel and sand of the Ortiz surface. This once expansive blanket ranges from a feather edge to 150 ft thick. Fig. 10 shows the principal remnants of the surface. The type area for the Ortiz surface is west of the Ortiz Mountains, and all other surfaces are mapped by correlation based on altitude, attitude, and maturity of development including thickness of related caliche. As explained in the chapter on geomorphology the deposits on the surface north of Ladron Mountains and west of Manzano and Los Pinos Mountains are new correlations that were formerly described as younger terraces.

At the type locality around the Ortiz Mountains the deposits have been referred to as Tuerto gravel (Stearns, 1953a, p. 476) and correlated with the Ancha beds of the Santa Fe area by Spiegel and Baldwin (1963, p. 58-59). Anderson (1960, p. 48-49) believed that there are two layers in the gravel; a lower one that was part of the pediment-forming material, and an upper one that could be partly a second level pediment and an alluvial fan buildup on the earlier gravel. Dissection of the Hagan Basin by tributaries of the Rio Grande have revealed the Tuerto gravel in numerous mesa segments especially in the drainage system of San Pedro Creek. Thickness ranges from 5 to 10 ft in the western ends to 100 ft or more near the reentrants of the fingers. Numerous outliers of the gravels toward the north in the direction of post-gravel tilting enable easy tracing and correlation to the gravel caps along the base of La Bajada escarpment, even north of Galisteo Creek. The Tuerto gravel segments in that area have some alluvial fan buildup that has been eroded from La Bajada fault scarp.

Composition of Tuerto gravel closely reflects the nearby source rocks. Source rocks for the Ortiz Mountain area are predominantly monzonite and syenite porphyries, some sandstone, especially silicified types, hornfels from metamorphosed Cretaceous shale, skarn from contact zones, and minerals such as quartz, epidote, calcite, magnetite, and some gold of low-grade placer occurrence. Along La Bajada escarpment, fragments may be reddish sandstones from Triassic, Jurassic, and Eocene formations or basalt and some Zia-type sandstone fragments farther north.

Several thick patches of probable Ortiz equivalents occur along the southeast flank of the Jemez Mountains. These are termed Mesita Alta gravel, a term first used by Soister (1952, p. 55). Thickness ranges from about 15 ft to as much as 70-80 ft near the source areas in the Jemez Mountains. Mesita Alta gravel is fairly resistant and forms steep slopes above less resistant underlying Santa Fe beds. Basaltic and silicic volcanic rocks prevail with fragments ranging from blocks to pebbles. Some early Tertiary sandstone, possibly from the Galisteo Formation, and granite and gneiss, probably from Santa Fe conglomerates (to the northeast), are also present.

Basalt-capped Mesa Prieta, about 20 mi west of San Ysidro, has long been considered a correlative of the Ortiz and is an important control point in reconstruction of the surface. The surface is cut on Cretaceous rocks, but gravel occurrence beneath the basalt has not been determined.

The greatest and most important remnant of the Ortiz surface is the 68-mi-long Ceja Mesa which lies between the Rio Grande and Rio Puerco. Ceja Mesa is the key to other Ortiz gravel correlations that are made in the southern part of the basin and is also the key to the original western slope and possible post-Ortiz warping of the basin. Determining sediment of the Ortiz surface is difficult because soil, caliche, and eolian deposits cover much of the surface. Furthermore, the sand and gravel appear generally thin to absent and lithologically are easily confused with the gravel of the Ceja Member of the Santa Fe. The uncertainty is shown by comparing the mapping of Ortiz pediment gravel and eolian deposits on Ceja Mesa west of Albuquerque in this paper with Lambert's mapping (1968, fig. 1) of Ceja alluvium and eolian deposits. He mapped little or no gravel identified as being Ortiz on Ceja Mesa other than his old undivided alluvium (Lambert, 1968, p. 187-191) and apparently he considered this alluvium as younger than an Ortiz surface. Thus, Lambert appears to have believed that any Ortiz materials present were removed before his old undivided alluvium was deposited. Such is the problem of identifying Ortiz material on the modified surface of Ceja Mesa. Wright (1946, p. 439-441) gave much attention to the Ceja Mesa (his Llano de Albuquerque) emphasizing the caliche development for the most part. Whether Wright's abnormally thick (148 ft) calichified section of sand and gravel is Ortiz gravel or Ceja sediments is not clear, although 60 ft of sand and gravel of the Upper buff member is shown beneath the calichified section.

In general there usually is present at least a thin (less than 20 ft thick) sand or gravelly sand on the Ceja-Ortiz surface. From about Los Lunas southward, on the more horizontal southern part of the surface, pebbly gravel is common in the surface soil and overlies a part of the Santa Fe that has no Ceja gravel on top. In available exposures the sand or gravelly sand again appears thin. Denny (1940, p. 87) measured about 13 ft of sand and gravel above Santa Fe beds along the eastern edge of the southern end of the mesa west of Abeytas.

Wright (1946, p. 438) calculated that the streams of the Ortiz surface were steeper than present tributaries to the Rio Grande. He believed that the opposite should be the case and reasoned from this that the Ortiz surface must have been subsequently tilted by renewed subsidence of the basin.

In the Monte de Belen embayment east of the Lucero uplift, gravel capping the dissected and faulted surface may also be Ortiz equivalent as explained in the chapter on geomorphology. In the northern part of this area, in particular in the northern part of T. 5 N., R, 2 W,, a fine remnant of Ortiz gravel overlooks the extensive Gabaldon badlands. This remnant consists of sand and gravel to about 30 ft thick locally; and the gravel consists of rocks clearly derived from the nearby Lucero uplift including large cobbles of basalt.

The gravel-capped eastern mesas from Albuquerque southward are newly correlated in this work as Ortiz. These mesas were formerly considered younger by Bryan (1938, p. 217) and Denny (1941, p. 229). Distinction between gravel of this surface is again difficult owing to the presence of considerable gravel in the underlying Santa Fe and considerable masking by eolian sand along the mesa edge.

With new correlations of the Ortiz surface which include La Bajada (Bryan, 1938) and Tio Bartola surfaces, (Denny, 1941, p. 236) all but very minor caliche blankets occur in connection with the Ortiz surface and gravel. Bryan and McCann (1938, p. 5) noted that considerable caliche development is characteristic of the Ortiz surface and its gravels, and that the surface ranges from 2 to 20 ft thick. They also noted that caliche development typically could be divided into a lower concretionary part; a middle, massive, finely granular mass; and an upper platy layer. Commonly there are variations of this development depending on composition, stability of the surface, climate, slope, and other factors. Lambert (1968, p. 113) noted that similar caliche developed in the top of the Upper buff (Ceja Member) and the pediment surface on which the Albuquerque International Airport is located. Soil and sediment, such as eolian sand, covers the caliche. However, this is not necessarily a superposition sequence as caliche clearly develops by infiltration and replacement several feet below the surface. Calcium carbonate content of caliche ranges from about 10 percent to nearly 100 percent. Commonly, dense and very white caliche may contain 50 percent or more of sand and silt.

Terrace deposits are described in the section on geomorphology by distribution, elevation, and correlation with regard to times of pause in downcutting of the inner valley. Most of the gravels are relatively thin veneers on river-cut surfaces. Some may be remnants of a temporary aggradation process which reversed the overall downcutting of the inner valley. Los Duranes deposits on the low Segundo Alto and Primer Alto terraces west of Albuquerque were thought by Lambert (1968, p. 161-163) to be of this origin. Gravel of the terraces is typically subrounded to rounded and especially in the lower parts consists of clasts foreign to the surrounding gravels. The terraces range in thickness to about 50 ft in many places. Some benches resembling river terraces may only be stripped surfaces on lenses of Santa Fe axial ground. Thick alluvial deposits of the larger valley bottoms are also described in the geomorphology chapter as are the gravels of alluvial aprons, fans, and cones.

Eolian sand and dust are quite prevalent in the basin. However, only the sand deposits accumulate in ways that are mappable. In general the deposits accumulate in blankets and dunes or combinations of both. Most commonly the dunes are transverse forms, but in the blanket deposits longitudinal streaks or low dunes prevail. Lambert (1968, p. 195-198) studied a small part of the basin dunes along Ceja Mesa and locally south of Albuquerque. He separated deposits generally into old and young late Quaternary, the old as stabilized and the young as active or less stable. The twofold classification is a simplification of the system as there have been many variations in time and area of stability and activity. The changes from stable to active may develop in intervals of a few years or decades. The dunes accumulate in many places depending upon topography and availability of sand source. Denny (1940, p. 255-256) mapped the well-known dunes in the area of the junction of the Rio Salado and Rio Grande. The principal belt occurs along the north side of the Rio Salado arroyo but others of the area occur along the steeper, west (leeward) side of the Rio Grande valley. The trends of the longitudinal dunes are irregular between N. 35°-50° E. Along Ceja Mesa the largest dunes, some up to 70 ft high, are along the western (windward) edge in a line of hills most of which are active (fig. 5). However, dunes are present in places down the windward slope in numerous small patches (for example, west of Dalies), Likewise dunes and perhaps remnant blanket sands are found along the eastern slopes of Ceja Mesa such as those west of Isleta and west of Albuquerque.

Small irregular dune piles occur locally along the north rim of Ceja Mesa overlooking the badlands to the north. Their distribution approximately parallels the probable westerly prevailing winds. Dunes and blankets are scattered widely in the areas of the typical Zia sandstones and along the alluvial bottoms of Jemez River where the river traverses the Zia terrane.

The eolian sand blankets of Ceja Mesa are distributed in a number of wide bands trending with the longitudinal streaks and alternating with bands of no appreciable sand on the Ortiz surface gravels or Santa Fe beds. Thus, from west of the Albuquerque volcanoes southward to west of Belen there are five bands, 3-9 mi wide alternating with "bare" pediment bands of unmappable sand blanket. Fig. 6 shows a typical area near Dalies. Note the band that crosses the northern part of the Cat Hills volcanic field and all the Wind Mesa volcanic field. The northern part of the Cat Hills flows are white with much sand, and this area stands in sharp contrast with the part of the field to the south that is out of the "sand path."

The largest area of sand blanket and dunes lies east of the Rio Grande along the western edge of the Ortiz surface between Tijeras Arroyo on the north and Abo

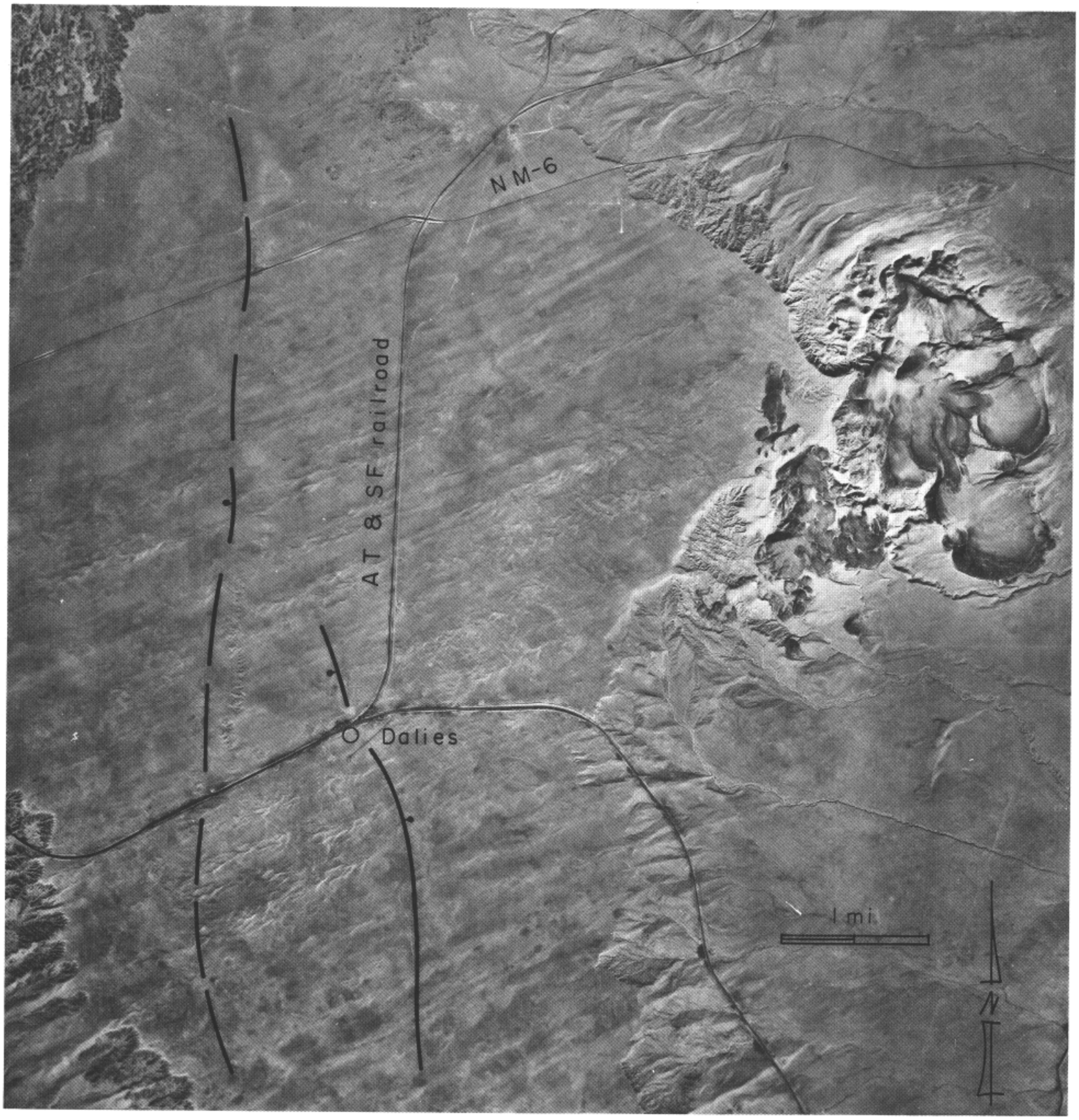


FIGURE 6—VERTICAL AIRPHOTO OF PART OF CEJA MESA AROUND DALIES. Shows well developed longitudinal dunes; Los Lunas volcano at right; Cat Hills basalt flows in northwest corner.

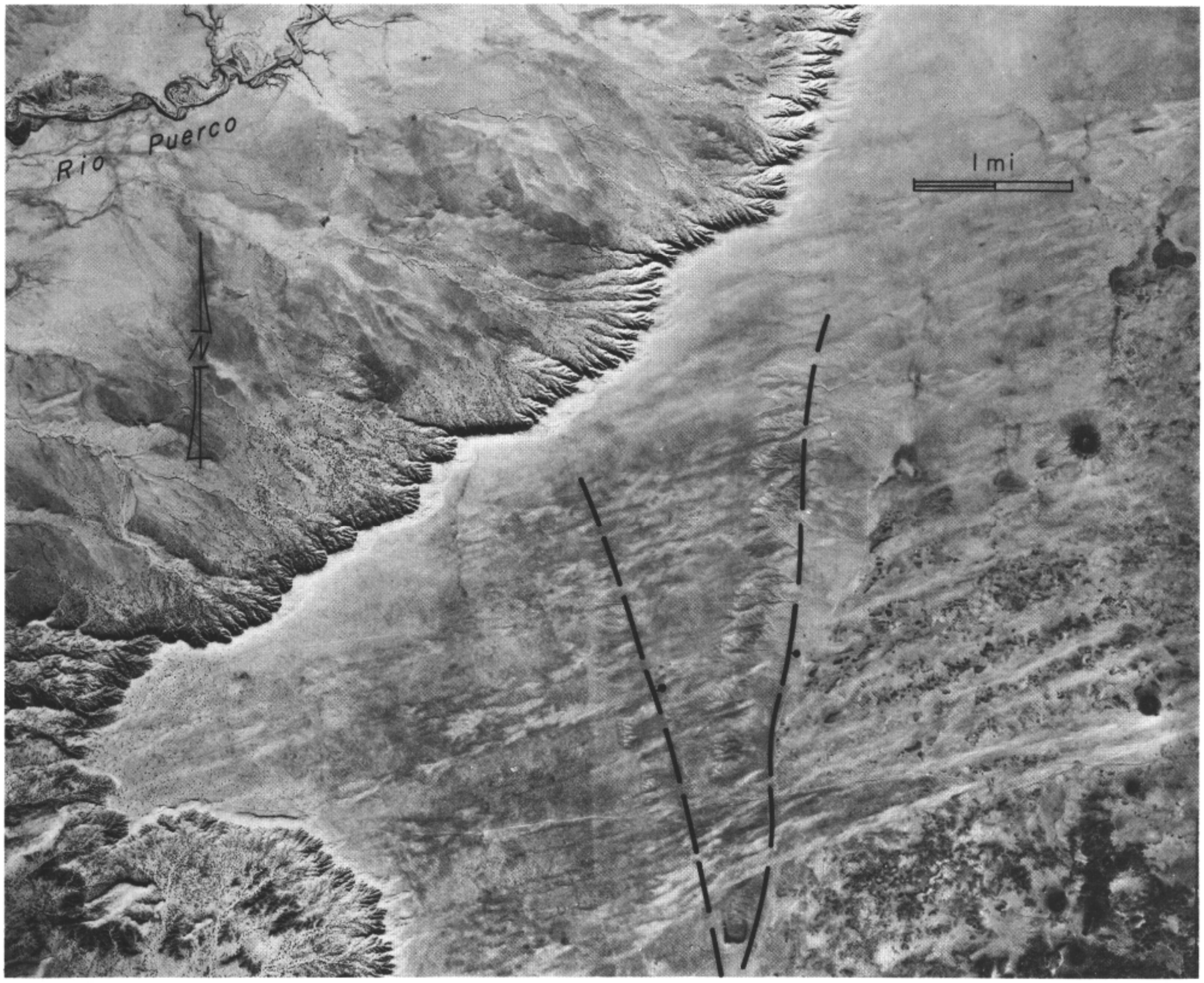


FIGURE 5—Vertical airphoto of western part of Ceja Mesa. About 14 mi west of Isleta, showing cliff and longitudinal dunes. Note narrow band of cliff dunes along western edge of mesa; Cat Hills lava flows and cinder cones.

Arroyo on the south (a north-south band about 33 mi long and up to 7 mi wide). The sand blanket and dunes lie on the well-developed caliche cap of the Ortiz surface and in places are piled up in low hills behind the edge of the mesa to heights of 15-40 ft with the uncovered pediment to the east in places lower than the sand hills. The field is fairly well stabilized but low longitudinal ribs or streaks are still clearly visible on airphotos.

At present the prevailing wind is out of the southwest, and this is strongly indicated by the active dunes along the Rio Salado. Similar directions are shown by the lineations on the blankets and dunes east of the Rio Grande running N. 45°-50° E. throughout their long north-south distribution. This contrasts with the sand streak trends on Ceja Mesa where they change gradually from N. 58° E. (south-southwest of Belen) to N. 78°-85° E. (northwest and north of the Albuquerque volcanoes). Lambert (1968, p. 197) questioned if the longitudinal dunes were all formed by prevailing winds out of the west or whether some were formed by strong prevailing winds out of the east-northeast. Obviously many of the longitudinal dunes west of Albuquerque are formed by a west-southwest prevailing wind. It might be quite a coincidence for an earlier prevailing direction to be just 180 degrees opposite. Nevertheless, there is some evidence of an opposite prevailing wind in the form of grooves in hard rock formed by wind sandblasting (Denny, 1941, p. 257-258). Fluting by sand abrasion occurs on the east sides of rocks and is in a direction between S. 80º W. and N. 80° W. at the small basalt patches about 2 mi west of Black Butte. Similar sandblast grooves have been described by Elston and others (1968) at Cerro Colorado, with similar evidence of origin by strong easterly winds.

The overall directional pattern in the basin suggests a possible funneling of westerly and southwesterly winds toward the Tijeras Canyon pass through the eastern bordering mountains. The more northerly trend of the dune directions east of the Rio Grande would be the result of wind deflection along the mountain front.

A very unusual buildup of travertine spring deposits occurs along the base of the Lucero uplift (fig. 7). These deposits were mapped by Kelley and Wood (1946). One location is a 3-mi strip along the eastern base of Lucero Mesa in T. 7 N., R. 2 W. Although most of the irregular buildup is probably Pleistocene, some local active deposition from springs is presently taking place.

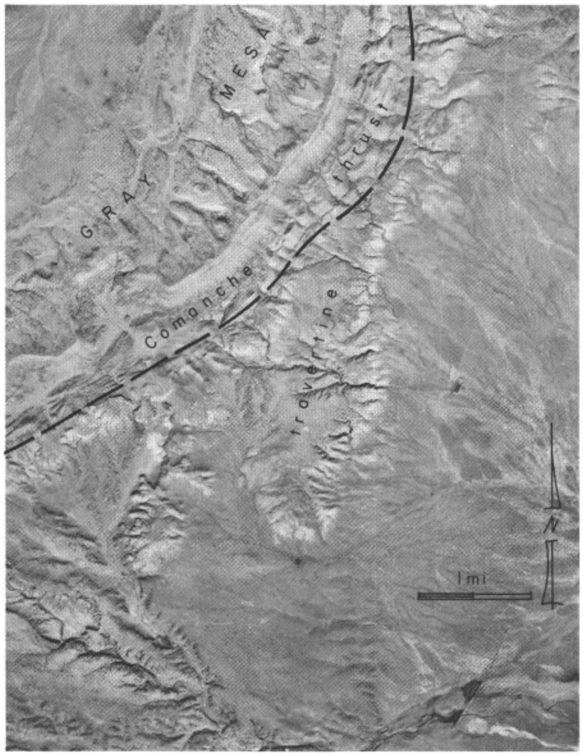


FIGURE 7—VERTICAL AIRPHOTO OF TRAVERTINE BANKS ALONG BASE OF GRAY MESA.

Kottlowski (1962, p. 20) described these deposits as having been used for ornamental stone. He analyzed many samples and found them rarely more than 85 percent calcium carbonate, the remainder probably being silt or sand. Much larger deposits occur in an interrupted 10-mi stretch from along the base of Gray Mesa to just north of Monte de Belen. These deposits formed as depositional banks or terraces along the Comanche fault zone. They are mostly dormant, although quite locally there is continuing deposition from small springs. The banks are up to 100 ft thick. Locally calcium carbonate deposition spread eastward onto and into the Ortiz pediment gravel at the base of the banks. Elsewhere the travertine beds can be found resting on the downthrown side of Comanche fault on gravel or on local Paleozoic beds. These travertine deposits are the largest in the state. In most locations these deposits are more than 90 percent calcium carbonate, and I have estimated that they contain about 200 million tons of travertine. During the 1960's Ultramarble Inc. of Albuquerque quarried the travertine at the east base of Gray Mesa for commercial use. The travertine was drilled in 6-ft cubic blocks and sawed into slab dimension stone. Striking use of this stone may be seen in the Capitol Building in Santa Fe. Numerous small travertine deposits occur quite locally around the basin but only one of the larger deposits at the base of Montezuma salient of the Sandia uplift is mapped. It is a patch about 20 ft thick, 1,000 ft wide, and 2,000 ft long and rests on Santa Fe gravel just west of the San Francisco fault along which the travertine precipitating solutions rose.

Igneous rocks

A dozen or so igneous centers, numerous flows, cinder cones, some sills and dikes, and a few tuff ring pyroclastic vents are distributed along the basin. The principal rocks are olivine basalt, but locally some eruptions are andesite. There is one latite plug, and a local rhyolite intrusion at a basalt center. Six principal volcanic centers dominate the occurrences. In order of decreasing area they are San Felipe, Cat Hills, Albuquerque, Wind Mesa, Isleta, and Los Lunas (geologic map). Three—Cat Hills, Wind Mesa, and Albuquerque—have remained the same since erupting except for some surficial and marginal erosion and faulting (fig. 8). The others have been partly or completely buried by Santa Fe deposits and subsequently uncovered by post-Ortiz erosion. The three largest fields are characterized by fissure-controlled eruptions which have spread up to 5 or 6 successive flow units from the fissures and aligned cones. Where cinder eruptions occurred, they were the last development in the field. Locally the cones have been intruded by small dikes, fingers, and small cone sheets. Some of the small occurrences, although lacking surface volcanic form, appear to represent intrusions in or very near the bases of volcanoes since removed by erosion. Only this brief summary is given here as greater detail of surface geology, petrography, chemistry, and petrogenesis of the basalts and andesites is the subject of a circular by Kelley and Kudo (in press),

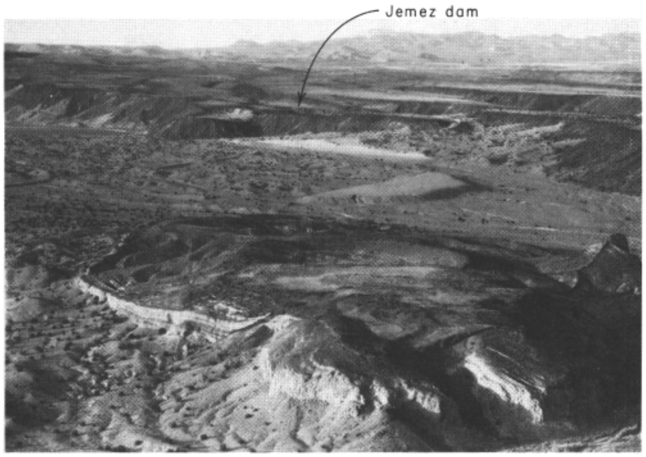


Photo by Donald A. Meyers

FIGURE 8—AIRVIEW NORTH OF CANJILON DIATREME. Diatreme in foreground, San Felipe basalt flows in middle distance, and Jemez Mountains in background.

Geomorphology

The geomorphology considered here is mostly confined to the erosional and depositional surfaces of the basin (fig. 9). Only slight reference is made to the geomorphic features of the uplifted borders. Normally it is best to explain structure as well as stratigraphy prior to geomorphology. Here, however, geomorphology is discussed before discussing the structure of the basin because many of the flat surfaces are much like stratigraphic units in furnishing clues to late warping and faulting in the basin.

The principal landforms which comprise the Albuquerque Basin are as follows: I) pediments, 2) dissected slopes, 3) fault scarps, 4) terraces, 5) alluvial slopes, 6) alluvial fans and cones, 7) major stream floodplains or valley bottoms, 8) eolian blankets and dunes, 9) volcanic fields, ridges, and cones. Most of these are shown on the geologic map and are treated here. Some are also discussed in the sections on stratigraphy, structure, and igneous rocks.

PEDIMENTS

The best known and one of the highest preserved surfaces occurs around the Ortiz Mountains. Johnson (1903, p. 174-175) possibly first described the surface as a pediment, and Ogilvie (1905, p. 34) in further description and analysis referred to it as the "conoplain of the Ortiz." Bryan and McCann (1936, p. 156) and Bryan (1938, p. 215) were the first to name the pediment and extend it by mapping and correlation to surrounding areas, especially in the Albuquerque Basin. The most notable and significant of these extensions is the Ceja Mesa between the Rio Grande and Rio Puerco valleys (Bryan, 1938, p. 219). Kelley and Northrop (1975, p. 70-71) describe a number of possible extensions of the Ortiz surface into and around the Sandia Mountains. Bryan (1938, p. 215) also hinted at possible equivalent surfaces in the southern part of the state and also into the Espariola Basin. Bryan and McCann (1937, p. 156) identified certain ridge spurs in the northern Nacimiento Mountains at altitudes of 8,300-8,400 ft which might be Ortiz surface remnants. Kelley and Wood (1946) and Wright (1946, p. 435, pl. 10) recognized Ortiz surfaces west of the Rio Puerco. Wright (1946, p. 437) further postulated that a small high bench at the base of the Manzano uplift might be an Ortiz remnant, but this is unlikely as it gradually descends westward merging with the East Mesa surface.

Bryan calculated that the Ortiz was graded to the Rio Grande at about 500 ft above its present elevations. In a sense the development of this widespread erosion surface was the culmination of the principal basin filling and basin deformation of the depression. However, since Ortiz time there have been more warping, tilting, and widespread faulting which has broken not only the Ortiz surface but also most younger surfaces. The main consequence of the post-Ortiz disturbances has been the erosional rejuvenation which changed the regimen of the drainage system from planation to incision and dissection. As a result, most of the expansive Ortiz surface has been destroyed, and in the wide valleys many levels of the basin fill have been exposed in one place or another.

Numerous older and higher surfaces than the Ortiz are known. Notable among these are the basalt-capped pediments on the crest of the Sierra Lucero (Kelley and Wood, 1946) at elevations of 7,700 ft; the northern top of the Nacimiento uplift at elevations of 10,000-10,500 ft (Bryan and McCann, 1936, p. 156); and around Mt. Taylor beneath lava-capped Mesa Chivato. Bryan and McCann (1938, p. 11) mistakenly thought Mesa Chivato, which is about 1,000 ft higher than Mesa Prieta, was a part of the Ortiz. However, slopes of the mesas are not such as to make that explanation likely. Higher surfaces in the area around Santa Fe are also possible. Reiche (1949, p. 1205) described physiographic evidence in the summits of the Manzanita uplift at elevations of about 7,500 ft that suggested an old erosion surface. The flats at the head of Juan Tabo Canyon and equivalent altitude benches or ridge shoulders at 6,800-7,000 ft along the Sandia front may also be older than Ortiz.

Some surfaces that have been presumed to be pediments are not pediments. These include Santa Ana Mesa, Borrego Mesa, and Chamisa Mesa. Bryan and McCann (1938, p. 8) and Soister (1952, p. 73) thought these were erosion surfaces to be correlated with the Ortiz surface. However, the flows of these mesas are inter-Santa Fe. The San Felipe flows and volcanoes were earlier buried by several hundred feet of sand and gravel; those of Borrego Mesa were intertongued with Santa Fe sand and gravel that is more or less tuffaceous due to influxes from older nearby Jemez volcanic rocks.

Although the Ortiz erosion surface is the best known and the most significant of the high surfaces in and bordering the basin, it has a number of problems regarding projection and correlation to adjacent areas. Ogilvie (1905) described this surface as a special type of pediment developed conically around circular or dome-shaped mountains such as the laccolithic Ortiz porphyry mountains. The Hagan Basin embayment of the Rio Grande trough lies just west of the Ortiz dome and partly beneath the cover of the Ortiz pediment (fig. 10). Presumably since the pediment is on the west side of the dome, it could slope westerly as does the built-up surface of the pediment cover (Tuerto gravel). Bryan (1938) did not describe La Bajada escarpment as a fault as was done later by Kelley (1952, p. 95) and Stearns (1953a, pl. 1). In addition to naming the Ortiz surface across the southern end of the fault, Bryan named a lower surface (La Bajada) at the base of the fault scarp around the village of La Bajada. Altitudes on the base of the Tuerto Gravel can be determined on modern topographic sheets at many places along the western edge of the Ortiz conoplain, along the San Pedro Creek drainages, and in numerous outliers of the gravel along the northeastern base of the Sandia uplift. Contouring of these points brings out the fact that the erosion (cut) surface in the northern part slopes northward at 50 ft per mi and at 150 ft per mi farther south in the Hagan Basin between the San Francisco fault on the west and La Bajada fault on the east. Ortiz pediment outliers along the eastern side of the Sandia Mountains are not shown on the geologic map for lack of sufficient scale and because of clutter of faults and bedrock map units. They may be seen on the geologic map of Kelley and Northrop (1975). Original slopes of the surface map were slightly less in the northern area before the crossing faults in T. 14 N. dropped the surface on their northern sides. The pediment undoubtedly would slope westward near and to the east of La Bajada fault zone as projected beneath the Ortiz conoplain slope.

Throw along the northern part of the San Francisco fault is slight, and very little or no post-Ortiz movement has occurred along it, especially north of Galisteo Creek. At the southern end of La Bajada fault, the Ortiz cut surface is at essentially the same altitude on both sides of the fault (T. 13-14 N.). Near La Bajada the Ortiz cut surface on the upthrown side is 500-600 ft above the buried downthrown surface on the west. Burial by outwash from the escarpment may be as much as 200-300 ft. Altitude of the Ortiz surface east of the Rio Grande is about 200 ft above the river. The Ortiz surface near the top of the escarpment at the Rio Grande is difficult to determine but is possibly 650-750 ft above the river. La Bajada faulting is described in more detail in the chapter on structure,

Some high Ortiz outliers along the northeast flanks of the Sandia Mountains (Kelley and Northrop, 1975, map 1) range from 6,400-6,800 ft. These are not useful in obtaining plausible correlations of Ortiz surfaces along the basin at the northern end or ramp of the Sandias. The reasons are they may have been slightly elevated by Pleistocene uplift, and the occurrences may be alluvial slopes above stabilized pedimentary base controlled in part by dip-slope stripping. The more reliable outliers for control lie either in the Placitas area or on the Montezuma structural salient (Kelley and Northrop, 1975, map 3). Two patches of gravel occur just north of Montezuma fault at 6,100-6,200 ft, and another remnant occurs on Lomas Altos Mesa on top of tilted Santa Fe fanglomerate at 6,000-6,100 ft. These are in fair agreement with the 6,100-ft and 6,200-ft contours of the Ortiz cut surface in the Hagan Basin. Somewhat removed from these is a string of small outliers along the ridge divide between Tongue and San Francisco Arroyos in adjoining secs. 3 and 34 in T. 13 and 14 N,, **R,** 5 E. These outliers have altitudes ranging from about 5,550 ft (on the west) to 5,740 ft (about 2 mi to the southeast). These altitudes, higher by 150-200 ft than nearby more widespread terrace levels, are at levels reasonably compatible with the trend and altitude of the Hagan Basin cut surface. If these are Ortiz remnants, it is important to note that these altitudes are a stratigraphic level in the Santa Fe that may be 400 ft higher than the inter-Santa Fe-San Felipe basalt flows (in the same ridge less than 2 mi to the west).

Anderson (1960, pl. 2) identified and mapped several small gravel-capped peaks and ridges 4-5 mi west of the Rio Grande between Peralta and Santo Domingo Canyons which he correlated as Ortiz surface remnants. These are at altitudes of 5,950-6,100 ft and slope toward the river (fig. 10). Soister (1952, fig. 5) had earlier mapped these gravels northwest of the basalts of Santa Ana Mesa and similarly correlated them as Ortiz. Smith, Bailey, and Ross (1970) also mapped these

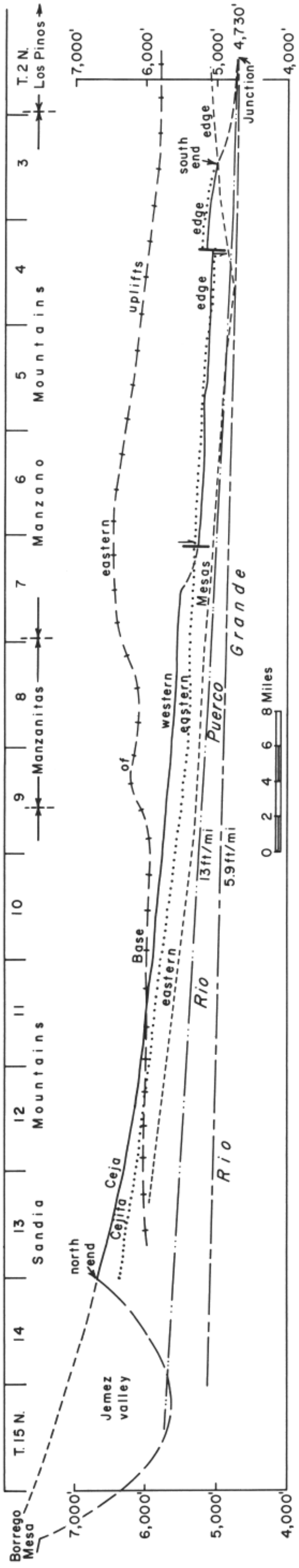


FIGURE 9—NORTH-SOUTH LONGITUDINAL PROFILES OF RIVERS AND EROSION SURFACES.

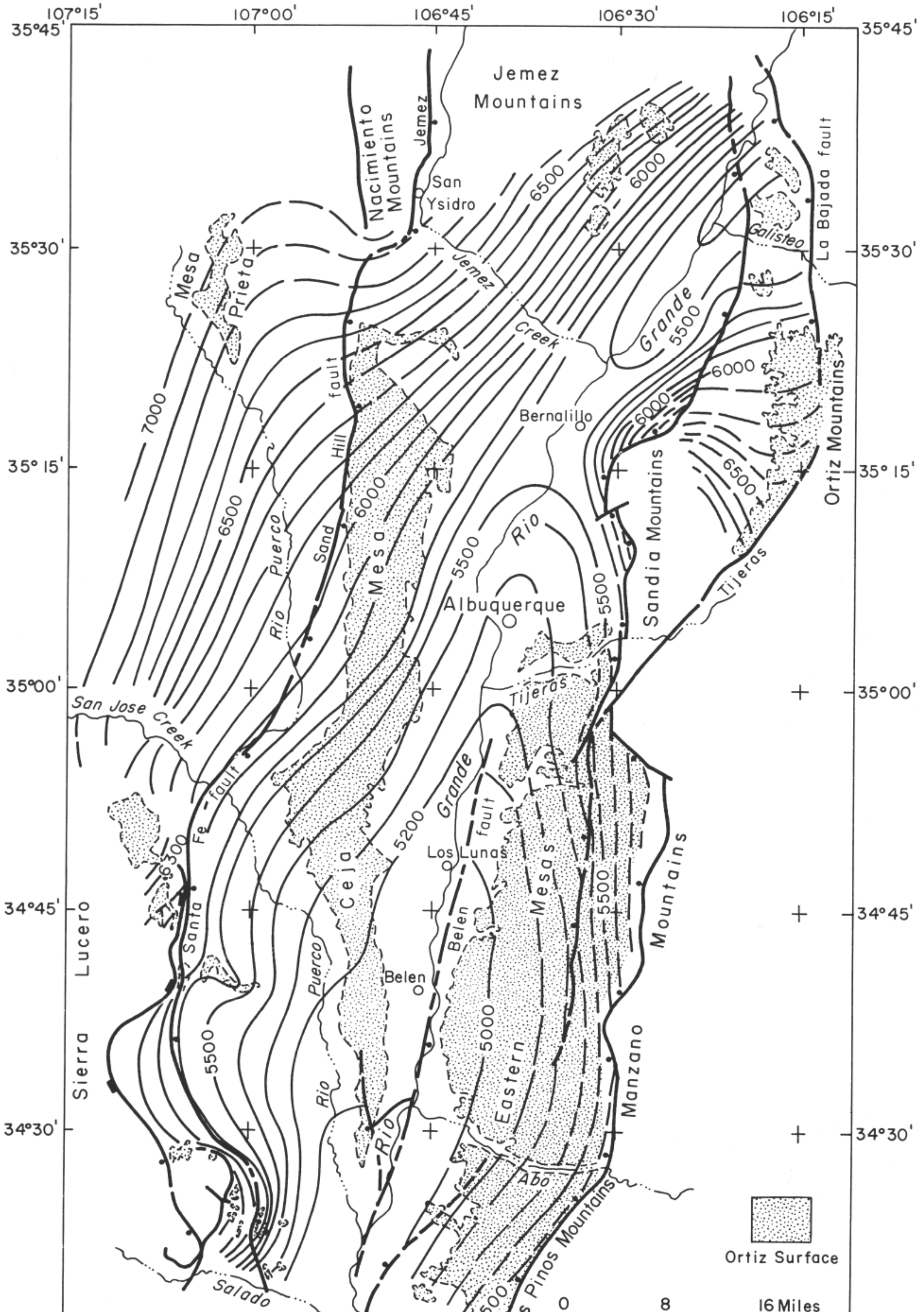


FIGURE 10—Ortiz surface reconstructed from elevations on remnants of the surface.

gravels as Pleistocene pediment gravels. Measurable slopes on these surfaces, toward the river, project them to levels of 250-350 ft above the river, and this is only slightly higher than the projection from east of the river, north of Galisteo Creek. Projections to the river in the San Francisco-Tonque divide are not meaningful since axial position of the Ortiz-Rio Grande drainages is uncertain although likely 1-2 mi east of its present position. Apparently its position is easily above the lower flows of the San Felipe eruptions. However, the main volcanic ridge of the field may have stood above a surrounding Ortiz surface.

In the Jemez area the Ortiz pediment of Soister (1952) slopes S. 37º E. at about 110 ft per mi. In its western (higher) part, it intersects and overlies the San Felipe flow; the general dip of the flow is easterly at 200-400 ft per mi. Gravel which overlies the eastern and southern edge of the San Felipe basalt is Santa Fe, not that of an Ortiz surface mapped as Mesita Alta gravel by Soister (1952, figs. 4, 5). The surface on which the San Felipe lower flow and basalt tuff rest is older and is an intra-Santa Fe depositional surface. The Mesita Alta gravel (Ortiz) lies unconformably across the northwestern edge of the San Felipe basalt field, and some of the flow may have been truncated before being covered by the gravel.

To the west of Santa Ana Mesa, the Mesita Alta gravel and the Ortiz surface have been widely removed in the Jemez Valley and Jemez Canyon areas. The northern end of Ceja Mesa is approximately 15 mi southwesterly across the valley where the next likely position of the Ortiz surface is. It is 24 mi to Mesa Prieta which others have also postulated to be Ortiz. Altitude control on the Ortiz erosion surface of the 63-mi-long Ceja Mesa is excellent, although some minor faulting complicates the projections locally (fig. 6). In the northern part the surface slopes S. 40°-50° E. at 60 ft per mi. West of Albuquerque the slope is S. 70° E. at 45-55 ft per mi. From about west of Los Lunas to the southern tip of Ceja Mesa (fig. 11), the slope is 10-15 ft per mi in a southerly direction. West-southwest of Albuquerque the Ceja is inclined S. 70° E. at about 65 ft per mi. This slope, projected to the mesa edge east of Isleta, is about 300 ft below (not above as Bryan (1938) and Wright (1946) had supposed) the mesa east of the Rio Grande (East Mesa). However, the surface probably flattens considerably as it crosses the axial position of the Ortiz drainage. Therefore, apparently the East Mesa surface is the Ortiz surface even though it is 300 ft lower than the eastern edge of Ceja Mesa (west of the river). This is an important point because Bryan (1938, p. 217), Wright (1946, p. 445), and numerous others have correlated the surface east of the Rio Grande from Albuquerque southward with Bryan's La Bajada surface which has been shown above to be Ortiz. Similarly, altitudes of the southern end of the Ceja correlate convincingly with those east of the river, and if the Ceja is Ortiz, then so is the cut surface of East Mesa. If Bryan and his co-workers had the modern topographic maps for control, they would have probably concluded the same. In a section of the valley north and south of Belen, the East Mesa surface descends to about 4,900 ft, which is about 250 ft lower than the rather flat Ceja surface. This is interpreted to be due to post-Ortiz faulting and slight tilting roughly paralleling the Rio Grande (Kelley and Northrop, 1975, p. 86). Discordance of the east and west surfaces in the Belen area has led to the designation of the east surface as a younger lower separate surface of pedimentation. The clear matching of the same two surfaces to the north and south of the Belen interval is compelling evidence of the likely existence of the river (Belen) fault.

West of the Rio Puerco along the Lucero border there is a local remnant of the Ortiz. This Ortiz remnant is at the top of the badlands break of the east limb of the so-called Gabaldon anticline of Kelley and Wood (1946) and Wright (1946, p. 425). The altitude averages from 5,600 to 5,700 ft, and its position fits well with the southwesterly extension of the 5,700-ft altitude of Ceja Mesa. The cut surface on which the Lucero Mesa basalt erupted is 200-600 ft above the Gabaldon remnant. Apparently post-Ortiz uplift along the Lucero front caused this higher altitude. The Gabaldon remnant has an extensive caliche cap that is equal to or greater than caliche development on the Ceja. The remnant is also warped with dips of 3-4 degrees to the S. 60° W. on the north, curving to S. 30° E. on the south. Southwest of the Gabaldon remnant there is a great swalelike surface drained by the wide fan of arroyos radiating into the Monte Largo embayment of the Lucero uplift. Ap-parently this drainage system lowered the Ortiz gravel cover slightly but over a broad expanse. Lowering the gravel cover modified it into a younger alluvial slope extending nearly to the Rio Puerco between Mariano Draw and Coyote Draw. Nevertheless, remnants of the Ortiz surface appear to still exist east of Monte de Belen and the Comanche fault along the boundary between T. 3 and 4 N. The high cut surfaces north and east of the Ladron are believed to be Ortiz. In particular these would include the Tio Bartola surface of Denny (1941, p. 228, 236) and the high fanglomerate capped surfaces above the Jeter fault, east of the Ladron Mountains. The remnants east of the Ladron Mountains are considerably dissected, but they can be readily traced from 6,200 ft near the Precambrian outcrop to as low as about 5,200 ft north of the Rio Salado, about 5 mi west of the Rio Grande. This level is logically correlated with the cut surface of East Mesa, along the northern edge of the Socorro constriction in T. 1 N., R. 2 E., or to the southern tip of the Ceja Mesa. Denny also mapped this as Tio Bartolo. The Tio Bartolo surface was correlated as La Bajada (Denny, 1941), but, as shown above the type La Bajada, is Ortiz.

Much of the earlier correlation was based on an assumption that pediment surfaces had some sort of universal stabilization slope of 40-50 ft per mi, and by using these, positions of about 500 ft above the axial drainage were calculated. Once this assumption was accepted, then it was postulated that a surface would rise up with similar gradients to a reasonably positioned surface on the opposite side of the axial drainage. Little or no allowance was made for tilting or faulting partly because of poor altitude control and lack of enough field mapping. Furthermore, the pediment surfaces are cut and more or less stabilized at a range of slopes depending upon type of rock, distance from mountain to base level, and the nature of precipitation and runoff.

New correlations and mapping of the Ortiz surface

FIGURE 11—Vertical airphoto of southern end of Ceja Mesa.

(fig. 10) result in a much greater area of the surface preserved and abandonment of the La Bajada surface and its former extensions. Fig. 10 (showing the configuration of the Ortiz surface as correlated and reconstructed in this work) presents the problem as to how much of the surface is as it was at the end of planation, and how much of it reflects later warping and significant modification by faulting. Numerous minor faults which break the surface were ignored in reconstruction. There are two rather contrasting parts to the surface. The larger part lies north of the Lucero uplift where the Colorado Plateau (Puerco fault zone) and the Jemez uplift mark the western border of the Ortiz Basin. Between the Puerco and the Jemez drainages (at Mesa Prieta), the surface slopes from as high as 7,000 ft to about 5,400 ft (between Albuquerque and Bernalillo), a rather uniform fall of about 1,600 ft in 34 mi and a gradient of about 47 ft per mi. Bryan's assumed slope, from the Ortiz surface to 500 ft above the river, figures to be about 48 ft per mi. The surface as reconstructed in fig. 10 is about 50 ft per mi. Evidence indicates some tilt of the surface by downthrow on La Bajada fault; therefore, the entire surface for the Albuquerque Basin as reconstructed (especially in the large asymmetrical northern part) contains an element of post-Ortiz sagging.

The part of the basin bounded by the Manzano-Los Pinos Mountains and Sierra Lucero is rather symmetrical; the east and west edges of the reconstructed surface are at about 5,800 ft in most places, except for being domed by several hundred feet around the Ladron Mountains.

The southeasterly slope in the northern part and near horizontal position in the southern part of Ceja Mesa may have resulted from an eastward tilt in the north and westward tilt in the south. But the positioning of the

Rio Grande and the Rio Puerco which left the southern end of the mesa near the axis of the original Ortiz surface may have caused the difference in slope.

DISSECTED SLOPES

At the height of Ortiz planation, very few dissected slopes exposing the basin fill existed. But with uplift and rejuvenation of the drainage system, the pediment and alluvial covers were widely stripped, and the valley system of today progressively developed. Maximum relief and exposure of basin fill were probably reached several tens of thousands of years ago when the Rio Grande and Rio Puerco valleys were several tens of feet deeper than today. With subsequent refilling of the valleys, the floodplain and valley alluvium widened, and the alluvial fans which formed along the bases of the dissected slopes were buried at their bases. At the same time, the slopes extended headwardly over the dissected Santa Fe. The area of dissected slopes is essentially the outcropping Zia member and Santa Fe Formation.

Dissected slopes in the basin fill circumscribe Ceja Mesa completely. Nearly complete stripping of the Ortiz surface in the northern part of Ceja Mesa resulted in broad low swales and intervening narrow ridge-line remnants of Ortiz alluvium. Similar slopes extend nearly uninterrupted along the eastern side of the Rio Grande and into the Hagan Basin. Another large area, where Jemez volcanic rocks surmount the basin fill, is between Jemez and Rio Grande valleys around the southern and southeastern flanks of the Jemez Mountains.

Dissected slopes are widespread west of the Rio Puerco. In the northern part of the Puerco area, the slopes are on Cretaceous rocks. From the Rio San Jose southward, the slopes are again in Santa Fe, and in the Santa Fe homocline of the Gabaldon badlands the thickest continuous exposure of the Santa Fe Formation in the Albuquerque Basin is seen.

The dissected slope terrain is commonly one of intricate and "fine-grained" topography. The largest area of badland dissection lies north of Ceja Mesa in the southern slopes of Jemez Valley. To some extent badland topography is seen along and south of NM-44. The best views are from almost inaccessible points along the Ceja rim where the badlands are seen as a veritable Bryce Canyon.

Another common type of dissected slopes results from fault scarps that are post-Ortiz. A number of faults with dissected basin-fill slopes and Ortiz gravel scarp slopes are mapped along Ceja Mesa. The largest of the dissected scarp slopes occurs along Hubbell Springs fault zone. This scarp is up to 125 ft high, and dissection exposes Permian, Triassic, and Ortiz surface and gravel. On the geologic map (in pocket), thin elevated gravel is mapped as a terrace *(Qt)* although it is part of the Ortiz (Q0). West of Rio Puerco a considerable number of faults with a throw of a few tens of feet expose Santa Fe, possibly the Ortiz surface and its gravel, and younger terrace gravel.

Others, generally much steeper dissected slopes, are those flanking lava-capped mesas such as the Albuquerque volcanoes, at Isleta, and most notably around Santa Ana Mesa. Large canyons have cut through a margin of the San Felipe lava flows at two places: Borrego Canyon (on the northeast) and Jemez lower gorge (on the south). Neither of these streams would have established such courses had they not been superimposed. Both streams probably flowed on the Ortiz surface, and in both areas the Ortiz erosion surface was as much as several hundred feet above the top of the basalt flows. With rejuventaiton, the streams were at first entrenched in the Ortiz gravel and then in Santa Fe gravel to finally become superimposed across the resistant basalt. Within canyon walls the streams maintained their position and finally cut through again into the easily eroded Santa Fe. Gravel still exists on the basalt locally at both the Borrego and Jemez gorges. Where the Jemez River was superposed across the San Felipe basalts near Jemez dam, there was probably a waterfall. For a time, until erosion cut through the basalt, the valley upstream widened and graded itself to the basalt level. This is supported by several of the lower ends of alluvial slopes descending to the basalt level along either side of the Jemez Valley upstream from the dam. This level is at the altitude (5,360 ft) of the lowest basalt position in the gorge near the dam.

TERRACES

During Quaternary dissection of the basin, numerous terraces were formed along the sides of the Rio Grande, Rio Puerco, and some of the larger tributary valleys such as Galisteo, Jemez, and Rio Salado. Several of the terraces have continuity up to nearly 20 mi, whereas others are short and quite local. Rarely do these occur at the same level on oppostie sides of the large valleys. The new correlation of the East Mesa of the Rio Grande valley with the Ortiz pediment causes the remaining surfaces to assume much less significance than formerly concluded.

In the Santa Domingo area there are small, considerably eroded remnants of two terraces. One (about 140 ft above the river) was named Peria Blanca, and another (about 80 ft above the river) Anderson (1960, pl. 2) named Rio Grande. A few small remnants of the Rio Grande terrace occur west of the river, south of San Felipe Pueblo. Anderson also traced small remnants of these for several miles up Galisteo and Santa Fe Creeks (east of the Rio Grande). He also recognized similar remnants up Peralta and Santo Domingo Arroyos (west of the Rio Grande). However, what he identified as La Bajada surface is shown here to be Ortiz surface. What Anderson identified as the Site terrace, possibly 20 to 30 ft above the river, is mostly narrow alluvial fan material bordering the floodplain. Locally, however, it has been undercut by a meander of the Rio Grande producing a terrace form, but it is not of river origin.

Northwest of the Sandias, west-northwest of Placitas, there are two distinct terrace levels. However, unlike the Peria Blanca and Rio Grande terraces, these terraces are not directly related to the Rio Grande. Instead, they parallel Las Huertas and Agua Sarca Creeks, tributaries from the Sandias to the Rio Grande. One of these terraces north of Las Huertas is 2 mi long, sloping from 5,740 ft at the base of a fault scarp to 5,550 ft. Projected to the Rio Grande position it is about 170 ft higher than the river. The lower side terrace is about 1 mi long and

5,450-5,350 ft in altitude and projects to the Rio Grande at about 130 ft above the river.

All the terrace-like, high-level gravels north of Tongue Arroyo and west of San Francisco fault are Ortiz gravels, although most have been lowered toward the Rio Grande by the San Francisco and other faults.

Several terraces occur along both sides of the Rio Grande between Bernalillo and Isleta. At Coronado Monument there is a small terrace 40-50 ft above the river. At Rio Rancho, north and south of Calabacillas Arroyo, there is a river terrace about 200 ft above the river. Just east of the Albuquerque volcanic field, on the surface of the University of Albuquerque, there is the Segundo Alto terrace, early recognized and named by Bryan and McCann (1938, p. 14). The Segundo Alto terrace is 100-130 ft above the nearby river level and is continuous for about 8 mi. Just south of 1-40 and extending southward for about 6 mi is a narrrow terrace termed Primer Alto by Bryan and McCann. The Primer Alto terrace is 55-60 ft above the river, and on this basis is to be identified with the terrace at Coronado and possibly with the Rio Grande terrace of Santo Domingo Basin.

Very few small terrace remnants occur at Sandia Pueblo and southward for 2-3 mi. These are 40-50 ft above the river and are also to be correlated with the Primer Alto and Coronado localities. A long stretch of low bluffs occurs west of the Pino-Bear Canyon reentrant in the Sandia Mountains. These are river meander truncations of the long alluvial slope that extended to the river plain. At Albuquerque there is a level of segmented terraces extending from just north of Embudo Arroyo to about I mi south of the University of New Mexico campus. This level which correlates with the Rio Rancho terrace (west of the river) appears to represent a river position just prior to the capture of old Tijeras Arroyo which debouched onto this surface through Campus and 1-40 distributaries (Kelley, 1969; 1974, p. 26).

One long low terrace and several small terrace remnants occur along the Rio Grande south of Tij eras Canyon to the junction with the Rio Puerco. The long terrace extends from around the Isleta volcano south for about 16 mi where it dies out near the A.T. & S.F. railroad northwest of Belen. The terrace is 3 mi wide and ranges from about 110 ft (above the Rio Grande at Isleta) to about 70 ft (above at its southern end). In general this terrace is about 100 ft lower than the edge of the mesa (Ortiz surface) east of the river. The Isleta-Los Lunas terrace 110 ft above the river is best correlated with the Segundo Alto terrace (100-130 ft above river).

No terrace remnants occur east of the Rio Grande between Albuquerque and a few miles south of Belen. A small terrace just east of Turn about 100 ft above the river correlates roughly with the Los Lunas terrace. South of Abo Arroyo there are two distinct terrace levels, one just southeast of the mouth of the arroyo and one about 2 mi east of La Joya, both about 200 ft above the river. There is nothing along the Rio Grande except the Rio Rancho and University of New Mexico terraces to correlate with these. These terrace levels are only about 80 ft below the Ortiz surface. The lower terraces in this area are also just east and southeast of La Joya and are 110 ft above the river, which would correlate with Los Lunas terrace.

The Rio Puerco valley has a very few small gravel terraces scattered between the Sandoval County line and 1-40 (all on the west side). They are about 80 ft above the Rio Puerco flats. There are two small terrace benches just south of NM-6 in secs. 4 and 5, T. 6 N., R, 1 W., the only ones anywhere along the east side of the entire length of the Rio Puerco in the Albuquerque Basin. Their altitude compares very closely to the surface that is basalt-capped along NM-6 and projected to the Rio Puerco along Garcia Arroyo. A number of remnant alluvial slopes, west of the Rio Puerco in T. 3-6 N., when projected to an estimated Rio Puerco position (somewhat west of its present position) also agree with the terrace remnants and the basalt-capped surface projections. The basalt flow which came from Cerro Verde volcano west of Sierra Lucero probably flowed in the Rio San Jose valley bottom, which was subsequently abandoned in favor of its present more direct route. This route junctions with the Rio Puerco. Thus, the terraces, alluvial slope projections, and the preserved wide Rio San Jose valley bottom combine to indicate a period in Pleistocene time when the Rio Puerco developed a widened, more mature valley of temporary aggradation. The discharge base of the Rio Puerco was some 80-100 ft above the present valley flats. Correlations with terraces along the Rio Grande are rather uncertain but the most likely would be with the Segundo Alto and Los Lunas terraces.

ALLUVIAL SLOPES

Alluvial slopes (Bryan, 1923, p. 86) are blankets on extensive surfaces which may be contiguous with but also separate from pediments or fans. They may, on the one hand, be flatter than the merging fans or cones; or they may be alluvial surfaces formed by coalescence of numerous closely-spaced washes. These slopes may form adjacent to certain mesas as well as beyond the fans or cones of mountain fronts. They may become common in mesa areas where capped by thin, relatively resistant rocks, or where the flanking dissected mesa slopes have become quite wide, or where the difference in resistance between cap and slope layers is not great. In some instances, where alluvial fans are greatly coalesced and extend for 10-15 mi from mountains, they may be referred to as alluvial slopes or bajadas.

A fine example of an alluvial slope is developed west of the Pino-Bear Canyon reentrant of the Sandias. This feature has developed by gradation and aggradational forces of well-supplied, closely spaced arroyos. The slope is 6-7 mi wide and 6-8 mi long and possesses a rather uniform gradient of about 175 ft per mi. It is bounded on the north by transition into a more dissected alluvial buildup of fans. To the south it is bounded by the Ortiz pediment and University of New Mexico terrace.

Many alluvial slopes are developed on the east flank of Ceja Mesa. The basal flow of the Albuquerque volcanoes erupted on an alluvial slope which descended to the east from the edge of the Ceja-Ortiz surface. Eruptions from a fault fissure occurred very near the edge of the mesa and almost immediately spread down an alluvial slope for at least 3-4 mi; and at one point in the northeast edge of the field, a small lobe descended to near the back edge of the Segundo Alto terrace. Along the southern edge of the surface the slope is 150 ft per mi, in the northern part 100 ft per mi. Another slope, with only thin patches of alluvium and soil, occurs on the long surface which NM-44 ascends (westward from the Rio Grande). The gradient is about 150 ft per mi for about 3 mi, and it has been much dissected by a few dip-slope arroyos. Another similar slope, covered with eolian sand east of the Wind Mesa basalt field, descends toward Isleta for about 2 mi at about 140 ft per mi.

The greatest area of alluvial slope development lies west of Rio Puerco. These slopes occur in a wide area from the southern part of T. 6 N. to the northern part of T. 3 N. and extend 4-5 mi west of the river. They are terminated on the east at altitudes of 5,000-5,100 ft, apparently by a late Pleistocene deepening of the Rio Puerco. Originally, however, they may have extended to the Rio Puerco when it was 50-100 ft higher and possibly half a mile or so west of its present course. Slopes range from 70 to 100 ft per mi. The southernmost of the slopes on the divide between Alamito Arroyo and Mariano Draw is traceable to Monte Largo embayment (geologic map) at the base of the Lucero uplift, and it is very likely only a slightly modified Ortiz bajada. In this area Denny (1941, fig. 2) identified three pediments Tio Bartola, Valle de Parida, and Canada Mariano (from high to low). Wright (1946, p. 446) correlated the Tio Bartola with La Bajada surface of Bryan (1938). The Tio Bartola is very small and much dissected at its type locality, close to the precipitous Ladrons. Possibly it is only a young, steep alluvial cone whose sharp dissection in places is into its Precambrian rock fan base, and as indicated it correlates well with the Ortiz surface. The dissection may have resulted from late, sharp doming of the Ladrons as described in the structure section. On the basis of my mapping, the Parida and Mariano pediments are more or less the same surface separated by the Coyote fault. Under descriptions of the Ortiz surface, I suggested that the Parida could very well be the Ortiz surface. If this is true, then the Mariano surface would also be Ortiz. Its lower eroded end, 8 mi east of the Coyote fault on the divide between Mariano Draw and Alamito Arroyo, is about 4,960 ft in elevation. About 3.5 mi due east of the lower end the Ortiz surface near the southern terminous of the Ceja Mesa is 5,100 ft in elevation. This is no great difference, and the two could have been once continuous through minor faults and warps whose existence was hypothesized by Denny (1941, p. 243).

ALLUVIAL FANS AND CONES

Two occurrences or types of alluvial fans are differentiated in the basin: those at the bases of uplifts, such as the Manzano, and those which debouch onto valley floors from adjacent mesas, such as the Rio Puerco.

An almost continuous series of alluvial cones and fans extend along the bases of the eastern uplifts from Los Pinos to Sandias. The upper edges of these are fairly straight with only minor extensions into narrow, steep canyons. The lower edge is transitional into alluvial slopes or flat mesa surfaces. Map boundaries are more or less arbitrary but in some instances there is a rather obvious change of slope from steep to less steep, and this may be accompanied by a playing out of distinct distributaries. On many if not most alluvial fans there is little or no abrupt change of slope, and fans may extend 10 to 15 mi or more with a nearly uniform slope. Map differentiation into fan versus plain form is based largely on physiography and on radiate versus parallel drainage. The eastern mesa fans, particularly along the Manzano base, appear to represent a rather late rise of the uplift and/or subsidence of the basin surface. Such tectonic rejuvenation is soon reflected in new or youthful fans or cones. If the tectonic change is largely due to basin subsidence, especially accompanied by down tilting toward the uplift, previous fan surfaces tend to be "swallowed," and new fans very soon bury the earlier fan form. In general, the more convex the new cone is, the more recent is the event, although to an extent the convexity is greater with small canyons than with larger ones. In addition to the great line of cones along the eastern uplifts, there are a few cones of note along the base of La Bajada escarpment, locally north of the Ladrons, and in the Monte de Belen and Navajo Gap area of the southern Luceros.

The geologic map (in pocket) shows a rather remarkable fringe of alluvial fans along the margins of the Rio Grande and Rio Puerco valleys. These fans are formed at the bases of the dissected slopes that border the valleys. They differ from the mountain fans in having more sutured indentions of the mesa slope and in development of little convexity onto the floodplain or valley bottom. Fans that do protrude onto the valley bottoms are generally small partially because of the smaller volume of debris and because of destruction by strong longitudinal flow on the floodplain. In a number of places suturing on the upside of these fans is coalesced by cutting out or burying of low divides of the dissected slopes. In a few places the fan develops almost to the mesa edge, and a surface is developed that is more of an alluvial slope than a fan. Several areas like this have developed along the western slope of Ceja Mesa in T. 6-12 N. Fans that build out onto the floodplain have been referred to as foot slopes or ladera (Bryan, 1938, p. 217). Where truncated by swings of the river to the valley sides, small conical benches may be formed. These are common along the Rio Grande as first noted by Keyes (1907) and by Bryan (1938, p. 218).

FLOODPLAINS AND VALLEY BOTTOMS

Several floodplains and large alluviated valley bottoms are distinguished on the geologic map. The two principal ones are Rio Grande and Rio Puerco. Also differentiated are several major tributary valleys such as Jemez, Rio Salado, Abo, and others.

The Rio Grande bottom land is by far the largest and most important, with the greatest irrigated acreage in the state. In the Albuquerque Basin the Rio Grande floodplain attains its maximum width of about 5 mi just south of Los Lunas. It is regularly 2-3 mi wide in the 75 mi between Bernalillo and the narrow San Acacia Canyon south of La Joya (fig, 12), Along this stretch there are two narrows, one at San Felipe Pueblo where the river bottom is 300 ft wide and another at Isleta where the river bottom is 1 mi wide (including the Isleta Pueblo basalt island 3,000 ft long across the floodplain),

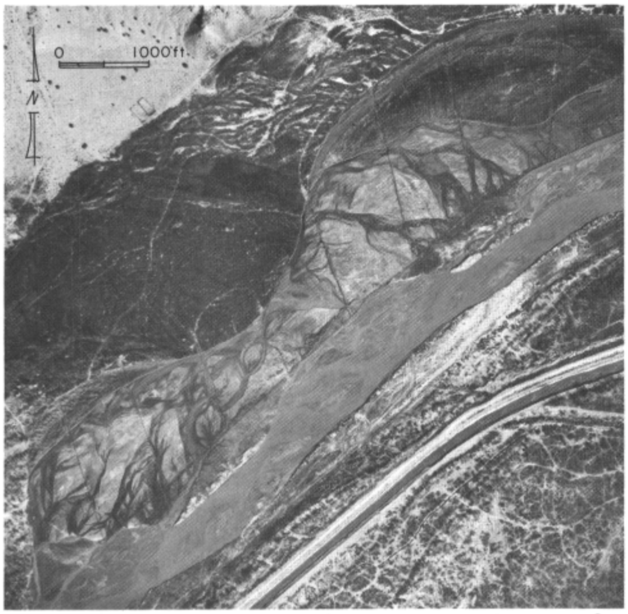


Photo by Limbaugh Engineers, Inc.

FIGURE 12—VERTICAL AIRPHOTO OF RIO GRANDE FLOODPLAIN 3 MI NORTH OF BERNALILLO.

In its straight course from the north end of the Sandias southward through the valley to San Acacia, the Rio Grande diagonally crosses from the east to west side of the valley.

The Rio Grande eroded its present valley in early Holocene to at least several tens of feet below river level, but for many hundreds of years has been aggrading its valley to its present level. This was probably the result of decrease in volume of flow and accompanying aridity with loss of protective vegetative cover. Happ (1948, p. 1192) presented evidence suggesting that the rate of sedimentation in the valley has greatly increased since 1870. Additionally, there is some possibility of channel obstruction at its lower end by uplift and/or sedimentation along the sides of the narrow canyon at San Acacia. Depth of the recent infill of the valley is difficult to determine without much drilling and careful logging of the holes. It cannot be assumed that the lithology of the fill will sharply differ from that of the underlying Santa Fe Formation. The Santa Fe Formation, often along the same course, possesses an axial river facies and like the present valley sediment consists of mud, sand, or gravel. Based on many shallow core samples of the floodplain, Pemberton (1964, fig. 4) showed that 60-97 percent of all samples had a grain size of 1 mm or less and 90-100 percent were 12 mm or less. Assuming gravel to be the only indicator of river action is a fallacy. This is not to say, however, that thickness or depth of the recent channel fill cannot be determined in some instances.

Bjorklund and Maxwell (1961, p. 22) placed the bottom of the late fill at 80-120 ft based on change in lithology and consolidation. Water quality might also be used (Walter Mourant, personal communication). Spiegel (Lambert, 1968, p. 217) ventured that the inner valley alluvium ranges from 63 to 80 ft thick between Cochiti Dam and El Paso. Lambert (1968, p. 216) examined samples from two wells in the Albuquerque area and picked a bottom for the late Quaternary fill at 120-130 ft.

Relief on the floodplain is generally no more than 5-10 ft excluding artificial levees and other man-made earthen forms. Generally the lowest area on the plain is at the river; however, locally there are lower areas far from the river and beyond broad gently outward-sloping natural levees. No gulleys exist along the Rio Grande, but numerous gulley drains have been dug across the plain to handle run-off from built-up irrigation ditches and to drain and clean what would otherwise be water-logged and alkali soils. Small water-table lakes exist in undrained low areas away from the river such as southwest of Isleta and west of the river opposite La Joya. Much of the Rio Grande has been channelized in recent years in order to facilitate flow and transport sediment down river.

The Rio Puerco winds southward through the basin, a distance of about 65 mi. Its valley bottom ranges from 0.1 to 1.5 mi wide. In contrast to the Rio Grande, it is an arid, barren plain with sparse grass cover or low bushes. Its most distinctive feature is a meandered gulley which is to 40 ft or so deep with steep to vertical walls indicating good compaction and cohesiveness of the sediment. Widths of the gulley range from as little as 200 ft to as much as about 900 ft. Widths are locally even greater where meanders double back sharply next to one another. In general the meander belt is nearer to the east side of the plain, perhaps owing to greater influx of material from the much larger tributaries on the west. Dissection of the walls is more common in the southern half of the valley than in the north.

According to Bryan (1928, p. 265) the gulleying of the Rio Puerco may have begun between 1885 and 1890. Before this there were reports that the Rio Puerco in the Cabezon area had no deep gulley, and there were large groves of cottonwood trees with high grass and weeds. At times of heavy rains water spread out of the shallow arroyo banks and covered the whole valley. Apparently farther south gulleying had begun much earlier. Lt. Abert (1848, p. 466-467) reported the Rio Puerco west of Albuquerque to have vertical banks "10 or 12 feet high." In T. 3 N. Bryan (1928, p. 276) cites survey notes by Federal land surveyor, J. W. Garretson, describing a gulley 132 ft wide and 20 ft deep. Bryan (1928, fig. 2) reproduced the Garretson survey together with a 1927 survey with much larger meanders and depth of 40 ft. The 1927 meander form of the gulley is almost identical with that of the 1954 photos used in my mapping. The gulley beginning in the mid-1800's may have progressed northward up the valley. Also early there may have been interrupted short gullies each with head banks. In time these would erode to form a single continuous gulley, and this may have been established by 1980. Possibly large runoff floods which occurred in the 1870's and 1880's may have given sudden impetus to the gulleying. The gulley may have reached its maximum depth in a period of two or three decades, when the present form was largely stabilized. The principal developments since that time have been widening and extension of tributary gullies into the adjacent flats and tributary arroyos.

A remnant of an ungulleyed stretch of the Rio Puerco still exists between 1-40 and Benevidez ranch head-

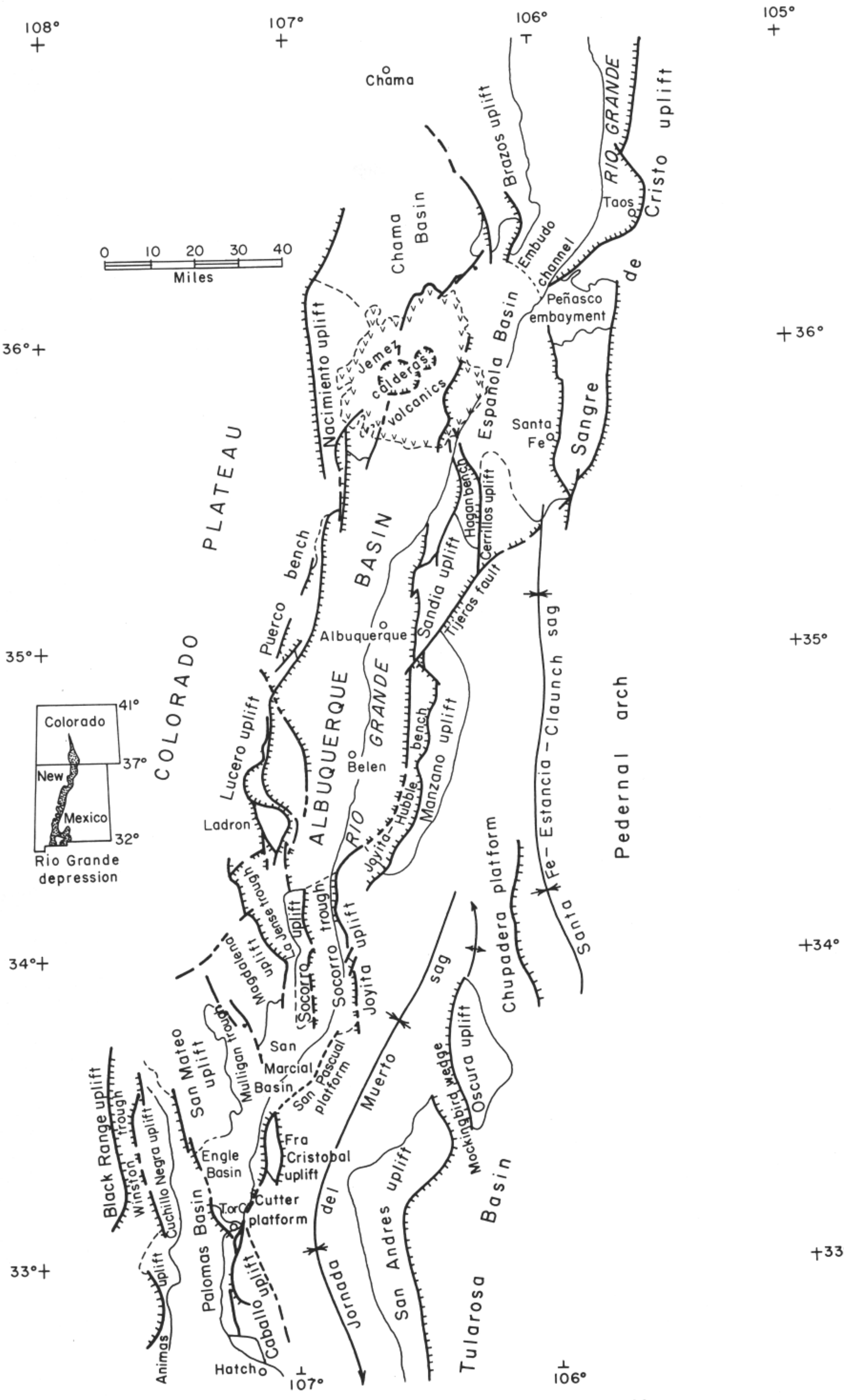


FIGURE 13—Tectonic map of Rio Grande rift system in New Mexico.

quarters (fig. 8). In this stretch of 9 mi there was a western tributary swale on the floodplain from 1-40 nearly to the headquarters. It was fed by several large washes from the west. Between the swale on the west side of the valley and the ungulleyed Rio Puerco on the east side of the valley is a low floodplain divide of perhaps 5 ft. Just prior to the beginning of the present gulley the Rio Puerco jumped its bank north of the headquarters. The Puerco flowed across the flats to the head of the west side wash where it stayed when the present gulley formed. The original shallow Rio Puerco on the east side is still quite evident and only slightly gulleyed at its junction with the present large gulley near 1-40.

That any more deepening will develop is unlikely since the process apparently has culminated. If so, from now on, barring some very unusual changes in the precipitation pattern, the gulley should fill itself. After all, the base for the stream is the Rio Grande and it, if anything, is aggrading.

It is commonly thought that the gulleying was initiated by loss of plant cover possibly accompanied by some abnormally heavy spring and summer storms. The common explanation by soil conservationists for the gulleying was overgrazing by domestic animals and soil and cover destruction by cultivation. Such an explanation suggests that gulleying is mostly a product of man and that prior to his coming to the Southwest there was no gulley. In geologic mapping one commonly sees deep gulleys that have .exposed in their walls the sides of earlier gulleys that were completely filled prior to cutting of the present gulley. The Rio Puerco valley had been aggrading itself gradually for many years prior to the gulley cutting. Aggrading of a valley may reach a stabilization level with broad flats and quite shallow washes. Water from the sides and upstream spreads in thin sheets and again and again spreads thin additions, thus gradually increasing the gradient to the mouth. The natural culmination of this pattern is the creation of too much gradient for the existing discharge patterns until "one day" the process is reversed in an effort to rid itself of the excess sediment. This process goes on repeatedly in the long cycles of sediment transport and deposition. So had there been no influences by man, the gulley would have developed sooner or later on its own. Corollary to this, the converse is also likely true; namely that the gulley will heal itself if left alone.

Other tributaries to the Rio Grande, such as Hell Canyon Arroyo, have situations similar to but on a smaller scale than the Rio Puerco. Most of them do not have gullies; these include the Galisteo, Tongue, Jemez, and Salado. Two, the San Jose (tributary to the Puerco) and Tijeras, have gullies in their lower reaches. The Salado, Jemez, and Abo have much eolian sand crossing or encroaching on their flats.

Structure

Structure is the essence of the geology of the Rio Grande depression. The depression is part of an orogenic belt dominated by a rift valley system that is intermontane through most of Colorado and New Mexico (fig. 13). The system is composed of a series of basins linked by narrow structural channels and constrictions. (Bryan (1938, p. 199-201) used the term, constriction, mostly in a physiographic sense, whereas Kelley (1952, p. 93-97) gave the term more of a structural connotation). Staggered uplifts border both sides of the rift valleys with the whole system being part of the tectonic Rockies belt of Eardley (1962, p. 390). From exposure and development of the many parts of the system, the Albuquerque Basin is perhaps only second to the Espanola Basin. Deformation and erosion have combined to expose the basin fill and lithologic variations in several places; internal structures are numerous with critical marginal faults exposed in a number of places. The bordering uplifts reveal a variety of structures (some Laramide). A number of deep wells have been drilled recently in the basin, and these have greatly fortified early basin history and substantiated basin depth.

The Albuquerque Basin is bounded on the west by the Colorado Plateau and the southern end of the Nacimiento uplift and bounded on the east by the eastward-tilted Sandia, Manzano, and Los Pinos fault blocks. The northern end is formed partly by broadening of the Nacimiento uplift eastward into the Jemez uplift and partly by convergence with La Bajada fault scarp which brings up prebasin rocks in the Cerrillos constriction (Kelley, 1952). The southern end of Albuquerque Basin is the Socorro constriction formed by convergence of the east and west borders. The structures on the east side are quite different in exposure, magnitude, and style from those of the west side, and this, together with considerable bilateral and longitudinal variation within the basin, gives the entire trough a marked asymmetry (fig. 9).

Basins such as the Albuquerque Basin are the parts of the original "Rio Grande depression" concept of Bryan (1938). Since Bryan's original designation such expressions as Rio Grande trough and Rio Grande rift have been used. Additionally such terms as rift valley, rift trough, fault trough, or rift zone might also have been appropriately used. However, in addition to being a structural and geomorphic feature, it is also a geographic feature as indicated by the name Rio Grande. Kirk Bryan intended the term, Rio Grande depression, to include linked system of basins and troughs largely followed by the Rio Grande, and that is the usage that I intended in 1952 with the suggestion of another term, Rio Grande rift. I was, however, partly motivated to use this term by the possibility of wrenching action along the depression. The Rio Grande depression or rift does have within its basins horsts, buried ridges, troughs, embayments, short branches, constricted channels, benches, and protruding wedges as well as its marginal uplifts. However, lateral basins such as most of the Jornado del Muerto, Tularosa, San Agustin and Estancia or uplifts such as San Andres, Oscura, Sacramento, and Guadalupe should be excluded. This is not to say that the rift zone does not extend north and south beyond the Rio Grande confines, but it does encourage singular belt-type usage of the term rather than a province usage such as with "Basin and Range."

Structures of the separate bordering uplifts and constrictions are described first. This is followed by structure of the basin proper including its form, folds, and faults.

BORDER FEATURES

EAST SIDE

The border on the east side is a line of west-facing fault escarpments that extend through most of its length. The 72-mi long escarpment is made up of four contiguous uplift blocks, each differing to some degree in tilting and internal structure. The uplifted blocks are (from south to north) Los Pinos, Manzano, Manzanita, and Sandia. These are separated by either oblique faults, slight change of direction, or magnitude of rise. Los Pinos uplift (fig. 14) plunges rather uniformly southwesterly to the end of the fault escarpment essentially coincident with the southern termination of the basin at the Socorro constriction (geologic map and fig. 13). The eastern mesa pediment cover has been removed by erosion (at about this point), and in the canyons to the south of the mesa escarpment, downfaulted basement formations are well exposed. Yeso (Permian) is dropped against limestone (Pennsylvanian) and red-brown Abo (Permian) beds. Los Pinos uplift terminates by southward plunging into a faulted nose as observed by Darton (1928a, p. 106) and illustrated by Wilpolt and others (1946). Los Pinos uplift is separated from the Manzano uplift to the north by Abo Canyon which has eroded across the range at a narrow place in the uplift structures. Throughout the length of Los Pinos and Manzano uplifts, a distance of about 45 mi, the vertical to steeply west-dipping Montosa thrust runs along the uplift, 0.5 to 5 mi east of the uplift-bounding trough fault. Throughout most of the length of the Montosa thrust, Precambrian is upthrust against or over sharply upturned or overturned Pennsylvanian beds with vertical separations that may range up to 2,000 ft or more (figs. 15, 19). From about midway of the Manzano southward to part of the Los Pinos, Stark (1956) mapped the Paloma thrust which probably is an imbricate branch or "flyer" from the Montosa. From mapping of schist units in the Precambrian, Stark was able to calculate a vertical separation of at least 2,400 ft. Near Abo Pass the Paloma thrust is only a few hundred feet east of the likely position of the buried frontal Los Pinos fault (late Tertiary uplift). The combined geometric effect of the thrust and uplift normal fault is that of a relatively narrow, westwardly inclined, horstlike plate. Most likely, as Stark thought, the Montosa and Paloma faults are Laramide as was earlier suggested by Reiche (1949, p. 1201-1205), whereas the rift or uplift-boundary faults are late Tertiary and Quaternary.

Very few prebasin beds are exposed at the base of Los

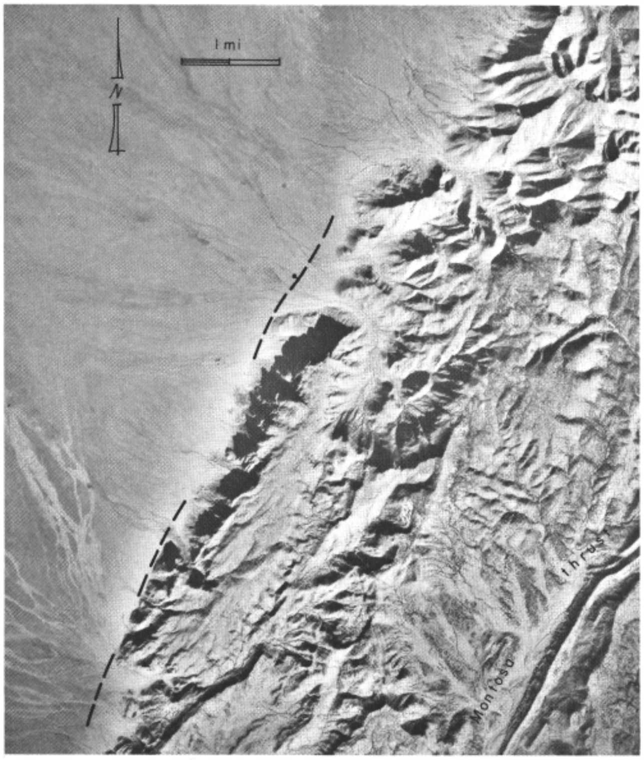


FIGURE 14—VERTICAL AIRPHOTO OF SOUTHERN PART OF LOS PINOS UPLIFT.

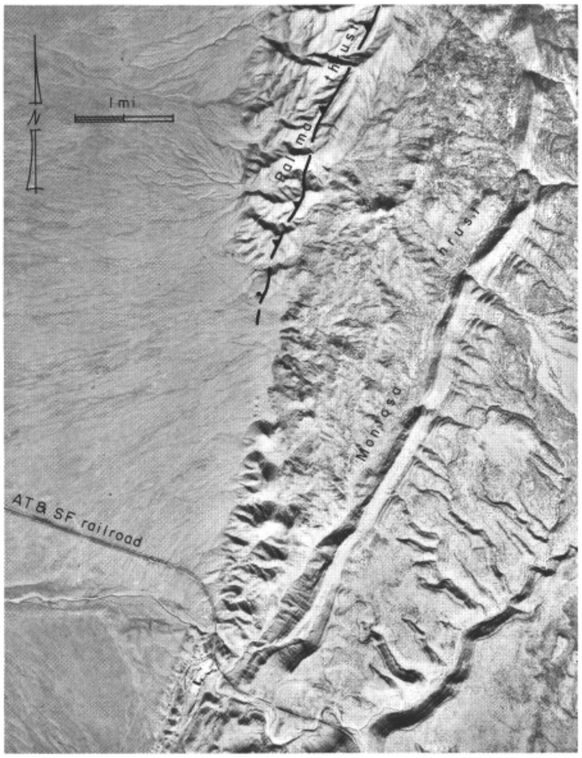


FIGURE 15—VERTICAL AIRPHOTO OF THE SOUTHERN END OF MANZANO UPLIFT, ABO ARROYO AND ABO PASS ALONG SOUTHERN EDGE. Note flat-lying Pennsylvanian beds sharply upturned at Montosa thrust.

Pinos to Manzano part of the uplifts. One Yeso outcrop (near the frontal fault about due east of Belen), when compared with Pennsylvanian caps on the top of the uplift (fig. 16), indicates upthrow of as much as about 5,000 ft. This is discussed further in the chapter on basin structure. The importance of the Montosa thrust to the Manzano uplift is best seen at the north end (T. 7 N.) where the fault curves westward down Los Seis Canyon to the front of the range. South of the curve the base of the Pennsylvanian in Guadalupe Peak is at 8,900 ft; just north of the fault in Los Seis Canyon it is at 6,700 ft (a vertical separation of 2,200 ft). The north-trending to northeast-trending faults in Los Moyos and Hell Canyons mostly jostle the fault blocks up and down but with little or no overall vertical change. Therefore, it may be concluded that the greater structural relief of the Manzano block as compared to that of the Manzanita is due to 1) Laramide uplift and not Basin-Range late Tertiary faulting, 2) renewed uplift on the Montosa fault during late Tertiary, or 3) all the thrusting being a part of the Basin-Range action instead of Laramide. The absence of large fault scarps on the reverse faults is enough to give little or no credence to the third alternative. The second possibility is also considered weak for lack of fault scarp and the mechanical problem of opposite movement on the thrust. The first reason is preferred because of the Laramide difference in structural relief, which incidentally is somewhat greater than the physiographic or crestal difference in relief. Heretofore, the easily noticed difference in relief has generally been presumed to be due mostly to differences in late Tertiary Basin-Range uplifting.

The Manzanita section of the eastern border extends from about Los Seis Canyon (sec. 3, T. 7 N., R. 5 E.) to Tijeras Canyon, a distance of 11 to 15 mi. The Manzanita Mountains are a considerably dissected plateau, some 20 mi wide, between the Rio Grande valley and Estancia Valley. East of the Sandia Mountains, the northern geologic boundary of the Manzanita uplift has been taken at the Chamisoso fault and the Tijeras Basin (Kelley and Northrop, 1975, Map 3). The Manzanita border is somewhat more irregular in its boundary with the basin than the Manzano or Sandia uplifts. The border is deformed by a number of north-trending to northeast-trending faults and open anticlines, and these have guided the direction of the principal canyons and ridges. From the point of view of tectonic analysis, noting this northeast structural grain, which varies from the adjoining uplifts, is important. This structural grain roughly parallels that of the large Tijeras fault and graben to the north. Therefore, the interior structures of the Manzanita along with the Tijeras fault are probably Laramide (Kelley and Northrop, 1975, p. 95). Relief along the physiographic front of the Manzanita is only some 1,500 ft. The structural relief ranges from about .1,000 ft in the central part to near 1,500 ft at the north and south ends. From the geologic map it is noted that the Manzanita front, with all of its local faulting, has an overall monoclinal form. The existence of large prominent faults bounding the base of the Manzanita is much less likely than appears to be the case for the Manzano or the Sandia. Instead, the Manzanita front appears to be set forward to the west by uplift on the northwest-trending Colorada fault (geologic map).

Photo by Donald A. Meyers

FIGURE 16—AIRVIEW EAST OF MANZANO MOUNTAINS AT BOSQUE PEAK. Pennsylvanian beds resting nonconformably on Precambrian crystalline rocks. Estancia Valley in background.

The Sandia uplift is the northernmost block of the great fault-line scarp that forms the east border of the Albuquerque Basin (fig. 17). On the south it is separated from the low Manzanita by Tijeras fault, which cuts diagonally northeastward across the border and continues many miles to the northeast. The uplift is about 22 mi long from its pointed southern end to the north end of the fault scarp along Rincon Ridge. From the west the impression is one of a simple eastward-tilted fault block. Yet on the eastern flank and in the north terminating ramp there is an amazing array of well-exposed faults, some of which are probably Laramide. The uplift is almost in a class by itself because of the nearly complete, little faulted stratigraphic sequence exposed on its northeastern homocline, into the adjoining Hagan Basin. The section is about 22,000 ft thick and ranges from Mississippian upward through Cretaceous, into Eocene, Oligocene, and even into the lower beds of the Albuquerque basin fill (Kelley and Northrop, 1975, map 3).

The frontal faults of the Sandia block are exposed in three places: near Tijeras Canyon, along the base of Rincon Ridge in a Holocene fan and fan-bedrock scarp, and in NM-44 roadcut southwest of Placitas where Santa Fe fanglomerate is downthrown against Mancos Shale (Cretaceous). The fault trace is also located by proximity to outcrops of downthrown and upthrown rocks.

Additional evidence of a fault near the base of the uplift is the existence of several large, slightly dissected, triangular fault-scarp facets and straightness of the base of the uplift.

Kelley and Northrop (1975, p. 95) have given reasons why the Tijeras fault is ancient (perhaps Precambrian and Laramide) with some possible Basin-Range adjustments in the Tijeras Canyon area. Reynolds (1954, p. 54) and Kelley and Reynolds (1954) described faults along the northeast edge of the uplift that are likely Laramide. Recently Kelley and Northrop (1975, p. 83) have described stratigraphic relationships, angular unconformities, and faults which indicate that both pre-Eocene-pre-Santa Fe and post-Eocene-pre-Santa Fe

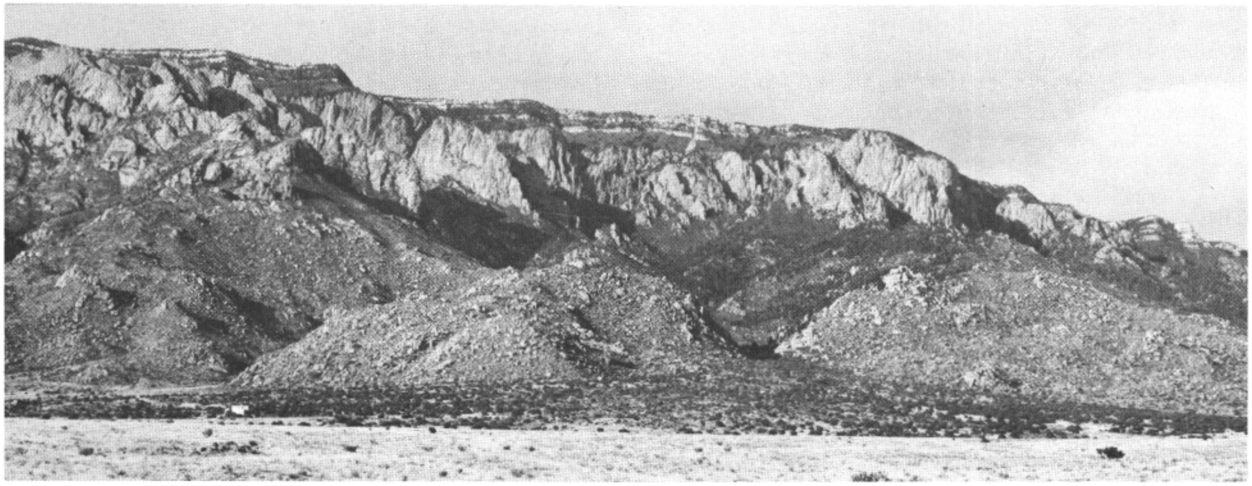


FIGURE 17—VIEW EAST AT SANDIA ESCARPMENT. Pediment surface on basin fill in foreground.

deformation occurred before basin and uplift faulting of late Tertiary age. Further aspects of the younger deformations is discussed in the section on structures.

The northern part of the Sandia uplift ends with a plunge similar to the southern part of the Los Pinos uplift, only with greater width and magnitude. The much broken nose is accentuated through its crossing by the easterly-trending Placitas fault. The Placitas fault (geologic map) has created a northerly-dipping structural ramp between the Rincon fault on the west and the San Francisco fault on the east. The ramp is about 4 mi wide, much faulted, and includes most of the central New Mexico stratigraphic units (from Mississippian beds to lower Santa Fe beds) through a distance of 4 to 5 mi. The Sandia structural ramp offsets the margin of the Albuquerque Basin eastward by about 4 mi. Further eastward expansion of the basin is also affected by the San Francisco fault veering north-northeasterly from its northerly trend. This veering occurs near its southern junction with the Placitas ramping fault. The San Francisco fault starts at the Montezuma prong of the Sandia uplift where the eastern uplifted side consists of Precambrian and upper Paleozoic strata. The fault is readily traceable for 18 mi, to perhaps as much as 24 mi, including an echelon fault which continues northward nearly to the northern boundary of the basin (near the mouth of White Rock Gorge on the Rio Grande). In the first 10 mi northward from Montezuma Mountain, the fault truncates eastward-dipping to northeastward-dipping strata (ranging from Mississippian to Pliocene) of the west limb of the Hagan Basin. The fault is entirely in Santa Fe beds where it crosses Vega de Los Tanos Arroyo, and the throw of surface outcrops diminishes to a few hundred feet or less. Santa Fe beds underlie about the eastern half of the Hagan Basin, and this area was referred to as the Hagan embayment of the Rio Grande depression (Kelley, 1952, p. 92). In the southern part of the Hagan Basin, the southerly trend of the base of the Santa Fe turns due east toward the southern projection of La Bajada fault. Thus, the remaining extent of the late Tertiary sedimentary embayment is delineated. The eastern border of the Hagan embayment is bounded by La Bajada fault which upthrows eastward tilted Mesozoic beds. The western limb of the Hagan Basin is the uplift border of the Albuquerque Basin, but this border fades northward into the subsurface thus allowing the basin to spread back of the border into the embayment.

La Bajada fault and imposing escarpment forms the northern end of the eastern border to the Albuquerque Basin. Toward its north end it curves north-northwesterly toward the Jemez uplift; as a result it becomes a part of the northern termination and constriction of the basin. The exposed part of La Bajada fault is 23 mi long, and the scarp rises in its northern part to about 700 ft. Beds ranging from Triassic to Cretaceous are upthrown and tilted eastward up to 20 degrees along the border, especially in the southern part. Between 1-25 and Santa Fe Canyon, the uplift structure is complicated by diagonal faults which drop Galisteo, Espinaso, and Zia beds against Jurassic and Cretaceous beds. In the northern part, Santa Fe and Zia-type sands are exposed in the scarp beneath thick basalt flows of the Cerros del Rio field. The northern end of the fault is covered by younger Bandelier Tuff. The southern end of La Bajada fault is covered by gravel of the Ortiz pediment. Development of the fault where it passes beneath the pediment gravel suggests considerable extension to the south curving into either or both the Tijeras and Barro faults. Kelley and Northrop (1975, p. 86) have suggested such a continuation of Tijeras and La Bajada faults may have formed an eastern border to the trough before rise of the Sandia uplift.

WEST SIDE

The western border of the Albuquerque Basin is markedly different from the eastern border. It is more irregular, quite varied in style of deformation, and in places has little or no faulting at the margin. The greatest structural relief is at the southern end where the sharp Ladron Precambrian mass is like a giant rivet driven up from below tacking down the southwest corner of the basin with the border. The Lucero uplift, some 28 mi long, is the nearest in resemblance to the eastern uplifts. North of the Lucero uplift is the big echelon fault system referred to as the Puerco fault belt (Kelley and Clinton, 1960, p. 52). North of the Puerco border the southern end and eastern side of the

Nacimiento uplift forms the basin border for a short distance. Northward into the Jemez Mountains country, Puerco-type faulting is evident again to a point where the great Jemez volcanic sequences cover the older border and the regular basin sediments. To the east of the volcanic cover, a final short stretch of the border structure and rocks is exposed along the Pajarita fault (Kelley, 1954). This point is arbitrarily taken to constitute the northern boundary of the Albuquerque Basin.

The Ladron Mountains are an upfaulted Precambrian block about 9 mi long and 5 mi wide. Ladron Peak in the northern part of the mountains has an altitude of 9,176 ft and rises 2,700-3,700 ft above surrounding areas. The western edge of the uplift is a 9-mi-long hogback of Pennsylvanian and Mississippian beds which strike rather consistently about N. 10° W. with westerly dips of 25-40 degrees prevailing. The contact with the Precambrian is normal in the southern part and downfaulted on the west in the northern part. The Precambrian rocks are predominantly granites and granite gneisses. On the southeast, volcanic rocks and volcanic fanglomerates are sharply dropped against the Precambrian along the Cerro Colorado fault. Locally small slivers of Pennsylvanian rocks are also prevalent along the fault. Near the northern end of the Cerro Colorado fault small patches of Permian, Jurassic, and Cretaceous rocks are present between the Popotosa Formation and the Precambrian. Typical reddish mudstones and sandstones of the Santa Fe rest conformably on the Popotosa fanglomerates in the southeastern foothills. Near the northern end of the Cerro Colorado fault a low-angle, east-dipping fault appears just to the west of the end of the Cerro Colorado fault. This fault was first studied by Bruce Black (1964, p. 62-68) at a time when uranium mineralization was discovered in the fault zone. The zone was extensively opened by prospecting and development, especially at the Jeter mine, and Black aptly named the low-angle shear zone the Jeter fault. Coincidentally at the same place near the northern end of Cerro Colorado fault, a small flat-lying plate of Pennsylvanian beds exists across the fault resting on both Precambrian and Popotosa beds. Black (1964, p. 72-76) explained this klippe as a gravity slideblock after having considered more complicated possibilities of low-angle thrusting from either the west or the east. Gravity sliding need not have been a great operation especially if the early Ladron uplift was anticlinal prior to the late faulting. Such geometry would have put the beds into better sliding position, and with the east limb stepfaulted, the source of the present klippe need not have come from more than a few thousand feet to the west.

The really enigmatic structure of the Ladron is the Jeter fault. The curved fault, dipping 20-35 degrees S. 80° E. to N. 10° E., is traceable for 5 mi around the east and north sides of the Ladron nearly always with Precambrian crystalline rocks forming the footwall. The hanging wall is typically reddish-brown to purplish-brown Popotosa, but locally consists of Baca sandstone or a coarse granite fanglomerate of the Santa Fe. The zone is highly brecciated and somewhat altered. Further, the Precambrian is considerably sheared for several inches below the 10-ft to 15-ft gouge zone. Black and I (as his thesis supervisor) puzzled much over this unusual structure and in the end he (1964, p. 68) concluded that the Jeter shear zone was due either to low-angle normal or to westward thrusting. He described possible younger over older thrusting from the east as being due to a sort of crimping action at a hinge line arising out of late eastward tilting along the east flank of the uplift. Black postulated, that the faulting could have resulted from domal uplift of the Ladron with a resultant sliding and slumping of sediment as doming increased the angle of repose. He further suggested that downthrow into the basin on the several faults lying to the east increased the ease of sliding off the eastern side of the mountain.

During the present work I have traced the Jeter fault nearly 1.5 mi farther northwestward around the mountain, and the known arc is about 90 degrees. Therefore, sliding into the Albuquerque Basin may be less of a point. On the north side the zone might possibly extend beneath cover to the Ladron fault. Along the east side, late movement on the Cerro Colorado fault may have dropped the Jeter zone beneath the surface. Additionally there is an arcuate fault around the south end of the uplift which might have had some relationship to uplift mechanics on the Jeter fault.

The suggestion of doming as a cause of the Jeter low-angle fault is logical. However, there is no arcuate fracture on the west side, instead only the long, straight Ladron fault. This fault appears to have continuity with the Comanche fault of the Lucero; however, the vertical separation is opposite. The pivotal point of the Comanche-Ladron fault where upthrow changes from west to east is about coincident with projection of the Jeter trace to the Ladron fault. Uplift or doming of the Ladron in late Tertiary time could be conceived as a sort of piercement with the block basing on the "flattish" rigid west side (Ladron fault). The upward rise on a fault with possible dip to the west could cause the uplift to crowd to the east and thus drag, shear, and brecciate the overlapping sediments along the Jeter fault.

In several respects the Jeter fault resembles the surface of turtleback forms at the Death Valley, California area (Curry, 1954; Wright and Otton, 1974). The latter authors favored an extensional origin with the younger overlying rocks sliding toward the Death Valley graben. Although several other explanations have been given for the complicated Death Valley turtlebacks the explanations suggested by Wright and Otton appear to be more parallel with the Ladron-Jeter surface. However, in the Ladron instance strong vertical penetration by the uplift is perhaps a greater element accompanying the subsidence of the surrounding basin.

The Lucero uplift extends from the northeastern edge of the Ladron to the Rio San Jose, a distance of about 32 mi. Its junctions to the Ladron on the south and the Puerco fault belt on the north are neither sharp nor clear-cut. One could make the point that the Ladron is simply a great promontory to the Lucero uplift and boldly project the Lucero fault around the north side of the Ladron. On the other hand, the Lucero may terminate in the Monte de Belen block because the downthrow on the east is 2,000-2,500 ft. If this were done, then a separate fault segment would be left between the Ladron and the Lucero with the same eastern downthrow to a covered pivotal point somewhere in sec. 24, T. 3 N., R. 3 W. On the north, junction with the Puerco fault zone may be more transitional than is apparent because of the cover by valley alluvium, lava flow, and landslides which apron the northern edge of Lucero Mesa and Lucero uplift.

From yet another point of view, one might conclude that there is no Lucero uplift and that the escarpment is simply the face of the broad eastern limb of the Acoma sag (Kelley and Clinton, 1960, p. 54). In other words there is no Lucero uplift as a late Tertiary counterpart of the graben, but rather a preexisting, westward-dipping Laramide homocline. West dips in the Lucero rarely get to 10 degrees. Generally only in the eastern few hundred feet, just west of the Comanche fault, are dips that reach what might be termed uplift steepness. It is this zone of the abrupt narrow anticline that gives oneness to the Lucero structure, at least in the 19 mi from just north of the Ladron to about Salado Arroyo. In the northern third of the uplift, this sharp buckle gives way to broader anticlines which in some respects may be part of the transition to the Puerco fault zone.

The front of the Lucero Mesa is generally sharp, well-defined, and narrow. Again there is some widening and less clear-cut sharpness in the northern third of the uplift The changes in the northern part may also be related to plunging of the southern structure in the more competent Pennsylvanian beds beneath the younger, less competent units of the Permian, Triassic, and Jurassic.

Perhaps the most striking feature of the Lucero Mesa is the sinuosity of the front, especially the great westward embayment at Monte Largo and Pato Arroyos and in a lesser way at Salado Arroyo. It was these aspects of the front, together with sharpness of the fault and some overturning along the zone, that led Kelley and Wood (1946) to show the fault (Comanche thrust) with moderate dip to the west and thus interpret the structure as involving horizontal shortening. Duschatko (1953), working with W. H. Bucher, concluded that most of the observable reverse faults and overturning, especially north of Gray Mesa, were due to near-surface gravity sliding along faults that were normal and dipping to the basin. According to Duschatko (field discussions) Bucher had urged that, inasmuch as the faults bordered the Albuquerque graben, they must be normal. The prevalence of Laramide deformation in New Mexico was not then generally recognized.

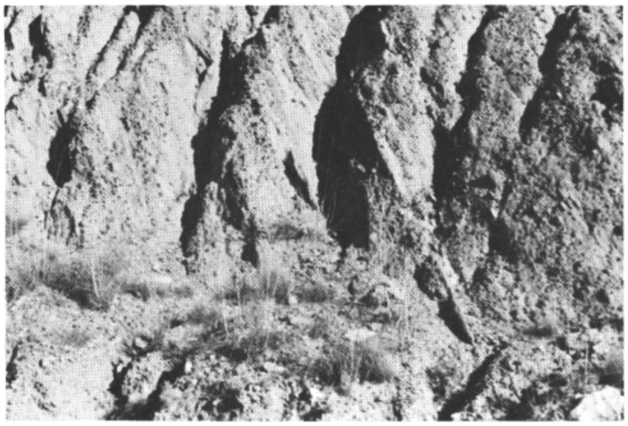


FIGURE 18—STEEPLY DIPPING SANTA FE GRAVEL IN NORTH SIDE OF RAILROAD CUT SEC. 10, T. 7 N., R. 2 W. Exposure is about 50 ft east of the Santa Fe fault where Jurassic beds are upthrown on the west.

Kelley and Wood (1946) mapped and named two faults along the Lucero front; these are Comanche thrust and Santa Fe fault. At no place along the Comanche thrust is Santa Fe Formation downthrown against the fault. It is only north of Comanche Arroyo that the Santa Fe beds are exposed against the frontal fault, and this is the Santa Fe fault (fig. 18). It was a mistake by Kelley and Wood to have labeled it Comanche in one place. The inner fault between Pennsylvanian and Permian should have been labeled Comanche, and it terminates by westward curving into the uplift in T. 7 N.

Duschatko (1953) also differed from Kelley and :Wood on the origin of the sharp, commonly anticlinal, buckle that is present in most places just west of the Comanche fault. He postulated the buckle to be a much modified remnant of a former west-facing Laramide monocline. To do this he probably visualized the Comanche normal fault as breaking through the upper part of the steep limb and dragging it back down on the footwall to the fault. The operation is almost too neat and difficult to reconcile when considering the narrowness of the anticline and its rather constant position just west of the fault. Other than for the narrow buckle, the long gentle rise of the beds out of the Acoma sag is more like the long gentle back of a monocline that would have faced eastward. An east-facing monocline would be compatible with the east-facing Ignacio monocline in the Puerco fault belt and would be in agreement with the mechanics of the grabening action of the Albuquerque Basin.

The position is maintained here that there have been at least two deformations along the Lucero front, an earlier possibly Laramide deformation (such as the Comanche fault zone), and the Rio Grande-Santa Fe fault (late Tertiary). The Santa Fe fault is well exposed in two places, one in the Santa Fe railraod cut where Santa Fe gravel beds dipping 45 to 65 degrees east are widely dragged down against steeply-dipping Jurassic gypsum beds, and the other in sec. 6, T. 6 N., R. 2 W. where reddish-brown sandstone and mudstone have been dragged to a 30 degree east dip against Chinle Shale (Triassic). Although exposures are lacking or poor, it is important to note that the Santa Fe fault is projected southward (geologic map) along the great travertine banks east of Gray Mesa to a connection with the Coyote fault scarp (Quaternary). The Coyote fault is chosen here to mark the eastern edge of the Monte Largo embayment. There are no identifiable Santa Fe beds downthrown against the Comanche fault in the embayment, only Permian rocks. The Santa Fe, shown on the geologic map within the embayment, is exposed in thicknesses of only a few tens of feet. One could question whether to map it as Santa Fe or younger pediment gravel. If it should be demonstrated by drilling in the embayment that Santa Fe beds are thin or absent, then the embayment would not be a part of the central or deep Albuquerque Basin but rather a pedimented rock shelf (Monte Largo, fig. 19) on the downthrown side of the Comanche fault. The projection of the Coyote fault to the Pelado fault east of the

Ladron is interesting; however, it is not traceable continuously on the surface.

The Puerco fault belt forms the western border for about 45 mi between the northern end of the Lucero to the southern tip of the Nacimiento uplift (just south of San Ysidro). The belt consists of many closely spaced faults which predominantly trend N. 10°-20° E. Hunt (1936, p. 63-66) first detailed these faults and the structure of the beds involved. He concluded all the faults to be normal, that fault striae are along the dip slip, and that fault dips ranged from about 45-80 degrees. The great majority of faults are downthrown on the west. Exceptions are a few small ones and the easternmost faults which drop trough-filling sediments down on the east. Most faults have throws of only tens or hundreds of feet but a few may have local throws in excess of 3,000 ft. Prevalent dip in the blocks is easterly, but there are several exceptions where local anticlines or synclines can be detected running through several fault slices. Several monoclines are also present, the best known of which is Ignacio (Kelley, 1955, fig. 2; Kelley and Clinton, 1960, p. 52, fig. 2) running northerly through Cationcito; another is a south-dipping one east of the Rio Puerco at the junction with Benevidez Arroyo; and another south of Bernalillo Mesa in the southwest corner of T. 15 N., R. 1 E. Campbell (1967, figs. 1, 2) mapped a significant part of the belt in the Caiioncito region and found the Ignacio monocline to be more complicated with a number of high-angle reverse faults (also dipping west) which add to the structural rise and relief of the monocline; the more common normal faults have the opposite effect. All the faults in the southern half of the belt terminate along a nearly straight north-south line against the undeformed Colorado Plateau beds thus producing a left echelon in their southern termination pattern.

Another prominent feature of the belt is the Apache graben (Wright, 1946, p. 421-422; Campbell, 1967, p. 60-65), which crosses 1-40 in a belt about 3 mi wide. The graben drops Santa Fe beds between east and west belts of Cretaceous. The west side fault (Apache West) is traceable for about 8 mi, but the east side fault (Apache East) is traceable for only 4-5 mi with Cretaceous upthrown on the east. If the fault extends farther north or south it is lost in poor Santa Fe outcrops.

In the southern part of the belt, formations strike roughly parallel to the faults, but in the northern half there are several areas of persistent swings in the strike toward due east. One of these is prominently expressed in a Gallup Sandstone cuesta near the Bermlillo-Sandoval County line. Another of these is expressed in Dakota Sandstone cuestas along the southern edge of T. 15 N. south of Bernalillo Mesa. This attitude continues to the east in the south-plunging end of the Nacimiento uplift and includes also the basin-filling Zia and Santa Fe beds. Additional southerly to southeasterly local dips occur in the Zia and Santa Fe (T. 12-14 E.). These diagonal and more or less anomalous dips suggest lateral movement between the Plateau and the Albuquerque Basin. Another suggestion for lateral movement is the fact of overall echelon arrangement of the Puerco faults. The principal geometric effect of the diagonal southeasterly dips is a plunging of the belt along and toward the basin edge. In Bernalillo Mesa near the northern end of the belt the base of the Dakota Sandstone is at an altitude of about 5,700 ft; southward near the Bernalillo County line, it is 4,500 ft in the subsurface; and still farther south toward 1-40, it probably is at 1,500-2,000 ft. Thus, the structural relief of the belt from north to south is about 4,000 ft.

There are a number of places where the upper Tertiary rests without fault contact on Cretaceous or Eocene beds. In the southern part of the belt Zia member or equivalent beds rest disconformably on Gibson (Menefee) beds of the Cretaceous. In the most northern part of the belt near the southern end of the Nacimiento uplift, Zia member rests on both Eocene (San Jose) and Cretaceous rocks ranging from Gibson to Mancos. The unconformable to conformable relationship might be more common in the Puerco belt were it not for so much modification by faults. This border segment of the Albuquerque Basin differs from most of the basin borders in not having an obvious, single, long, trough-bounding fault of large throw. In a sense then this boundary of the basin is without uplift blocks or forms, and as a result the Colorado Plateau province commonly appears to merge through relatively minor faults and flexures with the Rio Grande depression. As suggested by Kelley and Clinton (1960, p. 52) the Puerco fault bed is probably best considered to be a part of the Rio Grande trough. Hunt (1938, p. 78), however, points to unconformities between the Cretaceous and Santa Fe beds and some pre-Santa Fe faulting, all of which point toward Colorado Plateau-type Laramide deformation as well as later basin deformation. The easterly dips in the Cretaceous together with the array of west-dipping antithetic faults mark the belt as part of the rift extensional geometry.

The Puerco fault belt is either terminated or interrupted by the southern tip of the Nacimiento uplift, and as a result for a distance of about 5 mi the Nacimiento uplift forms a border to the Albuquerque Basin. Along this stretch Santa Fe, as well as the prebasin formations, dip up to 5-6 degrees southerly off the uplift. It is fairly well demonstrated that the Nacimiento is mostly a Laramide uplift. Along the end of the Nacimiento uplift, San Jose Formation (Eocene) rests on Mancos Shale (Cretaceous) with a considerable section of Mesaverde-type beds missing. These beds are present just a short distance west of a projected western front of the Nacimiento uplift. The rising of the Nacimiento uplift and its erosion prior to San Jose time is suggested. The San Jose Formation is thin ranging only to 200-300 ft thick and locally the overlying Zia member rests directly on Cretaceous. Thus, there is evidence of post-Eocene—pre-Miocene deformation, and since the Zia and Santa Fe are tilted southward slightly off the Nacimiento uplift, apparently some rejuvenation of the uplift occurred again in late Tertiary.

The eastern side of the Nacimiento is dropped principally along two north-trending faults, one the Sierrita fault with Permian and Triassic down against Pennsylvanian and Precambrian of the uplift, and the Jemez fault with Zia member dropped against Cretaceous to Pennsylvanian rocks. Although the Jemez fault could be a part of the Nacimiento uplift, it must at least partially be a late Tertiary structure because the Zia member is downthrown along the uplift for 12 mi

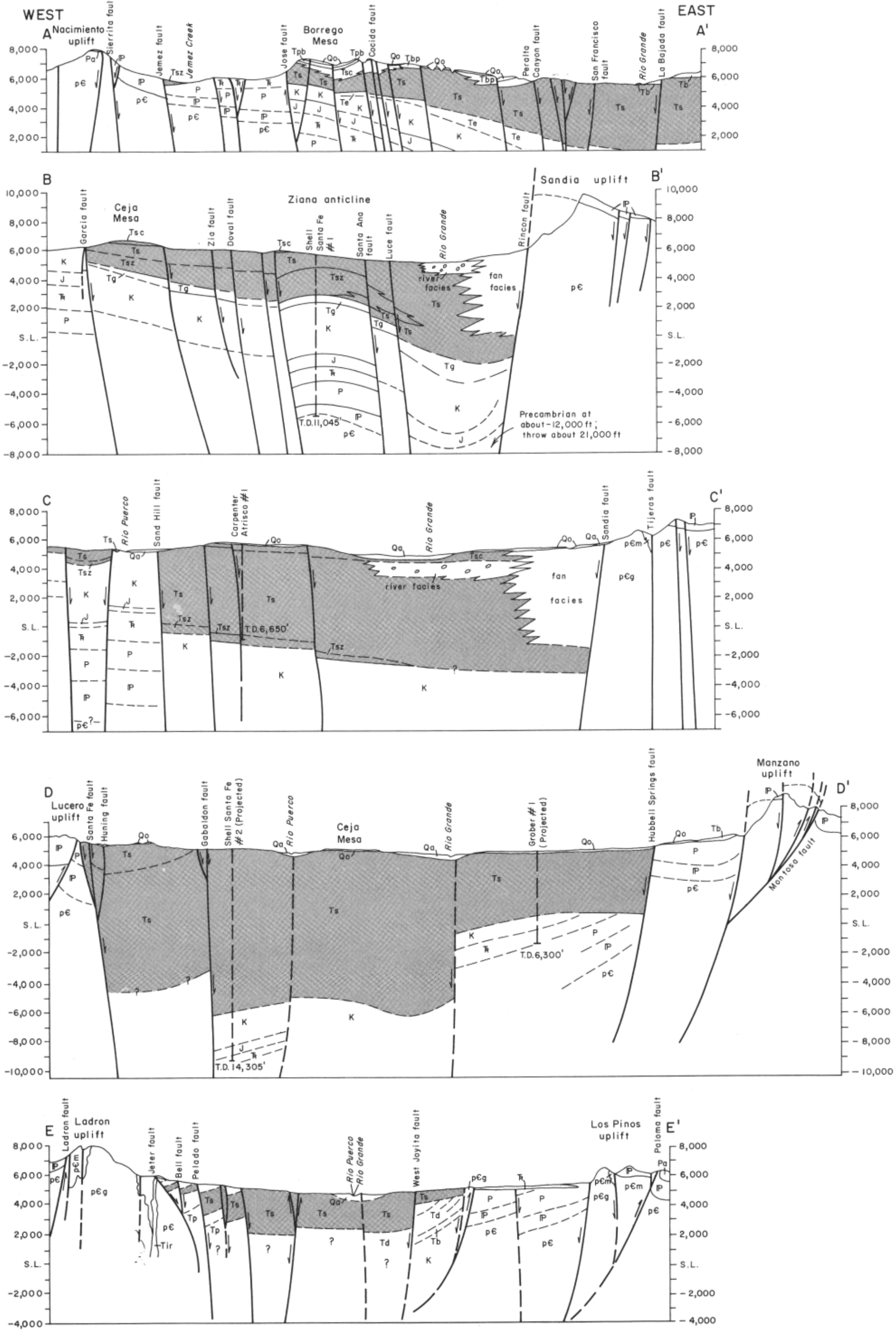


FIGURE 20—West-east structure sections across Albuquerque Basin. Datum is mean sea level.

northward. This is along the same general trend of the entire western basin border. Near the northern part of T. 16 N. in Jemez Canyon, the basin-filling Zia jogs eastward along the southern margin of the Jemez uplift for 6-8 mi where it is dropped again on the northeasterly trending Jose fault and lost in and beneath Jemez volcanic rocks. In this area the nature and course of the western border of the Rio Grande depression becomes obscure. However, it has long been a belief that the border would project north-northeastward beneath the great Jemez Mountains volcanic pile to faults along the west side of the Abiquiu-El Rito embayment (Kelley, 1952) which similarly drop basin units (Abiquiu and Santa Fe) against Mesozoic formations.

NORTH TERMINATION

The northern terminal border of the Albuquerque Basin as treated here is at the northern extremity of La Bajada fault. This escarpment and Cerros de Rio plateau also expose elements of the prebasin bedrock. The combination of these features, referred to as the Cerrillos constriction, was used as the mutual border for the Albuquerque (Santo Domingo) and Espanola Basin. A narrow troughlike connection referred to as the White Rock channel was conceived to link the two large, right-echeloned basins. The constriction is also partly formed by a southeastern corner of the Jemez uplift. This corner was drawn by the author in the late forties with the discovery of reddish-brown sandstone of the Galisteo. This sandstone was strongly tilted upward along the western side of Los Alamos fault (Kelley, 1948). The Galisteo exposed at this point may not be of sufficient magnitude or expanse to constitute a border to the basin; it may only be a downfaulted bench or intrabasin block lying east of a stronger more continuous linear western border beneath the Valles Caldera. Regardless, its presence is part of the constriction between the Albuquerque and Espanola Basins.

The principal support for prebasin bedrock blocks in La Bajada constriction comes from exposures of deformed Cretaceous, Eocene, Oligocene, and Miocene rocks exposed in Santa Fe Canyon where the canyon cuts through the fault scarp. Mancos Shale, Galisteo Formation, and Espinaso Volcanics occupy the canyon for 8 mi. Faulting and tilting of the rocks is considerable (Disbrow, 1956, pl. 1) and much of the outcrop trends cross the canyon. The distance from beneath the basalts of Cerros del Rio to White Rock Gorge on the Rio Grande is 12 mi. Only Santa Fe beds are exposed in the White Rock Gorge. If only one-third the distance had shallow prebasin rocks as at Santa Fe Canyon, then the White Rock channel would be constricted to about 12 mi as compared to 25-mi to 30-mi widths in the basin a short distance to the south. North termination of the basin is accomplished mostly through northward convergence by curving or jogging of the basin borders.

SOUTH TERMINATION

The southern end of the Albuquerque Basin is roughly along an easterly line connecting the southern ends of the Ladron and Los Pinos uplifts. The basin is about 24 mi wide near its southern end, just north of the Socorro constriction. Constriction of the basin is formed partly by southward convergence of the borders along the Lucero-Ladron border (on the west) and the Los Pinos (on the east). Narrowing by border convergence is paralleled by convergence of faults within the basin and by the Hubbell-Joyita bedrock bench. Constriction of the basin centers on the San Acacia-Socorro channel of mostly Santa Fe basin fill, which lies in a 12-mi-wide graben between the Ladron and Joyita Precambrian horsts. Basin convergence amounts to 16 mi from a 40-mi width north of the Ladrons and Los Pinos to 24-mi width between the Ladrons and Los Pinos uplifts. The San Acacia—Socorro channel (Kelley, 1952, p. 92) in the rift system connects Albuquerque Basin to the San Marcia! Basin.

BASIN FEATURES

Although faults with vertical separations of at least several thousands of feet bound the Albuquerque Basin in many places (geologic map, fig. 19, in pocket), the basin beds themselves are not widely or greatly deformed in outcrop. In fact folding and faulting within the sedimentary fill is not immediately obvious; the generally unconsolidated nature of the late Tertiary fill is largely responsible. Where resistant rocks such as basalt flows, gravel caps, or rare well-indurated sandstones occur, faults are much more in evidence. This situation is well demonstrated at San Felipe volcanic field where many faults dislocate the flows in obvious and striking manner (fig. 8). Yet only a few tens or hundreds of feet into the surrounding Santa Fe sediments, the faults are lost. Even though fault abundance at the San Felipe volcano may be somewhat anomalous, it is undoubtedly true that many more faults exist throughout the basin than can be detected. Even so folds and faults of great magnitude appear to be rare especially in the younger outcropping beds. Folds that are present are usually relatively local and usually with dips less than 25 degrees. The only fold which is extensive is that of the broad sag of the basin.

Most folds and faults are longitudinal to oblique with respect to the north-south trend of the basin. Transverse structures are rare and local such as the few on the geologic map north of the Sandia uplift and in the Hagan embayment.

Folding and faulting of the basin sediment probably occurred throughout subsidence of the basin. However, by the very nature of the filling and the restricted exposure of the older sediments, structures of early or even middle Santa Fe age are essentially undetectable even though some (as for example, post-Zia—pre-Santa Fe) could logically be expected (fig. 20). On the other hand, faulting and folding of late-Santa Fe and post-Santa Fe time can be commonly recognized by their relationship to erosion surfaces and several different surficial deposits. These are specified in the order of decreasing age: 1) post-Middle red member—pre-Ceja Member, 2) post-Santa Fe—pre-Ortiz gravels, 3) post-Ortiz—pre-high terraces, 4) post-high terrace—pre-low terraces, 5) post-low terraces, 6) post-alluvial fans. The key units for the above are the Ceja Member, Ortiz gravel, terraces, and fans. Faults or folds exist that fit each of the above intervals, but situations exist where all that can be known, for example, is that a structure is post-Santa Fe—pre-low terrace.

For purposes of description, structures are treated in sections on eastern and western areas.

EASTERN AREA

The eastern side of the basin is dominated by the great line of uplift-bounding faults. Although in a sense the line is one fault, its parts are named for the uplifts. From south to north they are: Los Pinos, Manzano, Manzanita, Sandia, Rincon, Placitas, and San Francisco. Los Pinos and Manzano faults are essentially one, being only slightly obscured or possibly joined locally by the Paloma thrust (Laramide) at Abo Pass. Its total length is about 47 mi. The Manzanita fault is only about 12 mi long with the southern 3 mi being a continuation of the Manzano fault. At Canada Colorada, about midway of the Manzanita fault, the front is jogged northwesterly for about 4 mi on the Colorada fault where the Manzanita continues northward again for about 5 mi to the Tijeras fault. Between the Colorada and Tijeras faults the basin margin is offset nearly 6 mi west of the southern end of the Manzanita margin. The Sandia Basin margin consists of the Sandia and Rincon faults; the Rincon fault being only slightly jogged west of the Sandia fault at Juan Tabo. The basin margin is about 24 mi long. West of Placitas there is a series of faults crossing the ramping end (Kelley and Northrop, 1975, p. 82-84) of the Sandia which steps the basin margin back to the east some 4 mi to the San Francisco fault (geologic map). The basin margin then follows the San Francisco fault for about 9.5 mi to its reentrant across the fault (at the termination of Espinaso Ridge). The last dying-out part of the San Francisco is all in the basin fill to its termination west of White Rock Canyon. The basal Santa Fe (Zia) occurs east of the fault along the base of Espinaso Ridge. The contact is normal and unfaulted as it forms the west and south margin of the embayment to a junction with La Bajada fault beneath Tuerto gravel of the Ortiz pediment. The basin margin then follows La Bajada fault for about 15.5 mi to the basalt-covered White Rock channel (Kelley, 1952, p. 92) through La Bajada constriction where the Santa Fe crosses the fault and continues in the subsurface into the Espanola Basin. The great line of faults along the eastern side of the Albuquerque Basin is about 108 mi long including about 7 mi of overlap across the Hagan embayment.

The Hagan embayment (also Hagan bench, fig. 18) is that part of the Santo Domingo Basin which lies east of Espinaso Ridge, and the term as used is sedimentary rather than tectonic. The northeastern part of the Hagan Basin includes, in addition to the embayment beds, prebasin rocks to the Montezuma prong and Madera salient of the Sandia uplift (Kelley and Northrop, 1975, map 1). The basin is sort of a half graben bounded by a wide north-south Espinaso monocline on the west and La Bajada fault on the east. Just east and north of the Zia outcrop band the Santa Fe flattens and dips east-northeasterly at 2-5 degrees toward La Bajada escarpment (in a bench between the San Francisco and La Bajada faults). Just north of the tip of Espinaso Ridge lowermost basin beds, Zia and lower Santa Fe are upthrown on the east side of the San Francisco fault against upper Santa Fe beds on the west. The Espinaso monocline terminates at the San Francisco fault. At this point the curvature of the monocline suggests left drag and displacement on the fault. Santa Fe beds on the downthrown (west) side opposite the Espinaso monocline are more or less flat-lying. A small swarm of transverse faults crosses the northern end of the monocline and some of these extend across the embayment to La Bajada fault. They are mostly downthrown on their north sides, but they may have had left separation as well. Notable among these is the Tano fault which brings up a wedge of Espinaso Volcanics. The Hagan embayment appears to be fairly flat east of the relatively steep dips in the belt of Espinaso Ridge. The San Francisco fault may die out at Peita Blanca, but on the geologic map there is an inferred, buried extension to a fault of similar throw about 2 mi west of White Rock Canyon. Throw is small on this part of the fault. Only minor faults are present east of the northern part of the San Francisco between the river and the north end of the Sandia. Dips in this area are less than 2-3 degrees and generally north-northeasterly.

One of the structurally more disturbed and complicated areas of the basin lies north of the Sandia Mountains involving the Sandia ramp of Kelley and Northrop (1975, map 3). This region involves a much faulted and folded area between the Rincon and San Francisco area. Basal Santa Fe fanglomerate has tilted as much as 45 degrees above an unconformity on more steeply dipping Cretaceous and Eocene beds. The basin beds were incompletely mapped by Kelley and Northrop, and in the present work greater complications have been discovered. The Rincon fault splays into the Valley View fault, Ranchos fault, and other faults downthrown to the basin and they have northward extensions at least to the Rio Grande. A new fault, Escala, is especially important. The fault possibly has several hundreds of feet of downthrow on the west and separates flat-lying, reddish Santa Fe mudstone and sandstone on the west from considerably tilted Santa Fe fanglomerate on the east and northeast. Here, too, is a pair of west-trending faults branching westward from the San Francisco fault at the north end of the Montezuma salient. The north part of the Sandia ramp (between the Escala and San Francisco faults) consists of a thick Santa Fe fanglomerate facies dipping northeasterly from 15 to 30 degrees. This attitude continues with some local disturbance across the paired west-trending faults into a striking exposure of reddish Santa Fe sandstone, mudstone, and fanglomerate and then into the arcuate Chavez monocline. The Chavez monocline extends across most of Maria Chavez Arroyo (secs. 4, 16, 19, T. 13 N., R. 5 E.) and the divide to the northeast. Nearly 3,000 ft of Santa Fe is exposed in the monocline where dips range from about 20 to 35 degrees. The monocline terminates abruptly against a curved fault which is a union of the Escala fault with a curved northeast-trending splay from the Valley View faults.

Geometry of the Chavez and Espinaso Ridge monoclines bear an intriguing similarity. Their separation is about 6 mi, and to relate them directly would require downthrow on the San Francisco fault followed in order by monocline folding and left separation. A narrower monocline occurs in the Permian and Triassic beds along the eastern side of Montezuma salient. Its left separation from the Chavez monocline is only about 0.5 mi but the same threefold sequence would appear to be required to relate the monoclines by former continuity.

There is east to northeasterly dip in the Santa Fe beds located east of the Rio Grande. The dips range from a few degrees to the locally high altitudes of the monocline. This predominant dip extends all the way from about 1 mi south of NM-44 to Tongue Arroyo and perhaps beyond. This distance (about 10 mi) parallels similar but higher dips in the border from the crest of the Sandias to the Hagan embayment. The structural relief from Sandia Crest to the Hagan embayment is as much as 4.5 mi in 17 mi or about a 14-degree slope. This amount of upward rotation in the border might cause a similar but lesser tilt in the basin. The overall easterly tilt in Santa Ana Mesa west of the river may also be a part of the influence of Sandia tilting.

West of the Sandias, exposures of Santa Fe are meager because of the strong Holocene alluvial fan development. The significant exposures are in the dissected slopes south and east of Bernalillo (near Albuquerque) or in Tijeras Arroyo. In all of this stretch there are no westward dips; beds are either nearly flat or 1-3 degrees toward the Sandias. No north-south faults are known west of the frontal zone and no prebasin beds have been penetrated by drilling west of the Sandias or in the Albuquerque area. The Norrins well drilled 4 mi west of the front (sec. 19, T. 11 N., R. 4 E.) to a depth of 5,024 ft encountered granite wash in the first 2,150 ft and "gray sand" and "shale" to the bottom, according to a driller's log (Stearns, 1953, p. 475, 505-506). No faults or offset beds are seen in either wall of Tijeras Arroyo, and there is no evidence of a step-down bench west of the Sandias as there is west of the uplifts to the south.

In the chapter on the east side border structures, several points are discussed. First, the Manzanita uplift south of the Sandias is characterized by north-northeast-trending Laramide faults and folds. These faults and folds follow the Tijeras rift trend. Also, the Manzano-Los Pinos border is in large part a Laramide uplift. The downthrow on the late Tertiary fault line along these parts of the basin margin is not nearly as great as that along the Sandia. Instead there is a step-down bench 2 to 6 mi wide on which there are few or no typical Santa Fe beds. The northern part of the bench is bounded by the Hubbell Springs fault zone (fig. 21). In this area rather flat-lying Triassic and Permian beds are beneath pediment and alluvial fan gravels (generally no more than 50 ft thick). Locally in T. 5 N., R. 4 E., along the inside of the bench and near the basin boundary, there are patches of tuffaceous Datil volcanic rocks and Baca (Eocene?) fanglomerates. At the north end of the bench there are additional small patches of Yeso (Permian) and Abo (Permian) beds.

South of the Hubbell Springs area the fault either dies out or is covered by fan and pediment alluvium. The fault is covered nearly to the southern end of the Los Pinos uplift where a bedrock bench reappears. Pediment gravel is relatively thin along its northeastern edge and apparently the prebasin rocks and prepediment faults exposed in this bench, referred to here as Joyita, would continue beneath the pediment for some distance northward, possibly to the Hubbell bench. Small inselbergs of Precambrian rocks and a water well (more than a mile west of the Manzano front drilled into Precambrian at a few hundred feet) both lend support to the bench existence between Hubbell Springs and La Joya. The West Joyita fault (Wilpolt and Wanek, 1951, sheet 1) would constitute the outer bench fault comparable to the Hubbell Springs fault. The two might be connected as suggested on the geologic map.

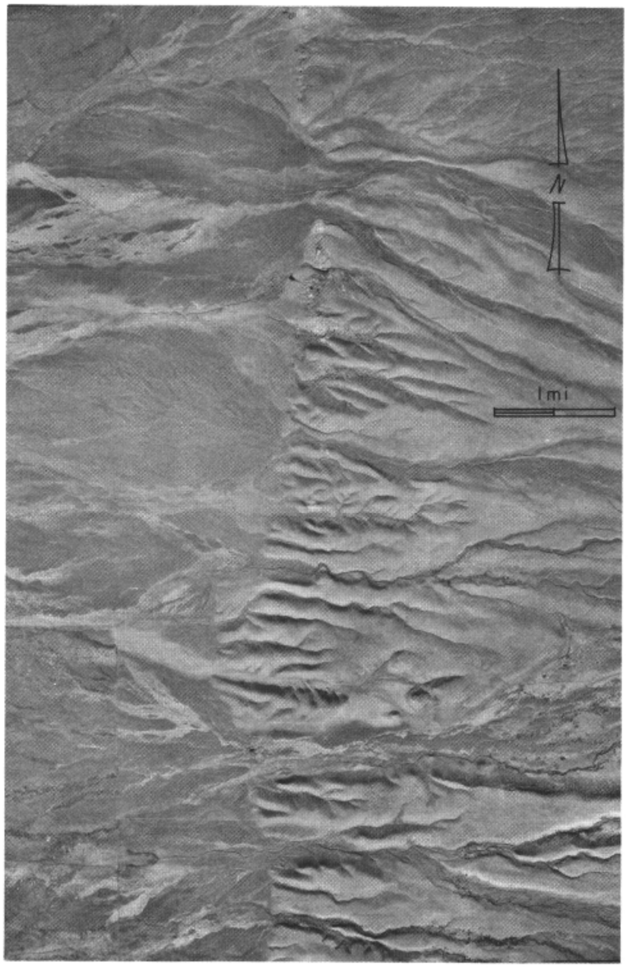


FIGURE 21—Vertical airphoto of dissected Hubbell Springs fault scarp. Scarp is as much as 130 ft high; Permian and Triassic beds are exposed beneath pediment gravel on the upthrown.

In the Joyita bench, which is a part of the Socorro constriction, rocks range from Precambrian to Oligocene. The bedded units, although considerably faulted and locally folded, dip generally 10 to 25 degrees westerly toward the West Joyita fault and the San Acacia channel. Most faults are longitudinal, striking N. 10°-15° E. with throws less than a few hundred feet. Exception to this is the East Joyita fault in the hills 2 to 3 mi east of the Rio Grande (Wilpolt and others, 1946). This fault uplifts Precambrian and Paleozoic rocks some 2,700 ft against downthrown Oligocene volcanic rocks on the east. The sharply horsted block is almost astride the axial position of the overall Albuquerque Basin. In Agua Torres Arroyo, just south of the covering pediment gravel, Santa Fe sand and gravel are downfaulted on the west against Cretaceous beds, but the fault dies out in Cretaceous terrane a short distance to the south. To the north this fault probably drops Santa Fe against

FIGURE 22—OBLIQUE AIRVIEW NORTH-NORTHWEST OF THE LADRON MOUNTAINS. The thick sequence of west-tilted beds in foregound is the Popotosa Formation. The Rio Salado canyon crosses the formation in the middle of the view. Mississippian and Pennsylvanian beds dip off the Precambrian along the upper left skyline. Cerro Colorado fault drops the Popotosa against the Precambrian along the foothills.

Precambrian granite. Wilpolt and others (1946) thought that this Precambrian inlier was brought up on its east side by the East Joyita fault as suggested on the geologic map.

Complication of structure and rocks exposed in the Joyita and Hubbell benches is direct evidence of the possibility of the considerable complications in basin bedrock geology that may underlie much of the relatively simple conditions in the Santa Fe.

The Hubbell-Joyita bench is essentially on line with the Sandia fault, and the two could be considered to be continuous across the minor offsetting by the Tijeras fault. Could the Hubbell-Joyita bench be a gigantic tectonic slide toward a deep main trough to the west?

WESTERN AREA

Basin structure west of the Rio Grande includes all the lower Rio Puerco area, the long Ceja Mesa, and the southern and southeastern flanks of the Jemez uplift. At the southern end of the western area is the structural entrance to the San Acacia-Socorro channel (Kelley, 1952, p. 92). The margin faults of the basin are the West Joyita (on the east) and the down-to-the-basin faults (along the eastern side of the Ladron uplift). Next to the Ladron is a narrow much faulted and tilted bench of Mesozoic beds and middle Tertiary volcanic fanglomerates of the Popotosa Formation (fig. 22). The thick Popotosa is to some extent prebasin, but lying partly conformably and partly in fault contact are nonvolcanic fanglomerates and reddish sandstone and mudstone of the Santa Fe. These beds are also considerably faulted (fig. 23), and the prevalent Santa Fe attitudes (in the 1-2 mi east of the upthrown Popotosa) are westward toward the Ladron uplift. However, a mile or so east of the Pelado fault, dips flatten and remain so through the rest of the area to the east side of the channel.

FIGURE 23—VIEW WEST OF LATE HOLOCENE NORTH-TRENDING FAULT SCARP EAST OF THE LADRON MOUNTAINS. The 30 ft scarp with shallow pull-away trench on downthrown side crosses the road to the Lazy C Bar J ranch near the middle of sec. 9, T. 2 N., R. 1 W.

At the Precambrian contact around the semicircular Ladron uplift on the east and north is the low-angle Jeter fault beneath which the Ladron domed itself in late Tertiary as described in the chapter on border features. Also partly concentric to the Jeter fault (and 1-2 mi to the east and north) is the Pelado-Coyote fault line which like the arcuate Jeter fault is also downthrown on the basin side. The Coyote fault, which is not traceable into the on-line Pelado fault, cuts across the wide Monte Largo embayment into the Lucero uplift, connecting the Coyote fault with the basin-bounding Santa Fe fault (Kelley and Wood, 1946) of the northern part of the Lucero uplift. The 4-mi-wide to 5-mi-wide Monte Largo embayment may be a bench similar to the Hubbell bench along the Manzano uplift; if so the embayment would not be underlain by thick Santa Fe deposits. From Monte de Belen south to the Ladron, Santa Fe appears to occupy the eastern downthrown side of Comanche fault. However, it may be mostly by onlap as the Comanche may be a Laramide fault. Around the north side of the embayment, especially around Gray Mesa, narrow outcrops of Permian beds lie against the Comanche fault on the basinward side.

In the remainder of the wide west side area, to about the northern end of Gray Mesa, there is a group of north-trending to north-northwest-trending faults in mostly flat-lying Santa Fe deposits. Included in the group are several in the southern end of Ceja Mesa earlier recognized by Denny (1941, p. 243). Between Alamo and Mariano Draws several of the faults cut segments of the Ortiz pediment gravels, and the westernmost of these (Huning) is extended (largely on physiographic basis) northwestward along the straight Comanche Arroyo. The largest and most significant of the faults is Gabaldon which is probably continuous from east of the Ladron uplift (T. 2 N., R. 1 W.) to South Garcia Arroyo in T. 7 N., R. 2 W. In the southern part of the Gabaldon fault, only minor throw is seen where it dislocates small pediments or alluvial slopes. In the northern part it may have large throw. In the area of the Gabaldon badlands (T. 5-6 N, R. 2 W.), the fault was mapped as the axis of the Gabaldon anticline (Wright, 1946, pl. 8 and Kelley and Wood, 1946) on the basis of opposed east and west dips especially in the Mohinas Mountain area. The appearance of an anticline evidently had been noted by Rio Puerco Oil Co., which drilled two adjacent wells in 1930 and 1931 to 4,021 and 6,466 ft (sec. 13, T. 6 N., R. 2 W.). Probably misidentification of some variegated Santa Fe as Morrison led to redrilling the structure in 1953 by Humble Oil & Refining Company. The Humble Santa Fe No. 1 well was drilled to 12,691 ft and was in Santa Fe beds to 9,925 ft.

Recently Shell Oil Company drilled another well on the "structure" about 1.5 mi to the south in sec. 18, T. 6 N., R. 2 W. to a total depth of 14,305 ft. Santa Fe was bottomed on Cretaceous at 11,030 ft.

All these wells were drilled east of the "axis" on the more gently dipping limb. To the west in the Gabaldon badlands is exposed one of the finest continuous sections of Santa Fe beds in New Mexico. Wright (1946, p. 407) measured a rough section totaling 4,100 ft thick. Logically, then, it was supposed that this thickness exposed in the west limb when added to the penetration thickness drilled near the crest or the presumed eastern limb would give something near a full section of the Santa Fe. The section west of the fault is about 2.5 mi wide with dips averaging 12-15 degrees. Dips east of the fault (except locally around the faulted basalt flows and plug at Mohinas Mountain) are only about half as steep, and they flatten to only a few degrees (less than 2 mi to the east) and remain essentially flat across the basin. Thus, there is no possibility of repeating a thick western section in the less tilted exposures to the east unless the east side is downfaulted. East of the Gabaldon fault in sec. 19, T. 6 N., R. 2 W., beds dip west 14 degrees and contain gravelly beds like the high part of the section west of the fault and not like the playa beds that are typical of the section just across the fault to the west. Thus, what was formerly thought to be an anticline on the basis of the east dips in Mohinas Mountain is likely to be a more complicated situation. Had any of the wells been drilled west of the fault the base of the Santa Fe might have been penetrated at much shallower depths.

The Gabaldon homoclinal strike west of the fault is exposed for almost 8 mi. It passes under alluvium to the north and under Ortiz gravel to the south. The unconformity at the base of the Ortiz is one of the better examples of considerable deformation and erosion prior to Ortiz time. At the northern end there is a slight turning of the strike toward the Lucero just before burial. At the southern end there are some small fault complications and a slight eastward swing of the strike just before truncation by southward nosing of the Ortiz gravel contact. The left curving of strikes at both the north and the south indicates a southward plunge of structure west of the fault. If the long west dip is not the limb of an anticline it is at least the east limb of a southward-plunging syncline which probably more or less parallels Comanche Arroyo. The curving strike of the Ortiz gravel rim is also a left or reversed "S" form.

Denny (1941, p. 240-242) postulated a set of graben-forming faults in the direction of the lower Puerco which possibly guided a western Ortiz tributary of the Rio Grande northward to eventually capture in order, the east-flowing Ortiz, Rio San Jose, and a postulated Ortiz middle Rio Puerco "Rio Chacra," (Bryan and McCann, 1938, p. 23) to form the present course. Such faults, although possible, are not in evidence except for the Cat Mesa fault which might continue down the west side of the Rio Puerco and the Puerco fault (geologic map). The northern part of the Cat Mesa fault is much in evidence because of the prominent Cat Mesa basalt flow brought to the surface along the east-facing fault scarp.

A number of other north-trending faults occur along Ceja Mesa from just south of Belen to north of the Albuquerque volcanic field. Faults from Wind Mesa southward are downthrown both east and west, but at Wind Mesa most are downthrown on the east. In the Cat Hills and Albuquerque volcanic fields eruptions apparently rose on some of these faults, but the Wind Mesa volcanic field has faults that appear to have formed toward the end of the eruptions which they locally dislocate. On the other hand, faults used as conduits for the eruptions have not subsequently broken the flows as in the San Felipe volcanic field farther north.

West of Los Lunas volcano considerable folding and erosional truncation of Santa Fe beds is exposed in the dissected slopes beneath the Ortiz gravel of Ceja Mesa. Flows of the volcano also rest unconformably on the deformed Santa Fe. Faulting at the volcano appears to be younger than the folding and eruption. Volcanic eruptions were discussed in the chapter on igneous rocks.

A zone of staggered faults extends along the eastern edge of Ceja Mesa from west of Isleta to north of the Albuquerque volcanoes. The southern fault is downthrown west whereas the northern ones are down on the east. The zone is named Nine Mile because the zone crosses 1-40 at the top of Nine Mile Hill.

Along the western side of Ceja Mesa (from about 1-40 northward) there are a number of faults in the Santa Fe that have affinities with those of the Puerco fault belt. Most are downthrown on the east and appear to have small throws. Some are pre-Ceja Member, some post-Ceja and pre-Ortiz pediment, and some post-Ortiz accompanied by rather obscure fault scarps. In the Rio Puerco valley west of the Ceja Mesa, basal Zia Sandstones occur in a number of places unconformably on Cretaceous rocks, and estimates of the thickness of the total Santa Fe exposed to the top of the Ceja Member are possible. The formation apparently doesn't exceed 1,000 ft in several places and could hardly exceed 1,500 ft anywhere in the outcrop. The situation is also similar off the northern point of Ceja Mesa around the type locality of the Zia member. However, running easterly through the badlands north of Ceja Mesa the Santa Fe thickness increases to 2,000-3,000 ft and perhaps continues to increase into the Rio Grande axial area and toward the Sandia uplift. Exactly how the increase takes place is not as clear as might be expected. It could be by a vortex-type of sedimentary thickening and wedging as occurs in the Newark half grabens and/or due to contemporaneous down-to-the-east faulting.

In 1948 the Carpenter Atrisco #1 well was drilled north of 1-40 in sec. 28, T. 10 N., R. 1 E. to a depth of 6,650 ft without reaching the bottom of the Santa Fe. The location is only 1.8 mi east of the western Ceja escarpment. Projections of reasonable bases of the Santa Fe in the Rio Puerco valley only 6-7 mi to the west intersect the well at depths of only about 1,500-2,000 ft. Obviously there must be either some considerable unexposed faulting or dip increase in the subcrop.

There are several faults mapped along the line of projection west of the well. One of these unexposed faults could be an extension of the basin-bounding Santa Fe fault which passes beneath alluvium of the Rio Puerco near the northern end of the Lucero uplift. The possible connections are shown on the geologic map. East of the Lucero uplift the Santa Fe appears to be 10,000 ft or more thick as shown by the deep Exxon and Shell wells and surface exposures of Gabaldon badlands. The small fault west of the Carpenter well offsets the Ceja Member by only a few tens of feet; in the main Santa Fe outcrops of the valley slope, both fault trace and offsetting are essentially unexposed. Although there is the possibility of small surface throw which had been reactivated on an earlier, larger inter-Santa Fe fault, it is more likely that a larger fault lies beneath Rio Puerco alluvium. The best possibility is that the prominent Sand Hill fault, first identified by Bryan and McCann (1937, p. 808, 821-822), extends south as shown on the geologic map. In the northern part of the fault the throw does not appear to be large (Bryan and McCann, 1937, p. 822), but it could be more than is apparent and increases considerably by earlier movement in depth and by larger throw to the south. The evidence or perhaps lack of evidence favors one or more concealed faults along the Rio Puerco valley which would lower the base of the Santa Fe by at least 4,000 ft between the Cretaceous outcrops and the Carpenter well. Furthermore, inasmuch as nowhere near the minimum thickness of 6,650 ft shown in the well exists in the outcrop area, the fault must have moved more than one time. On the eastern downthrown sides of the faults the sediment would have been preserved whereas the western upthrown sides would either be bypassed by sediment or stripped of it. Examination of well cuttings from the Carpenter well indicates a Zia-type sandstone from 5,750 to 6,250 ft with a very definite brown shale below that which continues to the bottom of the hole. The relationships brought out in this area may exist in a number of other areas of the basin.

When Bryan and McCann (1937, p. 808) mapped the stratigraphy and structure along the Ceja escarpment, they delineated and named the principal faults, and these names are used here although the form and the extent differ somewhat. The Sand Hill fault was mapped as a north-trending fault zone and included what I termed the Garcia fault. They did not connect the Garcia with the main Sand Hill fault, but it may connect beneath pediment patches on the Ceja rim in the southwest corner of T. 1 N., R. 13 E. I have mapped a branch of the Sand Hill fault northeasterly across the dissected mesa where it displaces pediment remnants with observable downthrows on the east of only a few tens of feet. The Garcia fault has considerably more downthrow (as for example in sec. 7, T. 1 N., R. 13 E.) where the Ceja Member is dropped nearly to a juxtaposition with the Zia member. Overall, the Garcia is of large magnitude and has displacements more in category with the main Sand Hill fault. This suggests the Garcia to be part of a possible continuous western basin boundary which may be projected through unexposed stretches from the Ladron to the Jemez successively along the Coyote, Santa Fe, Sand Hill, Garcia, Tenorio and Jemez faults. The Navajo-Pilares fault in the eastern part of T. 12-13 N., R. 1 W. is a similar down-to-the-basin fault in the zone with considerable throw and jostling effect on the downthrown side. In sec. 30, T. 13 N., R. 1 E. (geologic map) Ceja gravel is against Cretaceous shale with all the middle and lower parts of the Santa Fe cut out by downthrow on the east. In T. 12 and 13 N., R. 1 W. and R. 1 E., the zone of faults between the Moquino on the west and the Sand Hill-Garcia on the east is the most disturbed stretch of the western basin margin from the northern part of the Lucero to the northern end of the basin. Through most of this distance Santa Fe beds are either flat-lying or dipping easterly at low angles. In the zone, on the other hand, the Santa Fe is jostled with units that are repeated northward along the zone across a prevailing southeasterly dip of 5-15 degrees.

The long Ceja Mesa terminates in a northerly to northeasterly facing escarpment facing the Jemez Valley. The escarpment slope is a wide badlands of generally poor accessibility but with fine exposures of all the Santa Fe members. The Santa Fe beds dip rather uniformly south to southwesterly 5-10 degrees through most of the badlands. To the south in the sloping Ceja Mesa, dips are gently eastward in a long slope to the Rio Grande. The result is a broad southeasterly plunging syncline which roughly follows Los Montoyas Arroyo. The Los Montoyas syncline is bounded on the east by Ziana anticline (Black and Hiss, 1974, p. 369, pl. 2) which was drilled by Shell Oil Company (Santa Fe Pacific #1) in 1972 to Precambrian, a total depth of 11,045 ft. Considerable complications by cross faults in the northern part of T. 13 N., R. 2 E. occur on the anticline a few miles north of the well. Near the cross faults the west limb is steepened to as much as 25 degrees. The anticline may be traced north of the well for about 6 mi where it is covered along the wide Jemez Valley bottom. Its existence north of the valley is doubtful. The anticline probably extends southward also about 6 mi from the well. The east limb dips generally less than 5-10 degrees and extends nearly to the Rio Grande. The west limb is narrower with dips under 10 degrees except locally as noted above.

Several northerly-trending faults cross the badlands. Because of trend, linkage, and southward termination these appear to be related to the Nacimiento and Jemez uplifts. The Jemez fault forms the boundary between the Nacimiento uplift and the basin. Along it the Zia member is downthrown against border formations ranging from Pennsylvanian to Eocene. To the east two nearly parallel faults, Zia and Doval, extend across the badlands, each dropping the Santa Fe on the east. The Zia may have throw of as much as 200 ft, and the Doval, as much as 100 ft. The basinward direction of downthrow is opposite to the western downthrow of several faults emanating from the Jemez uplift (directly to the north). The latter group is a part of the northern terminal border structure which constricts the basin in an east-west direction along the northern part of T. 16 N. In this stretch of 6 mi mostly across R. 2 E., the Zia either laps onto or is faulted against Triassic and Permian rocks. Most of the faults extend from bedrock southward into the Zia, and they are therefore late Tertiary. Because of westward downthrow, the faults are antithetic parts of the east downthrow of the basin on the Jemez and other faults. Attitudes of the Santa Fe beds in this area are variable, especially in the western part, but beginning in R. 3 E. easterly dips prevail at least to the Rio Grande. The western boundary of this easterly inclination is about on line with the Ziana anticline axis.

About in the center of R. 3 E. along T. 13-17 N., downthrow on the great set of northerly-trending faults changes from west to east, and the long and generally prominent Santa Ana fault marks the change. The prevalence of eastward downthrow extends across a belt nearly 12 mi wide along the northern boundary and margin of the basin, nearly to Cochiti. To the south, however, across Santa Ana Mesa and the San Felipe volcanic field, the prevalence disappears largely because of an influence appearing to stem from the Sandia uplift and the strong downthrow to the west of the adjoining basin margin. In this area east downthrow prevails all across the Jemez Valley badlands from the Jemez fault to the southern end of the Cocida fault. East of the Cocida there is a swarm of faults in the southwestern part of the San Felipe volcanic field (Kelley, 1954). These faults form the southward-diverging stepped San Felipe graben (figs. 8, 24) between the Cocida and Algodones faults. The graben is about 2 mi wide in the northern part and 5 mi wide along the southern edge of Santa Ana Mesa. The structural depth is about 200-300 ft. Step segments within the graben are slightly echeloned and small narrow horsts interrupt the general subsidence. The Algodones fault, which forms the major eastern margin of the graben, is traceable across the Rio Grande to a merging with the frontal Rincon fault of the Sandia uplift. Thus, the San Felipe graben may project southward into a marginal trough of sorts at the base of the Sandia uplift.

A new fault, Borrego, has been found along the northeastern side of the San Felipe volcanic field. Its importance has been discovered as the result of mapping a basalt tuff, which is basal to the eastern part of the field, for some distance into Santa Fe beds (Kelley and K udo, in press). Vertical separation of this horizon is as much as 300 ft, the largest of all the faults of the field.

In describing the numerous faults of the northern part of the Albuquerque Basin, it is easy to lose sight of the dominance of the generally prevailing west to east dip of basin beds. Although the dips are low (3-6 degrees) the overall tilted nature of the basin toward the Sandia uplift and other east side structures is a most important aspect. There are the several local exceptions such as the low Los Montoyas syncline, the accompanying Ziana anticline, and the steep Chavez monocline (north of the Sandias). With this regional easterly inclination there also appears to be a marked increase in thickness, and with this there must be increase in dip with depth. The maximum thickness is unknown but could be 5,000 to 10,000 ft. Thus, the fill in this part of the basin is a great wedge which may have been 1,000 ft or less at the western margin and 10,000 ft or so in the deepest part next to the eastern border. This type of structure in which sedimentation matches tilting subsidence is referred to as a vortex monocline.

FIGURE 24—AIRVIEW EAST ALONG JEMEZ RIVER. Step-faulted basalt flows of the southern end of San Felipe volcanic field are the east side of the San Felipe graben. Rio Grande beyond flow-capped mesas; Ortiz Mountains and pediment in upper left distance. Jemez dam now occupies the entrance into the gorge.

Discussion—origin and development

PRE-RIFT SETTING

The Rio Grande trough system involving formation of basins, grabens, and tilted fault blocks probably began to develop in Miocene. However, too much emphasis on time of beginning is pointless as some structures of the Laramide deformation may have been the same as some formed in late Tertiary. Furthermore, all the trough structures certainly do not date from one time. A single high-angle fault may produce a half graben, and sagging between two monocline uplifts may produce a basin. There is the question as to what constitutes the Rio Grande depression, trough, or rift system of late Tertiary. Perhaps most would agree on a system of horsts and grabens expressed by ridges and valleys that are distributed mostly along the Rio Grande. Nearly as much agreement would exist on the high angle of the faults, and somewhat less certainty would prevail that all the faults are normal. Some would also insist that there must be geometric evidence of extension across the system. Many of these features, uncertainties, and problems also exist for the Laramide especially in the Colorado Plateau.

Prior to late Tertiary the Rio Grande country may have had many of the aspects of the Colorado Plateau plus those of the eastern Rockies. There is much evidence in the Rio Grande country of Laramide uplifts. Both the eastern and western borders of the Albuquerque Basin have structures that are compressive in aspect or otherwise incompatible with the geometry of the late Tertiary features. In the northern part of the Rio Grande country and especially in Colorado, the Laramide Rockies are bipronged or bilateral with the western prong uplifted against the Colorado Plateau and the eastern prong against the High Plains. Between the "fronts" are a number of local uplifts and especially the depressions known as the Colorado "Parks." These features are mostly Laramide but in places in the "parks" there is additional late Tertiary subsidence. The San Luis, Espanola, and Albuquerque Basins are medial Laramide Rockies, and it is therefore likely that pre-late Tertiary or Laramide basins or troughs preceded and determined much of the locale of the late Tertiary basins and faults. Even though exposure is widely lacking in the depression, evidence is present in the borders of some Laramide deformation, and a broadly spaced north-south structural grain appears to have been established. The Nacimiento uplift had already formed and the Lucero front was at least developed to an asymmetrical monocline of Colorado Plateau style. To the east there was the Los Pinos to Sandia line of uplifts asymmetrical toward the east. At the level of erosion of the time, they were perhaps very steep monoclines but possibly with some breaking by thrusts. The west-facing escarpments of today were nonexistent. In their place most likely were long low-dip slopes across the present Albuquerque Basin, although lesser monoclines and local small uplifts in the basin area cannot be ruled out. There was no Jemez volcanic pile or accompanying domal form.

Recent deep drilling in the Albuquerque Basin has penetrated considerable thicknesses of Cretaceous beds similar to those cropping out in the adjoining San Juan Basin and Hagan embayment. Therefore the Albuquerque Basin area was not uplifted enough to have caused widespread removal of Cretaceous and older beds. The area was probably more like the San Juan Basin in preservation of Cretaceous but yet not so subsided as to have accumulated widespread thick early Tertiary beds. A thick early Tertiary (Galisteo) formation occurs north in the Hagan area, but if it existed widely elsewhere in the area, some late Laramide or middle Tertiary uplifting appears to have resulted in its stripping. Some comparable beds referred to as Baca existed in the southern part of the area but these beds are not very thick.

DETERMINANTS OF LOCATION

Thus it was, in a preestablished north-south structural grain (possibly with some early rifting in a Colorado Plateau-type setting), that the new rifting began its development in Miocene. Although it is not rigorously determined, the best supposition is that the new deformations were formed in an extensional stress field. The questions are then: why and how did the rifting develop? In the northern part of the Rio Grande belt, the trough is intermontane with respect to western and eastern prongs of the Laramide Rockies. In the general latitude of Albuquerque, however, a western Laramide structure other than the short minor Ignacio monocline is not in evidence. Nevertheless, spacial and hence possible genetic relationship of the trough to earlier Laramide deformation is indicated. An important point is: why are the principal graben-bounding faults where they are? It has been commonly said that the Laramide orogenic belt existed as a wide compressional uplift (about 80 mi wide) between the Nacimiento-San Pedro upthrust on the west and the Las Vegas to Cimarron upthrust boundary on the east. When the Laramide east-west compressional stresses ceased, the arched belt collapsed midway to form a rift valley. On the other hand, it may be that an intermontane furrow was a part of the early Rockies. In many places southward along the rift belt, bipronged or bilateral uplifts are not evident, as between the Puerco fault belt and the Sandia uplift. Possibly a furrow may exist without strong uplifts on both sides. Bipronged Laramide uplifts appear to be present across the southern part of the Albuquerque Basin. However, if a Laramide furrow existed it would have been between two uplifts both facing east.

There is a possibility that some graben-bounding normal faults form over, or near to, root zones of older thrusts or core areas of overturned folds. Eardley (1962, p. 300, 342, 385) showed several sections suggesting genetic relationships between graben normal faults and root areas of thrusts or cores of overturned folds. Relationships of this sort were mapped along the northern and southern ends of the Caballo Mountains (Kelley and Silver, 1952, p. 163). Similar proximity of basin fault to overturns exists in the Fra Cristobal Range. Stark (1956, p. 1) mapped and sectioned parts of the Manzano and Los Pinos uplifts in which the graben fault converges with the root zone of Laramide thrusts. Basin-Range faults superimposed on the Laramide overthrust belt of southwestern Wyoming and adjoining southeastern Idaho show similar relationships. Although most of these thrusts are low angle, the positioning of the graben faults could be, near the bottom of the steep "sledrunner" part of the overthrusts. Notable among these are the Salt River Range fault (in Star Valley graben west of the Absaroka overthrust), the Montpelier normal fault (west of a complex belt of overthrusts and overturned folds), and the Wyoming Range normal fault (along Greys River and west of the Darby thrust). Leech (1967, p. 320-321) reports several instances in connection with a review of the Rocky Mountain trench where imbricate branches upward from low-angle thrusts appear to have been used later in graben subsidence.

In the Manzano-Los Pinos occurrence, juncture of the normal fault with the thrust at depth suggests reversal of movement on the Laramide fault. The possible localization of a basin boundary fault by an older reverse fault is quite conjectural at this stage of our understanding. Nonetheless, searching for the problem of positioning of the rift zone faults in addition to the cause of subsidence is important.

The rather marked coincidence of the trough trend to the Laramide orogenies may be taken by some workers to indicate that the Rio Grande trough is not a rift valley. As pointed out by Dennis (1967, p. 126) "true rifts are unrelated, or only incidentally related, to orogeny, whereas grabens not related to rifts tend to be associated with late or post-orogenic events." The Rio Grande trough or rift as accepted in this work is restricted to the line of basins and grabens closely related to the Rio Grande. This trough belt of linked linear trending deep basins and grabens appears to have strong tectonic relationship to the principal or accentuated Laramide orogenic belt. The axis of the trough or rift appears to be nearly coincident with, and rooted in, the axis of the Laramide eastern Rockies and hence is epiorogenic.

GROWTH AND GEOMETRY

Based upon available well cuttings and surface stratigraphic sections, the Santa Fe of the Albuquerque Basin is in most areas coarser and more gravelly in its upper part. There is very little evidence of gravel in the samples from deep wells or in the lower parts of the thicker tilted surface sections. Popotosa fanglomerate east of the Ladron Mountains is an exception along with local fanglomerates near the northern end of the Sandia uplift. The paucity of coarse material extending through the lower one-half to three-fourths of the Santa Fe and its appearance in several facies and areas in the upper parts suggest lower, slowly rising source areas in most of early Santa Fe time and more rapidly rising higher uplifts in late Santa Fe time. More subdued slower forming uplifts might have been monoclinal flexures and related faults, in which instance the trough in its early stages of formation may have been more sag than graben. Colorado Plateau uplifts and basins are well known for this progression from flexures to faults.

Mapping for this study has brought out the existence of benches marginal to both sides of the basin especially in its southern part. Along the eastern side the Hubbell Springs fault with Paleozoic and Mesozoic beds brought to or near the surface has long been known (Read and others, 1944; Reiche, 1949, p. 1204). On the west the Coyote-Sand Hill fault trend also appears to develop benches as does the Gabaldon fault (in a more local way). Additionally distributive dropping toward the axis of the basin is shown by numerous lesser faults, and these are in places interspersed with complementary antithetic faults.

In recent years a number of deep wells which penetrated the basin fill and bottomed in Cretaceous or older rocks have been drilled in the basin. All the wells are inside the known marginal benches, and they all show Cretaceous or Eocene beneath the Santa Fe. The marginal bench areas, on the other hand, commonly have outcrops ranging from Precambrian to Eocene. The conclusion from this arrangement is that the central graben zone subsided first, thus preserving the

TABLE 9—DEEP WELLS DRILLED IN ALBUQUERQUE BASIN.

Well	Location	Total depth (ft)	Base of Santa Fe	Subcrop Formation
Shell #3 Santa Fe	sec. 28, T. 13 N., R. 1 E.	10,276	4,185	Cretaceous
Shell #1 Santa Fe	sec. 18, T. 13 N., R. 3 E.	11,045	2,970	Eocene
Shell Isleta Central	sec. 7, T. 7 N., R. 2 E.	16,346	12,110	Cretaceous
Humble #1 Santa Fe	sec. 18, T. 6 N., R. 1 W.	12,691	9,925	Cretaceous
Shell #2 Santa Fe	sec. 29, T. 6 N., R. 1 W.	14,305	11,030	Cretaceous
Harlan et al. #1	sec. 5, T. 6 N., R. 2 E.	4,223	2,835	Cretaceous
Grober #1 Fuqua	sec. 19, T. 5 N., R. 3 E.	6,300	4,500	Cretaceous
Shell #1 Laguna-Wilson	sec. 8, T. 9 N., R. 1 E.	11,115	Spudded in Santa Fe	

prebasin deposits while stripping occurred along the then bordering uplifts (now the bench areas). The last and in places the greatest subsidence included both the central trough and marginal benches while the great uplifts (now forming the borders) were uplifted. In other words, the first grabening was narrow and in subsequent steps expanded to its present width. If the trough began at full width and later stepped down in the central area, Cretaceous and Eocene would more commonly be preserved on the marginal benches. So many factors are involved (such as time interval between successive steps and rate and vigor of filling) that it is not easy to distinguish between grabening by which the axial area is early or late. However, an extensional rift zone would appear to develop the narrow graben first, followed by adjacent subsidence steps. This might take the form of caving action toward the early axial graben.

Another complicating probability is that some graben faults may not be at the surface. They may have formed during early or middle basin filling and been buried by later deposits. Some buried faults with large throws may have been propagated later to the surface with only small throws. These growth faults have been presented in the chapter on stratigraphy to explain the rather rapid increase in thickness of the Santa Fe in short distances into the subsurface.

The body of this report was organized to consider features on the east side separately from those on the west side; doing likewise in considering origin may be helpful. Perhaps the most important concept developed in this study has been the postulating of structural benches and steps within the basin. Most important of these is the Joyita-Hubbell bench. Downthrow on its west side faults could be as great or greater than downthrow of the bench with reference to the prominent uplifts to the east. In other words the bench edge zone could be the principal eastern structural boundary of the Rio Grande trough from well into the Socorro constriction on the south to the Tijeras fault and the Sandia uplift on the north. This may be especially true when it is realized that 65-70 percent of the western relief of the Manzano uplift is not trough relief but rather is relic from the Laramide and that the structural relief of the Manzanita Plateau above the Hubbell part of the bench is hardly 1,000 ft. The Hubbell Springs fault scarp of possible early Holocene is the principal means by which the fault is identified. If it were not for the late movement, the existence of the old fault would be unknown. Furthermore, there may be parallel buried faults west of the Hubbell Springs scarp forming steps into an axial trough. Based on only the scarp, throw on the fault would be no more than 150 ft. If this is the total displacement on the fault, then the Triassic and Permian exposed in the scarp would be no more than 50 ft or so beneath the surface on the downthrown side. This possibility needs to be determined by drilling or by some other way. More likely, however, is that the Hubbell Springs scarp displacement is merely renewed late movement on an older fault of great displacements. The marked gravity inflection which parallels the fault is strong support for a growth fault. If one grants the growth fault character of the Hubbell Spring fault and its possible magnitude, then the next question is whether it pre-dates or post-dates the frontal faults of the uplift. Absence of Santa Fe beds in thicknesses of more than a few tens of feet is perhaps the best evidence that the Manzano-Los Pinos faults are younger and that only the Laramide mountains existed when the Hubbell Springs and Joyita fault began to drop the central part of the Rio Grande trough. If the major displacement of the Hubbell Springs fault were later than the back bench or uplift frontal faults, it should have more physiographic expression than it does, and the Triassic and Permian rocks, which surface the fault now, might have been more likely stripped prior to a later dropping of the bench.

Although the Los Pinos to Sandia line of uplift bordering the basin has a degree of geomorphic oneness, there is considerable difference in structure and possibly origin, especially north and south of the Tijeras fault and fold zone. South of the fault the Manzanita to Los Pinos section is tilted very little whereas to the north the Sandia section is markedly tilted. Furthermore, the Sandia front stands 2-6 mi westward of the straight Manzano-Manzanita front. Sandia uplift has no known structural bench, yet its frontal fault is roughly on line and perhaps to a degree continuous with the Hubbell Springs fault. Sandia uplift may not have experienced its principal uplift until late Santa Fe time as explained by Kelley and Northrop (1975). The Sandia block may have been a bench in the beginning from the point of view of basin tectonics. At such time the back of the bench may have been defined by a fault zone that extended from the Tijeras to La Bajada faults. The Sandia with its great structural relief and youthful escarpments may have had early structural continuity in both space and time with the postulated early Hubbell Springs fault and again later in time with the Manzano-Los Pinos faulting. The youthfulness of the Sandia is well illustrated by fan, terrace, and pediment scarps and by its fresh triangular fault-scarp facets. Perhaps also related to the late rise of the Sandia block is the expansive eastward inclination of the Santa Fe formations across the basin which coincides in latitude with the Sandia block.

The Hagan embayment along the northern end of the eastern side of the trough is also a bench. In this area the San Francisco fault, which to the south participates in uplift of the Sandia tilted block, becomes a bench fault comparable in position to the Hubbell Springs fault. La Bajada fault and bordering small Cerrillos uplift are comparable to the back-bench, Manzano-Los Pinos faults. This Hagan bench, which also includes the embayment, has appreciable thickness of Santa Fe Basin deposits on it, but the sediment is not derived from either the Sandia or Cerrillos uplifts. Displacements along the northern end of the San Francisco fault involve middle to high Santa Fe beds and Ortiz pediment. The San Francisco fault is also quite likely a growth fault, and it obviously had a protracted period of growth during uplift of the Sandia. Its northern end probably grew both northward and upward with time. The small pediment displacement may be only a fraction of the displacement at depth. The La Bajada back-bench fault scarp is post-Ortiz, but it is reasonably clear (especially along its southern part) that it is also an older fault. Although La Bajada fault scarp is post-Ortiz pediment, it must have had earlier uplift which caused erosion of Santa Fe beds on the upthrown side.

In summary, the east side of the trough originated by repeated downthrow often on the same principal faults. Apparently the trough was narrower in the beginning. Most of the outer faults marking the prominent uplift came later and widened the basin. An exception may be the Sandia fault, which might have been a bench fault early and an uplift fault later.

The western side of the trough appears also to possess benches but with the present information they are less certain. Available evidence and mapping suggest the possibility of multiple benches or, perhaps more appropriately, steps down toward the trough axis. The main possibilities of steps or benches occur west of the Gabaldon and Coyote faults. To be significant benches, each surface fault would have to be an extension upward of a preexisting buried fault, hence a growth fault having increased displacement at depth. A more certain bench appears to be west of the Santa Fe-to-Sand Hill section where only relatively thin patches of Santa Fe members lie in the Puerco area west of the fault. There are several other possibilities of step-down slices in the western side of the trough as for example Cat Hills, Nine Mile, Jemez, Jose, and Zia. Unlike the east side there is little evidence to indicate that the inner benches or steps are older. There is little or no evidence that the Lucero uplift is part of the trough structure to the extent of being a counterpart uplift of trough subsidence. The uplift structure is instead largely a Laramide feature. There is no later Tertiary scarp corresponding to the large, young Sandia and Manzano scarps. Therefore, the Santa Fe-Coyote fault line is comparable in style and possibly age to the Hubbell Springs bench fault. The same is probably true of Moquino, Navajo, Tenorio, Sierrita, Jemez, and Jose faults in the northern area; this is also probably the case for the larger faults around the eastern side of the Ladron uplift. This is not to say that the west side faults had no Quaternary movements, for many have small scarps.

From the Sandias northward across the basin, eastward to east-northeastward bed inclinations prevail, although there are local reversals (as along the Ziana anticline). In this same area and especially across the northern end of Ceja Mesa, nearly to the northern end of the Sandias, the north-trending faults are mostly down on the east. In a very real way the trough in this portion is a half graben. A considerable part of the downward tilt appears to have been contemporaneous with deposition throughout most Santa Fe time. This is shown by a considerable increase in thickness toward the more rapidly subsiding eastern part. Down faulting on the western side appears to be less than 1,000 ft, whereas on the east it could be as much as 20,000-25,000 ft.

Late modification to a low southward tilt has taken place in the areas south and southeast of the Nacimiento uplift as seen along the northern flank of Ceja Mesa. Thus, the Laramide Nacimiento uplift either experienced some renewed late Tertiary uplift or the basin warped downward on the southern Nacimiento buttress. This tilt also appears to have affected the early Pleistocene Ortiz surface to a lesser degree.

The half-graben aspect of the northern part of the basin prevails across the southern flank of the Jemez Mountains, although it is considerably interrupted by numerous, generally small, Pleistocene faults and is obscured stratigraphically by influxes of volcanic debris and flows in the Santa Fe. This tilt is broadly seen in the Santa Fe basalt flows that cap the prominent Chamisa, Borrego, and Santa Ana Mesas. The entire 9-mi-wide San Felipe volcanic field is tilted eastward at inclinations of 1-3 degrees, a feature which is strikingly visible from many points to the south in the Rio Grande valley. These dips prevail nearly to the basin-bounding La Bajada fault where they flatten and are gently dragged upward.

Toward the end of Pliocene, the long and more or less steady rate of subsidence of the basin appears to have come to a halt. Some local moderate deformation occurred in and along the margins and borders of the trough. Specifically involved were tilting of the Gabaldon fault block, marked folding in the Sandia ramp area including the Chavez monocline, tilting and faulting east of the Ladron, and other lesser areas of deformation. This was also accompanied by warping along the margins and the beginning of a period of tectonic and depositional quiescence leading to widespread planation and development of the Ortiz erosion surface. Some minor warping, local faulting, and very gradual rise of borders may have continued through Ortiz time, and widespread faulting and warping followed culmination of pedimentation. The rather widespread pedimentation that was thought to be younger than Ortiz by earlier workers is most likely a part of Ortiz, although locally modified in minor ways by stripping and/or subsequent buildup of alluvium on the surface.

MODELING MECHANICS

Through the years a number of hypotheses have been proposed for the origin of fault troughs. This is not surprising as there are many variations in the geometry, tectonic settings, rocks, and geologic histories of the world's larger troughs. The principal differences among the explanations are primarily whether the trough forms by extension or shortening across its length. The term trough is perhaps preferable because few or no genetic connotations are involved. This term is especially applicable following Scott (1907, p. 347) because his descriptions of a "trough fault" is a graben whether the two faults bounding a downthrown wedge dip inward or outward. Unlike the geometrically equivalent term, graben, a depression or valley is also generally implied. Gregory (1896) referred to the depressions or valleys of East Africa as subsidence strips bounded by two parallel rifts. Here the term rift is a synonym for fault. Willis (1928, 1938) emphasized the two possible opposed origins of fault troughs by clearly distinguishing two genetic types, 1) the rift valley due to arching and collapse by "keystoning" or gravity collapse, and 2) ramp valley produced by upthrusting of the opposing uplifts and forcing down of the depressed wedge. In earlier writings we see the double usage of rift, and perhaps to a lesser degree ramp, for either a single fault or for a set or conjugate system of faults. At the same time the term rift has been used for wrench or strike-slip faults and applied on occasion to such faults as the San Andreas of California (Noble, 1926) and the Alpine group of New Zealand. For many structural geologists wrench faults consist of two geometric types: 1) the *rift* which is longitudinal or parallel to the surrounding structural grain and 2) the *tear* which is transverse to the grain. Fault troughs or grabens are also a product of or associated with a number of the great transcurrent fault belts of the world. Notable among these are the Dead Sea, San Andreas of California, and Alpine of New Zealand. Subsidence as well as uplift commonly occurs in slices and blocks adjacent to or between large transcurrent faults. In New Zealand dropped blocks, grabens or half grabens either preceded or accompanied largely strike-slip movement.

When the term Rio Grande rift was suggested in 1952 (Kelley, p. 102), it was largely because of a belief in a possibility of significant longitudinal displacement in the trough. It was not intended to imply an origin by either extensional rifting (dilation) or by ramping. For better or worse the Rio Grande trough together with a considerable group of auxiliary troughs is becoming known as the Rio Grande rift. It is also tacitly assumed that the faults are normal and extensional to the bottom of the crust in their mechanics. With this and the emphasis on plate mechanics in regional tectonics there comes an almost automatic "pull apart" concept for the trough.

What is the evidence for the several possible mechanical origins in the Albuquerque Basin beginning first with that of longitudinal slip and separation? Along the San Francisco fault north of the Sandia uplift, strikes of beds commonly curve left as they near the fault. Although this geometry might result from the fault following the axis of a plunging anticline, the fact that such drag commonly occurs in only a narrow strip lends support to left slip. Similar drag also occurs on the Ranchos splay fault west of Placitas on the Sandia ramp. On the west side of the trough at the Moquino fault similar left drag of Santa Fe beds on the downthrown side occurs. Additionally, there is left offset of the outcrops of about 2 mi on opposite sides of the fault. However, no horizontal or low-raking slickensides have anywhere been observed on the relatively few good exposures of fault surfaces along the trough. Furthermore, the curved and jagged bounding faults appear to negate much strike slip.

Perhaps the border faults are not the ones along which significant strike slip may have occurred. The Dead Sea trough has long been thought to have been controlled by early left-slip rifts (Willis, 1938; Quennell, 1956; Neev, 1975) which localized the subsidence faults either concurrently or upon release of the transcurrent stresses. Perhaps such early Laramide strike-slip rifts occur beneath the Rio Grande trough. Suggestion and support of such derivation and mechanics is found in offset of the southern wedge-edge of the Todilto Formation (Jurassic) across central New Mexico. Intersection of the edge on the west side of the trough is near the northern end of the Lucero uplift and its trend to the west is about N. 60° W. On the east side of the trough the estimated edge is about at Tijeras Canyon and its trend is roughly east. A left offset of the edge is conservatively 20-25 mi. Admittedly such discordance could be due to original erosional curving, but this is contrary to the more regular projected regional trends of the wedge both to the west and east of the trough.

Strike slip on transcurrent motion along the trough is further suggested by left obliquity of border uplifts with respect to overall trend of the trough. This is to say that the oblique border uplifts and associated grabens diverge to the left away from the Rio Grande trough. This arrangement is especially marked along the west side as with Brazos, Nacimiento, Magdalena, and San Mateo uplifts. On the east where obliquity is less prominent, it is shown by Cerrillos, Sandia, Fra Cristobal, and Caballo uplifts. Although most faulting within the basin is longitudinal there are a number of left diagonal faults and folds as in the Gabaldon area and in the San Felipe graben. Extensional mechanics is suggested normal to these uplifts especially where accompanied by grabens. The whole tectonic pattern further suggests a counterclockwise rotational stress system with which left transcurrent movement along the axis of the Rio Grande trough would be compatible.

Perhaps the prevailing mechanism postulated for the creation of a fault trough is extension or stretching of the crust. This might be accomplished by doming, broad epeirogenic rise, magma rise or swells, differential rate of drifting of subplates, or combinations of these. Gregory (1920) proposed two parallel faults which might be normal to least stress action. Geometrically two perfectly parallel faults would require that both dip in either the same direction (and hence one would be reverse) or that one be vertical and the other dip away (and be reverse in order) to allow extensional subsidence. Gregory's idea appears to have been that the parallelism would allow the wedge to subside easily by melting and spreading of the root. No doming or keystoning would be required. With Willis (1929, p. 83) doming and a keystone wedge created by either two vertical faults (two vertical faults, say 30 mi apart, would by geometry of a sphere converge on each other), or one or both inclined toward one another, was envisioned to facilitate the subsidence. Herrick (1904, p. 393) pictured such doming and collapse for the Albuquerque Basin, and Hunt (1938, p. 78) considered it also. However, that doming existed as envisioned is doubtful.

Eardley (1962, p. 510) ventured that the Rio Grande trough was developed by the Colorado Plateau subplate moving westward away from the plate to the east. He specifically used the Texas lineament as a left wrench zone along which the plateau plate shifted. Chapin (1971, p. 194) followed Eardley and additionally postulated a mantle bulge beneath the Rio Grande rift. Both Eardley and Chapin assumed continental drifting and that somehow the plate east of the rift got hung up or was slowed while the western part continued to move. Since the rift was not considered to extend south of the Texas lineament, the plateau plate was envisioned as moving westward along the lineament to the extent of the trough dilation. If such strike shift took place during the time of the principal Rio Grande subsidence in late Tertiary, there is remarkably little evidence of it along the Texas lineament. Current evidence appears to be that the lineament features are partly Precambrian (Swan, 1975, p. 1288) or possibly Laramide (Keith, 1975, p. 1140).

Perhaps a better explanation of the postulated dilation could come from an underriding plate suddenly slowed or halted. As a result, a sort of expansional rebound of the compressed underplate, the crustal maximum horizontal stress would change to a minimum (dilational) stress *(a3)* and give rise to trough rifting, especially over the leading edge of the underplate.

The possibility that all or parts of the borders of the basin and the trough are ramps and that the subsided keel has been pressed down as the compressive ramps rode upward is not given much consideration along the Rio Grande. However, the concept should not be completely discarded as the borders are not without evidence in a few places. There are a few places in the Rockies, such as the Wind River uplift of Wyoming, where geophysical data have strongly indicated that blocks once interpreted as normal fault uplifts are either overthrusts or ramplike in geometry. Along the base of the Sandia uplift there is an exposure in which the Precambrian granite is strongly sheared in undulating flat-lying form with shear lineation normal to the uplift. Near the west base of the Fra Cristobal uplift east of Elephant Butte reservoir a spur ridge contains an exposure of a flat fault surface with Precambrian granite lying on Ordovician limestone. However, a steep frontal fault with Holocene fan scarp lies a short distance to the west. Additionally small low-angle thrusts of small throw, cutting slightly tilted uplift beds, are not rare (Kelley and Silver, 1952, p. 145, pl. 10B).

Attitudes of the large frontal uplift faults (where well exposed) range from dips of about 55-90 degrees toward the basin. The steeper of these could readily descend beneath the uplift. Whether any of these evidences of shortening structures are late Tertiary is difficult to demonstrate. In any event no reverse faults have been detected in the basin beds so far.

In conclusion, the most compelling geometry of the basin is the near exclusiveness of normal faults which dip both easterly and westerly forming what may be inferred as conjugate systems. Homothetic and antithetic relationships are present near the borders, and overall patterns resemble those of other large subsidence troughs, especially for parts of the Rhine graben. However, in addition to these extensional structures there is the evidence of some transcurrent tectonic action across the trough in the form of drag, offsets, and obliquity of internal fault trends and of border uplift arrangements. The Laramide has important antecedents for the rift; continued attention should be given to tracing the possible relationships.

References

Abert, J. W., 1848, Report of Lieut. J. W. Abert, of his examination of New Mexico, in the years 1846-'47: U.S. 30th Cong., 1st sess., Senate ex. doc. 23, 130 p. Reprint ed. 1962 with foreword by W. A. Keleher: Albuquerque, Horn and Wallace, 182 p.

Anderson, E. C., 1955, Occurrences of uranium ores in New Mexico: New Mexico Bureau Mines Mineral Resources, Circ. 29, sec. 1, 25 p.; sec. 2, 7 p.; suppl., 6 p.

Anderson, J. E., 1960, Geology and geomorphology of the Santo Domingo Basin, Sandoval and Santa Fe Counties, New Mexico: M.S. thesis, Univ. New Mexico, 110 p.

Bailey, R. A., Smith, R. L., and Ross, C. S., 1969, Stratigraphic nomenclature of volcanic rocks in the Jemez Mountains, New Mexico: U.S. Geol. Survey, Bull. 1274-P, p. 1-19

Baldwin, Brewster, 1956, The Santa Fe Group of north-central New Mexico: New Mexico Geol. Soc., Guidebook 7th field conf., p. 115-121

Beloussov, V. V., 1962, Basic problems in geotectonics: New York, McGraw-Hill, 809 p.

Bjorklund, L. J., and Maxwell, B. W., 1961, Availability of ground water in the Albuquerque area, Bernalillo and Sandoval Counties, New Mexico: New Mexico State Engineer, Tech. Rept. 21, 117 p.

Black, B. A., 1964, The geology of the northern and northeastern parts of the Ladron Mountains, Socorro County, New Mexico: M.S. thesis, Univ. New Mexico, 117 p.

Black, B. A., and Hiss, W. L., 1974, Structure and stratigraphy in the Shell Oil Co. Santa Fe Pacific No. I test well, southern Sandoval County, New Mexico: New Mexico Geol. Soc., Guidebook 25th field conf., p. 365-370

Bruning, J. E., 1973, Origin of the Popotosa Formation, north-central Socorro County, New Mexico: M.S. thesis, New Mexico Inst. Mining and Technology, 132 p.

Bryan, Kirk, 1923, Erosion and sedimentation in the Papago country, Arizona: U.S. Geol. Survey, Bull., 730-B, p. 19-90

, 1925, Date of channel trenching (arroyo cutting) in the arid southwest: Science, v. 62, p. 338-344 , 1928, Historic evidence on changes in the channel of Rio Puerco, a tributary of the Rio Grande in New Mexico: Jour. Geology, v. 36, p. 265-282

______, 1938, Geology and ground-water conditions of the Rio Grande depression in Colorado and New Mexico: Washington, Regional Planning, pt. 6, Rio Grande joint inv. upper Rio Grande Basin, Nat. Res. Comm., v. 1, pt. 2, sec. 1, p. 197-225

Bryan, Kirk, and McCann, F. T., 1936, Successive pediments and terraces of the upper Rio Puerco in New Mexico: Jour. Geology, v. 44, no. 2, pt. I. p. 145-172

______, 1937, The Ceja del Rio Puerco, a border feature of the Basin and Range province in New Mexico: Jour. Geology, v. 45, p. 801-828

______, 1938, The Ceja del Rio Puerco: a border feature of the Basin and Range province in New Mexico: Jour. Geology, v. 46, p. 1-16

Campbell, J. A., 1967, Geology and structure of a portion of the Rio Puerco fault belt, western Bernalillo County, New Mexico: M.S thesis, Univ. New Mexico, 89 p.

Chapin, C. E., 1971, The Rio Grande rift, Pt. I: modifications and additions: New Mexico Geol. Soc., Guidebook 22nd field conf., P. 191-202

Church, F. S., and Hack, J. T., 1939, An exhumed erosion surface in the Jemez Mountains, New Mexico: Jour. Geology, v. 47, p. 613-629

Cope, E. D., 1875, Report on the geology of that part of northwestern New Mexico examined during the field-season of 1874: U.S. War Dept., Chief Engr., ann. rept., 44th Cong., 1st sess., House ex. doc. I, pt. 2, v. 2, App. G-1, p. 981-1017

Cordell, L. E., Joesting, H. R., and Case, J. E., 1973, Gravity map of Albuquerque-Grants area: U.S. Geol. Survey, Open-file map

Cordell, L. E., and Kottlowski, F. E., 1975, Geology of the Rio Grande graben: Geology, v. 3, p. 420-424

Curry, H. D., 1954, Turtlebacks in the central Black Mountains, California: California Div. Mines, Bull., v. 170, p. 53-59

Dallmus, K. F., 1958, Mechanics of basin evolution and its relation to the habit of oil in the basin, *in* Habit of oil: Am. Assoc. Petroleum Geologists, symposium, p. 883-931

Darton, N. H., 1922, Geologic structure of parts of New Mexico: U.S. Geol. Survey, Bull. 726-E, 275 p.

_____, I928a, "Red beds" and associated formations in New Mexico: U.S. Geol. Survey, Bull. 794, 356 p.

_____ 1928b, Geologic map of New Mexico: U.S. Geol. Survey, scale 1:500,000

Debrine, B., Spiegel, Zane, and Williams, D., 1963, Cenozoic sedimentary rocks in Socorro valley, New Mexico: New Mexico Geol. Soc., Guidebook 14th field cord., p. 121-131

Dennis, J. G., 1967, International tectonic dictionary, English terminology: Am. Assoc. Petroleum Geologists, Intl. Geol. Cong., Comm. for the Geol. Map of the World, Mem. 7, 196 p.

Denny, G. S., 1940, Tertiary geology of the San Acacia area, New Mexico: Jour. Geology, v. 48, p. 73-106

____ , 1941, Quaternary geology of the San Acacia area, New Mexico: Jour. Geology, v. 49, p. 225-260

Disbrow, A. E., 1956, Geology of the Cerrillos area, Santa Fe County, New Mexico: M.S. thesis, Univ. New Mexico, 67 p.

Duchene, H. R., 1973, Structure and stratigraphy of Guadalupe Box and vicinity, Sandoval County, New Mexico: M.S. thesis, Univ. New Mexico, 100 p.

Duschatko, R. W., 1953, Fracture studies in the Lucero uplift, New Mexico: U.S. Atomic Energy Comm., RME 3072, Tech. Inf. Serv., 49 p.

Eardley, A. J., 1962, Structural geology of North America: New York, Harper and Row, 2nd ed., 743 p.

Elston, W. E., and others, 1968, Striated cones: wind abrasion features, not shatter cones, *in* Shock metamorphism of natural materials: Maryland, Mono Book Corp., p. 287-290

Emmanuel, R. J., 1950, The geology and geomorphology of the White Rock Canyon area, New Mexico: M.S. thesis, Univ. New Mexico, 65 p.

Evans, G. C., 1963, Geology and sedimentation along the lower Rio Salado in New Mexico: New Mexico Geol. Soc., Guidebook 14th field conf., p. 209-216

Freund, Raphael, 1967, Rift valleys, *in* The world rift system: Geol. Survey of Canada, Paper 66-14, p. 330-344

Galusha, Ted, 1966, The Zia Sand Formation, new early to medial Miocene beds in New Mexico: Am. M us. Novitates, no. 2271, 12 p.

Galusha, Ted, and Blick, J. C., 1971, Stratigraphy of the Santa Fe Group, New Mexico: Am. M us. Nat. History, Bull., v. 144, art. 1, 128 p.

Gregory, J. W., 1896, The great rift valley: London, John Murray, pt. 3, p. 213-236

_____ . 1920, The African rift valleys: Geog. Jour., v. 56, p. 13-42

Happ, S. C., 1948, Sedimentation in the middle Rio Grande valley, New Mexico: Geol. Soc. America, Bull., v. 59, p. 1191-1216

Hayden, F. V., 1869, Preliminary field report of the U.S. Geol. Survey of Colorado and New Mexico: U.S. Geol. Survey, 3rd Ann. Rept., 155 p.

Herrick, C. L., 1898a, The geology of the environs of Albuquerque, New Mexico: Am. Geologist, v. 22, p. 26-43; reprinted 1899, Univ. New Mexico, Bull. 17, Geol. ser., v. 1, no. 1, p. 26-43

______, 18986, The geology of the San Pedro and the Albuquerque districts: Denison Univ. Sci Labs., Bull., v. 11, art. 5, p. 93-116; reprinted 1899, Univ. New Mexico, Bull. 21, Geol. ser., v. 1, no. 4, p.93-116

_____ , 1900, The geology of the White Sands of New Mexico: Jour. Geology, v. 8, p. 112-128: Univ. New Mexico, Bull. 23, Geol. ser., v. 2, pt. 1, 17 p.

______, 1904, Block mountains in New Mexico: a correction: Am. Geologist, v. 33, p. 393

Herrick, C. L., and Johnson, D. W., 1900, The geology of the Albuquerque sheet: Denison Univ. Sci. Labs., Bull., v. 11, art. 9, p. 175-239; Univ. New Mexico, Bull. 23, Geol. ser., v. 2, pt. 1, no. 1, 67 p.

Hills, G. F. S., 1948, The rift valleys of Africa: Am. Jour. Science, v. 246, p. 171-181

Hoge, H. P., 1970, Neogene stratigraphy of the Santa Ana area, Sandoval County, New Mexico: Ph.D. thesis, Univ. New Mexico, 140 p.

Hunt, C. B., 1936, Geology and fuel resources of the southern part of the San Juan Basin, New Mexico, pt. 2, the Mount Taylor coal field: U.S. Geol. Survey, Bull. 860-B, p. 31-80

______, 1938, Igneous geology and structure of the Mount Taylor volcanic field: U.S. Geol. Survey, Prof. Paper I89-B, 80 p. Jacobs, R. G., 1956, Geology of the central front of the Fra Cristobal Mountains, Sierra County, New Mexico: M.S. thesis, Univ. New Mexico, 45 p.

Joesting, H. R., Case, J. E., and Cordell, L. E., 1961, The Rio Grande trough near Albuquerque, New Mexico: New Mexico Geol. Soc., Guidebook 12th field conf., p. 148-152

Johnson, D. W., 1902-03, The geology of the Cerrillos Hills, New Mexico: Columbia Univ., School Mines Quart., pt. 2, Paleontology, 1902, v. 24, p. 173-246; pt. 1, General geology, 1903, p. 303-350, 456-500; pt. 3, Petrography, 1903, v. 25, p. 69-98

, 1932, Rock fans of arid regions: Am. Jour. Science, 5th ser., v. 23, p. 389-420

Keith, S. B., 1975, 100-50 m.y. tectonic patterns in central Arizona and their implications for Cordilleran orogenesis: Geol. Soc. America, Abs. with Programs, v. 7, no. 7, p. 1140-1141

Kelley, V. C., 1948, Geology and pumice deposits of the Pajarito Plateau, Sandoval, Santa Fe, and Rio Arriba Counties, New Mexico: Univ. New Mexico pumice project, Univ. New Mexico, Library File Rept., 16 p.

, 1952, Tectonics of the Rio Grande depression of central New Mexico: New Mexico Geol. Soc., Guidebook 3rd field conf., p. 92-105

, 1954, Tectonic map of a part of the upper Rio Grande area, New Mexico: U.S. Geol. Survey, Oil and Gas Inv. Map 0M-157

, 1955, Regional tectonics of the Colorado Plateau and relationship to the origin and distribution of uranium: Univ. New Mexico, Geol. ser., no. 5, 12 p.

, 1956, Rio Grande depression from Taos to Santa Fe: New Mexico Geol. Soc., Guidebook 7th field conf., p. 109-113

, 1963, Geologic map of the Sandia Mountains and vicinity, New Mexico: New Mexico Bureau Mines Mineral Resources, Geol. Map 18

, 1974, Albuquerque-its mountains, valley, water and volcanoes: New Mexico Bureau Mines Mineral Resources, Scenic Trip No. 9, revised, 106 p.

Kelley, V. C., and Clinton, N. J., 1960, Fracture systems and tectonic elements of the Colorado Plateau: Univ. New Mexico, Geol. Ser. No. 6, 104 p.

Kelley, V. C., and Kudo, A. M., in press, Volcanoes and related basaltic rocks of the Albuquerque-Belen Basin, New Mexico: New Mexico Bureau Mines Mineral Resources, Circ. 156

Kelley, V. C., and Northrop, S. A., 1975, Geology of Sandia Mountains and vicinity, New Mexico: New Mexico Bureau Mines Mineral Resources, Mem. 29, 136 p.

Kelley, V. C., and Reynolds, C. B., 1954, Structure of the Sandia Mountains, New Mexico (abs.): Geol. Soc. America, Bull., v. 65, p. 1272-1273

Kelley. V. C., and Silver, Caswell, 1952, Geology of the Caballo Mountains: Univ. New Mexico, Geol. Ser. No. 4, 286 p.

Kelley, V. C., and Wood, G. H., Jr., 1946, Lucero uplift, Valencia, Socorro, and Bernalillo Counties, New Mexico: U.S. Geol. Survey, Oil and Gas Inv. Prelim. Map 47

Keyes, C. R., 1907, Aggraded terraces of the Rio Grande (New Mexico): Am. Jour. Science, 4th ser., v. 24, p. 467-472

, 1908, Rock-floor of intermont plains of the arid region: Geol. Soc. America, Bull., v. 19, p. 63-92

Kottlowski, F. E., 1953, Tertiary-Quaternary sediments of the Rio Grande valley in southern New Mexico: New Mexico Geol. Soc., Guidebook 4th field conf., p. 144-148

, 1962, Reconnaissance of commercial high-calcium limestones in New Mexico: New Mexico Bureau Mines Mineral Resources, Circ. 60, 77 p.

Lambert, P. W., 1968, Quaternary stratigraphy of the Albuquerque area, New Mexico: Ph.D. thesis, Univ. New Mexico, 329 p.

Lee, W. T., 1907, Water resources of the Rio Grande valley in New Mexico and their development: U.S. Geol. Survey, Water-Supply Paper 188, p. 3-56

Leech. G. B., 1967, The Rocky Mountain trench, *in* The world rift system: Geol. Survey of Canada, Paper 66-14, p. 307-329

Lensen, G. J., 1958, A method of horst formation: Jour. Geology, v. 66, p. 579-587

Leopold, L. B., Wolman, M. G., and Miller, J. P., 1964, Fluvial processes in geomorphology: San Francisco, W. H. Freeman, 522 p.

Marcou, Jules, 1856, Resume of a geological reconnaissance extending from Napoleon, at the junction of the Arkansas with the Mississippi, to the Pueblo de Los Angeles, in California, *in* Whipple, G. W., Report of explorations for a railroad route near the 35th parallel: U.S., 33rd Cong., 2nd sess., Senate ex. doc. no. 78, v. 3, pt. 4, p. 165-175

Meyers, D. A., 1971, Geologic map of the Bosque Peak quadrangle, Torrance, Valencia, and Bernalillo Counties, New Mexico: U.S. Geol. Survey, Geol. Quad. Map GQ-948

, 1972, Geologic map of the Capilla Peak quadrangle, Torrance and Valencia Counties, New Mexico: U.S. Geol. Survey, Geol. Quad. Map GQ- 1008

Meyers, D. A., and McKay, E. J., 1970, Geologic map of the Mount Washington quadrangle, Bernalillo and Valencia Counties, New Mexico: U.S. Geol. Survey, Geol. Quad. Map GQ-886

Neev, David, 1975, Tectonic evolution of the Middle East and the Levantine basin (easternmost Mediterranean): Geology, v. 3, no. 12, p. 683-686

Noble, L. F., 1926, The San Andreas rift and some other active faults in the desert region of southeastern California: Seismol. Soc. America. Bull., v. 17, no. 1, p. 25-39

Northrop, S. A., 1945, Earthquake history of central New Mexico (abs.): Geol. Soc. America, Bull., v. 56, p. 1185

, 1947, Seismology in New Mexico (abs): Geol. Soc. America, Bull., v. 58, p. 1268

, 1961, Earthquakes of central New Mexico: New Mexico Geol. Soc., Guidebook 12th field conf., p. 151-152

Ogilvie, I. H., 1905, The high-altitude conoplain; a topographic form illustrated in the Ortiz Mountains: Am. Geologist, v. 36, p. 27-34

Pemberton, E. L., 1964, Sediment investigations-middle Rio Grande: Am. Soc. Civil Engineers, Proc., v. 40, paper 3833, Jour. Hydraulics Div., no. HY 2, pt. 1, p. 163-185

Quennell, A. M., 1956, The structural and geomorphic evolution of the Dead Sea rift: Geol. Soc. London, Quart. Jour., v. 114, pt. 1, p. 1-18

Ramberg, 1. B., 1975, Gridded fault patterns in a late Cenozoic and a Paleozoic continental rift: Geology, v. 3, p. 201-205

Read, C. B., Wilpolt, R. H., Andrews, D. A., Summerson, C. H., and Wood, G. H., 1944, Geologic map and stratigraphic sections of Permian and Pennsylvanian rocks of parts of San Miguel, Santa Fe, Sandoval, Bernalillo, Torrance, and Valencia Counties, north-central New Mexico: U.S. Geol. Survey, Oil and Gas Inv. Prelim. Map 21 [19451

Read, C. B., and Wood, G. H., Jr., 1947, Distribution and correlation of Pennsylvanian rocks in late Paleozoic sedimentary basins of northern New Mexico: Jour. Geology, v. 55, p. 220-236

Reagan, A. B., 1903, Geology of the Jemez-Albuquerque region, New Mexico: Am. Geologist, v. 31, p. 67-111

Reiche, Parry, 1949, Geology of the Manzanita and north Manzano Mountains, New Mexico: Geol. Soc. America, Bull., v. 60, p. 1183-1212

Reiter, Marshall, Edwards, C. L., Hartman, Harold, and Weidman, Charles, 1975, Terrestrial heat flow along the Rio Grande rift, New Mexico and Southern Colorado: Geol. Soc. America, Bull., v. 86, no. 6, p.811-818

Renick, R. C., 1931, Geology and ground-water resources of western Sandoval County, New Mexico: U.S. Geol. Survey, Water-Supply Paper 620, 117 p.

Reynolds, C. B., 1954, Geology of the Hagan-La Madera area, Sandoval County, New Mexico: M.S. thesis, Univ. New Mexico, 82 P.

Rittenhouse, Gordon, 1944, Sources of modern sands in the middle Rio Grande valley, New Mexico: Jour. Geology, v. 52, no. 3, p. 145-183

Ross, C. S., Smith, R. L., and Bailey, R. A., 1961, Outline of the geology of the Jemez Mountains, New Mexico: New Mexico Geol. Soc., Guidebook 12th field conf., p. 139-142

Ruetschilling, R. L., 1973, Structure and stratigraphy of the San Ysidro quadrangle, Sandoval County, New Mexico: M.S. thesis, Univ. New Mexico, 79 p.

Sanford, A. R., Budding, A. J., Hoffman, J. P., Alptekin, 0. S., Rush, C. A., and Toppozada, T. R., 1972, Seismicity of the Rio Grande rift in New Mexico: New Mexico Bureau Mines Mineral Resources, Circ. 120, 19 p.

Scott, W. B., 1907, An introduction to geology: New York, Wiley, 2nd ed., 816 p.

Shand, S. J., 1938, Earth-lore, geology without jargon: New York, Dutton, 144 p.

Slack, P. B., 1973, Structural geology of the northeast part of the Puerco fault zone, Sandoval County, New Mexico: M.S. thesis, Univ. New Mexico, 74 p.

______ , 1975, Tectonic development of the northeast part of the Rio Puerco fault zone, New Mexico: Geology, v. 3, p. 665-668

Smith, H. T. U., 1938, Tertiary geology of the Abiquiu quadrangle, New Mexico: Jour. Geology, v. 46, p. 301-319

Smith, R. L., Bailey, R. A., and Ross, C. S., 1970, Geologic map of the Jemez Mountains, New Mexico: U.S. Geol. Survey, Misc. Geol. Inv., Map 1-571

Soister, P. E., 1952, Geology of Santa Ana Mesa and adjoining areas, New Mexico: M.S. thesis, Univ. New Mexico, 126 p.

Spiegel, Zane, 1945, Geology and ground-water resources of northeastern Socorro County, New Mexico: New Mexico Bureau Mines Mineral Resources, Ground-water Rept. 4, 99 p.

, 1961, Late Cenozoic sediments of the lower Jemez River region: New Mexico Geol. Soc., Guidebook 12th field conf., p. 132-138

Spiegel, Zane, and Baldwin, Brewster, 1963, Geology and water resources of the Santa Fe area, New Mexico: U.S. Geol. Survey, Water-Supply Paper 1525, 258 p.

Stark, J. T., 1956, Geology of the South Manzano Mountains, New Mexico: New Mexico Bureau Mines Mineral Resources, Bull. 34, 49 p.

Stark, J. T., and Dapples, E. C., 1946, Geology of the Los Pinos Mountains, New Mexico: Geol. Soc. America, Bull., v. 57, p. 1121-1172

Stearns, C. E., 1943, The Galisteo Formation of north-central New Mexico: Jour. Geology, v. 51, p. 301-319

. 1953a, Tertiary geology of the Galisteo-Tonque area, New Mexico: Geol. Soc. America, Bull., v. 64, p. 459-507

1953b, Early Tertiary vulcanism in the Galisteo-Tonque area, north-central New Mexico: Am. Jour. Science, v. 251, p. 415-452

Stewart, J. H., 1971, Basin and Range structure: a system of horsts and grabens produced by deep-seated extrusion: Geol. Soc. America, Bull., v.82, p. 1019-1044

Swan, M. M., 1975, The Texas lineament-tectonic expression of a precambrian orogeny: Geol. Soc. America, Abs. with Programs, v. 7, no. 7, p. 1288-1289

U.S. Coast and Geodetic Survey, 1948, Abstracts of earthquake reports for the Pacific Coast and the Western Mountain region: MSA-56, Oct., Nov., Dec. 1947, 56 p.

, 1956, Abstracts of earthquake reports for the Pacific Coast and the Western Mountain region: MSA-90, April, May, June 1956, 19 p.

Wayland, E. J., 1921, Some accounts of the geology of the Lake Albert rift valley: Geog. Jour., v. 58, p. 344-359

Willis, Bailey, 1928, Dead Sea problem: rift valley or ramp valley?: Geol. Soc. America, Bull., v. 39, p. 490-542

, 1938, Wellings observation of Dead Sea structure: Geol. Soc. America, Bull., v. 49, p. 659-667

Willis, Bailey, and Willis, Robin, 1929, Structural geology: New York, McGraw-Hill, 518 p.

Wilpolt, R. H., MacAlpin, A. J., Bates, R. L., and Vorbe, Georges, 1946, Geologic map and stratigraphic sections of Paleozoic rocks of Joyita Hills, Los Pinos Mountains, and northern Chupadera Mesa, Valencia, Torrance, and Socorro Counties, New Mexico: U.S. Geol. Survey, Oil and Gas Inv. Prelim. Map 61

Wilpolt, R. H., and Wanek, A. A., 1951, Geology of the region from Socorro and San Antonio east to Chupadera Mesa, Socorro County, New Mexico: U.S. Geol. Survey, Oil Gas Inv. Map 121

Wislizenus, F. A., 1848, Memoir of a tour of northern Mexico, connected with Col. Doniphan's expedition, in 1846 and 1847: U.S. 30th Cong., 1st sess., Senate misc. doc. 26, 141 p.

Wood, G. H., Jr., and Northrop, S. A., 1946, Geology of the Nacimiento Mountains, San Pedro Mountain, and adjacent plateaus in parts of Sandoval and Rio Arriba Counties, New Mexico: U.S. Geol. Survey, Oil and Gas Inv. Prelim. Map 57

Woodward, L. A., 1975, Geometry of Sierrita fault and its bearing on tectonic development of the Rio Grande rift: Geology, v. 3, p. 114-116

Wright, H. E., 1943, Cerro Colorado, an isolated non-basaltic volcano in central New Mexico: Am. Jour. Science, v. 241, p. 43-56

1946, Tertiary and Quaternary geology of the lower Rio Puerco area, New Mexico: Geol. Soc. America, Bull., v. 57, p. 383-456

Wright, L. A., and Otton, J. K., 1974, Turtleback surfaCes of Death Valley viewed as phenomena of extensional tectonics; Geology, v. 2, p. 53-54

Index

CONTENTS OF POCKET

Geologic map
Tectonic map (fig. 19)

NEW MEXICO BUREAU OF MINES & MINERAL RESOURCES

A DIVISION OF NEW MEXICO INSTITUTE OF MINING & TECHNOLOGY

MEMOIR 33 GEOLOGIC MAP

SYMBOLS

Geologic contact, dashed where approximately located

High-angle fault presumed to be normal or strike slip, showing trace and direction of anticlinal or synclinal direction of plunge; dashed where uncertain; dotted where concealed; ball on apparent downthrown side; arrow shows direction of dip; showing inferred component of lateral slip

High-angle thrust fault: dashed where uncertain; dotted where concealed

Overthrust fault: dashed where uncertain; dotted where concealed

Trace of axial surface of anticline, showing plunge

Trace of axial surface of syncline, showing plunge

Strike and dip of beds

Strike and dip of overturned beds

Strike and dip of foliation

Horizontal beds

Oil-test hole, dry

Prospect

Wind direction on eolian blankets

Direction of distributary flow on alluvial fans

EXPLANATION

Qa | Qfa

Alluvium

Qa: *Arroyos;* **Qfa:** *Fans*

Qf

Alluvium

Floodplains

Ql

Landslide

Qe | Qed

Eolian sand

Qe: *Blankets;* **Qed:** *Dunes*

Qt

Gravel terraces

Qc

Caliche

Qp

Gravel pediments

Qo

Ortiz pediment gravel and surface

Fanglomerate ranging from large boulders to pebbles

Ts | Tsc | Tsz

Santa Fe Formation

Ts: *Undivided: pinkish, light-olive-drab and white sandstone; gray and brown mudstone; arkose, conglomerate, and fanglomerate.* **Tsc:** *Ceja Member, "Upper buff" of Bryan and McCann: grayish sand and pebbly conglomerate.* **Tsz:** *Zia member, "Lower gray" of Bryan and McCann: white sandstone with some reddish and greenish mudstones and gravel*

Tp

Popotosa Formation

Volcanic and granitic fanglomerate, mudstone, sandstone, and local andesitic flows; southern part of basin only

Te

Espinaso Formation

Volcanic fanglomerate with local leucocratic flows and tuff; northern basin only (includes also volcanics of Bland Canyon)

Td

Datil Formation

Volcanic fanglomerate and tuff; southern part of basin

Tba

Baca Formation

Nonvolcanic conglomerate; southern part of basin only

Tg

Galisteo Formation

Variegated sandstone, mudstone, and conglomerate; northern part of basin only

K | Kmv | Km

Mesaverde and Mancos Formations

K: *Undivided.* **Kmv:** *Mesaverde Formation.* **Km:** *Mancos formation: sandstone, shale, and coal; includes Dakota Formation at base of Mancos*

J

Morrison, Entrada, and Todilto Formations

Sandstone, mudstone, gypsum, and limestone

Ꝓ

Santa Rosa and Chinle Formations

Reddish-brown mudstone, sandstone, and conglomerate

P | Ps | Py | Pa

San Andres, Yeso, and Abo Formations

P: *Undivided.* **Ps:** *San Andres Formation.* **Py:** *Yeso Formation.* **Pa:** *Abo Formation: reddish to white sandstone, mudstone and gypsum*

IP

Madera and Sandia Formations

Marine limestone, shale, and sandstone with local conglomerate; includes thin Mississippian locally at base

CENOZOIC IGNEOUS ROCKS

Qb

Basalt flows of Albuquerque and Cat Hills fields

Vesicular olivine basalt flows and cinder

Qbt

Bandelier Tuff

Buff to white rhyolitic tuff and breccia

Tbr | Tbp

Rhyolite

Tbr: *Bearhead Rhyolite of Jemez area: flows, tuffs, and intrusions.* **Tbp:** *Peralta Tuff Member of Bearhead Rhyolite*

Tpb | Tpa

Paliza Canyon Formation of Jemez area

Tpb: *Intermediate to basaltic flows, tuffs, and breccias; also includes underlying basalt flow of Chamisa Mesa.* **Tpa:** *Andesites*

Tc

Canovas Canyon Rhyolite of Jemez area

Flows, tuffs, and intrusions

Tb | Tbc | Tbt

Basaltic flows and cinders of San Felipe, Cerros del Rio, Wind Mesa, Lucero Mesa, Cat Mesa, Isleta and lesser centers

Tb: *Undivided.* **Tbc:** *Cone.* **Tbt:** *Tuff*

Ta

Andesite flows and intrusions of Los Lunas, Tome, and Black Butte

Ti | Tib | Ti | Tir | Tib | Til

Shallow dikes and sills

Ti: *Undivided.* **Tib:** *Basalt.* **Til:** *Latite.* **Tir:** *Rhyolite*

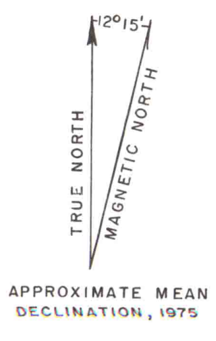
p€ | p€g | p€m

PRECAMBRIAN ROCKS

p€: *Undivided: granite, gneiss, schist, quartzite, and greenstone.* **p€g:** *Granitic plutons.* **p€m:** *Metamorphic rocks: gneiss, schist, quartzite, and greenstone*

INDEX MAP OF NEW MEXICO

SHOWING AREA OF THIS REPORT



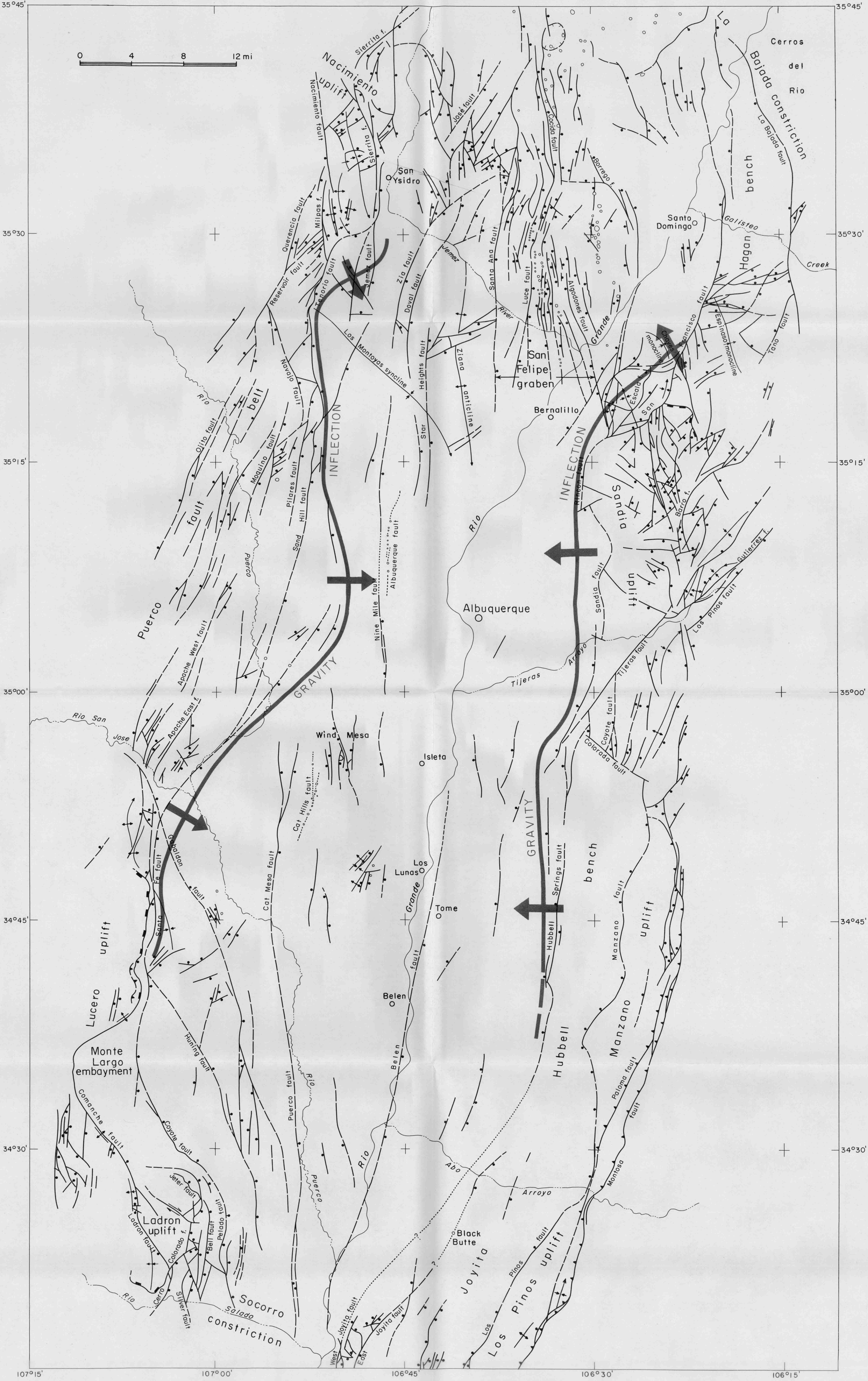
APPROXIMATE MEAN DECLINATION, 1975

GEOLOGY OF ALBUQUERQUE BASIN

by Vincent C. Kelley, 1977

SCALE 1:190,000

NEW MEXICO BUREAU OF MINES & MINERAL RESOURCES A DIVISION OF NEW MEXICO INSTITUTE OF MINING & TECHNOLOGY MEMOIR 33 FIGURE 19



TECTONIC MAP OF ALBUQUERQUE BASIN