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Geology of Santa Ana Mesa and Adjoining Areas, Sandoval County, New Mexico

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GEOLOGY OF SANTA ANA MESA AND
ADJOINING AREAS, NEW MEXICO - SOISTER

GEOLOGY OF SANTA ANA MESA
AND ADJOINING AREAS,
SANDOVAL COUNTY, NEW MEXICO

By

Paul E. Soister

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In Partial Fulfillment

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Maps not included in this copy.
Check CSWR copy.

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INTRODUCTION

GEOGRAPHY

The area embraced by this report comprises approximately 225 square miles of the southeastern one-quarter of Sandoval County, New Mexico. This area is bounded on the east by the Rio Grande and on the south and west by Jemez Creek. The Canon de San Diego Grant and the Santa Fe National Forest lie immediately north of the area. Part of the Santo Domingo Pueblo Grant is included in the northeastern corner.

This area occupies part of the northern tip of the Mexican Highland section of the Basin and Range Province as outlined by Fenneman (1931, pp. 379-393). The eastern edge of the Colorado Plateau Province lies less than 10 miles to the west.

The greater part of the area forms the northern part of the Albuquerque-Belen Basin of the Rio Grande depression; the northeastern edge lies in the Santo Domingo Basin. The Rio Grande depression lies in "the belt of faulting and uplifts" which extends from Colorado through central New Mexico and southward into Mexico (Eardley, 1951, pp. 376 and 391).

Altitudes range from about 5,250 to 6,100 feet in

INTRODUCTION

Location

The area discussed in this report consists of approximately 325 square miles of the southeastern quarter of Sandoval County, New Mexico. This area is bounded on the east by the Rio Grande and on the south and west by [illegible] Creek. The Canada de Cochiti Grant and the Santa Fe National Forest lie immediately north of the area. Part of the Santo Domingo Pueblo Grant is included in the north-eastern corner.

This area occupies part of the northern tip of the Mexican Highland section of the Basin and Range Province as outlined by Fenneman (1931, pp. 379-395). The [illegible] edge of the Colorado Plateau Province lies less than 10 miles to the west.

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the southwestern one-third of the area, 5,900 to 6,500 feet on Santa Ana Mesa, 6,100 to 6,600 feet in the Mesita Alta part, and from 7,200 to 7,500 feet on Borrego Mesa.

Much of the area is inaccessible except by foot, horse, or four-wheel-drive vehicles because of steep mesa slopes, sandy or bouldery arroyos, and boulder-strewn terrain. The top of Santa Ana Mesa may be reached by automobile on a road ascending the mesa slopes just south of San Felipe Pueblo. The northern and eastern sections of this mesa are accessible by unimproved roads, but the north-trending fault scarps prevent driving to the western part.

The paved State Road 44 links Bernalillo with San Ysidro and runs subparallel to and south of Jemez Creek. From a junction 2 miles west of Bernalillo a paved road may be followed to the observation point overlooking the Jemez dam site. Jemez Creek is crossed by an auto bridge at Zia, but a wide arroyo prevents ordinary automobiles from going northward from the pueblo. State Road 4, also paved, goes north from San Ysidro through Jemez Pueblo. About 2 miles south of Jemez Pueblo, a wagon road may be followed eastward for 2 miles, to a point west of Chamisa Mesa. Four-wheel-drive vehicles may go a few miles farther east along a wagon road through the San Ysidro Grant.

From just north of Jemez Pueblo, a good gravel road goes east and northeast through Vallecitos. From this road, about 1-1/2 miles northeast of Polica (Paliza) campground, a poor lumber road may be followed southward by four-wheel-drive vehicles to the top of Borrego Mesa.

The area northeast of Santa Ana Mesa may be reached via a poor road which branches west from the San Felipe-Santo Domingo road about 6 or 8 miles north of San Felipe. The sandy Borrego Canyon impedes travel into the Ojo del Borrego Grant.

Most of the inhabitants of the region are pueblo Indians, although there are also a few other ranchers and farmers. The Indian pueblos along Jemez Creek are Jemez, Zia, and Santa Ana; San Felipe Pueblo lies on the west bank of the Rio Grande a few miles above the mouth of Jemez Creek. The small village of San Ysidro lies just west of the big bend of Jemez Creek. Small farms make up the village of Lower Vallecitos along Vallecitos Creek. The absence of perennial streams in the interior of the area studied probably accounts for the lack of inhabitants there.

Brayer (1938) traces the history of the grants of this area (except for the Ojo del Borrego Grant). He states (op. cit., p. 77) that the Santa Rosa de Cubero Grant is still held by non-Indian title holders and the [illegible], a small [illegible] [illegible] the [illegible] [illegible] Vallecitos. From this [illegible] [illegible] a [illegible] [illegible] Indian [illegible] [illegible] [illegible] [illegible] [illegible] [illegible] [illegible] [illegible] [illegible] [illegible] top of [illegible] Mesa.

The [illegible] [illegible] of Santa Ana [illegible] may be reached with a four wheel drive [illegible] from the [illegible] Santo Domingo road about 4 or 5 miles south of the village. The sandy [illegible] [illegible] [illegible] into the Rio [illegible] Borrego Creek.

Most of the inhabitants of the region are pueblo Indians, although there are also a few other ranchers and farmers. The Indian pueblos along Jemez Creek are Jemez, Zia, and Santa Ana; San Felipe Pueblo lies on the west bank of the Rio Grande a few miles above the mouth of Jemez Creek. The small village of San Ysidro lies just west of the big bend of Jemez Creek. Small homes make up the village of Lower Vallecitos along Vallecitos Creek. The absence of perennial streams in the interior of the area studied probably accounts for the lack of inhabitants there.

[illegible] [illegible] [illegible] the [illegible] of the [illegible] of this area [illegible] the [illegible] and [illegible] [illegible]. [illegible] [illegible] [illegible] [illegible] [illegible] [illegible] [illegible] [illegible] [illegible] [illegible] [illegible] [illegible] [illegible] [illegible] [illegible]

San Felipe Indians refuse to buy it, claiming it is already theirs. The San Felipe Indians graze horses, cattle, and sheep on top of Santa Ana Mesa ("Black Mesa" of Brayer).

Santa Ana Pueblo land is unsuited for agriculture, and these Indians have secured almost 5,000 acres of land in the Rio Grande Valley, south of San Felipe, for this purpose. Most of them live where they farm, returning to the old pueblo only in winter and on ceremonial occasions. (Brayer, 1938, pp. 95-98).

At Zia Pueblo ("Sia") the land is very poor and the Jemez Creek water is almost entirely used for irrigation farther upstream. Farming is carried on in a small area adjacent to Jemez Creek, although, according to Brayer (1938, p. 98), "The pueblo is, perhaps, the poorest of all New Mexico Indian pueblos from the standpoint of adequate agricultural land." The Ojo del Borrego Grant has been added to Zia Pueblo's land and is used for grazing purposes.

Jemez Pueblo has very good farming land, with adequate water, on the alluvial flat of Jemez Creek south and west of the pueblo.

Almost the entire area studied is used for the grazing of small numbers of cattle, sheep, and horses. The lava-capped Borrego and Santa Ana Mesas, and the Mesita Alta, form high surfaces which support good stands of grass

Sandia Indians [illegible]

Santa Ana Pueblo land [illegible]

sandia. The Ana [illegible]

sheep on that of Santa Ana [illegible]

Santa Ana Pueblo land [illegible]

and these Indians have ... [illegible]

in the Rio Grande Valley, [illegible]

purpose. Most of these [illegible]

the old pueblo only [illegible]

(Bryan, 1929, pp. 95-96).

At Zia Pueblo ("Sia") [illegible]

Jemez Creek water is almost [illegible]

farther upstream. Farming is [illegible]

adjacent to Jemez Creek, [illegible]

(1929, p. 96). "The pueblo [illegible]

New Mexico Indian pueblos from [illegible]

agricultural land." The [illegible]

added to Zia Pueblo's land [illegible]

Jemez Pueblo has very [illegible]

quate water, on the alluvial [illegible]

west of the pueblo.

Almost the entire [illegible]

grazing of small numbers of [illegible]

The Laguna and Acoma and [illegible]

also, from that [illegible]

for grazing in the early spring, after the snow melts, and in the late summer - early fall rainy season. For the remainder of the year, however, forage is very poor. The southwestern part of the area is underlain by the predominantly sandy Santa Fe formation and in general has poor forage, even after the rainy season.

Pinon and juniper trees are scattered over most of the area, and this is the principal source of fuel for many of the inhabitants of the region. Occasional logging is done on the high Borrego Mesa where several species of pine trees grow.

CLIMATE

The present climate of the region is arid to semiarid continental. The annual rainfall ranges from about 8 inches in the lower southwestern part of the area to perhaps 15 or 20 inches on Borrego Mesa, the highest part of the area. Evaporation at Albuquerque for the years 1900-1903 averaged 83.5 inches per year (Lee, 1907, p. 31), and 100 inches is generally considered the approximate rate of evaporation at the present time.

Most of the precipitation is due to thunderstorms of the rainy season (July-September), and a little is derived from the light winter snows. As most of the summer

storms come from the Gulf of Mexico, the high Sandia Mountains probably help to increase the dryness of the area, and the Nacimiento Mountains intercept much of the precipitation in storms from the west.

Antevs (1948, p. 176) gives a table for the Great Basin which separates the past 9,000 years into three climatic periods. He calls this time the "Neothermal", and believes this is a better term than "Recent". His term "Altithermal", for the period 5000 B.C. - 2500 B.C. (warm and arid), is apparently the "Climatic Optimum" of many geologists.

As to the climate of this region during Pleistocene time, not much has been written. Kirk Bryan has investigated the effects of post-Pleistocene climates on aggradation and degradation in the Southwest. Ernst Antevs has been active in correlating physiographic and depositional features with glacial and post-glacial climatic variations. Ellis (1935) discussed glaciation in northern New Mexico. Glaciation on Cerro Blanco, about 140 miles south of the mapped area, was reported by S. B. Talmage and confirmed by Ellis (1935, P. 24).

Most workers conclude that the lack of extensive glaciation in New Mexico has been due, not to high temperatures, but to low precipitation. Inasmuch as evaporation is also low as a result of low temperatures during glacial

periods, Russell (1933, p. 929) states that even areas having a precipitation of only 8 or 9 inches per year must be considered as having a humid climate.

Stearns (1942, p. 867) reports finding fossil marmots at La Bajada Hill, a few miles northeast of this area, at an altitude of 5,900 feet. He concludes (op. cit., p. 878) that "...climatic changes in New Mexico during Wisconsin time may have been greater than formerly supposed..." because this is about 4,000 feet lower than the minimum altitude at which marmots are now found in the nearby Sangre de Cristo Mountains.

From the existing evidence, it seems probable that during Pleistocene time this part of New Mexico had an alpine climate, with low precipitation and evaporation, and frequent changes of temperature from below to above the freezing point. Frost-wedging and allied weathering phenomena must therefore have been much greater than they are today. A large amount of coarse clastic materials occur, usually as terrace gravels, throughout this general part of the Rio Grande region. The writer believes that much of this material may originally have been derived by such weathering.

PURPOSE AND SCOPE OF REPORT

The foremost purpose of this report is to outline the general geology and geomorphology of the mapped area. Secondarily, the relationship of the Santa Fe formation of late Tertiary age to older strata is explored. Presence of basalts and other volcanics in the Santa Fe formation is shown. Evidence indicating the probable contemporaneity of part of the Chicoma volcanic group and of the Santa Fe formation is discussed.

Aerial photographs and the Brunton compass were used in field mapping. The hand lens and the binocular microscope were used in examination of rock samples; no thin-section studies were made. A large stereoscope was used in the study of the geomorphic forms.

Most of the area is underlain by the Santa Fe formation, and it has been possible to map members within the formation. The extensive alluvial and volcanic cover hinders detailed mapping of the structure over much of the area, although the basalt sheets have made possible the detection of faults which may otherwise have gone undetected. The best outcrops are found on the mesa escarpments where gully erosion has removed talus and soil cover. Outcrops may also be found in badland areas at the edges of various

terraces; however, each of these outcrops consists of only a small thickness of beds which can seldom be correlated from one outcrop to another.

Two maps were made for this report -- a geologic and a geomorphic map. Although most of the area is mantled by a variable thickness of alluvium (sand, soil, terrace gravels, etc.) these deposits have not been mapped except where they are of major importance. The geomorphic map shows the various land forms in a genetic sense, and these forms are described in the section on Geomorphology.

ACKNOWLEDGMENTS

The writer is indebted to Dr. V. C. Kelley, of the University of New Mexico, who first aroused interest in the problem, and whose instructive guidance influenced many phases of the work. Dr. J. P. Fitzsimmons discussed certain aspects of the geomorphology and methods of mapping the geomorphic forms. Thanks are due Dr. S. A. Wengerd for also reading and criticizing the manuscript during its preparation. Mr. John Monteverde and Mr. David Soister accompanied and assisted the writer on a few of the field trips.

GENERAL GEOLOGY

STRATIGRAPHY

Introduction

The emphasis of this report is on the deposits and history of late Cenozoic time. Outcrops of pre-Cenozoic rocks make up only a very small proportion of the mapped area.

The pre-Cenozoic stratigraphy of north-central New Mexico is fairly well known. Table 1 is a brief outline of this stratigraphy. The oldest Paleozoic rocks found in this part of the state consist of a thin interval of Mississippian limestone and shale which can be found in only a few localities. The Pennsylvanian and later Paleozoic systems and the Mesozoic systems are all represented in northern New Mexico. The Paleozoic rocks are quite prominent in the north-trending mountain ranges through the central part of the state. The Mesozoic rocks outcrop over most of the San Juan Basin, in the northwestern part of the state.

Pre-Cenozoic Rocks

The outcropping pre-Cenozoic rocks of the mapped area

[illegible]

[illegible]

[illegible]

[illegible] of [illegible]

[illegible] [illegible] portions of the region. area.

The [illegible] stratigraphy of northwestern New Mexico [illegible] Table [illegible] outline of [illegible]. The oldest Paleozoic rocks found in this part of the state consist of a thin interval of [illegible] and shale which can be found in some [illegible]. The Pennsylvanian and later Paleozoic [illegible] and the [illegible] are all represented in [illegible]. The Paleozoic rocks are quite [illegible] ranges through the [illegible]. The Mesozoic rocks [illegible] northwestern part of [illegible]

[illegible]

[illegible]

TABLE I

PRE-CENOZOIC STRATIGRAPHY*
(maximum thicknesses approximate)

System	Formation	Principal Lithology	Thickness (feet)
Cretaceous	Mesaverde formation	Sandstone	0 - 2,500
	Mancos shale	Shale	0 - 1,500
	Dakota group	Sandstone	0 - 270
Jurassic	Morrison formation	Sandstone, siltstone, shale, clay	0 - 1,000
	Todilto formation	Gypsum, limestone	0 - 250
	Entrada sandstone	Sandstone	0 - 180
Triassic	Chinle formation	Sandstone, Shale, siltstone,	0 - 1,000
Permian	San Andres formation	Sandstone, limestone	0 - 200
	Yeso formation	Sandstone, siltstone	500
	Abo formation	Sandstone, siltstone, clay	700
Pennsyl-vanian	Madera limestone	Limestone	1,300
	Sandia formation	Sandstone, limestone	300
Missis-sippian**	(?)	Sandstone Limestone, shale	300(?)
Total Thickness:			3,100 - 10,000
Pre-Cambrian		Granite, gneiss, schist, quartzite	

*Mainly after Northrop and Wood (1946), and Harrison (1949).

**Work in progress (1952) in the Nacimiento Mountains by Gus K. Armstrong, a student of the University of New Mexico.

consist of Lower Permian, Upper Triassic, Jurassic, and Upper Cretaceous formations which have been described by Northrop and Wood (1946) and by Harrison (1949). These rocks outcrop only in the northwestern part of the area.

The Permian rocks include the Meseta Blanca and San Ysidro members of the Yeso formation, and the Glorieta sandstone and an upper unnamed member of the San Andres formation. These beds are of red, orange, and brown siltstone and silty sandstone.

The Triassic rocks are included in the Chinle formation. The Agua Zarca member, at the base, is of conglomeratic sandstone, while the upper part of the formation consists of dark-red, reddish-brown, and purple shale, siltstone and sandstone.

The Jurassic rocks include beds of the Entrada sandstone, the Todilto limestone and gypsum, and the Morrison formation.

Upper Cretaceous rocks are represented by two inliers of beds of the Mancos shale just southeast of Chamisa Mesa. These beds include black claystone and light-green, olive green, and greenish-gray shale with thin beds of sandy limestone. The limestone contains abundant fossil remains, mainly of *Inoceramus labiatus*. The lowermost beds of the Santa Fe formation overlie the Mancos shale

here with a slight angular unconformity (Plate I).

No rocks of an age intermediate between Mancos and Santa Fe occur in the mapped area. The older formations are unconformably overlain by the Santa Fe formation.

Pre-Santa Fe Cenozoic Rocks

Although pre-Santa Fe Tertiary formations have been described in many localities in the Rio Grande region, no outcrops of them were found in the mapped area. If equivalents of the early Tertiary Torrejon, Puerco, or Wasatch formations of the San Juan Basin were ever deposited here, they have either been completely removed by erosion or their remnants are buried by the Santa Fe formation.

The Galisteo formation, of Eocene or Oligocene age, rests unconformably upon the Mesaverde formation in the Hagan area. It is 925 feet thick about 8 miles southeast of San Felipe (Stearns, 1943, p. 308), but thins rapidly toward one of its sources in the northwest (op. cit., p. 314). Its wedge edge must therefore underlie the Santa Fe formation somewhere near the present Rio Grande. About 1,000 feet of Espinaso volcanics overlie the Galisteo formation in the Hagan Basin. These volcanics were probably derived from the east (Stearns, 1943, p. 313), and they are either thin or absent in the mapped area.

Plate I. Mancos shale unconformably overlain by sandstone of Chamisa Mesa member of Santa Fe formation. Sec. 30, T 16 N, R 3 E. View northeast.

The Jemez Mountains, to the north, are underlain predominantly by volcanic rocks of Cenozoic age, generally called the Chicoma formation. This mass of volcanics should probably be termed a group, rather than a formation (V. C. Kelley, oral communication), because it includes "... several thousand feet of andesite and latite lavas with some basalt, rhyolite, and volcanic breccia" (Smith, 1938, p. 939). The Cerrito Negro rhyolite (?) described in this report may be a distant, small outlier of the Chicoma volcanic complex. Age of the Chicoma volcanic group is uncertain. Most authors tentatively assign it to the Miocene by correlating this volcanism with that of the San Juan Mountains of Colorado (Ross, 1931, p. 185; Smith, 1938, p. 958). Others state that it is middle to late Tertiary (Kelley, 1950, p. 15). Most workers have heretofore agreed that the Chicoma volcanics are clearly older than the Santa Fe formation (Smith, 1938, p. 958). The present writer is inclined to agree with V. C. Kelley (oral communication), who states that the Chicoma volcanic group "... probably intertongues with everything from Espinaso to youngest Santa Fe."

North of the Jemez volcanic area, the Abiquiu tuff (Miocene?), at least 1,200 feet thick, underlies the Santa Fe formation (Smith, 1938, p. 944). The Abiquiu tuff is described (op. cit., p. 950) as being a broad, irregular,

piedmont fan deposit which, to the south, "...appears to have lapped against the Chicoma volcanic mass after active volcanism ceased." The contact between the Santa Fe formation and the Abiquiu tuff is gradational and Smith suggests intertonguing of the two formations. V. C. Kelley (oral communication) agrees with the writer that the Chamisa Mesa member of the Santa Fe formation, as herein described, may be equivalent in part to the Abiquiu tuff, and has pointed out that the Bodega Butte member is Abiquiu in character in many ways.

Denny (1940a, pp. 75-81) describes "...the presence of a heretofore undescribed basin deposit (the Popotosa formation) which represents the transition period between the volcanic activity of Miocene(?) time and the basin deposition of Santa Fe (Pliocene?) time." This is in the lower Rio Puerco area, approximately 80 miles to the south. The age of the formation is given as late Miocene. The Popotosa formation unconformably overlies volcanic rocks of supposed Miocene age and is in turn unconformably overlain by the Santa Fe formation. Bryan and McCann (1937, pp. 817-818) report remnants of water-laid pre-Santa Fe volcanic tuff lying unconformably upon Cretaceous rocks a few miles southwest of lower Jemez Creek; there has been no mention made as to whether or not this tuff is correlative with the Popotosa formation.

[illegible]

[illegible]

Plate II. Concretionary weathering characteristic of some sandstone in Chamisa Mesa member. Sec. 32, T 16 N, R 3 E.

Santa Fe Formation

General Statement

The alluvial deposits which partly fill the Rio Grande depression near Santa Fe, New Mexico, were first described by Hayden in 1869. He named these deposits the "Santa Fe marl." Bryan (1938, p. 205) states that "The main body of sedimentary deposits of the Rio Grande depression . . . is considered to be of the same general age and to belong to the Santa Fe formation." Fossils of Miocene and Pliocene age have been found in various places in the Rio Grande region in beds which are more or less correlative with those at the type locality.

It is now generally agreed that the Santa Fe formation is of Miocene and Pliocene age, although the exact time boundaries are seldom agreed upon. Almost certainly, the ages of earliest and latest Santa Fe deposits vary slightly from place to place. It seems doubtful that deposition would begin and cease contemporaneously over the entire area covered by the Santa Fe formation. The majority of workers give the age as late Miocene and early Pliocene (Denny, 1940, p. 678). Wood, et al. (1941, p. 31) state that the formation is predominantly of Barstovian and Clarendonian age. Frick

[illegible]

[illegible]

The alluvial deposits which nearly fill the Rio Grande depression near Santa Fe, New Mexico, were first described by Hayden in 1869, who named these deposits the "Santa Fe marl." Bryan (1938, p. 205) stated that "The main body of sedimentary deposits of the Rio Grande depression . . . is considered to be of Pliocene general age and to belong to the Santa Fe formation." Fossils of Miocene and Pliocene age have been found in so many places in the Rio Grande region in beds which are more or less correlative with those at the type locality.

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(1933, p. 549) states that although "...the Santa Fe marls have been currently interpreted as of Upper Miocene age..." recent investigation based on fossils found in the formation near Santa Fe "...indicates that the accumulations of this portion of the Rio Grande basin range from the Mid-Miocene to Pleistocene. The Pleistocene occurs in remnants of aeolian origin that here and there cap the irregular Pliocene-Miocene surface."

Bryan and McCann (1937, p. 806) state that "On some maps, Pleistocene and Recent deposits are included in the Santa Fe." This confusing of later deposits with Santa Fe deposits has several causes: (1) similarity of sedimentary materials in both; (2) erosion and redeposition of Santa Fe materials occurred both during and after Santa Fe time; (3) poor consolidation plus extensive volcanic and alluvial cover limit the area of outcrop; (4) great lateral variation of deposits prevents accurate correlation between outcrops; (5) lack of fossils prevents close dating of most beds. Bryan (1938, p. 209) states that deformation "...has become one of the principal criteria for distinguishing the formation from the Quaternary sand and gravel." This rule is not infallible because (1) isolated outcrops of Santa Fe beds may appear undeformed, and (2) post-Santa Fe or Quaternary deformation has been reported in many parts of the Rio Grande

area: Abiquiu area (Smith, 1938, pp. 961-962); Espanola Valley (Denny, 1940b, p. 690); Cerros del Rio area (Emmanuel, 1950, pp. 23-24); near San Ysidro (Bryan and McCann, 1937, p. 820); Lucero Mesa (Kelley and Wood, 1946); lower Rio Puerco area (Wright, 1946, pp. 415 and 421); and the west base of the Magdalena Mountains (Bryan, 1938, p. 215). Also, Atwood and Mather (1932, p. 31) state that during the Quaternary the San Juan "...region has been subjected to almost constant crustal warping."

As to depositional environment, "Although earlier workers interpreted the formation as a lacustrine deposit, recent studies support the fluviatile hypothesis proposed by Davis..." (Denny, 1940, p. 678). The numerous workers have shown that the Santa Fe formation contains deposits of several environments: alluvial fan, floodplain, river channel, lake and playa, as well as volcanic. Bryan (1938, p. 205) states that the basins of deposition were of two main types: "basins with a through-flowing river and basins with enclosed drainage."

Sources of the sediments are found in the mountains and high plateaus bordering the Rio Grande depression and in the various volcanic areas, especially the Jemez Mountains.

In this area several members of the formation have been set forth. Bryan and McCann (1937) divided the Santa Fe

[illegible] area [illegible], [illegible] [illegible], [illegible] Magdalena
[illegible] [illegible], [illegible] and [illegible] [illegible]
[illegible] [illegible] [illegible] [illegible] and [illegible]
[illegible] [illegible] [illegible] [illegible]. the
[illegible] [illegible] [illegible] [illegible] and the [illegible]
base of the [illegible] sequence ([illegible], [illegible], p. [illegible]).
Also, [illegible] and [illegible] ([illegible], p. [illegible]) state that during the
[illegible] [illegible] the [illegible] had been subjected to a
most [illegible] crustal warping."

As to depositional environment, "Although earlier workers interpreted the formation as a lacustrine deposit, recent studies support the [illegible] hypothesis proposed by Davis..." (Denny, 1940, p. 628). The numerous workers have shown that the Santa Fe formation contains deposits of several environments: alluvial fan, floodplain, river channel, lake and playa, as well as volcanic. Bryan (1938, p. 207) states that the basins of deposition were of two main types: "basins with a through-flowing river and basins with enclosed drainage."

Sources of the sediments are found in the mountains and high plateaus bordering the Rio Grande [illegible] basins and in the various volcanic areas, especially the Jemez [illegible].

In this area several members of the formation have [illegible] [illegible] [illegible] [illegible] [illegible] [illegible] into three members: Lower Gray, Middle Red, and Upper Buff members in the area a few miles southwest of lower Jemez Creek. At least the lower and middle members are present in this area; but different names are given to them here. The Chamisa Mesa member is the approximate equivalent of the Lower Gray member, and the Santa Ana member is equivalent to the Middle Red member. However, other members are present also, and they are described in following sections of this paper.

Chamisa Mesa Member

The Chamisa Mesa member crops out in most of the western part of the area. The beds are poorly exposed, in general, due to their covering by coarse volcanic debris, soil, and wind-blown sand, and in the northwestern part by the Borrego Mesa lava flows. Also, most of the beds are poorly consolidated. The best outcrops are found on the mesa escarpments where the usual cover of lava debris has been removed. The best sections occur west of the south end of Chamisa Mesa, from which the member is named, and in the west-central part of the Ojo del Borrego Grant.

Various types of bedding are seen in individual beds; some are even-bedded and others show aqueous cross-bedding. (Plate III). Many lenticular beds are present,

till [illegible]. Loess, sand, Mankato drift, and [illegible]
surfaces in the area's [illegible] portions of the [illegible]
Basin. At least the lower and middle members are present
in this area, but different names are given to each bed.
The Carlile Shale occurs in [illegible] equivalent of
the Lower Gray member, and the [illegible] is equivalent
to the [illegible]. Unconsolidated deposits are
present also, and these are described in following sections
of this paper.

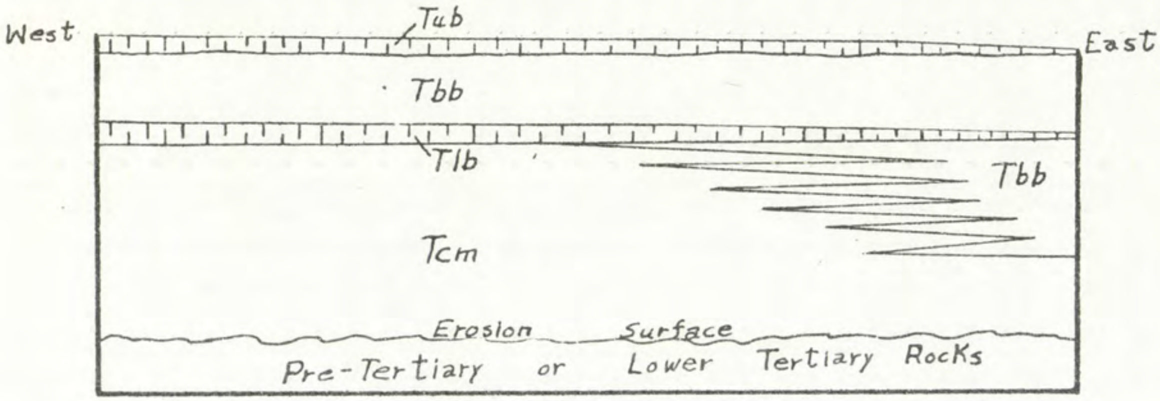
[illegible]

The [illegible] crops out in most of the
western part of the area. The beds are poorly exposed, in
general, due to their covering of loess, [illegible] drift,
soil, and wind-blown sand, and in the northwestern part by
the [illegible]. Also, most of the beds are
poorly consolidated. The best outcrops are found in the
area [illegible] where the [illegible] cover of [illegible] has
been removed. The best outcrops occur west of the south
end of [illegible] from which the [illegible] and
in the southwestern part of the [illegible].

[illegible]

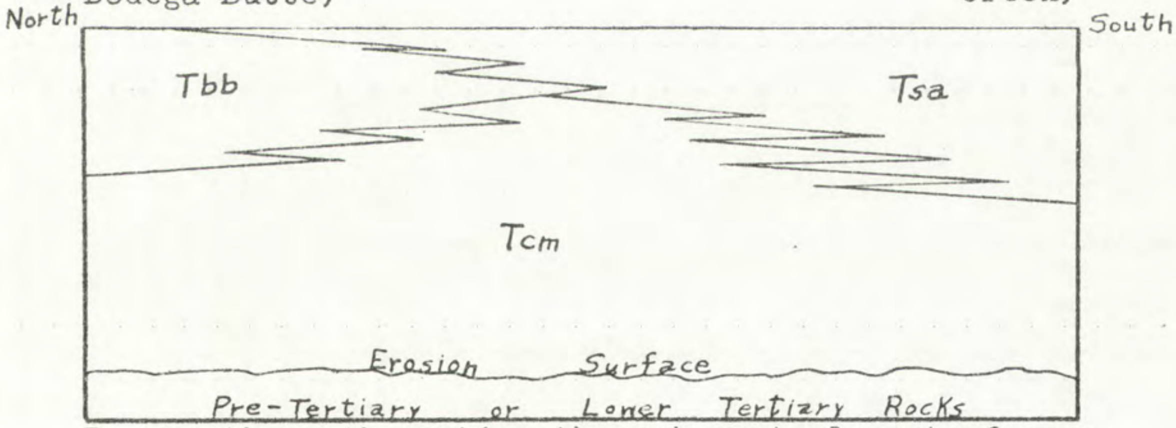
[illegible] and [illegible] where [illegible]
beds, [illegible] [illegible]

(North of Chamisa Mesa) (Near Bodega Butte)



A. East-west section through northern part of area.

(Near south end of Bodega Butte) (Vicinity Jemez Creek)



B. North-south section through central part of area.

Figure 2. Generalized diagrams of mutual relationships of the main members of the Santa Fe formation. Chamisa Mesa member (Tcm), Bodega Butte member (Tbb), Lower Borrego Mesa basalt (Tlb), Upper Borrego Mesa basalt (Tub), Santa Ana member (Tsa).

and there are few persistant marker beds. Most of the cement consists of $CaCO_3$, and much of it is concentrated to form thin, irregular lenses or concretionary masses in sandstone. A few silica-cemented beds are present.

The predominant lithologic type in this member is sandstone. Most of this is fine-to medium-grained, fairly well sorted, and light-gray to tan. Grains are mainly sub-rounded, and consist almost entirely of clear to light-colored quartz. A few thin beds of limestone, clay, and siltstone, and lenses of pebble conglomerate are also present.

The character of the sand leads to the belief that most of it has been derived from Cretaceous sandstones, especially the Mesaverde formation. It is, therefore, at least a second-cycle sand.

The upper part of the Chamisa Mesa member was measured 3½ miles east of the section outlined in Table 2. Lateral variations prevent accurate correlation of beds of the two localities. Thickness of the measured section is 707 feet. There is little variation in the characteristics of the lower 547 feet of this section, which consists entirely of sandstone. Most beds are medium-to thick-bedded and even bedded, and many in the lower half of this section show very even aqueous cross-bedding. Colors are tan, pinkish-tan, and tan-gray. Grains are sub-rounded to rounded, fine

TABLE II

GENERALIZED SECTION OF CHAMISA MESA MEMBER

(Top) Lithology	Thickness (Feet)
Sandstone and siltstone -- Gray to light-brown, poorly consolidated, argillaceous.	400
Sandstone and siltstone --- Gray to medium-brown, medium-bedded, slightly calcareous.	150
Quartzite --- Light to medium-brown, medium- to thick-bedded, very resistant.	5
Sandstone --- Light-brown with minor gray beds, medium- to thick-bedded, resistant, calcareous, very fine-grained to medium-grained, silty.	37
Clay --- Light-green, non-calcareous.	3
Sandstone --- Tan to light-brown, medium-bedded, calcareous, very fine-grained to medium-grained, silty.	12
Bentonite --- White, friable, with scattered specks of carbonaceous material.	0.5
Sandstone --- Tan, medium- to thick-bedded, fine-grained to medium-grained.	45
Sandstone --- Medium-brown, thick-bedded, resistant, siliceous, very fine-grained to fine-grained.	1
Sandstone --- Medium-gray, thick-bedded, siliceous, very fine-grained to fine-grained, silty.	1
Sandstone --- Light- to medium-brown and gray, thin- to thick-bedded, even-bedded, slightly to very calcareous.	76

TABLE II

GENERALIZED SECTION OF CHAMISA MESA MEMBER
(continued)

(Top) Lithology	Thickness (Feet)
Limestone --- Light-gray, thick-bedded, fairly soft due to clay and fine quartz silt impurities. Contains fragments of silicified plant stems which average one-tenth inch in diameter and are vertically striated.	1-2
Siltstone and sandstone --- Light-brown and gray, thin- to thick-bedded, even-bedded, slightly to very calcareous.	46
Limestone --- White to light-gray, hard, fairly pure. Contains silicified stems as in limestone below.	1
Sandstone --- Light-gray, thick-bedded, slightly silty.	1-3
Limestone --- White to light-gray, hard. Contains fragments of silicified plant stems which average one-tenth inch in diameter and are vertically striated; some are as much as one-half inch in diameter and are jointed.	1
Sandstone --- Light-brown, thick-bedded, fine-grained to medium-grained, fairly well sorted. Contains minor lenses of light-green clay.	41
Sandstone --- Light-gray, massive, mainly semi-consolidated, fine-grained to medium-grained. Aqueous cross-bedding common but usually masked due to poor consolidation. In the lower part of this interval, the cement consists mainly of light-colored clay, some of which is bentonitic; scarce to abundant $CaCO_3$ makes up most of the cement in the upper part. Hard, irregular,	

TABLE II

GENERALIZED SECTION OF CHAMISA MESA MEMBER
(continued)

(Top) Lithology	Thickness (Feet)
layers and lenses cemented by $CaCO_3$, averaging 6-8 inches in thickness, are very common. Epigenetic concretions of sand grains cemented by $CaCO_3$, usually quite spherical and averaging one-half inch in diameter, are common (Plate II); some concretions up to 5 inches in diameter were noted, and the large ones have a vague concentric structure. There are also aggregates of small concretions. Most sand grains of this interval are clear to white, sub-angular to sub-rounded quartz grains; a few red or pink grains are also present, but ferro-magnesian minerals are rare; a few grains of biotite and muscovite were noted locally.	550-650
Total Thickness	1370-1475

to medium, and mainly quartz with minor feldspar and rare dark minerals. Sorting is fair to very good.

Above this sandstone there is a 70-foot interval of granulitic to pebbly, tan-gray sandstone; pebbles and granules are mainly of pink granite and various felsites. This interval represents a gradation of the Bodega Butte member, on the east, into the upper part of the Chamisa Mesa member, on the west. Over this interval lies a 50-foot bed of tan, massive, resistant, siliceous, medium-grained sandstone which has a few scattered pebbles and cobbles of volcanic tuff and felsites which are deeply weathered. The Lower Borrego Mesa basalt overlies this sandstone conformably. Although the upper part of this section is mapped as belonging to the Bodega Butte member, some of the beds actually belong to the Chamisa Mesa member; the scale used limits the accuracy of the mapping.

Northward along the western escarpment of Borrego Mesa, the Chamisa Mesa member thins to a feather edge; this thinning appears to be due to nondeposition as a result of the existence of highlands in that direction during early Santa Fe time.

Southward from the Chamisa Mesa-Bodega Butte area, toward Santa Ana Pueblo, the principal lithologic variation is the replacement of some beds of sandstone by green and

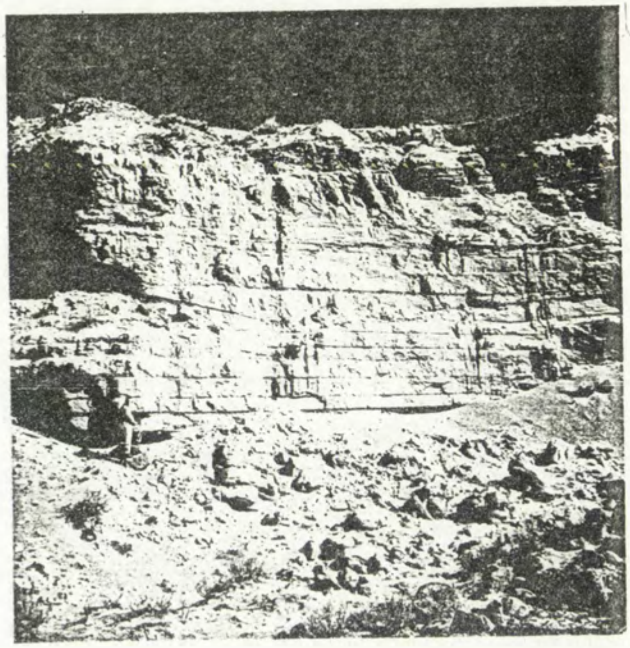


Plate III. Even-bedded and cross-bedded sandstone in Chamisa Mesa member. At southwest corner of Santa Ana Mesa.

red shaly clay and siltstone. Some of the concretionary sandstone is present here also. Minor lenses of granule and pebble conglomerate (red granite or gneiss, quartzite, and chert) are found in scattered localities, particularly in the area just north of Zia Pueblo. However, sand and sandstone make up practically all of the Chamisa Mesa member of the Santa Fe formation.

At the base of cliffs in Borrego Canyon, just above the big bend, semi-consolidated sand crops out. The lithologic characteristics of this sand and its stratigraphic position allow its correlation with the Chamisa Mesa member. Above this sand, granules and small pebbles of granite, chert, and felsite fragments are scattered through sandstone. This marks the beginning of the Bodega Butte member; the lower part of this member intertongues with and grades into the upper part of the Chamisa Mesa member.

Maximum thickness of the Chamisa Mesa member in the central part of the mapped area cannot be directly determined, but may reach as much as 2,000 feet. Origin and deposition of sedimentary materials in this and other members of the Santa Fe formation is described under Regional Relations (page 48).

Bodega Butte Member

In the general area north and east of Bodega Butte, the Santa Fe formation is composed mainly of a volcanic fanglomerate, herein termed the Bodega Butte Member. This fanglomerate overlies much of the Chamisa Mesa member, intertonguing with its upper beds. The beginning of deposition of this fanglomerate is seen in the scattered granules and pebbles in the lowest beds, as mentioned above. A generalized stratigraphic section, measured in the southern part of the Ojo del Borrego Grant, is presented in Table 3.

Strata are thin-to thick-bedded, some aqueous cross-bedding is present, and rapid lensing-out of beds is characteristic. Conglomeratic sandstone and conglomerate are the predominant lithologic types. Coarse particles include mainly sub-rounded pebbles and cobbles of felsite, tuff, red granite and gneiss, chalcedony, and chert. Sand grains are somewhat similar to those of the Chamisa Mesa member.

Most of the materials in this member have been derived from the central Jemez area, to the north. Pyroclastic and other extrusive rocks make up much of this material, recording contemporaneous volcanism. However,

TABLE III

GENERALIZED SECTION OF BODEGA BUTTE MEMBER

Lithology (Top)	Thickness (Feet)
Sandstone --- Tan to gray, thin- to thick-bedded, even-bedded to very irregular, slightly to well consolidated; contains numerous granules and pebbles. Some beds contain large quantities of stream-worn lithic and pumiceous tuff fragments.	225
Graywacke, conglomerate, and sandstone --- Graywacke beds are dull gray, thin- to medium-bedded, even-bedded, medium-grained to coarse-grained, granulitic, and siliceous; grains are mainly coarse, angular basalt (up to 65 per cent in some beds), and fine grained to medium-grained sub-rounded quartz with minor feldspar. Conglomerate beds are brownish-gray, thin- to medium-bedded, calcareous or siliceous; coarse particles consist mainly of felsites, and red granite and gneiss. Some conglomerate beds resemble concrete. $CaCO_3$ and silica cement. A few conglomeratic sandstones are present.	250
Sandstone --- Light-brown, massive, poorly consolidated, non-calcareous, fine-grained to medium-grained, fairly well sorted; scattered granules and pebbles of felsites.	45
Conglomerate, conglomeratic sandstone, and sandstone --- Conglomerate is tan-gray or gray; the cement is mainly silica; most beds non-calcareous. Pebbles and small cobbles include felsites, pink fine-grained granite, red gneissoid granite, quartzite, chalcedony, and chert fragments. A very well rounded one-foot boulder of Glorieta(?) sandstone was noted. Sandstone is medium-brown to	

materials in the sandstone beds were perhaps derived from the northwest or west and thus represent an intertonguing of beds of the Chamisa Mesa member. These are too thin, however, to be separately mapped.

About 1½ miles north of Bodega Butte, the amount of pyroclastic material in the upper beds is greater than it is to the east, whereas coarse particles of other rock types show a decrease (Plate VI). Very little coarse material is found below these tuffaceous beds here, demonstrating that the underlying conglomerate, to the east, has intertongued with or graded into sandstone of the Chamisa Mesa member to the west.

Practically all the tuffaceous beds lie between the Lower and the Upper Borrego Mesa basalts. Traced northwestward onto Borrego Mesa, the normal sedimentary material in this interval gradually decreases, and the amount of pyroclastic and felsite detritus increases. Thus, between the two lavas on the upper escarpment of Borrego Mesa, north of Chamisa Mesa, no outcrops were found, but the float consists of (1) light to medium-gray, hard and compact lithic tuff; (2) white to light-gray pumiceous tuff; (3) medium reddish-brown and light-gray rhyolite to andesite types; (4) light-gray, pumiceous perlite; (5) medium-gray normal perlite; and (6) obsidian. Most of these fragments

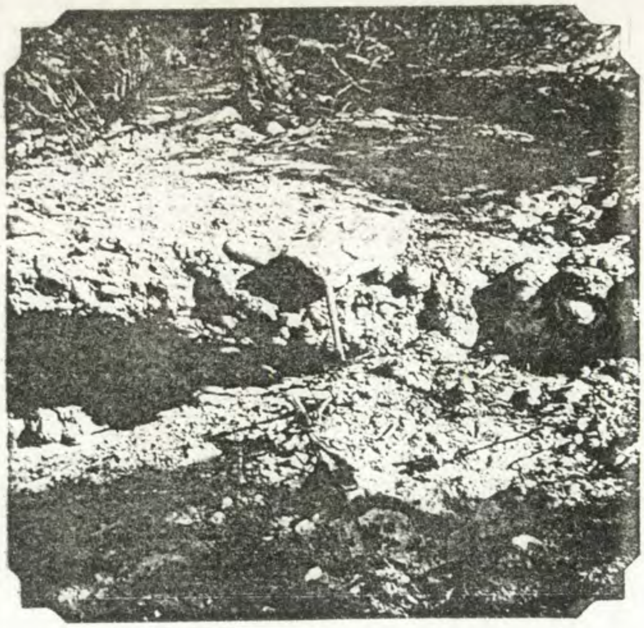


Plate V. Conglomerate in the Bodega Butte member. East of Bodega Butte.

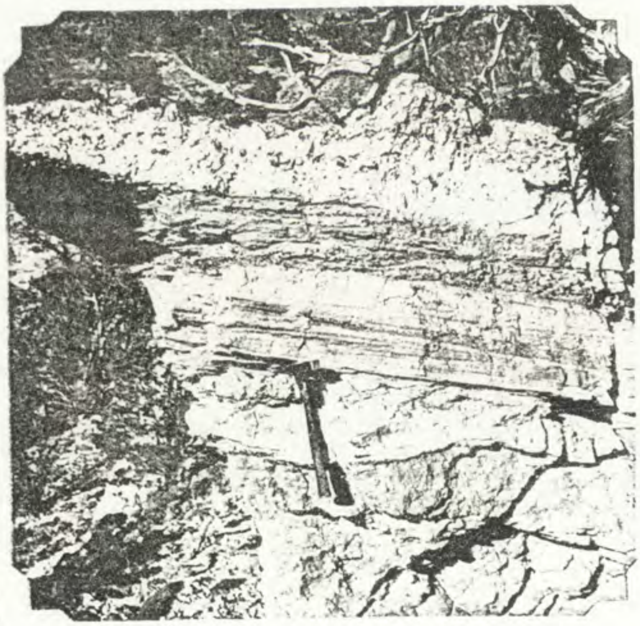


Plate VI. Tuffaceous to argillaceous sandstone in the Bodega Butte member. Northwest of Bodega Butte.

intertongue with the Santa Ana member. Southeastward from this butte relations of this member with the Santa Ana member are obscured by the San Felipe basalt, but the same intertonguing of the two is probable. The intertonguing mentioned here is not sharply defined, for few beds can be traced very far; it is rather more of a gradation than a sharp intertonguing of individual beds. Contemporaneous deposition of materials from the different sources has produced strata which are not distinctive of either member but have characteristics of both.

Lower Borrego Mesa Basalt

At least two distinct and persistent lava flows cap Borrego Mesa. These two cliff-forming flows are separated by the thick slope-forming mass of pyroclastic and sedimentary materials described in the preceding paragraphs.

The lower basalt on the upper escarpment of Borrego Mesa is very resistant to erosion, and forms vertical cliffs everywhere except where broken by faults. It ranges in thickness from about 30 feet in the vicinity of Bodega Butte to at least 70 feet on Borrego Mesa east of Jemez Pueblo; on Chamisa Mesa the average is about 45 feet. It is thickest at the north.

Columnar jointing is absent or only poorly developed.

The lava shows coarse spheroidal weathering in many places, and is there changed from black to a greenish color due to chloritization (V. C. Kelley, oral communication). Spherical amygdules of calcite are found in this lava, usually concentrated in certain zones. The diameter of the amygdules is as much as 1½ inches, averaging about one-third of an inch. The calcite is of the Iceland spar variety, with a rhombohedral crystal habit. In some places, baked and hardened xenoliths of siltstone or sandstone are found in the basalt.

Different flow-units are present in this basalt. For example, the following general section of the basalt, from the base upward, was noted south of Bodega Butte: (1) base scoriaceous and reddish; (2) dense; (3) greenish and spheroidally weathered; (4) scoriaceous; (5) greenish, spheroidally weathered; (6) scoriaceous, amygdaloidal; (7) dense, amygdaloidal. At the exposures north of Bodega Butte, this basalt has at least three scoriaceous intervals in it and is 60 feet thick.

This lava was extruded from vents to the north which are now covered by later accumulations of volcanic beds. It flowed over sandstone of the Chamisa Mesa member probably during middle Santa Fe time.

Mesa member, as well as throughout the Santa Ana member, north of Santa Ana Pueblo, beds of these two members apparently intertongue or intergrade in this locality. The contact given, therefore, is an arbitrary one.

This member is a fan deposit derived largely from Permian and Mesozoic red beds of the southern part of the Sierra Nacimiento.

The following table is a representative section of this member as measured on the southwest escarpment of Santa Ana Mesa, from which the member takes its name. The section is capped by the San Felipe basalt.

Intervals in the upper part of this member may be traced eastward a few miles to the Rio Grande. Although individual beds vary in a short distance, there is little variation eastward between the more distinctive intervals; the general effect seems to be a slight reduction in size and quantity of coarse particles.

Northward, along the west escarpment of Santa Ana Mesa, coarse particles decrease in size and quantities in shorter distances than they do eastward. Also, the entire member apparently thins at the expense of the Chamisa Mesa and Bodega Butte members. Talus on escarpments prevents accurate tracing of beds.

On the escarpment of Santa Ana Mesa about 2 or 3

TABLE IV

GENERALIZED SECTION OF SANTA ANA MEMBER

Lithology (Top)	Thickness (Feet)
Sandstone and Siltstone --- Light pinkish-brown to orange-brown, medium- to thick-bedded, mostly well cemented by $CaCO_3$, argillaceous; scattered pebbles and cobbles in some beds.	200-225
Siltstone and Sandstone --- Pinkish-brown to medium-brown, well cemented by $CaCO_3$; grains range in size from silt to medium sand, and include quartz with minor feldspar, biotite, and muscovite.	60
Sandstone --- Dark reddish-brown, thin-bedded, calcareous, ferruginous, argillaceous, conglomeratic; alternate hard and soft beds; sand grains are mainly sub-angular to sub-rounded and sorting is poor to fair.	107
Sandstone --- Light-brown to medium-brown, medium bedded, poorly consolidated, calcareous, argillaceous, slightly conglomeratic; mostly sub-rounded quartz grains.	94
Conglomerate --- Light to dark reddish-brown; coarse particles are granules and pebbles with scattered cobbles, and rock types include red granite and gneiss, limestone, basalt, quartzite, and weathered tuff. Minor 6-12-inch beds of sandstone are present.	72
Sandstone and Shale --- Thin, hard layers of calcareous, very fine-grained to fine-grained, well-sorted sandstone alternates with calcareous, red clay shale, and with poorly consolidated, conglomeratic sandstone.	37

TABLE IV

GENERALIZED SECTION OF SANTA ANA MEMBER
(continued)

Lithology	Thickness (Feet)
(Top)	
Conglomerate and sandstone --- Reddish-brown, thin- to medium-bedded and poorly consolidated. Sandstone is calcareous and fine-grained to medium-grained.	12
Sandstone --- Tan to medium-brown, with some bleached spots; hard beds cemented by $CaCO_3$ alternate with poorly consolidated beds; fine-grained to medium-grained, argillaceous. Contains a few fragments of tuff and scattered sub-angular granules which are mainly red granite.	33
Sandstone --- Medium-brown to reddish-brown, thin- to medium-bedded, alternatingly consolidated and semi-consolidated, conglomeratic; coarse particles are sub-rounded granules and pebbles of chalcedony, red granite and gneiss, sandstone, quartzite, and basalt; andesite-rhyolite rock types are absent or rare.	69
Conglomerate --- Reddish-brown, thin- to medium-bedded; coarse particles, predominantly pebbles are same as in the 69-foot interval. Contains abundant cobbles and scattered boulders; a sand matrix makes up 60 per cent of the sediments.	18
Sandstone --- Medium-brown to reddish-brown, thin- to medium-bedded; slightly calcareous, poorly consolidated beds alternate with very calcareous, hard beds. Two 1-foot beds of reddish and medium-brown clay shale near middle of interval.	23

TABLE IV

GENERALIZED SECTION OF SANTA ANA MEMBER
(continued)

(Top) Lithology	Thickness (Feet)
Sandstone --- Light-brown to pinkish-brown, medium-bedded, argillaceous; lenses of semi-consolidated sand and silt alternate with beds of hard calcareous sandstone. Numerous possible fossil tracks, trails, and worm burrows.	32
Sandstone --- Reddish-brown, conglomeratic, argillaceous.	20
Conglomerate --- Pebbles and scattered cobbles.	4
Siltstone and Sandstone --- Medium-brown, poorly consolidated; sandstone is very fine-grained. Clay lenses.	21
Sandstone --- Tan to brown, medium- to thick-bedded, poorly consolidated, argillaceous; with minor pebble lenses.	30
Conglomerate and conglomeratic sandstone --- Contains granules, pebbles, and small cobbles of red granite, white silty limestone, quartzite, and chert.	3
Sandstone with clay lenses --- Tan to brown with minor gray beds, medium- to thick-bedded, some aqueous cross-bedding, poorly consolidated, argillaceous, poorly to well sorted; $CaCO_3$ cement in harder beds, and clay with some $CaCO_3$ forms cement for others. Sand grains are very fine-grained to medium-grained, sub-angular quartz, feldspar, and minor dark minerals. Beds stained by clay. A 2-foot bed of clay shale near top of interval is dark reddish-brown, fairly hard, non-calcareous, and silty. Thin pebble lenses near top; pebbles include limestone, pink and red granite, basalt, chert, flint, tuff, and quartzite.	116
Total thickness	950-975

miles south of San Felipe Pueblo, two beds of light-gray silty sandstone are present. They intertongue with the reddish-brown strata of the Santa Ana member, thinning southward and westward. They become thicker to the north, and the intervening beds thin somewhat. Materials composing these sandstones appear to have been derived chiefly from the breakdown of light-colored granite such as is present in the Sandia and Sangre de Cristo Mountains. Perhaps 60 per cent of the grains are clear quartz; biotite and muscovite are abundant; some feldspar is present, and there are numerous tiny grains of magnetite, and some apatite and rutile (?). Grains range in size from coarse silt to medium sand and are mainly angular to sub-angular. These beds probably represent an intertonguing of materials from the eastern side of the Rio Grande depression with the Santa Ana member. Similar intertonguing is probably present, at depth, with the Chamisa Mesa and Bodega Butte members.

Upper Borrego Mesa Basalt

This basalt flow forms most of the cap for Borrego Mesa, as well as for Bodega Butte. It is an olivine-bearing, dark-gray to black, slightly vesicular basalt. Poor columnar jointing is developed, and the rock shows little or none of the chemical weathering present in the lower

sills north of the [illegible], [illegible]
silty sandstone are preserved. These intertongue with the
reddish-brown arkose of the Santa Ana member, [illegible]
southward and westward. Their modern [illegible] of the [illegible],
and the intertonguing beds thin southward. Materials composing
these sandstones appear to have been derived mainly from the
basement of light-colored granitic rock as is present in
the [illegible] and Sangre de Cristo Mountains. Perhaps 50 per
cent of the grains are clear quartz, biotite and muscovite
are abundant, some feldspar is present, and there are [illegible]
tiny grains of magnetite, and some epidote and rutile(?).
Grains range in size from coarse silt to medium sand and
are mainly angular to sub-angular. These beds probably
represent an intertonguing of materials from the eastern side
of the Rio Grande depression with the Santa Ana member.
Similar intertonguing is probably present, at depth, with
the Chamita [illegible] and [illegible] members.

Upper [illegible] Basalt

The small [illegible] north of the [illegible] for the [illegible]
Mesa, as well as for [illegible]. [illegible]
[illegible] to black, [illegible]. Some
[illegible]
[illegible]

basalt.

This flow is also thinner than the lower one, averaging perhaps 15 feet to 40 feet in thickness. Areal extent and variation in thickness are much the same in both flows. The surface underlying this lava shows slight channeling, particularly at Bodega Butte. These channels mark small stream courses present during deposition of the upper, tuffaceous beds of the Bodega Butte member. A possible source of part of this basalt flow is seen at the plug in the southeast one-fourth of the Ojo de San Jose Grant.

San Felipe Basalt

The basalt capping Santa Ana Mesa, herein termed the San Felipe basalt, has been mentioned by several writers. Herrick (1900, p. 3), and Darton, et al. (1916, p. 84) believe that this basalt is of Recent age. Of Santa Ana Mesa, Bryan (1938, p. 208) states that "This complex plateau consists of the stripped surfaces of the interbedded and deformed basalt of Santa Fe age and two flows that are younger than the Santa Fe." Wright (1946, pp. 390-391) shows this basalt as interbedded in the Santa Fe formation.

At least two, and possibly three, main flow units make up most of the San Felipe basalt. Two or more flow units are present in many places, especially in the south-basalt.

This flow also [illegible] the [illegible] ing perhaps 15 feet to 30 feet [illegible] and variation in thickness [illegible]. The surface underlying this lava [illegible] particularly at [illegible] stream courses [illegible] tuffaceous beds of the [illegible] source of part of this basalt flow [illegible] the southeast one-fourth of the [illegible]

San Felipe Basalt

The basalt capping Santa Ana Mesa, [illegible] San Felipe basalt, has been mentioned by several workers. Herrick (1900, p. 3), and [illegible] et al. ([illegible], p. [illegible]) believe that this basalt is of [illegible] age. Of Santa Ana Mesa, Bryan (1919, p. [illegible]) states that "[illegible] consists of the [illegible] surface of the [illegible] formed basalt of Santa Fe age and [illegible] than the Santa Fe." [illegible] basalt [illegible]

[illegible]

[illegible] make up most of the [illegible] which are present [illegible] eastern part of Santa Ana Mesa. The basalt is vesicular to scoriaceous at the contact of flow units. Above the Jemez dam site, sedimentary material a few inches thick can be found between the two main flow units which form the San Felipe basalt there. This sedimentary material is mostly red, even-bedded, silty sandstone.

Two apparently separate flow remnants occur east of the Rio Grande, opposite San Felipe Pueblo, interbedded with Santa Fe sediments. These flows are in direct line with the lava on the mesa above San Felipe. However, as pointed out to the writer by Dr. V. C. Kelley, these remnants have a steeper dip eastward than does the flow on the mesa. Dr. Kelley regards these two beds as intra-Santa Fe flows which are older than the basalt now present on Santa Ana Mesa. Two of the possible solutions to the problems of these outcrops are: (1) that these remnants are older flows from the San Felipe volcanoes and may be represented by basalt which is now buried by later flows on Santa Ana Mesa; (2) that these remnants are one and the same bed and of the same age as the flows on Santa Ana Mesa, and are separated from each other and from Santa Ana Mesa by two north-trending normal faults. North of these two flow remnants and east of the Rio Grande, the San Felipe basalt caps a small butte that is known as Mesa San Felipe. (Plate XIII).

feet it is dense, medium-gray, and contains relatively large green olivine crystals disseminated throughout; the upper 20 feet is vesicular, dark gray, and has less olivine. Basalt in the vicinity of the various cones appears to be slightly coarser grained, the feldspar crystals give it an intergranular texture, and it appears to contain slightly less olivine than that farther from the cones. Also, red to brown scoria covers the slopes of these cones to an undeterminable depth. Columnar jointing is imperfectly developed at edges of the lava. At the small dam in the NE¼ Sec. 29, T 15 N, R 4 E, the top surface of the lava was seen uncovered, and it exhibits hexagonal (columnar) jointing.

The lava seems to have been extruded from cones aligned along two major north-trending fault zones, the minor one near the west edge and the major one east of the center of the mesa. The major cone is the large one in the western part of Santa Rosa de Cubero Grant. There is a small plug, with radiating dikes, intruding highly disturbed strata of the Santa Ana member just south of the mapped area and near the west bank of the Rio Grande (Plates XV and XVI). This is called the "Bernalillo Volcano", and may represent a feeder for part of the San Felipe flow. It is virtually in line with the western system of cones.

The writer believes that the San Felipe basalt is predominantly of upper Santa Fe time. Although no recognizable beds of Santa Fe sediments overlie this basalt on Santa Ana Mesa, the very close relationships of the underlying sediments and the basalt are unmistakable. The basalt lies conformably on the sedimentary beds; this may be seen along the northern and southern escarpments of the mesa, and especially on the escarpments in the vicinity of San Felipe Pueblo. Also, the sedimentary material found between flow units of the basalt near the Jemez dam site is identical with that underlying the flow. Another criterion is that of deformation. The degree to which the basalt has been deformed is comparable to the degree of deformation of the underlying sedimentary beds.

Regional Relations

Geologists mapping the Santa Fe formation north of the Albuquerque-Belen Basin have not attempted to break it down into different members, although they have mentioned the different depositional environments and the materials involved. On the other hand, Bryan and McCann (1937, p. 811) have divided the formation into three members, as mentioned on page 20 of this report. About 8 miles south of San Ysidro the lower member is 1,511 feet thick and decreases south-

[illegible]

greater quantity of water [illegible] [illegible]. [illegible] [illegible] [illegible] [illegible] [illegible] [illegible] [illegible] [illegible] [illegible] [illegible] [illegible] [illegible] [illegible] [illegible] [illegible] [illegible] [illegible] [illegible] [illegible] among [illegible] and [illegible] [illegible] [illegible] of the [illegible] [illegible] [illegible] [illegible] [illegible] [illegible] [illegible] [illegible] [illegible] with that [illegible] for the [illegible]. [illegible] [illegible] [illegible] the degree to which the [illegible] has been formed is correlative to the degree of [illegible] of the underlying sedimentary beds.

Regional Relations

[illegible] the [illegible] of the [illegible] [illegible] [illegible] [illegible] [illegible] [illegible] [illegible] [illegible] [illegible] [illegible] [illegible] [illegible] [illegible] [illegible] [illegible] ward, the middle member is 331 feet thick and increases slightly southward, and the upper member, which cannot be accurately measured, is thin but increases greatly southward (Bryan and McCann, 1937, pp. 816-817). This threefold division of the Santa Fe formation has been traced as far as about 55 miles south of lower Jemez Creek (Wright, 1946, p. 401).

There is a strong similarity between beds of the Lower Gray and Middle Red members of the Ceja del Rio Puerco area and the Chamisa Mesa and Santa Ana members of the southern Jemez region. In both areas the lower member is mainly light-gray to tan sand with resistant calcareous layers and in many places shows concretionary structure upon weathering. Beds are lenticular, often irregularly bedded and crossbedded. Gravel is present only in small scattered lenses. The second member, in both areas, has about the same reddish-brown color, and beds are more silty and clayey than in the lower member. However, near Jemez Creek, the Santa Ana member is highly conglomeratic, but the Middle Red member in the Ceja del Rio Puerco area is only slightly conglomeratic.

The character and distribution of these two members of the Santa Fe formation lead to the belief that these deposits constitute alluvial fan deposits derived from the

ward, the middle member is [illegible]
slightly [illegible], and the upper member, which [illegible]
[illegible]
[illegible] (Thompson and Thomas, 1949; [illegible]). This [illegible]
fold division of the [illegible]
for an about 45 miles [illegible]
[illegible]

There is a strong similarity between [illegible] lower Gray and Middle Red members [illegible] area and the [illegible] and upper region. In both areas the lower member is mainly light-gray to tan sand with resistant calcareous layers and in many places shows concretionary structure upon weathering. Beds are lenticular, often irregularly bedded and cross-bedded. Gravel is present only in small scattered lenses. The second member, in both areas, has about the same reddish-brown color, and beds are more silty and clayey than in the lower member. However, [illegible] areas, the White [illegible] member is slightly conglomeratic, but the Middle Red member in the [illegible] area.

The apparent [illegible] distribution of [illegible] where the [illegible] of the [illegible]
[illegible]

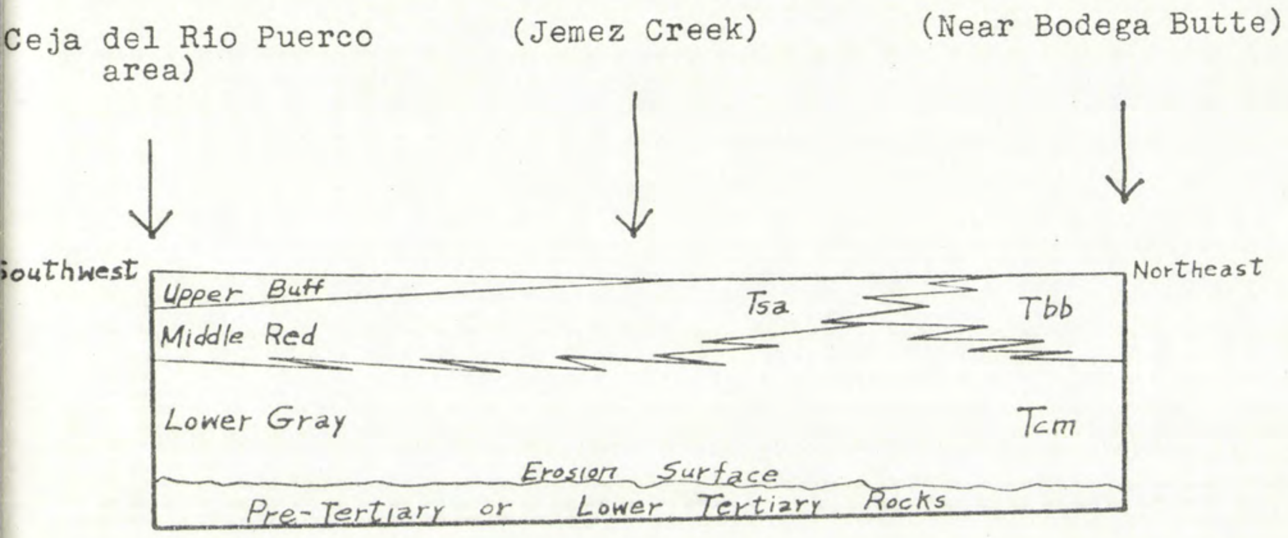


Figure 3. Generalized diagram of probable relationships of the principal members of the Santa Fe formation in the southern Jemez and Ceja del Rio Puerco areas.

Nacimiento Mountains. Bryan and McCann (1937, pp. 814-817) believe that the Mesozoic sandstones furnished most of the materials for these two members, but that the Middle Red (i.e. Santa Ana) member may owe its color to the greater proportion of materials derived from Permian and Triassic red beds. These views are in accordance with those of the writer. It might be added that pebbles of red granite present in both members show that the Pre-Cambrian core of the Nacimiento Mountains was probably exposed in early Santa Fe time.

The presence of basalts and other igneous rocks interbedded with normal sedimentary materials of the Santa Fe formation has been noted by many workers. Smith (1938, pp. 954-955) noted thick basalts and some tuffaceous material in the Santa Fe formation in the Abiquiu area. Emmanuel (1950, p. 8) reports basalts interbedded in late Santa Fe deposits in the Cerros del Rio area. Harrison (1949, p. 164) mapped dikes of Santa Fe age in the Hagan area. Basalt is interbedded in the Santa Fe formation in the lower Rio Puerco area (Wright, 1946, p. 412). Needham (1938, p. 285) has said that "...several andesite flows are found within the Santa Fe formation near Socorro." Hunt (1934, p. 189) remarked that "...the sheet basalts around Mt. Taylor seem to be about the same age as the lower part of the Santa Fe, Tesuque formation). Bryan and McCann (1937, pp. 118-120) believe that the [illegible] sandstone(?) [illegible] the materials for these two members, but that the upper red (i.e. Santa Ana member) may owe its color to the greater proportion of materials derived from Permian and Triassic red beds. These views are in association with those of [illegible]. [illegible], it might be added that [illegible] are present in both members such that the Pre-Cambrian core of the Nacimiento mountains was probably exposed in early Santa Fe time.

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[illegible]

[illegible]

[illegible]

and the Mt. Taylor eruptions are therefore probably middle or late Miocene."

Bryan (1938, p. 209) states that "...water-laid rhyolite ash, containing large fragments of rhyolite and obsidian and one small rhyolite flow, attains a thickness of over 1,000 feet..." on the west side of the Santo Domingo Valley, and "...this body of tuff...is interbedded with... river gravels and basalt flows of Santa Fe age. It records a period of volcanism in the Sierra de los Valles during Pliocene time." This thick body of tuffaceous material is almost undoubtedly correlative with the Bodega Butte member of the Santa Fe formation as described in this report.

In the western part of the area, the Santa Fe formation may be seen resting upon an erosion surface cut on pre-Tertiary rocks. Volcanic material of any kind is rare in the formation here below the upper part of the Chamisa Mesa member. Therefore, if there was pre-Santa Fe volcanism in the Jemez Mountains area, the evidence has been removed or stream drainage was easterly, so that none of the material was deposited in the mapped area. To the east, in the Ojo del Borrego Grant, the lower part of the Bodega Butte member is seen resting on sands of the Chamisa Mesa member much lower in the section than to the west.

The great amounts of volcanic detritus and the basalt

flows of this area interbedded in the Santa Fe formation record very active Chicoma volcanism of probable late Miocene-early Pliocene time. Kelley's statement (1950, p. 15), that "The Chicoma group...appears to have equivalents of the Espinaso formation, the Abiquiu tuff, and the Santa Fe formation", is thus partially substantiated. The lithology, thickness, and stratigraphic relations of the various members of the Santa Fe formation in the southern Jemez area demonstrate that volcanic eruption was going on during much of Santa Fe time and that alluvial fans built up from these volcanics intertongued with and graded into fans composed of normal sediments. Thus, the statement by Denny (1940, p. 75) given on page 16 of this report, that the Popotosa formation is transitional between volcanic activity and Santa Fe basin deposition, seems inadequate and misleading in view of the fact that volcanism and basin-filling have been contemporaneous during Santa Fe time. Sediments regarded as Santa Fe deposits in other parts of the Rio Grande area may be of the same age as the Popotosa formation.

The Upper Buff member of the Santa Fe formation, in the Ceja del Rio Puerco area, contains gravels which include quartzite, chert, agate, and andesite and other volcanic rocks. Source of the volcanic fragments is said to be the Chicoma volcanics of the Jemez Mountains, and this

member is interpreted as being a fan deposit (Bryan and McCann, 1937, pp. 815-816). The writer believes that the southern Jemez area may have been too high by Upper Buff time to receive much sediments, and thus may have held a pediment cut across the Chamisa Mesa, Santa Ana and Bodega Butte members. It is worth noting that the Upper Buff member increases in thickness southward, away from the Jemez region and toward the center of the Albuquerque-Belen basin, (Bryan and McCann, 1937, p. 817). Southward along the Ceja del Rio Puerco the grain size gradually decreases and volcanic pebbles gradually disappear from this member, which may be traced for 70 miles (Wright, 1946, p. 404). Part of the sediments of the Upper Buff member of the Ceja del Rio Puerco area may have been derived from the upper part of the Bodega Butte member of the Borrego Mesa area.

Cerrito Negro Rhyolite(?)

The small butte known as Cerrito Negro, in the San Ysidro Grant 2 miles east of Jemez Creek, has the appearance of a volcanic plug. The rhyolite(?) is found on the top of the butte but is obscured on its slopes by talus, sand, and soil. It does not have the columnar jointing of basalt, but weathers into rounded boulders.

The rock is grayish-brown, hard, and compact rhyolite(?)

porphyry. Numerous phenocrysts of quartz are set in a microgranular groundmass. The phenocrysts average about 2 mm in diameter, although some are as much as 5 mm in diameter. Upon weathering, the resistant phenocrysts stand out to give the rock a very rough surface.

Two other patches of this rhyolite(?), capping small hills, occur about 1½ miles to the southeast. There the rhyolite(?) is underlain by tuff-breccia ranging up to 15 feet in thickness. The tuff-breccia is well-consolidated, creamy-tan in color, and contains crystal as well as tuff fragments. Crystal fragments are mostly clear quartz; many have some very well developed crystal faces and exhibit conchoidal fracture on their broken sides. The matrix is very fine, somewhat felty-textured, and tends to become powdery.

Two references are made to the Cerrito Negro rhyolite(?) in the literature. Renick (1931, p. 113) calls it a "...cap of Tertiary rhyolite on the Cerrito Negro." Darton's map (1928b) shows it as "phy" and, in the legend, it is grouped under "Intrusive rocks, mostly porphyries."

Mesita Alta Gravel

This gravel occurs near the center of the mapped area (Figure 4, Geologic Map), where it caps the Mesita Alta

surface. The greatest thickness was found on the surfaces extending southeastward from near the center of the Ojo del Borrego Grant, where it is 30 feet or more thick. On the isolated hill about one mile east of the center of this grant, the gravel is 14 feet thick.

On the flat mesa surfaces the gravel is generally fairly well consolidated. On the isolated hill, mentioned above, boulders form about 70 per cent of the deposit, which is well cemented and has a matrix of light-brown, slightly calcareous, siliceous sand. Caliche is the important cement on the small mesa tops.

Source of individual fragments is apparent from the lithology: (1) felsite and small amounts of pre-Tertiary sedimentary rocks, from the Jemez Mountains; (2) basalt from lavas of the Borrego Mesa-Bodega Butte areas; (3) pink and red, fine-grained granite, granite gneiss, chalcedony, and felsites eroded from the underlying conglomeratic beds. The first two are generally of boulder or cobble size, whereas the third source furnishes minor amounts of small cobbles and pebbles.

This gravel is of pre-canyon-cutting age, as is the Puye gravel (V. C. Kelley, oral communication). It caps fairly flat surfaces high above Borrego Canyon and adjacent canyons. Owing to the fact that these canyons probably

were cut during late Pleistocene, the gravel must be of early Pleistocene age. Perhaps it represents material derived largely by (1) alpine weathering during the ice ages of the Pleistocene, (2) rapid normal erosion of a rejuvenated Chicoma volcanic area (Emmanuel, 1950, pp. 31-32), or (3) a combination of these two processes.

The Mesita Alta gravel is younger that the San Felipe basalt. This may be seen near the Domingo azimuth mark, where the San Felipe basalt overlies sandstone of the Bodega Butte member of the Santa Fe formation. The basalt is in turn overlain by up to thirty feet of unconsolidated sand, gravel, and soil that is interpreted as being equivalent to the Mesita Alta gravel.

The surface originally covered by the Mesita Alta gravel has been dissected during late Quaternary time. The coarse material subsequently eroded from this gravel now extends as an unconsolidated veneer over the slopes which lead down from the remnants of that surface.

Pediment and Terrace Gravels

Many of the terraces and pediment remnants within a mile or two of Jemez Creek are covered by water-worn, subangular to well-rounded pebbles and cobbles of quartzite, red granite and gneiss, schist, chert, and some limestone were not during this glaciation, the [illegible] [illegible]

[illegible]

plain [illegible] by (2) [illegible] [illegible] [illegible]

[illegible]

by Chilcott [illegible] [illegible] 1950 [illegible]

(3) a combination of these two processes.

The Pestle Hill gravels overlie [illegible] benches. This may be seen near the [illegible] where the [illegible] gravels [illegible] [illegible] of the [illegible] formations. The [illegible] turn overlain by up to thirty feet of [illegible] gravel, and that this is [illegible] of [illegible] the Pestle Hill gravel.

The surface originally covered by the Pestle Hill gravel has been dissected during late Quaternary times. The coarse material subsequently eroded from this gravel has tended to accumulate rather than [illegible] down from the remnants of [illegible] surface.

Pediment and Terrace Deposits

Many of the [illegible] [illegible] [illegible] [illegible] of [illegible] are [illegible] [illegible] mantled by well-rounded pebbles and cobbles [illegible] The gravels [illegible] and rare sandstone. Source of most of this material is the older rocks exposed in the Nacimiento and Jemez Mountains. The softer sandstone and limestone fragments are common in the vicinity of Jemez Pueblo, near the source, but they decrease downstream. The same type of hard, resistant fragments is common along the Rio Grande also, although quartzite is probably more common than granite and gneiss there.

In the low, dissected area southwest and south of Borrego Mesa and west of Santa Ana Mesa, basalt boulders and cobbles make up the pediment and terrace gravels almost exclusively. In this area, coarse fragments of other rock types are rare or absent. The material is derived from basalt flows exposed on Borrego and Santa Ana Mesas. Rareness of other rock types is due to the fact that the Santa Fe formation is almost entirely free of coarse conglomerate in this area.

These gravels are mainly unconsolidated. However, in the vicinity of Jemez Pueblo, a hard, siliceous, pebble-cobble conglomerate unconformably overlies massive gray sand of the Chamisa Mesa member. The matrix is very coarse, sub-angular, arkosic sand and granules. The pebbles and cobbles consist of basaltic to rhyolitic extrusive rocks, brown sandstone, fine-grained epidotized granite gneiss,

chalcedony, tuff, and light-gray limestone. Caliche forms part of the cement. The thickness is very irregular, but 15 feet was the greatest noted. Detritus carried by Jemez Creek from the rocks exposed in the Nacimiento and Jemez Mountains was deposited during cutting of the San Ysidro surface.

Adjacent to the ridge of Permian rocks exposed about 1½ miles northeast of Jemez Pueblo, a conglomeratic, arkosic sandstone has been formed. The sandstone cobbles, as well as the sand, were derived from the nearby Permian rocks.

In the northeastern part of the area, north of Santa Ana Mesa, the gravels are similar in lithology to the Mesita Alta gravel. This is due to the fact that they were derived mainly from that gravel or from the same sources.

Alluvium

Silt, sand, and basalt gravel make up most of the present alluvium in stream courses. Most of this is derived from the Santa Fe formation and from the numerous lava beds of the vicinity.

Along that part of Jemez Creek above the big bend at San Ysidro, a fairly wide river flat has been developed, with sand, silt, clay, and minor gravel lenses. In the stream bed in that area, gravel from the nearby highlands, chalcedony, chert, and [illegible], limestone, [illegible] gravels are present. The thickness [illegible] 1) feet was the greatest [illegible] Creek from the rocks exposed in the Sacramento and [illegible] Mountains was deposited during erosion of the [illegible] surface.

At [illegible] in the valley of [illegible] about 12 miles northeast of [illegible], a conglomeratic, [illegible] sandstone has been formed. The sandstone pebbles, as well as the sand, were derived from the nearby Permian rocks.

In the northeastern part of the area, north of [illegible] and Mesa, the gravels are similar in lithology to the Mesita Alta gravel. This is due to the fact that they were derived mainly from that gravel or from the same sources

Alluvium

Silt, sand, and basalt gravel make up most of the present alluvium in stream courses. Most of this is derived from the Santa Fe formation and from the [illegible] of the vicinity.

Along the part of [illegible] Creek above the [illegible] valley is fairly wide [illegible] with sand, silt, clay, and minor gravel lenses. In the stream [illegible] mainly pebbles and small cobbles, is predominant. Below the big bend, the bed of Jemez Creek becomes more and more sandy as a result of erosion of the soft Chamisa Mesa member. Sand dunes are present along Jemez Creek below Zia Pueblo. One such area occurs on the north bank, in Sec. 36, T 15 N, R 2 E, where winds from the south have driven sand from the stream bed onto the bank; the sand is covering and killing the trees as it accumulates, thus forming the shrub-coppice type of dune. Another locality of dunes occurs in the lee of the south bank of the stream, in Sec. 27, T 14 N, R 3 E. These are transverse dunes, the crests of which shift with each strong wind-storm. The sandy Chamisa Mesa member is the source for most of this dune sand.

The tributaries of Jemez Creek in the area have mainly sandy beds in their lower reaches and become more and more gravelly with basalt detritus toward their heads in the lava-capped mesas. In the lower parts of a few of these streams, gully dissection is in progress. This will be discussed later, in the section on streams.

In the northeastern part of the area, stream beds contain a mixture of sand and gravel. Small sheets of magnetite sands have been observed in this area, as well as along the southern parts of Santa Ana Mesa. The magnetite is probably derived from the local basalts.

[illegible] perhaps not much [illegible], it [illegible]. Near the big bend, the bed of Seneca Creek [illegible] more and more sandy as a result of erosion of the soft [illegible] beds. Sand dunes are present along Seneca Creek below [illegible]. The dunes also occur on the north bank, in sec. [illegible], T 15 N, R 2 E, where winds from the south have driven sand from the stream bed onto the bank; the sand is covering and killing the trees as it accumulates, thus forming the shrub-coppice type of dune. Another locality of dunes occurs in the lee of the south bank of the stream, in sec. [illegible], T 15 N, R 1 E. These are transverse dunes, the crests of which shift with each strong wind-storm. The sandy [illegible] Member is the source for most of this dune sand.

The tributaries of Seneca Creek in the area have mainly sandy beds in their lower reaches and become more and more gravelly with basalt detritus toward their heads in the basalt-capped mesas. In the lower parts of a few of these streams, gully dissection is in progress. This will be discussed later, in the section on streams.

In the northwestern part of the area, stream beds contain abundant sand and gravel. Small amounts of [illegible] have been concentrated in this area, as well as along the southern part of [illegible], for [illegible] [illegible].

Vertical banks of massive-bedded, silty sands in some of the dissected floodplains closely resemble beds in the Santa Fe formation.

STRUCTURE

Regional Structure

The mapped area lies in the Rio Grande fault belt, and it extends from near the western border to within a few miles of the eastern border of that belt. Lee (1907, p. 19) early described the Rio Grande region as consisting "...of a series of block mountains with troughlike depressions intervening between them." Bryan (1938, p. 197) says that the Rio Grande flows "...through a series of structural basins..." which "...forms a structural depression that is referred to...as the Rio Grande depression." Kelley (1951, p. 127) states that the Rio Grande Valley "...is part of a belt of intense fracturing..." and "...that fracturing along the central part of the belt is more intense than along the margins...The structure is complex and in some places it is troughlike and in others trenchlike."

Bryan (1938, p. 200) delimits the Santo Domingo and Albuquerque-Belen Basins, stating that the former extends northward from San Felipe and the latter extends southward

from there. Also, he says that at San Felipe "...the depression as a whole is offset to the west about 20 miles." This offset appearance is due to the way the north end of the Sandia Mountains appear to jut out into the depression and the narrowing of the valley by Santa Ana Mesa. The general stratigraphy of Santa Fe beds which cross the above-stated border of the two basins leads the writer to conclude that the two are closely related in structural history.

The Jemez fault, trending generally northward just west of San Ysidro, separates the present Rio Grande depression from the Nacimiento Mountains. Bryan and McCann (1937, p. 824) estimate the throw of the Jemez fault, west of Lower Vallecito, at 3,000-4,000 feet, with the lower part of the Santa Fe formation lying east of the fault and the Pre-Cambrian lying west of it. "The north-trending Nacimiento-San Pedro range is a narrow but complexly folded and faulted mountain belt that has moved westward above a steep overthrust." (Northrop and Wood, 1946).

The Sandia Mountains provide the boundary for the Rio Grande depression a few miles southeast of the area studied. They are a fault-block range which has been uplifted and tilted to the east; high-angle faults border the range on the west. Paleozoic and Mesozoic rocks at the northwestern end [illegible] Range. Also, [illegible] to the east [illegible] the [illegible] [illegible] in the [illegible] [illegible] [illegible] This [illegible] [illegible] in the [illegible] of the [illegible] Mountains [illegible] and the [illegible] of the [illegible] by [illegible] and [illegible]. The general [illegible] of [illegible] across the [illegible] horizon [illegible] that the [illegible] is [illegible] that the [illegible] closely related to [illegible] history.

The [illegible] fault [illegible] generally [illegible] of San Ysidro, [illegible] the present [illegible] the Nacimiento Mountains. [illegible] (1957, p. [illegible]) [illegible] of the [illegible] of Lower [illegible] at 3,000-4,000 feet, with the lower part of the Santa Fe formation lying east of the fault and the Pre-Cambrian lying west of it. "The north-trending Nacimiento-San Pedro range is a narrow but [illegible] folded and faulted [illegible] that was moved westward above a [illegible]." ([illegible] and [illegible], [illegible]).

The Nacimiento Mountains [illegible] boundary for the [illegible] [illegible] [illegible] [illegible] [illegible] fault [illegible] of the uplift are shown by Darton (1928a, fig. 26, p. 101) to be dipping about 24° toward the mouth of Jemez Creek. These rocks are unconformably overlain by Santa Fe sediments.

Perhaps the entire area studied may be characterized as a series of gently tilted fault blocks. Santa Fe beds are tilted eastward or southeastward at an average of about 5°, although in the eastern part of the area the tilting is more variable. Also, in the eastern part, as recorded in Santa Ana Mesa, low horsts and shallow grabens have been formed. There are indications that the structure of the pre-Santa Fe rocks is much more complex, but it cannot be mapped by surface methods. The pre-Tertiary structure is perhaps similar to that of the Santa Fe formation but with higher and more variable dips.

Several miles to the north, in the Espanola Valley, Denny (1940b, pl. 1 and p. 678) shows that the Santa Fe formation on the east side of the Rio Grande trough has a general westward dip of 5°-10°. As this is also apparently true northwest of the Sandia Mountains (Darton, 1928a, fig. 26, p. 101), the general structure of the Rio Grande depression here seems to be that of a broad and shallow faulted asymmetrical syncline with its east limb the steeper. The axis lies east of the Rio Grande.

Folds

Folds in the pre-Tertiary beds of this region, if present, are obscured by the Santa Fe formation. Some folds may have been formed during the late Laramide deformation.

In the Santa Fe formation itself, folds are rare and obscure. Small-scale drag-folding is to be seen along some faults. The westernmost outcrop of Mancos shale at the south foot of Chamisa Mesa shows slight anticlinal folding due to drag; dip of the strata near the fault is 6° east, and the beds curve gently to a dip of 16° east. Such folds are too small to be mapped on the scale used, but are probably rather common in the area.

A few small folds not directly connected with faults were noted. They appear to have resulted from slight differential compression during movements of the fault blocks. One such fold occurs on the ridge immediately west of Bodega Butte. Others were noted north of Zia Pueblo and also south of Chamisa Mesa.

Faults

High-angle normal faults are numerous over almost the entire area studied, and a few high-angle reverse faults may be present. Most of these have a general north

trend although many vary by a few degrees east or west. Therefore, strike faults are the most common type. A few small transverse fractures are present. At least one rotational fault is represented, and there is some evidence of others.

The magnitude of the throw on the faults is as much as 1,000 feet. Chamisa Mesa is separated from Borrego Mesa by a major fault downthrown to the west. The throw increases southward. The rotational fault on Santa Ana Mesa (Secs. 6, 7, 18, and 19, T 14 N, R 4 E) has a throw of at least 400 feet in places. Probably an average throw for the majority of these faults is 50-100 feet in the Santa Fe formation, and perhaps greater in the older rocks.

In that part of the area not covered by lava flows, faults are found and traced only with difficulty because of, as stated by Bryan (1938, p. 209), "...the lack of distinctive horizons..." as well as the extent of alluvial cover. Presence of faults may be detected by various bits of evidence.

Where sedimentary beds of the Santa Fe formation form the surface rocks, clastic dikes of siliceous sandstone are the most important evidence (Plates VII and VIII). In places, only a short extent of a dike is seen above the alluvium-covered surface, and in some cases it

is impossible to determine the relative movement on the fault. Some dikes show no internal structure while others have an irregular lamination nearly parallel to the fissure walls. The average width of the dikes is about 8-12 inches, but one cemented zone 3 feet in width was observed. Most cannot be traced more than a few hundred feet without interruption.

Materials of the different Santa Fe beds in the vicinity of the dikes are quite similar, and it is therefore impossible to determine the exact source beds of the dike material. The dikes were injected during the late Pliocene-early Pleistocene period of faulting. Since that time, several hundred feet of overlying sediments have been eroded away from these beds. Factors contributing to the frequency of clastic dikes in this area are (1) the fact that these beds were near or below the water table at time of formation of dikes, and (2) the large amounts of relatively loose sand available. Some of the localities in which clastic dikes were observed are as follows: Secs. 28, 29, 32, 33, T 16 N, R 3 E (en echelon fault system); Secs. 21, 28, 29, 33, T 15 N, R 3 E; Sec. 12, T 15 N, R 2 E; southwest part of the Ojo del Borrego Grant.

Another criterion for the recognition of faults is the displacement of strata; this is most easily seen on

Plate VII. Sand dike along fault zone in Chamisa Mesa member. Sec. 28, T 16 N, R 3 E. View north.

Plate VIII. Sand dikes along fault zone in Chamisa Mesa member. Sec. 32, T 16 N, R 3 E. View southeast.

mesa escarpments. The trace of some faults may be observed; for example, from the observation point overlooking the Jemez dam site, a normal fault dipping about 55° east may be seen on the northern escarpment. This and other faults may be traced southward due to faulting of different intervals of the Santa Ana member next to each other. Breaking of lava-flow surfaces by faults is recorded by the conspicuous scarps that are formed (Plate XIV).

The western part of Santa Ana Mesa has been uplifted about 350-400 feet along a high-angle rotational fault. The southern end of this fault has the downthrown side to the east and the northern end is downthrown on the west; however, the general effect has been to uplift the block west of this fault, so that the upthrown side of the northern part dips away from the fault at moderate angles. Santa Ana Mesa, especially the western and southern parts of it, has undergone considerable faulting with attendant warping and tilting. Faults in other sections of the area studied may be as numerous but are obscured by alluvium.

The age of most faults is post-Santa Fe and probably late Pliocene or early Pleistocene. Some pre-Santa Fe faults cut older rocks northeast of Jemez Pueblo. It is possible that the major faults cutting Santa Fe beds are pre-Santa Fe faults which have experienced post-Santa Fe

with angular unconformity, rocks ranging in age from Permian to Cretaceous. These older rocks, in general, dip away from the Nacimiento and Jemez Mountains at higher angles than does the Santa Fe formation. Thus, the structure of the older rocks in at least the western half of this area is complex and is probably associated with the Nacimiento folding and faulting. The character of this structure is not obvious. However, the early Tertiary Nacimiento asymmetrical fold suggested by Kelley (1950, p. 105) may have been bordered by minor north-trending compressional folds which subsequently have been broken by faults.

The structural history of the Rio Grande depression is imperfectly known. Kelley (1951, p. 127) states that the development of the Rio Grande fault belt "...probably began in early Tertiary time when mostly thrust faults and sharp folds were formed." It may thus have originated during the late Laramide orogeny which initiated highlands bordering it on the east and west.

Sometime later, presumably during Miocene time, "...normal faulting of the Basin-and-Range type appears to have been inaugurated..." (Northrop and Wood, 1946). The structural depressions resulting from this faulting and down-warping became the site of deposition of the Santa Fe

Sandia Mountains undoubtedly occurred at this time, and the range may owe much of its present relief to such movement. It seems logical to suspect that the violently explosive Bandelier volcanic activity of the central Jemez region may have accompanied this period of deformation.

Another important period of normal faulting occurred after the development of the Mesita Alta surface, probably during Pleistocene time. This faulting is recorded wherever resistant rocks cover that surface, as is the case in the Mesita Alta area. Parts of the surface were tilted slightly during this faulting. Minor intermittent readjustments along some faults have been made until and during Recent time.

GEOMORPHOLOGY

GENERAL STATEMENT

The type and distribution of geomorphic forms of this region are dependent primarily upon the distribution of rocks of differing resistance and secondarily upon the geologic structure. Resistant basalt flows cap mesas in the northern and eastern parts of the mapped area. Less resistant sedimentary strata of the Santa Fe formation underlie these mesas as well as most of the remainder of the area.

Borrego Mesa on the north and Santa Ana Mesa on the east, with their outlying buttes and small mesas, stand high above most of the dissected portions which are devoid of the protecting hard caps. The two mesas are connected by small, gravel-capped, step-like mesas herein collectively termed the Mesita Alta. The altitude gradually increases from southeast to northwest. The Mesita Alta surface, as hereinafter described, is correlated with the widespread Ortiz erosion surface of Bryan and McCann (1936, p. 156).

Below the steep mesa escarpments, most land forms are of the destructional type. These include remnants of younger erosion surfaces, terraces, badland forms, hogbacks, cuestas, and more obscure forms.

[illegible]

[illegible]

The type and distribution of geomorphic forms in this region are dependent in part upon the distribution of rocks of differing resistance and particularly upon the geologic structure. Resistant basalt [illegible] in the northern and western parts of the map area, and resistant sedimentary strata of the [illegible] formation underlie these areas as well as most of the remainder of the area.

[illegible] on the north and [illegible] on the west, with their outlying buttes and small mesas, stand high above most of the dissected pediments which are devoid of the protecting hard caps. The two mesas are connected by small, gravel-capped, mesa-like areas herein collectively termed the [illegible]. The altitude [illegible] decreases from southeast to northwest. The [illegible] surface, as previously described, is correlated with [illegible] surface of [illegible] and [illegible]

[illegible]

[illegible]

[illegible] surfaces, terraces, [illegible]

Distribution of the geomorphic forms is shown on the geomorphic map (Figure 5). These forms are described in the following sections of this paper. Escarpments and slopes, although separately mapped in certain cases, are discussed with the surfaces which lie above them.

Since the beginning of dissection of the Ortiz surface, erosion has continued, with slight interruptions during which only minor surfaces have been cut. Therefore, in the mapped area, the stage attained in the cycle of erosion is determined by the degree of removal of the Ortiz surface. Borrego Mesa and Santa Ana Mesa are mainly undissected and are thus in a youthful stage. The area north of Santa Ana Mesa retains remnants of the Ortiz surface but has attained a maximum relief, and it is therefore in early maturity. The southwestern part of the area, which has no remnants of the Ortiz surface but has high relief in places, is in the late mature stage.

GEOMORPHIC FORMS

Borrego Mesa

Borrego Mesa is a high tableland that stretches southward from the southern margin of the volcanic Jemez Mountains. Less than half of the mesa lies in the mapped

area. As described by Renick (1931, p. 37), Borrego Mesa is roughly tongue-shaped in plan, trending about N 25° E.

The surface slopes gently to the southeast and has an average altitude of 7,400 feet. There is an abrupt descent of 1,200-1,400 feet from the top of the mesa to the lower dissected area (Plate XIX). Plate XIII shows the more gradual descent to the southeast, into the Bodega Butte-Mesita Alta area and to Santa Ana Mesa. To the northeast, outside the mapped area, the surface of Borrego Mesa merges with the high domal forms of the acidic lavas of the Bear Springs area.

The surface of the mesa is flat to gently rolling. Low fault scarps occur locally, and deep canyons have been cut along a few faults. The escarpments of the mesa are fairly steep, and they are thinly armored by talus from the capping basalts except for a few localities where gullies have formed.

The southern part of Borrego Mesa is underlain by gently dipping beds of the Santa Fe formation. The Chamisa Mesa member forms the base of the escarpments in most places; the upper part of escarpments is formed by the Lower Borrego Mesa basalt and the Bodega Butte member, and the mesa is capped mainly by the Upper Borrego Mesa basalt. Chamisa Mesa, a segment of Borrego Mesa, is capped by the

Lower Borrego Mesa basalt due to the complete removal, by erosion, of the overlying beds. On the upper escarpment of Borrego Mesa, the two lava beds hold vertical cliffs. The intervening beds of the Bodega Butte member are easily eroded and thus form a slope of 25° - 30°, approximately the angle of repose (Plate X).

Segments have been separated from the main mass, by faulting and by erosion, to form small mesas and buttes. Chamisa Mesa has been partially cut off by down-faulting and is tilted eastward at a higher angle than has the main part of Borrego Mesa. This relationship is very conspicuous from the south and southeast.

Mesita Alta Surface

Small, flat-topped, gravel-capped mesas northwest of Santa Ana Mesa and southeast of Borrego Mesa have herein been collectively termed the Mesita Alta, and the erosion surface (pediment) represented is termed the Mesita Alta surface.

The erosion surface ranges in altitude from 6,000 to 6,600 feet. In general, the altitude increases from southeast to northwest, partly due to faulting, and partly due to original slope of the surface. The easternmost remnants slope gently toward the Rio Grande and would reach it at a

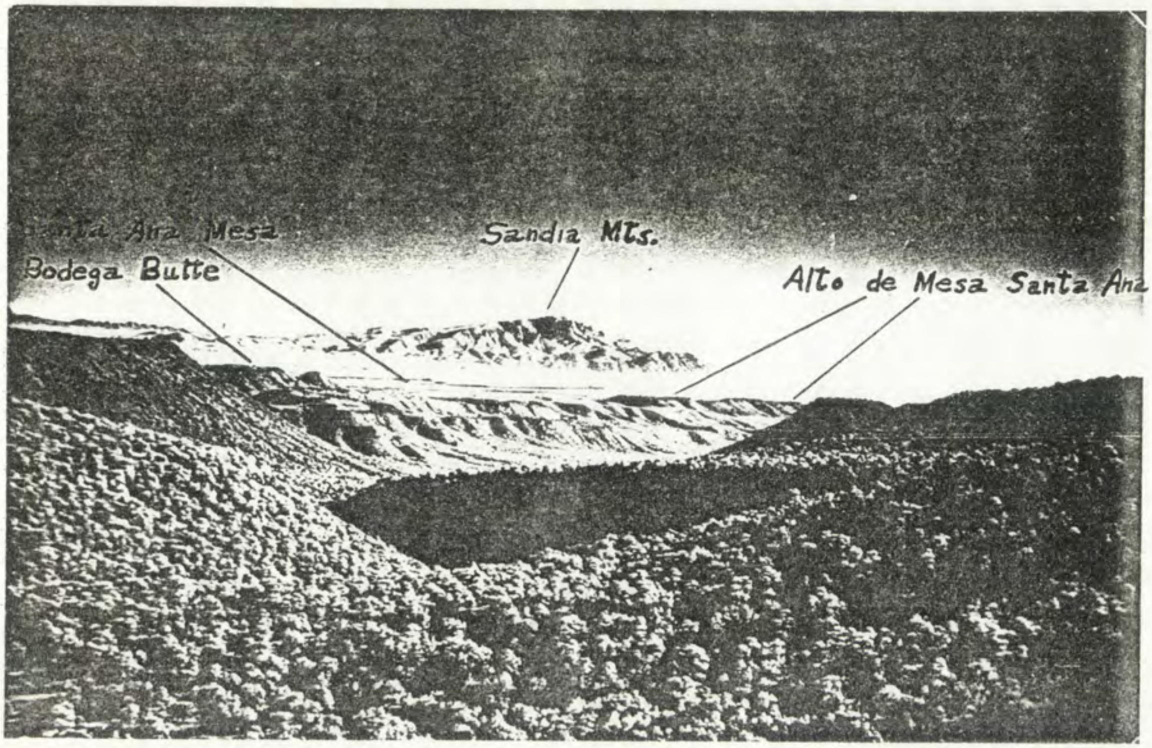

Plate IX. Southern part of Borrego Mesa and the area southeast of it.

level about 500 feet above its present altitude. To the northeast, remnants of this surface may be seen for several miles as accordant summits of ridges in the area known as Cochiti Mesa (Figure 1). To the southeast, the Mesita Alta surface appears to merge with the Santa Ana Mesa surface. This is due to the fact that sediments from the Mesita Alta area have been deposited over the northwestern edge of the San Felipe basalt, completely masking it. At the edge of Santa Ana Mesa, near the Domingo Azimuth mark, Mesita Alta material may be seen overlying but not underlying the basalt.

Most of the remnants of the Mesita Alta surface are flat and almost level but a few are tilted slightly, especially near Bodega Butte. The slopes descending from the surfaces are in general smooth and often fairly steep. In places, oversteepening has caused the formation of badlands, especially near the base of the slopes.

The Mesita Alta gravel, partly cemented and ranging in thickness from about 5 to 30 feet, caps the small mesas. A thin soil of caliche and windblown silt and sand has formed over this gravel. The porous gravel forms a thin, unconsolidated, protective veneer over the slopes descending from the mesa surfaces except where gullying has caused its removal. The Bodega Butte member of the Santa Fe formation unconformably underlies the Mesita Alta gravel in this area.

Santa Ana Mesa

Santa Ana Mesa is a broad, basalt-capped tableland. It lies north of Jemez Creek and west of the Rio Grande, but a few small segments of the original mesa lie on the opposite side of these streams.

The mesa covers about 85 square miles, and in plan it is roughly sub-circular in shape. Its profile varies, depending on the viewpoint. From the west and northwest its western part, the Alto de Mesa Santa Ana, has the appearance of a moderately high mesa with a relatively flat surface (Plate XVIII). From several miles to the southeast the eastern part of the mesa appears only slightly higher than remnants of erosion surfaces and terraces, but the largest of the cones on the mesa is conspicuous from this direction. As seen from some distance to the east or northeast the mesa itself appears rather low, but the large cones known as the "San Felipe Volcanoes" are conspicuous.

Santa Ana Mesa has an average altitude about 1,000 feet lower than Borrego Mesa. Steep escarpments lead down 500-1,000 feet to the dissected area on the west and south. On the east, however, the mesa's surface rises only about 300-500 feet above the Rio Grande Valley. To the north, Borrego Canyon, which is 300-600 feet deep, separates the mesa from a badland area.

The surface of the mesa is, in general, broadly undulating. The principal features modifying this aspect are (1) fault scarps, and (2) volcanic cones. The fault scarps, in almost all cases, trend generally north. They are, on the average, about 40-150 feet high and are covered by talus from the basalt cap. Landslide blocks are found on some scarps. The western part of Santa Ana Mesa has been relatively upfaulted and upwarped along a rotational fault to about 400 feet higher than the central part.

Dominating the mesa surface are the San Felipe Volcanoes, a system of cones lying, in north-south alignment, about a mile east of the center of the mesa. These cones may be termed "embryonic domes" for they are "...lava cones which have piled themselves up to very moderate heights over the sources of outflow of great sheet flows..." (Cotton, 1944, p. 75). Craters of some are imperfectly preserved, but most have had their craters destroyed by erosion. Adventive cones and a few small spatter cones are present on the slopes of the larger cones.

Small conelike features, with a rough north-south alignment, are present on the western part of Santa Ana Mesa and apparently represent a second system of cones. These are rather low and obscure, and are overshadowed by the uplifted western part of the mesa. The general character

The [illegible]

[illegible]

[illegible] and (2) volcanic [illegible]. The latter

[illegible] generally [illegible]. They

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on the summit. The western half of [illegible]

[illegible]

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canoes, a system of craters lying, in [illegible] alignment,
about a mile east of the center of [illegible]. These cones
may be termed "Laki-type [illegible] craters" for they are [illegible] lava cones
which have piled themselves up to very moderate heights
over the sources of outflow of great sheet flows....
([illegible], [illegible], p. 75). Craters of some are [illegible]
preserved, but most have had their craters destroyed or
[illegible]. Attractive cones with a few small spatter mounds are
present on the slopes of the [illegible] ridge.

[illegible] with a [illegible]

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Plate XI. Surface of Santa Ana Mesa; part of San Felipe Volcanoes in background. Basalt debris in foreground is from a fault scarp. View northeast from Sec. 18, T 14 N, R 2 E.

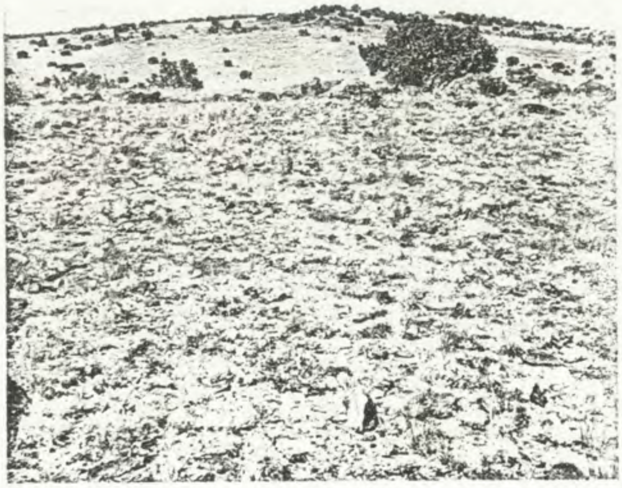


Plate XII. One of the small cones of the San Felipe Volcanoes. Seen from a similar cone a short distance to the south; foreground is part of the flat central area of latter cone, and a section of the broken peripheral wall is barely noticeable one-third of the way from top of plate. View north.

of these low cones is the same as that of some of the less conspicuous ones of the San Felipe Volcanoes (Figure 4).

Strata underlying Santa Ana Mesa to the base of its escarpment include the Bodega Butte member of the Santa Fe formation to the north and the Santa Ana member to the south. The San Felipe basalt is the cap-rock for the mesa. This basalt is covered by a thin veneer of soil. However, the northwestern and western parts of the mesa have a thickness of up to at least 30 feet of soil, sand and gravel, which is partly equivalent to the Mesita Alta gravel. Boulders and cobbles of basalt are strewn over the surface in places. Upper parts of the cones are covered by reddish to brown scoriaceous to vesicular basalt fragments. The escarpments of the mesa are similar to those of Borrego Mesa except that gullied landslide scars are more numerous. Basalt talus covers the remainder of the escarpments. In places this talus is slightly cemented by caliche and has a matrix of sand and silt.

Beds underlying the mesa have very gentle dips. However, in all probability, the strata immediately adjacent to the volcanic vents are highly disturbed as can be seen at the Bernalillo Volcano. Faults, with a general north trend, break the strata and are recorded by scarps at the surface. Fault blocks, including horsts and grabens, have

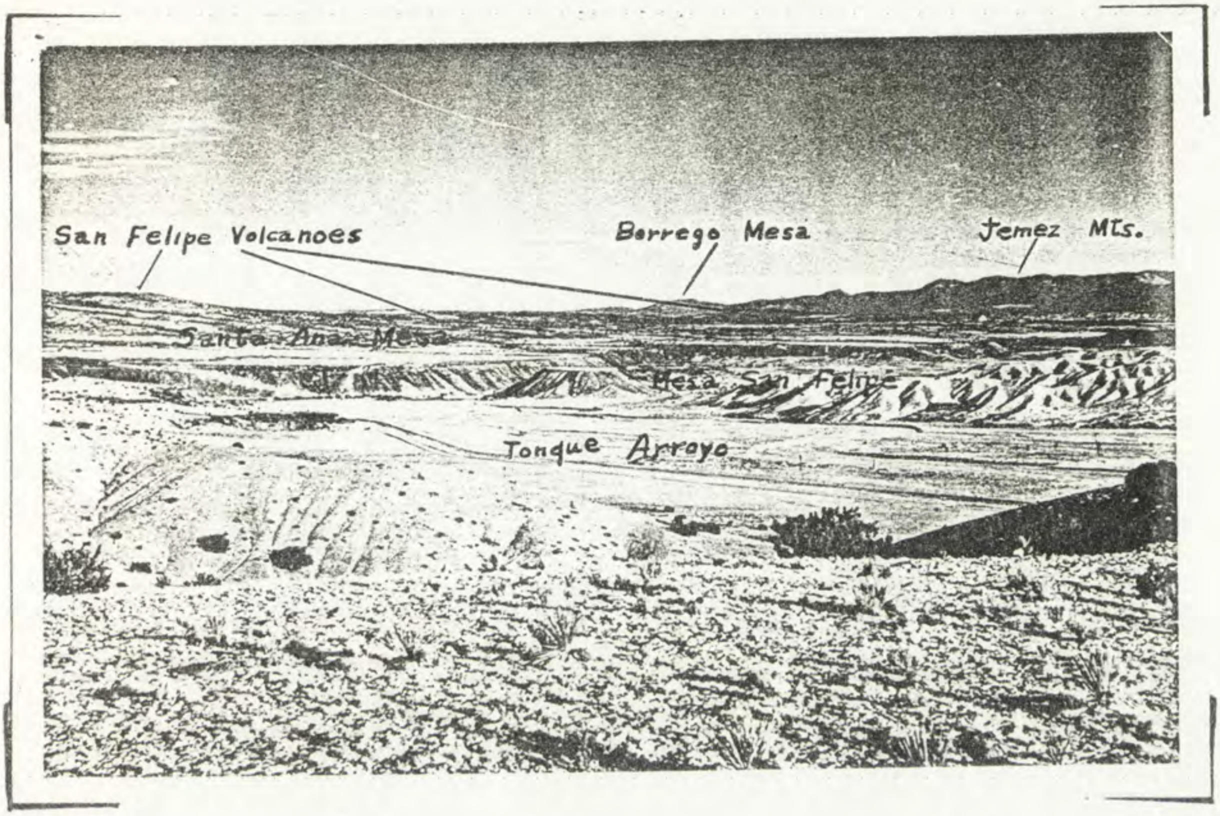


Plate XIII. Northeastern part of Santa Ana Mesa. Note small Mesa San Felipe and its possible slight displacement relative to Santa Ana Mesa. View northwest from Sec. 28, T 14 N, R 5 E.

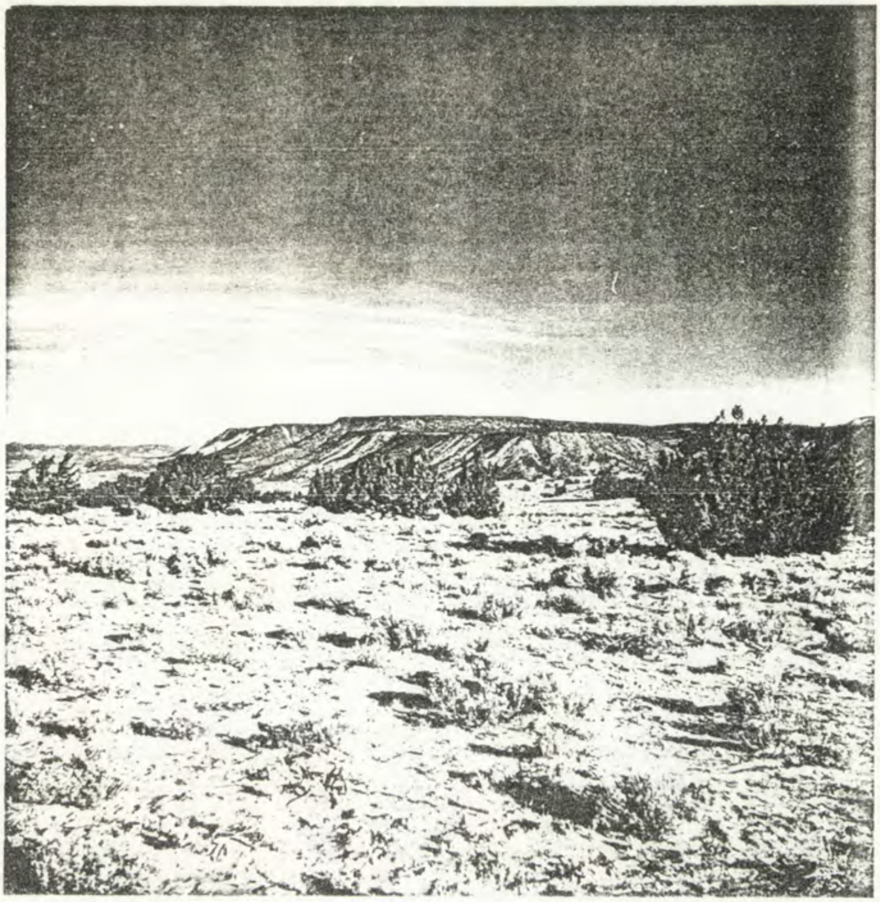


Plate XIV. Faulted southern end of Santa Ana Mesa as seen from small mesa south of lower Jemez Creek. View northwest.

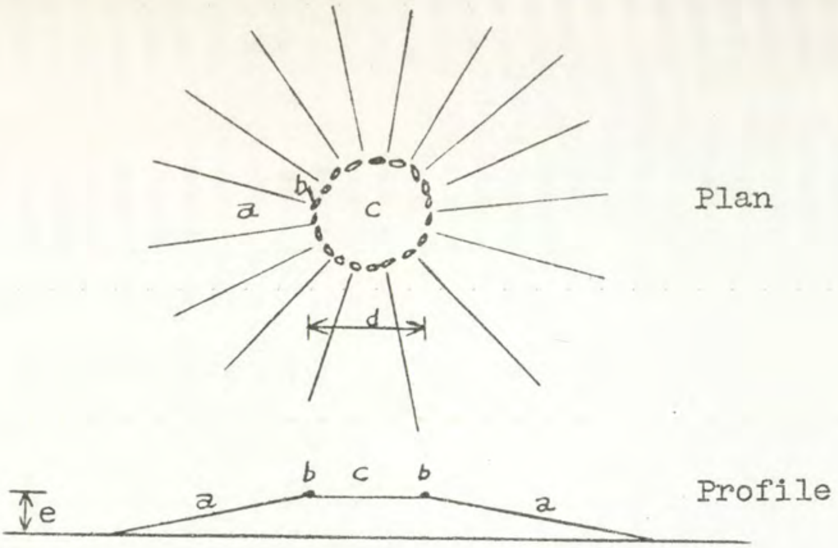


Figure 6. Diagram of low cones on Santa Ana Mesa.

a. Slopes about 8° and is mantled largely by cobble-size, reddish to brown, scoriaceous basalt and a few large fragments of dense basalt.

b. Broken and incomplete low peripheral wall of fragments of dense, hard, intergranular-textured, olivine-bearing, slightly reddish, medium-gray basalt; roughly circular in plan.

c. Flat central area; covered mainly by cobble-size, red-brown, scoriaceous to vesicular basalt, but with a few large fragments of dense gray basalt; possibly underlain by agglomerate.

d. Diameter about 50-180 feet.

e. Height typically about 20-30 feet.

Figure 7. General east-west profile of Santa Ana Mesa.

been produced, especially in the western and central parts of the mesa. Their scarcity on the eastern part of the mesa is probably due to some post-deformational volcanism.

Zia Terraces

In the dissected area south and southwest of Borrego Mesa, the most prominent topographic forms are a few lines of hills and ridges which may be termed "gravel-protected terraces" (Plates XVII and XVIII). They rise from a few feet to 300 feet or more above the surrounding area. These hills and ridges range from flat-topped terraces to those with rounded summits. The flat-topped terraces are most common at the south, near Zia, and the ridges with rounded summits are most common at the north. In plan they are mostly elongate south-southwestward, and in profile they slope gently in this same direction.

These forms are more or less thoroughly, though thinly, covered by coarse detritus which is almost entirely an unconsolidated gravel of sub-angular to rounded basalt cobbles and boulders. Other rock types are rare to absent except near Jemez Creek, where sub-rounded to rounded cobbles and pebbles of red granite, gneiss, schist, quartzite, and some sedimentary rocks are also present. Caliche and windblown materials are mixed in with the gravel in

Plate XVII. One of the Zia terraces, covered by basalt detritus. View northwest from Sec. 33, T 16 N, R 3 E.

Plate XVIII. Dissected area south of Borrego Mesa. Note general absence of outcrops and the cover of aeolian sand. View south from Sec. 28, T 16 N, R 3 E.

most areas, but in some places sandstone of the Chamisa Mesa member of the Santa Fe formation may be seen immediately underlying the coarse debris.

These terraces mark the approximate courses of former streams of relatively high gradient, and the coarse gravel is channel gravel. This view is supported by the following facts: (1) the coarse basalt gravel is more or less rounded and shows some sorting; (2) evidence indicates that this basaltic material is not the remains of lava flows in place; (3) the gravel is concentrated on these hills and ridges, and coarse fragments in the low surrounding areas are rare and scattered; and (4) the ridges occur as long lines which strongly resemble stream courses. Source of the gravel was Borrego Mesa, and the controlling major stream was the ancestral Jemez Creek. The gradient of these streams varied from about 225 feet per mile just below Borrego Mesa to about 150 feet per mile near Jemez Creek.

San Ysidro Surface

In the area south and west of Borrego Mesa are found remnants of a low, incompletely developed, late Quaternary erosion surface which slopes gently toward Jemez Creek and is herein termed the San Ysidro surface (Plate XIX). Altitudes along the surface decrease from

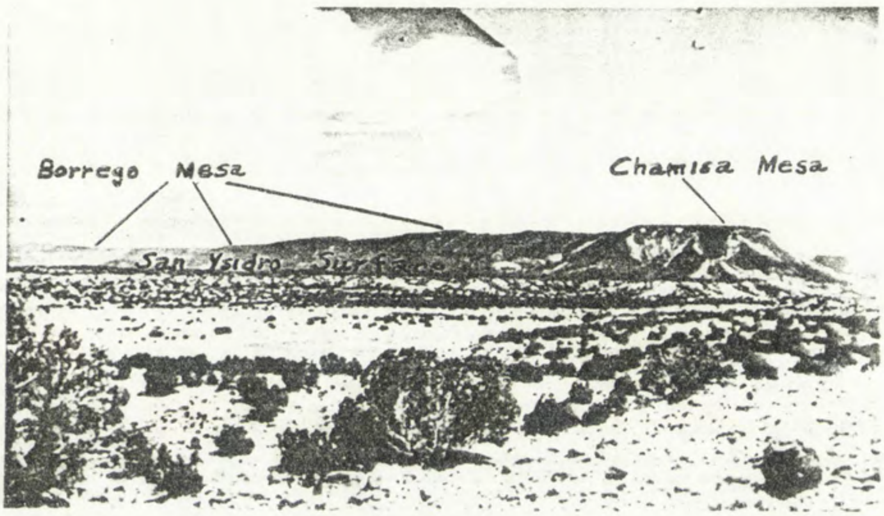


Plate XIX. Part of the San Ysidro surface and the high western escarpment of Chamisa and Borrego Mesas. View northeast from Sec. 27, T 16 N, R 2 E.

about 6,100 feet west of Bodega Butte to 5,650 feet near Jemez Creek. In general, the average grade of the surface is about 60 feet per mile; but it is about 100 feet per mile near Borrego Mesa.

The surface is fairly smooth to slightly rolling. The Zia terraces and, locally, hogbacks and cuestas rise above it and were preserved due to their superior resistance to erosion. Most of the surface is mantled with soil and wind-blown silt and sand, but conglomerate underlies this material near Jemez Pueblo. Near Jemez Creek the surface is covered by gravel consisting of pebbles and cobbles of granite, gneiss, quartzite, chert, limestone, and other rock types derived from the older rocks exposed to the north. Low piles of pumiceous volcanic dust are present in many places. The surface truncates the deformed beds of the Chamisa Mesa member of the Santa Fe formation and, near Vallecito Creek, it truncates older rocks.

The scattered remnants of this surface represent an erosion surface which was imperfectly graded to Jemez Creek when it flowed at an elevation about 100 feet higher than at present. The altitude of these remnants indicates that it may be correlative with the Segundo Alto surface (Bryan, 1938, p. 217) of the Rio Grande Valley. In this connection, it is interesting to note that Bryan (op. cit., pp. 217-218)

correlates the Pena Blanca surface (Santo Domingo Valley) with the Segundo Alto. Also, he states that bodies of pumice have been found on surfaces of the Pena Blanca stage near Cochiti. This pumice may possibly be of the same age as that found on remnants of the San Ysidro surface by the writer. Both occurrences are approximately equidistant from Cerro Redondo, which is the source given by Bryan for the pumice in the Santo Domingo Valley.

Hogbacks and Cuestas

Hogbacks and cuestas are rare in this area due to the fact that few beds are sufficiently resistant to erosion to maintain such forms. The most prominent ones lie west and south of Bodega Butte. The beds which form these hogbacks are composed of resistant, siliceous, fine-grained to medium-grained sandstone of the Chamisa Mesa member of the Santa Fe formation. These beds dip eastward at 6°-25° and trend slightly east of north.

Two small hogbacks capped by hard, white limestone of the Chamisa Mesa member lie about 2 miles southeast of Chamisa Mesa. These ridges trend northwest and their strata dip about 22° southwest. They were produced by step-faulting and tilting.

Two prominent ridges lying 1-2 miles northeast of

formation of badlands with steep to vertical banks and deep gullies. Large streams near the base of the high topographic forms cause oversteepening of slopes and subsequent formation of badlands.

Rolling Transitional Surfaces

In the southeastern part of the area there are surfaces which are transitional between the San Ysidro surface or badlands and the Recent terraces or stream courses. These surfaces have a gently rolling and sloping aspect. Small sand hills and shallow gullies are the principal forms present. Few, if any, outcrops are to be found in such areas because soil and wind-blown sand form a mantle.

These surfaces are not quite in grade with the present streams, although nearly so. However, the present accelerated gully erosion, if continued, will form badlands at the expense of these surfaces.

Recent Terraces

Recent terraces occur along the main streams and some of their tributaries. They are present from the lower to the higher parts of the area. Their height above the present stream courses ranges from a few feet up to as much as 50 feet. Along some streams, terraces of different

heights are found on the opposite banks or along the same bank.

These terraces commonly occur as fairly flat and level benches cut on the Santa Fe or older formations at the base of higher topographic forms. Others are formed on Recent floodplain alluvium. Some terraces are protected by a veneer of gravel.

Formation of terraces of different heights along a given stream is due to the lateral cutting of the stream during lowering of baselevel. Lower Jemez Creek is an example of such a stream. Terraces have been formed on late valley fill due to the present widespread arroyo cutting. These terraces are being converted to badlands and destroyed by this same process. Destruction of other types of terraces is brought about by undercutting by the stream along which they were formed.

Streams

The Rio Grande is the master stream of this region, flowing almost due south from Colorado through the length of New Mexico. It follows a zone of faulting and may thus be classed as a subsequent stream in a regional sense. Near San Felipe the altitude of the river is 5,100 feet. Its gradient is 6 feet per mile between Cochiti and San Felipe

and decreases to 5 feet per mile near Bernalillo. The floodplain is rather wide and flat and is being aggraded by the meandering river. Bryan (1938, p. 218) states that the channel and floodplain have been rising in the past few years due to deposition. Happ (1948, p. 1192) says that, in the Middle Rio Grande Valley, the floodway is being aggraded about 0.08 feet per year or one foot in twelve years.

Approximately two-thirds of the area studied is drained by Jemez Creek and its tributaries. This stream may be considered perennial from the vicinity of Zia Pueblo headward and intermittent from Zia to its mouth at the Rio Grande. Lower Jemez Creek has a very wide sandy course, with a gradient of 14 to 18 feet per mile from Jemez Pueblo to the mouth. Happ (1948, p. 1211) estimates that it contributes 12 per cent (or 1440 acre-feet per year) of the sediment to the Rio Grande in the Middle Rio Grande Valley. The U. S. Corps of Engineers is now engaged in building a dam at the entrance to the narrow canyon on Jemez Creek (SW ¼ Sec. 32, T 14 N, R 4 E). The purposes of this dam are (1) flood control and (2) sediment storage. Most of the reservoir's 160,000 acre-feet capacity is to be used for sediment storage; impounded flood waters are to be released into the Rio Grande slowly.

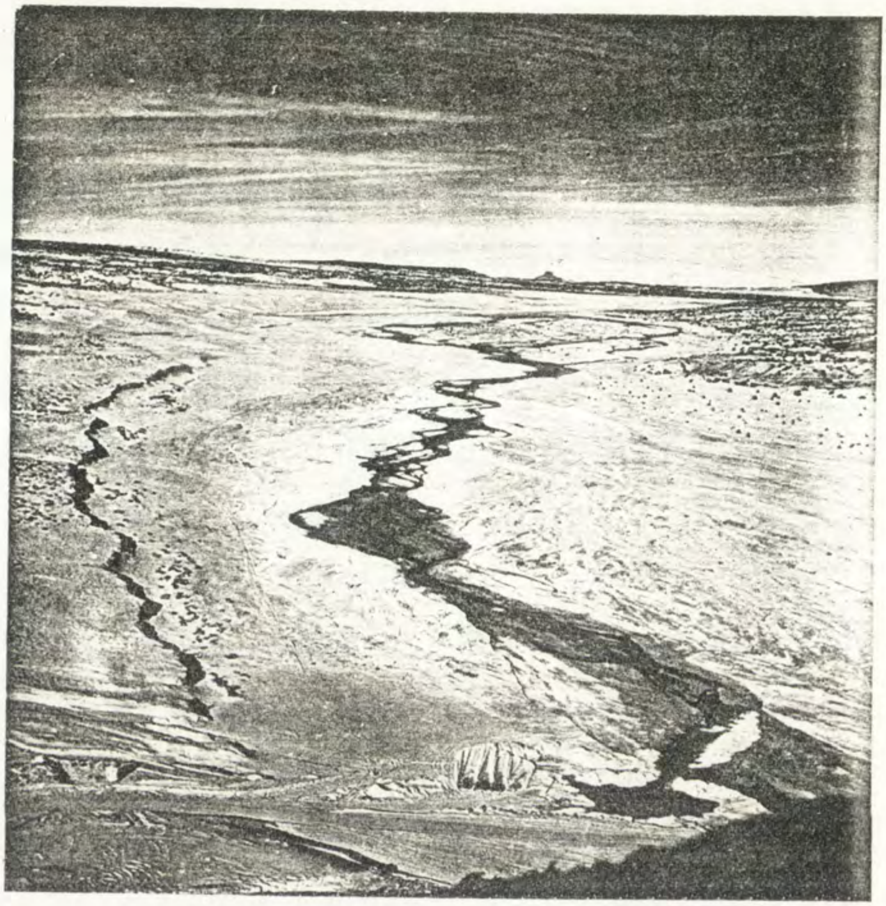


Plate XX. Lower Jemez Creek as seen from Jemez dam observation point. View northwest from Sec. 5, T 13 N, R 4 E.

The deeply incised Borrego Canyon stream is adjusted to the structure only in its upper course. Its gradient, from Borrego Spring to near the Domingo azimuth mark, is 82 feet per mile.

On Santa Ana Mesa the master streams are subsequent streams flowing at the base of fault scarps. Their gradients are too gentle, except at the edges of the mesa, to allow them to cut rapidly into the resistant and porous basalt. They are joined by small consequent streams, as well as by a few small subsequent streams which follow minor transverse fractures. The drainage of the eastern part of this mesa is radial consequent from the large cones. Jemez Creek receives part of the mesa's drainage, and that on the east goes directly into the Rio Grande. No important streams flow off the north or west sides of the mesa.

GEOMORPHIC HISTORY

Santa Fe Time

Throughout Santa Fe time this section of the Rio Grande depression was part of a depositional basin. Coalescing alluvial fans were built out from the highlands surrounding the basin, and playas occupied much of the central areas of the basin. Ridges of hard pre-Tertiary rocks, rising above the erosion surface upon which the Santa Fe formation has been deposited, were probably the principal relief features in the mapped area. Locally, volcanic cones may have been present.

The relief in the mapped area remained low, and the surface was one of aggradation during Santa Fe time. In the latter half of Santa Fe time, basalt flows and other volcanic activity occurred in the Jemez Mountains. Basalt flowed over deposits of the coalescing alluvial fans at the southern edge of the Jemez Mountains, and in the northern part of the mapped area. The basalt-covered area never attained topographic prominence until later, however, and sedimentary material was deposited over the basalt.

The Albuquerque-Belen basin was an enclosed basin during much of early Santa Fe time. Thick playa deposits of Middle Red time occur in this basin (Wright, 1946, p. 404).

During Ortiz time, the relief of the surface of the mapped area was much lower than it is today. The Borrego Mesa-Bodega Butte area was one of low mesas and buttes. These formed the south-facing front of the Jemez highland region above the Ortiz surface. In the western part of the area, the erosion surface sloped gently southward away from a moderately high Borrego Mesa. It was partly drained by the ancestral Jemez Creek, which then had a more southerly course than at present. In the eastern part, the cones of the San Felipe flows were the dominating topographic features.

Early Post-Ortiz Time

After development of the Ortiz surface, another period of faulting in the Jemez region resulted in the separation and tilting of segments of the Mesita Alta surface. The Alto de Mesa Santa Ana was uplifted slightly for the second time. This deformation and/or other events led to the rapid lowering of the regional baselevel of the Rio Grande; this lowering ultimately totaled about 300 feet.

The ancestral Jemez Creek was unable to cut down as rapidly as the Rio Grande. Consequently, a stream flowing southeastward across the southern edge of the San Felipe basalt succeeded in cutting a deep canyon, and it captured

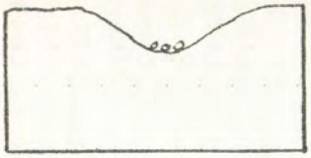
has been very slow. This has resulted in the inversion of relief; Figure 6 outlines the process involved. The Zia terraces, as herein designated, are the result of this process. They are now the dominating topographic features in the western part of the mapped area south of Chamisa Mesa.

Segundo Alto Time

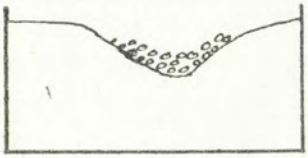
The baselevel of the Rio Grande, and therefore of Jemez Creek, was finally stabilized at a level about 300 feet below that of Ortiz time. A lower and less extensive erosion surface, the Segundo Alto, was cut along the Rio Grande. The San Ysidro surfáce, as herein designated, is tentatively correlated with the Segundo Alto surface. The Zia terraces stood as lines of ridges and hills above the undulating San Ysidro surface.

Recent Time

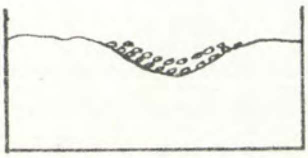
Since the development of the San Ysidro surface, the baselevel of the Rio Grande and of its tributaries in this part of the Rio Grande depression has been lowered and stabilized several times. Consequently, minor terraces at various levels have been formed along most streams. Many stream courses show signs of Recent cut and fill.



a. Deep channel cut by stream.

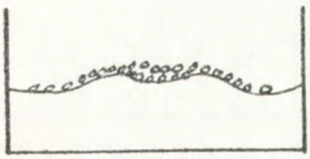


b. Main stream channel receives abundant basaltic detritus from Borrego Mesa.

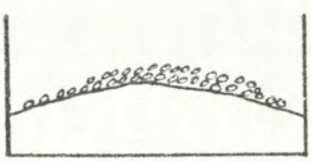


c. Erosion of inter-stream areas is accelerated relative to main channels.

d. New streams begin on soft sedimentary rocks between main streams.



e. New streams are able to cut down more rapidly than the gravel-protected channels.



f. Erosion has proceeded below level of old channels, and undercutting allows gravel to migrate laterally to cover slopes down to lower levels.

Figure 8. Diagrams showing mode of formation of Zia terraces.

Bryan (1925, p. 339) reports that Gregory named the present period of degradation the "Recent epicycle of erosion". Badlands have resulted from this continuing degradation, especially at or near the base of the more prominent topographic forms.

ECONOMIC GEOLOGY

WATER RESOURCES

Three streams, surrounding the mapped area on three sides, are the only perennial streams. They are Vallecito Creek on the northwest, Jemez Creek on the west and south, and the Rio Grande on the east.

Vallecito Creek has its source in the high area just south of the center of the complex Jemez volcanics. Permeable basalts and tuffs are good aquifers in that area. Springs furnish most of the flow for this and other streams during the drier months of the year. Springs feeding this creek are mainly of two types: (1) those at the contact of permeable volcanic rocks and underlying relatively impermeable sedimentary or volcanic rocks; (2) those formed along fault zones. Vallecito Creek enters Jemez Creek immediately north of Jemez Pueblo.

Jemez Creek is the master stream of much of the Jemez region, with a drainage area of 1,038 square miles and a length of approximately 65 miles. It begins in the Valle Grande. Other perennial streams which begin in the high central Jemez region are tributaries to it. Analyses have been made of water in and along Jemez Creek under various conditions by different persons. The dissolved cattle overgrazing [illegible] quality of the bodies of [illegible] water [illegible] (Clarke, 1924, p. 411). The amount of dissolved salts in Jemez Creek is increased as great as in the stream's upper portion at it is below the mouth of the Rio Salado at San Ysidro. This is due to the fact that the water drains areas of the Chinle Formation outcrops along the course of the Rio Salado. This effect may be noted in Table 4 (page [illegible]). Renick ascribed the high amount of chlorine in water along Jemez Creek and Salado (1931, p. 60) that "...it is probably derived from the Permian and Triassic formations over which Jemez Creek flows."

Mineral content of water in the lower course of Jemez Creek is increased by three major factors: (1) heavy irrigation along upper Jemez Creek; (2) heavy rainfall on the Rio Salado watershed, and (3) addition of water from the mineral springs which occur along the fault zone west of the Nacimiento Mountains. The high concentration of the Rio Salado's water is noticed, at times, as far as the Rio Grande. Clarke (1924, p. 77) states that the [illegible] general area, mainly at the foot of the high mesas and in fault zones. Just below Chamisa Mesa, in the center of Sec. 30, T 16 N, R 3 E, a small contact spring occurs where a bed of quartzite in the Chamisa Mesa member outcrops in an arroyo. In the south-central part of the next section east (Sec. 29), a permanent though small spring, Ojo Chamisa, occurs along a fault zone. These are the only springs noted in the entire area south and southwest of Borrego Mesa to Jemez Creek.

Reagan (1903, p. 99) reported that "Indian Springs" extend in an east-west direction "...in a narrow belt of land about a mile..." north of San Ysidro, and suggested that they are along a fault there. He described these springs as alkaline, but not depositing springs, and said that they are cold in the west but increase in temperature to the east, and that those east of Jemez Creek have a temperature of about 120° F. However, Reagan noted that they were continually being covered by debris from arroyos. The location mentioned may be near the southern boundary of Secs. 20 and 21, T 16 N, R 2 E, where small marshes now occur. In this connection, note the much higher content of Na and K, SO_4, and Cl of sample No. 5 over sample No. 4 in the table. These buried thermal springs may be adding such salts to Jemez Creek by effluent seepage.

Springs along Vallecito Creek have been mentioned on a previous page. The only other spring of any importance is Borrego Spring, in the Santa Fe National Forest immediately north of the boundary of the Ojo del Borrego Grant. It also occurs along a fault and is in a deep canyon below thick volcanics.

Water for grazing stock, other than from springs or streams, is obtained by two methods. (1) Small earth dams are built across arroyos to catch and hold storm water. (2) Windmill-operated wells are constructed and equipped with steel tanks. Four of these wells have been noted in this area: (a) center Sec. 12, T 15 N, R 2 E; (b) on edge of Ojo del Borrego Grant and Secs. 9 and 10, T 15 N, R 3 E; (c) east-central part of Ojo del Borrego Grant; and (d) southeast $\frac{1}{4}$ Sec. 20, T 15 N, R 5 E.

Data on subsurface water of the area is entirely lacking except along the streams, as outlined previously. The San Felipe basalt is fairly permeable as a result of columnar jointing, and the numerous faults breaking the surface increase the vertical permeability of this mesa. The Santa Fe formation, underlying most of the area to a depth of a few hundred to a few thousand feet, is highly porous and permeable. Some impervious lenses (clay, quartzite, or quartzitic sandstone) do exist and are of

relatively small extent with small perched water tables. Also, if wells were drilled on the up-dip side of cemented fault zones, they might encounter small flows of artesian water from below such impervious beds. Such water should be of good quality because contaminating agents seem to be absent (except near the western boundary of the area). The water table is, in general, nearer to the surface at the foot of the highest mesas, and increases in depth farther away from them.

MINERAL DEPOSITS

No economic mineral deposits are being worked in the mapped area, nor has any mining gone on in the past as far as the writer has been able to determine. One deep prospect shaft was found, however, in the southwest part of the Ojo del Borrego Grant, south of Bodega Butte. It is sunk in the Lower Borrego Mesa basalt. Gold and silver have been mined in the Bland mining district about 15 miles to the north, but the ore-bearing rocks apparently do not occur in this area.

In the southeastern part of the Ojo del Borrego Grant a manganese-bearing brecciated clastic dike occurs along a north-trending fault. The dike material is mainly sand from the enclosing sandstones and massive black rock

the nearest railroad, at Bernalillo. Also, the steep escarpment would make hauling of the material rather difficult, although conveyor belts about 2 miles long would allow loading of trucks at the road near Lower Vallecitos.

There has been very little petroleum exploration in the Rio Grande trough, largely because of the thickness of Santa Fe and later sediments. However, the southwestern part of the mapped area may have no more than 2,000 feet of Santa Fe beds. The Mancos shale underlies the Santa Fe formation south of Chamisa Mesa, and is probably the underlying formation over most of the general area between Chamisa Mesa, Zia Pueblo, and Santa Ana Pueblo. The Mancos shale and the underlying Dakota sandstone are two important formations in the San Juan Basin, and may contain oil or gas here. The depth to the Mancos is probably not over 2,000 feet at any point, and the top of the Dakota may thus lie between 3,000 and 4,000 feet below the surface, at a maximum. Pennsylvanian rocks may also prove to contain oil here; Northrop and Wood (1946) report the presence of a subsidiary basin of that age in this general region. Fault traps are the main types which would exist here, although minor, faulted, pre-Santa Fe folds may also be present.

TABLE V

ANALYSES OF WATER SAMPLES
(Parts per Million)

Sample No.	1	2	3	4	5	6	7
Date (Mo./Yr.)	9/24	9/24	9/24	9/24	7/49	9/24	4/50
Source of Data	A	A	A	A	B	A	B
SiO_2	59	56	48	49	47	41	25
Fe	.13	.20	1.2	.17	.07	.48	.15
Ca	40	73	58	63	62	91	108
Mg	15	20	15	9.0	9.4	17	17
K and Na	187	115	180	91	147	198	237
HCO_3	403	310	478	290	327	210	239
SO_4	80	42	41	16	37	277	365
Cl	96	100	106	94	143	154	196
F					1.4		0.9
NO_3	18	80	6.0	.50	0.4	30	0.5
B					0.5		
Dissolved solids (ppm)	700	628	693	466	608	933	1070
Hardness as $CaCO_3$	162	264	206	194	193	297	340

Samples on which only total ppm was given: (Clark, 1929, pp. 16-27).

8 500 about average; 280 minimum; 1,182 maximum.

9 12,000 about average; 5,000 to 21,720 range; 2,762 after one cloudburst.

10 1,660 normal; 650 in spring; 4,898 during much irrigation upstream; 5,348 when floodwater from one cloudburst arrived from Rio Salado.

11 285 normal; 2,550 after heavy rainstorm on Rio Salado during a dry summer.

Locations:

1 Well, "on east side of Jemez," 125 feet deep.

2 Well, south end of Jemez Pueblo, 100 feet deep.

3 Well, in alluvium at San Ysidro, 13 feet deep.

4 Jemez Creek, near Jemez.

5 Jemez Creek, at San Ysidro diversion dam.

6 Well, "about 200 yards south of Santa Ana", 30 feet deep.

TABLE V

ANALYSES OF WATER SAMPLES
(Parts per Million)
(continued)

Locations:

7	Well, Jemez dam site, water level at 12 feet.
8	Jemez Creek, at San Ysidro.
9	Rio Salado, at bridge south of San Ysidro.
10	Jemez Creek, at Zia.
11	Rio Grande, at Bernalillo bridge.

Sources of data:

A	Renick, 1931, pp. 78-79.
B	U. S. Geological Survey, Ground-Water Branch, Albuquerque, New Mexico.

clay in the subsiding depression. Small lakes existed for some time, and limestone, silt, and sand were deposited in them. Subsidence of the depression may have been so slow that only very fine material was deposited in small ponds, lakes, and on alluvial fans. Most of the materials for these deposits were derived from the lower Tertiary and Cretaceous formations. The sediments formed the Chamisa Mesa member of the Santa Fe formation. Some volcanic activity in or near this region during this time is recorded by the seams of bentonite and the bentonitic clay in some sandstone.

After deposition of several hundred feet of these sediments, alluvial fans bearing large amounts of pebbles and cobbles of fine-grained red granite and gneiss and felsitic rocks began coalescing with the fans from the west. These later fan deposits came from volcanic and Pre-Cambrian to Mesozoic terrains in the north and northwest, including the Chicoma volcanic center. This material is part of the Bodega Butte member of the Santa Fe formation.

While the alluvial fan deposition was going on, there occurred a period of extensive basaltic flows from the Chicoma volcanic centers. These basalts flowed down over the coalescing fan deposits in this and surrounding areas, but did not halt that deposition. The flows did, however,

greatly diminish the coarse detritus in the volcanic fan materials. Streams from the west and northwest continued carrying sand eastward, and this sand was deposited over the basalt.

During deposition of the volcanic fanglomerate, an apparently accelerated uplift in the Sierra Nacimiento gave rise to slightly higher gradients in the upper portion of alluvial fans to the southeast and coarser materials were deposited. Also, more sand, silt, and clay now came from the Triassic and Permian red beds. These sediments make up the Santa Ana member of the Santa Fe formation.

There was some explosive volcanism in the central Jemez area before the thick basalts, mentioned above, were extruded. However, a greater amount of explosive extrusion took place a short time after the basalt flows. Fragments of lithic and pumiceous tuffs, perlite, and basalt were deposited by low-gradient fan streams flowing southward from the central Jemez Mountains, along with sand and silt derived mainly from sedimentary beds to the northwest and west. These two types of materials were deposited in all combinations of mixtures as the fluctuating conditions dictated. Following deposition of several hundred feet of this material, other basaltic flows broke out and veneered the surface of the fans, preventing further sedimentation in this area.

The thick mass of volcanic fanglomerate is included in the Bodega Butte member of the Santa Fe formation in this area.

The volcanic activity may have been accompanied by some uplift in the Jemez area, decreasing in magnitude outward from the central part. The uplift apparently initiated erosion in this area and the Upper Buff member of the Santa Fe formation was deposited as a wedge of sediments which was thin or absent over most of the southern Jemez area and increased in thickness southward. Shifting stream channels carried volcanic debris far southward to be deposited in the Upper Buff member as far as the lower Rio Puerco area.

At about this same time, the physiographic basins of the Rio Grande depression were integrated by a southward-flowing river, the ancestral Rio Grande. The channel of this river lay east of the area studied, but its floodplain lay partially within the eastern edge of the area. Deposition of sediments in the southern Jemez region may have ceased by this time, except for deposition on or near this floodplain.

During very late Santa Fe time, basaltic eruptions of the Hawaiian type occurred near the edge of this river floodplain, apparently from two systems of cones aligned along fissures. The very fluid lava flowed over the gently sloping erosion surface and down onto the floodplain. This

represents the principal flows herein called the San Felipe basalt.

During deposition of the Upper Buff member farther south, and perhaps very shortly after extrusion of the San Felipe basalt, tensional forces caused extensive normal faulting of the Basin-and-Range type; this may have been in late Pliocene time. This faulting resulted in the elevation of the bordering highlands and further subsidence of the Rio Grande trough. The Santa Fe deposits were faulted and tilted toward the center of the depression. Subsidence must have been greatest to the south, so that deposition ceased in the Santa Ana Mesa region. A period of erosion ensued during which the Ortiz (i.e., Mesita Alta) surface was formed, truncating the deformed Santa Fe deposits.

Finally, the regional baselevel was lowered and then stabilized at a level about 300 feet below that of Ortiz time. A lower and less extensive surface, the Segundo Alto (i.e. San Ysidro?), was cut along the Rio Grande. Further lowering of baselevel has occurred until the river reached its present position. Minor terraces or partial erosion surfaces were formed between and following the formation of the two main surfaces. Badlands, hogbacks and cuestas, and other minor topographic features have been formed as a result of the continuing degradation of the area.

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