BUREAU OF ECONOMIC GEOLOGY
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TO ACCOMPANY MAP—GEOLOGIC
QUADRANGLE MAP NO. 37

GEOLOGY OF BOFECILLOS MOUNTAINS AREA, TRANS-PECOS TEXAS

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INTRODUCTION

The Bofecillos Mountains area of Trans-Pecos Texas contains a Tertiary volcanic vent and a varied sequence of lava flows, tuff, ash-flow tuff, and associated conglomerate, sandstone, and mudrock; after most of the volcanic activity had ceased, the area was block faulted and later dissected into a rugged high-standing terrain with striking exposures. The present study is a continuation of mapping in Trans-Pecos Texas supported by the Texas Geologic Atlas project of the Bureau of Economic Geology; emphasis in this report is placed primarily on the volcanic stratigraphy and the structural and geomorphic evolution of these rocks to their present stage.

The Bofecillos Mountains area, as used in this report, consists of about 275 square miles in the Lajitas and Redford (1:62,500) partial quadrangles, which are bounded on the north by Lat. 29° 30′ N., on the east by Long. 103° 45′ W., and on the southwest by the Rio Grande. Most of the area is in southeastern Presidio County, but the easternmost part is in southwestern Brewster County. Most of the area is on the south half of the Big Bend ranch.

State Ranch Road 170 along the Rio Grande provides access to the area from the south; a graded road into the Big Bend ranch affords access from the north; from the east, the abandoned Marfa-Lajitas road down Fresno Canyon was traversable in 1967 by 4-wheel drive vehicles; other non-graded ranch roads provide access into the central part of the area for 4-wheel drive or pick-up vehicles.

Redford and Lajitas are the only sizable communities in the area. They are farming and ranching towns. Lajitas is also a base of operation for quicksilver prospectors and a highway maintenance crew. Both towns have small trading posts and cater to the increasing tourist trade.

The silt-capped flood-plain of the Rio Grande is extensively cultivated; cotton, stock feed, onions, and cantelope are the major crops. The dissected upland is ranched; livestock includes sheep, goats, and to a lesser extent cattle and horses. Deer are abundant and bring additional money to ranchers in fees for hunting rights during the open season. Candelilla is locally abundant north of Lajitas and is harvested for the wax it yields.

The region is arid; annual precipitation is about 10 inches. Most rain falls in the late summer and early autumn, and during this time flash floods commonly occur along major arroyos. Maximum temperature during the summer is normally above 100°; the overnight temperaatures frequently drop more than 30°. Vegetation in the area is typical of desert regions in the Southwest and includes cactus, lechugilla, catclaw, ocotillo, mesquite, creosote bush, and grasses. Cottonwood grows in valleys where water is available. Salt cedar is present in thickets along the Rio Grande.

The first report on the geology of the Bofecillos Mountains was a brief reconnaissance made by C. C. Parry (1857) in connection with the 1857 Mexican-U. S. boundary survey headed by Emory. Parry dealt primarily with the striking physiography along the course of the Rio Grande, describing bolson and pediment development in basins, and igneous rocks which crop out in canyons.

Discovery and development of mercury deposits along the Terlingua Monocline in the late 19th century brought many geologists into the area. Reports by Blake (1895), Turner (1900, 1906), Spalding (1901), B. F. Hill and Phillips (1902), R. T. Hill (1902), B. F. Hill (1903), Phillips (1905), Kirk (1905), and Udden (1907, 1918) outlined the early history of exploitation and the distribution and origin of the deposits; Udden's work, in particular, fitted the Terlingua district into its regional geologic setting. Ross (1935, 1937, 1941) and Yates and Thompson (1959) explained the geologic factors controlling ore emplacement and further described the regional stratigraphy and structure.

The Solitario Dome, immediately northeast of the map area, was cursorily mentioned in many reports on the Terlingua district, but the first publication on the Solitario itself was by Powers (1921). Sellards (1932) published in abstract form a summary of work done in 1929; a geologic map of this complex structure was forthcoming the following year (Sellards, Adkins, and Arick, 1930). Lonsdale's (1940) report on igneous rocks of the Terlingua-Solitario region provided a framework for later petrologic studies. J. L. Wilson (1954) studied the Paleozoic rocks in the Solitario and revised the geologic map. Herrin's doctoral dissertation at Harvard University (1958) included the most detailed geologic map (scale: ca. 1:24,000) available at present.

Maps and reports sponsored by the Bureau of Economic Geology carried Tertiary stratigraphy from the north and provided a basis upon which to proceed southward. Tascotal Mesa quadrangle (Erickson, 1953) and the Presidio area (Dietrich, 1966) adjoin the map area on the north.

A geologic report on the Big Bend National Park immediately southeast of the area (Maxwell et al., 1967) provides a detailed study of the geologic history of this adjacent area and a stratigraphic tie into the Bofecillos Mountains from the southeast. In 1959–1960 Dietrich and Maxwell (in preparation) made a reconnaissance of the Bofecillos Mountains and recognized the continuity of certain volcanic units known to the north and southeast.

Arenal (1964) made a geologic reconnaissance map of Mexico adjacent to the Bofecillos Mountains area in a study of coal and lignite deposits in Upper Cretaceous strata of the area. The International Boundary and Water Commission (1955) prepared a series of (1:50,000) geologic strip maps along the Rio Grande which extend upstream from Del Rio to a point in the map area 4 miles west of Lajitas.

Theses and dissertations from The University of Texas at Austin cover the area west and northwest of the Bofecillos Mountains. McCarthy (1953) and Dietrich (1954) mapped the geology of the westernmost part of the Bofecillos Mountains area at a scale of about 1:24,000. This report is an abridgement of a University of Texas doctoral dissertation (McKnight, 1968).

STRATIGRAPHY

CRETACEOUS STRATA

About 2,200 feet of Cretaceous strata are exposed in the map area in erosional lowlands, domes, and horsts where Tertiary volcanic rocks have been removed by erosion.

COMANCHE SERIES

Comanche strata are exposed along the eastern edge of the map area in the Solitario Dome, the Terlingua Monocline, and Mesa de Anguila, and near the center of the map area in Rancherias Dome. Following the usage of Maxwell et al. (1967), the Comanche Series comprises eight formations.

Buda Limestone
Del Rio Clay
Santa Elena Limestone
Sue Peaks Formation
Del Carmen Limestone
Telephone Canyon Formation
Maxon Sandstone
Glen Rose Limestone

Of these only the Santa Elena, Del Rio, and Buda Formations are exposed in the Bofecillos Mountains area.

In preparation of their report, Maxwell et al. (1967) mapped the north face of Mesa de Anguila about 1 mile southeast of Lajitas. Although within the Big Bend National Park, exposures of Santa Elena and Del Rio extend several hundred feet north of the area actually mapped in their report. To avoid a gap in mapping, the south boundary of the Bofecillos Mountains area was extended up the face of the Mesa to abut against their map area, thus including the Santa Elena and Del Rio exposures. Because these formations are not exposed elsewhere in the Bofecillos Mountains area, their descriptions in this report are paraphrased or quoted from Maxwell et al. (1967).

Santa Elena Limestone

About 740 feet of Santa Elena Limestone (Maxwell et al., 1967) is exposed at the type section at the mouth of Santa Elena Canyon, 10 miles southeast of the area mapped in this report. Maxwell et al. correlated it with the Georgetown Formation above the Duck Creek Limestone in most of central or northeast Texas. Santa Elena is exposed in the southeastern part of the map area on the north face of Mesa de Anguila.

According to Maxwell et al. (1967, p. 47):

> In the Park . . . the Santa Elena is a hard, light gray or white limestone when fresh but weathers to dark gray or shades of brown. It is usually finely crystalline in beds as much as 10 feet thick . . . silicified fossils, especially rudistids, and rounded nodular chert masses are common in the massive beds. In some places the upper part of the formation contains soft marly intervals interbedded with the hard, massive limestone so that weathering and erosion produce a terraced topography. . . . Locally, the massive-bedded, cherty, rudistid-bearing ledges are difficult to distinguish from the underlying Del Carmen. In general, the Santa Elena differs from the Del Carmen in that it has a lighter color, a smoother surface due to less chemical weathering, and most of the contained chert is nodular rather than in layers.

Undifferentiated Comanche Limestone

A 300- by 100-foot block of unfossiliferous massive micritic limestone is exposed beneath flaggy limestone of the Boquillas Formation at the west end of Rancherias Dome near the center of the map area. The limestone underlies the Boquillas with apparent conformity along the 100-foot contact, but the exposure is poor; the contact may be a fault. The general character of the rock resembles that of the Del Carmen or Santa Elena limestones exposed east of the map area on the flanks of the Solitario Dome and in the Big Bend National Park. Part of the rock is contact metamorphosed to marble or skarn by a nearby intrusion of gabbro. Identification of this limestone is uncertain, and it is therefore mapped as undifferentiated Comanche Limestone (Kc).

Del Rio Clay

The Del Rio Clay (Hill and Vaughan, 1898, pp. 236–237) is traceable from its type locality at Del Rio, Texas into West Texas. This report follows Maxwell et al. (1967) in using the name "Del Rio" rather than its prior-named equivalent, the Grayson Marl (Cragin, 1894, pp. 44–48) of northeastern Texas, because the clay in the map area more closely resembles that of the type Del Rio than the marl of the type Grayson. Del Rio is exposed in the map area along the north face of Mesa de Anguila about 1 mile southeast of Lajitas; Del Rio is also present east of the map area beneath mapped Buda Limestone in Fresno Canyon on the west flank of the Solitario Dome.

According to Maxwell et al. (1967, pp. 51–52):

> . . . About 100 feet of Del Rio occurs on top of Mesa de Anguila . . .; it is mostly light blue and greenish clay that weathers yellow. Scattered bands of thin siliceous limestone and brown ferruginous clay with *Haplostiche texana* are found in the lower half of the outcrop and gray calcareous nodules occur in the top foot. Fossils characteristic of both the lower and upper Del Rio are present. Adkins (1933, pp. 392–393) reported upper Del Rio fossils from the Terlingua district, where the formation is 120 to 180 feet thick, and in the Solitario, where it is about 125 feet thick.

Buda Limestone

Vaughan (1900, p. 18) applied the name "Buda" to replace the preoccupied "Shoal Creek Limestone" of R. T. Hill (1889, pp. xxiii-xxiv); the type locality is along Shoal Creek in Austin, Texas. This limestone has been traced with nearly continuous exposure into Trans-Pecos Texas. It is exposed southwest of Lajitas on the north face at Mesa de Anguila, along the eastern edge of the map area as the caprock of a hogback on the west side of the Solitario, and in an isolated klippe 200 feet long forming the upper plate of the Shelter Thrust in adjacent Fresno Canyon.

The 70-foot-thick Buda is poorly bedded to massive, nodular, white, micritic limestone; fossil molluscs are rare, and other phyla are absent. The contact with the underlying Del Rio Clay is covered; Moon (1953) reported a possible diastem between the two formations in the Agua Fria quadrangle, about 2 miles northwest of the Bofecillos Mountains area. The contact with the overlying Boquillas Formation is abrupt and perhaps disconformable. An undulating surface at the top of the Buda has about 6 inches of relief in a few feet of laterally exposed contact; it is overlain by the Boquillas Formation.

GULF SERIES

The section of Gulf strata in the Bofecillos Mountains area is a gradational sequence which may be divided lithostratigraphically into three parts: a lower part of interbedded limestone and clay; a middle clay; an upper part of interbedded sandstone and clay. Stratigraphic nomenclature of this section has been progressively redefined by successive workers (fig. 1).

The nomenclature in this report follows the usage of Maxwell et al. (1967), but the Boquillas is not subdivided into members on the map. Thus the contacts are consistent with those of Yates and Thompson (1959), whose area adjoins the map area to the southeast.

Boquillas Formation

The Boquillas Formation (Maxwell et al., 1967) crops out extensively along the eastern border of the map area in erosional lowlands and along the flanks of the Solitario Dome. Small exposures in an up-faulted block near the western edge of the map area, and in Rancherias Dome near the center of the area, indicate that the Boquillas underlies the volcanic rocks in most of the map area. It is about 1,000 feet thick.

The Boquillas Formation is composed of interbedded calcareous clay and thin-bedded argillaceous micritic limestone. Some of the limestone beds are sandy or silty. Unweathered surfaces of the limestone and clay are gray to black; the rock weathers cream white, yellow, or buff brown. The percentage of clay increases up the section: the lower beds are almost entirely limestone; the upper half of the formation is mostly clay. In the lower part of the Boquillas, clay partings cause the limestone to break into thin flaggy plates; in the upper part chalky limestone is interbedded with marly clay. The Boquillas contains abundant fossils, particularly *Inoceramus, Ostrea*, Foraminifera, and ammonites.

As a consequence of the greater percentage of clay, the upper part of the Boquillas is, in general, less resistant to erosion than the lower part. Where tilted, the resistant limestone beds of the Boquillas commonly form a series of cuestas; where flat-lying the profile is characterized by stairstepped ledges.

The contact between the Boquillas and the overlying Pen clay is gradational. The upper beds of the Boquillas are progressively thinner and more shaly. Limestone beds are chalky and the ledges progressively less prominent.

Pen Formation

Pen Formation (Maxwell et al., 1967) crops out in the southeastern part of the map area and in Rancherias Dome; it is about 200 feet thick. Fresh outcrops of Pen are gray, but weathered surfaces are yellow or buff. Bedding is visible only on unweathered surfaces or where the clay was

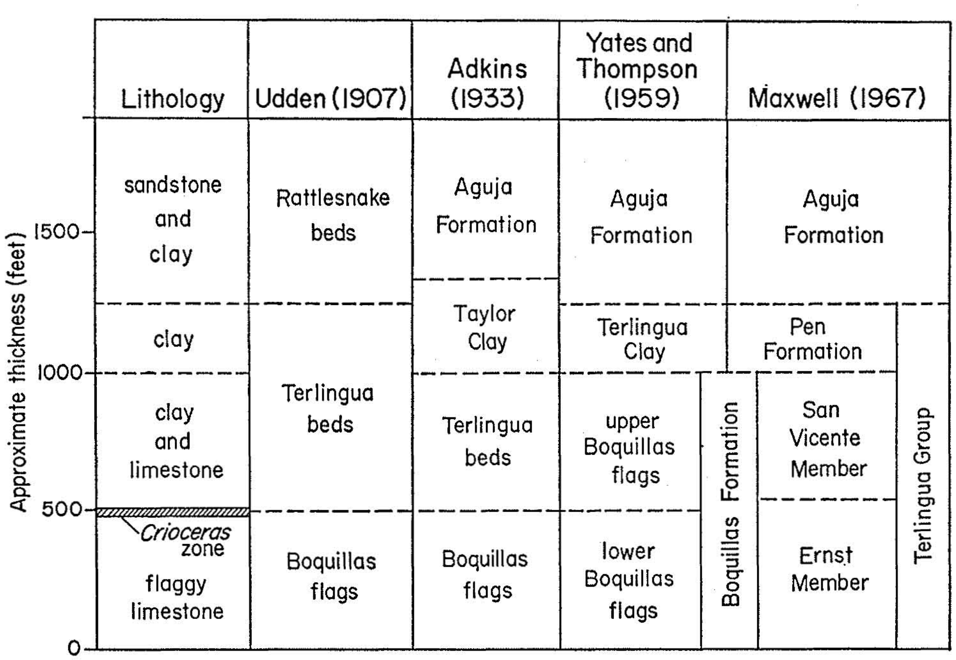


FIG. 1. Nomenclature of Gulf Series used by some workers in southern part of Big Bend region, Texas.

baked by nearby intrusions. The Pen forms smooth slopes except for thin ledges of limestone near the base. The clay is probably montmorillonitic because it commonly exhibits a "popcorn" weathering surface. Some parts of the Pen are gypsiferous. *Inoceramus* is sporadically abundant near the base.

The Pen is less resistant to erosion than the underlying Boquillas and the overlying Aguja; it normally forms a lowland belt of rounded hummocky topography between the two more resistant formations. The contact between the Pen clay and the overlying Aguja Formation is gradational. The upper part of the Pen contains thin beds of sandstone like those in the overlying Aguja Formation.

Aguja Formation

The Aguja Formation (Yates and Thompson, 1959) is present in the southeastern part of the map area in a 1,500- by 3,000-foot exposure on the south flank of Contrabando Dome. Maximum thickness is about 70 feet. The Aguja consists of interbedded gray to gray-green and brown sandstone and shale. The maximum thickness of individual sandstone beds is 1 foot; most beds are a few inches thick. Some of the thicker sandstone beds are cross-bedded.

A few lignite seams are present in the exposure, all less than an inch thick. The Aguja contains abundant fossils, most of which are pelecypods including *Ostrea*, some *Inoceramus*, and a few rudistids.

Beds of Aguja in the area are flat-lying or gently dipping. Abundant thin beds of sandstone form weak ledges on slopes.

TERTIARY ROCKS

DEVELOPMENT OF STRATIGRAPHY AND NOMENCLATURE

Classification and nomenclature of Tertiary strata in the Bofecillos Mountains are based largely on earlier mapping in adjacent quadrangles to the north and mapping of the Big Bend National Park to the southeast (fig. 2). A reconnaissance study by Dietrich and Maxwell (in preparation) through the Bofecillos Mountains revealed the relationship of the Chisos Formation (Maxwell et al., 1967) to the Buck Hill Group (Goldich and Elms, 1949) which has been mapped to the north by various workers. Throughout most of the map area, the Mitchell Mesa Tuff rests directly above, or a few feet above, the Tule Mountain Trachyandesite Porphyry, the highest member of the Chisos Formation.

A basal conglomerate of the Pruett (Jeff) is present in the Buck Hill and Tascotal Mesa quadrangles and what is probably the same conglomerate is present in the Bofecillos Mountains area. At the eastern edge of the area, the conglomerate is overlain by Alamo Creek Basalt, the lowest member of the Chisos Formation in the Park. Therefore, based upon nearly equivalent tops and bases, the Chisos Formation of the Big Bend National Park is very nearly equivalent to the Pruett and Duff Formations of the Buck Hill Group.

From their reconnaissance, Dietrich and Maxwell (in preparation) defined the Bofecillos Group as consisting of:

Rawls Formation
Santana Tuff
Fresno Formation
Mitchell Mesa Tuff
Chisos Formation

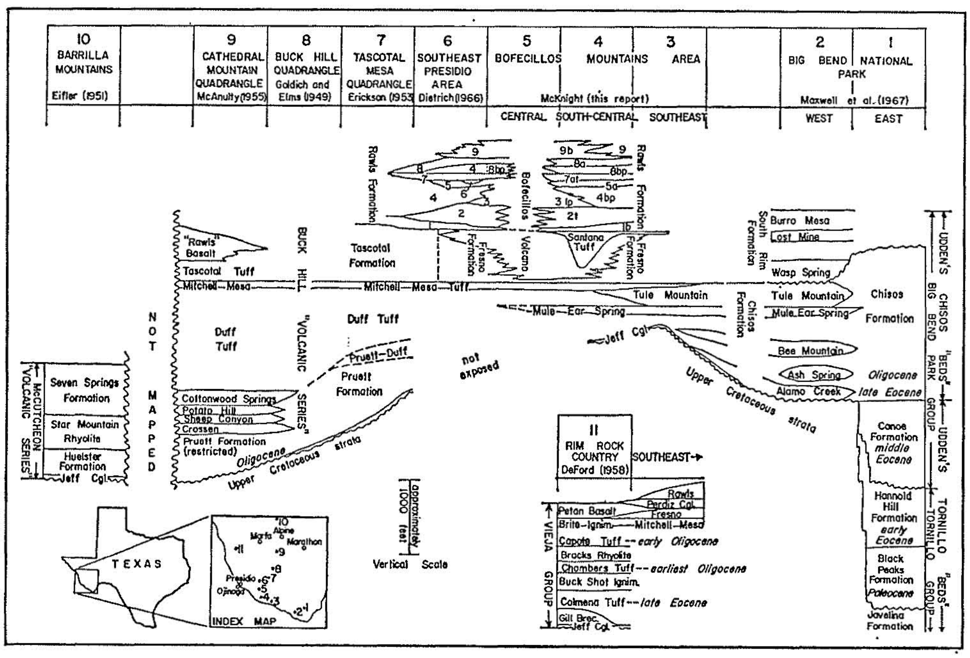


FIG. 2. Tertiary volcanic strata mapped by various workers in Big Bend region, Texas.

They replaced the name "Tascotal" by "Fresno" because the stratigraphic interval between Mitchell Mesa and Rawls in the Bofecillos Mountains is largely lava flows—quite different from the Tascotal Formation at its type locality in Tascotal Mesa. The Santana, an ash-flow tuff, is present in the southern part of the Tascotal Mesa quadrangle and thickens markedly to more than 500 feet near the Rio Grande.

This report follows the formation nomenclature of Dietrich and Maxwell (in preparation) except that the Jeff Conglomerate at the base of the Tertiary section is mapped separately (fig. 3). Dietrich and Maxwell extended from the Big Bend Park the four formal members mapped here in the Chisos Formation—Alamo Creek Basalt, Bee Mountain Basalt, Mule Ear Spring Tuff, and Tule Mountain Trachyandesite Porphyry. Dietrich's (1965) informally numbered subdivisions of the Rawls Formation are adopted here, with slight modification as members. Further subdivision of formations and members records local complexities in the stratigraphy of the Bofecillos Mountains area.

Jeff Conglomerate

Description.—The name Jeff is applied to a conglomerate at the base of the Tertiary which is correlated in this report with the Jeff Conglomerate of Eifler (1951) in the Barrilla Mountains about 100 miles to the north. In the Bofecillos Mountains area, the formation lies with angular unconformity on Gulf rocks. Where observed, relief on the base of the Jeff is less than 3 feet in 100 feet of laterally exposed contact. The Jeff crops out in erosional lowlands in the southeastern part of the map area in nearly every exposure of the base of the lower Chisos Formation. The presence of Jeff at depth near the center of the Bofecillos Volcano is documented by an outcrop of Jeff in Rancherias Dome. Elsewhere in the map area the base of the Tertiary section is covered by younger volcanic rocks.

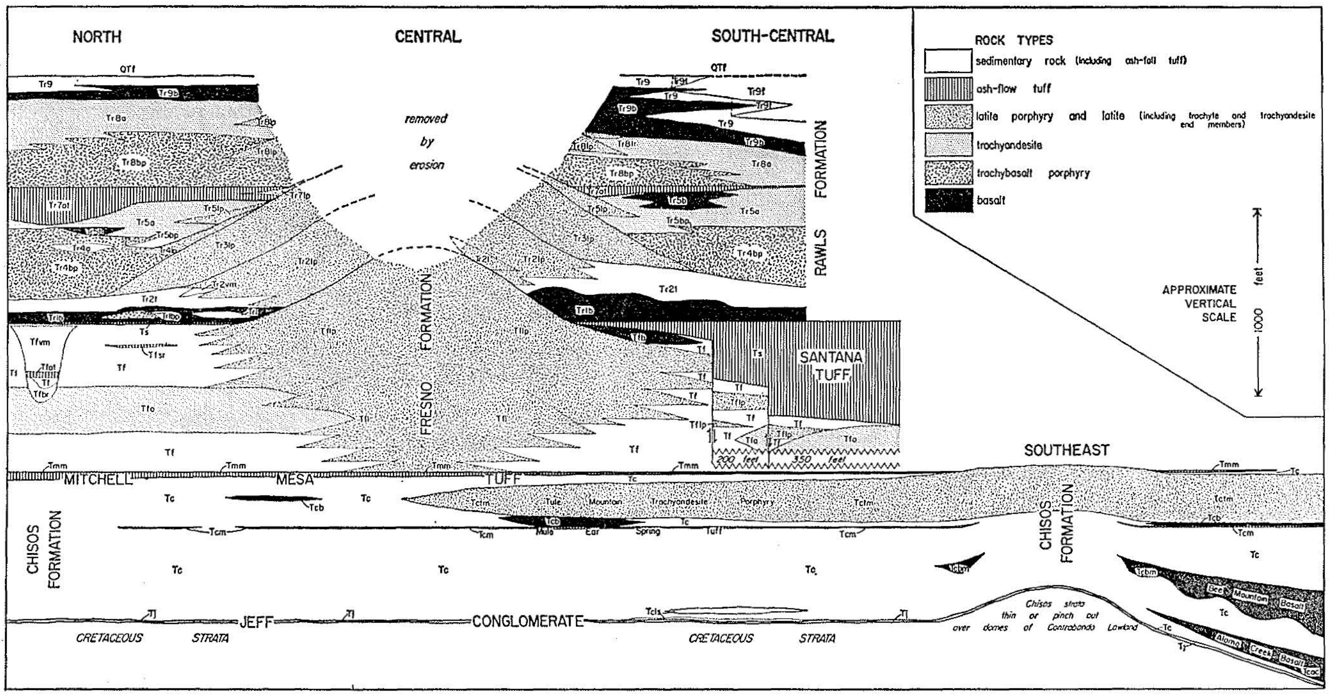
The rock is a conglomerate of well-rounded limestone cobbles and boulders with interbeds and lenses of sandstone. Largest boulders are 12 inches in diameter; average diameter is about 6 inches. Interstitial to the boulders is well-cemented sandstone; the rock commonly breaks across boulders, rather than around them. Bedding in the conglomerate is faint or absent, but bedding and cross-bedding are common in the sandstone. The formation ranges from a few feet to 20 feet thick.

The limestone boulders and pebbles look like Comanche, Del Carmen, Santa Elena, and Buda Limestones exposed on the Terlingua Monocline and in the Solitario, but because the fragments are uniformly well rounded, the source was probably more distant. In most places, the Jeff contains no igneous pebbles at all, but in a few places, particularly in Fresno Canyon, it contains weathered, rounded, vesicular pebbles of igneous rock up to 6 inches in diameter. Angular pebble- to boulder-size fragments of petrified wood are abundant (up to 5%) at a few localities; elsewhere petrified wood is absent.

Correlation.—The Jeff Conglomerate extends over much of the Big Bend region of West Texas. Zimmerman (1950) and Barnhill (1950) traced it from its type locality in the Barrilla Mountains to the northern Davis Mountains, and Brand and DeFord (1962) reported it near the southwestern corner of the Kent quadrangle. DeFord (1958) and subsequent workers correlated it with the basal conglomerate in the Rim Rock Country. Eifler (1951) suggested correlation of Jeff Conglomerate with the basal conglomerate of the Pruett Formation, described by Goldich and Elms (1949) and later workers. Closest reported outcrops of the two conglomerates are 55 to 60 miles apart; mapping in the area between the two exposures is incomplete, and future workers in the southern Davis Mountains may find other outcrops of similar conglomerate. On the basis of nearly identical descriptions of the basal conglomerate by Goldich and Elms (1949) and Eifler (1951), Eifler's correlation is accepted here, and the Jeff is thereby extended into the Buck Hill area. The extension of Jeff Conglomerate into the Bofecillos Mountains from the Buck Hill area requires correlation of outcrops separated about 15 miles across the Solitario, because the stratigraphic interval of the conglomerate is not exposed on the flanks. This correlation is almost certainly valid, on account of the similarity of rock type and of overlying and underlying strata.

Areal extent and environment.—If the above correlations are correct, the Jeff Conglomerate crops out in the Bofecillos Mountains, in the Davis and Barrilla Mountains, in the southern part of the Kent quadrangle, in the Rim Rock Country, and an undetermined distance into Mexico. It was probably a more or less continuous gravel sheet which covered much of West Texas before the major accumulation of volcanic strata and associated sedimentary rock. The gravel was probably left as a residuum on a planation surface that surrounded local topographic highlands. Jeff Conglomerate is not preserved and possibly was not deposited (1) in the Cathedral Mountain area (McAnulty, 1955); (2) on a northwest-trending ridge between the north-central part of the Presidio area (Dietrich, 1965) and the Pinto Canyon area (Amsbury, 1959); (3) on the Terlingua Monocline and the Solitario Uplift (this report); (4) elsewhere to the northwest and west of the Bofecillos Mountains. These areas were probably topographically high and may have served as sources of detritus for Jeff and later conglomerates.

Poor sorting, lack of bedding, and heterogeneous distribution of sandstone lenses in the Jeff suggest a fluvial environment of deposition. Eifler (1951, p. 344) observed that "the thickness is uniform over too great an area for the deposit to be a piedmont alluvial fan, although the sandstone and gravel might have been spread very thin in front of a piedmont fan." Great areal extent and lack of relief on the base of the Jeff preclude origin from actively downcutting streams in the manner of stepped terrace or pediment gravels like those in the West today.



EXPLANATION

BOLSON FILL

QTf

RAWLS FORMATION

Member 9: Tr9f, fill; Tr9, undifferentiated sedimentary rock and tuff; Tr9b, basalt

Member 8: Tr8tr, trachyte; Tr8a, trachyandesite; Tr8lp, latite porphyry; Tr8bp, trachybasalt porphyry

Member 7: Tr7at, ash-flow tuff; Tr7lp, latite porphyry

Member 6: not present in Bofecillos Mountains area

Member 5: Tr5a, trachyandesite; Tr5lp, latite porphyry; Tr5bp, trachybasalt porphyry; Tr5b, basalt

Member 4: Tr4bp, trachybasalt porphyry; Tr4a, trachyandesite; Tr4lp, latite porphyry

Member 3: Tr3lp, latite porphyry

Member 2: Tr2t, tuff and interbedded sedimentary rock; Tr2lp, latite porphyry; Tr2l, latite; Tr2vm, volcanic mudflow

Member 1: Tr1b, basalt; Tr1bp, trachybasalt porphyry; Tr1, undifferentiated sedimentary rock and tuff

SANTANA TUFF

Ts, ash-flow tuff

FRESNO FORMATION

Tfb, basalt; Tf, undifferentiated sedimentary rock and tuff; Tflp, latite porphyry; Tfl, latite; Tfa, trachyandesite; Tfvm, volcanic mudflow; Tfat, ash-flow tuff; Tfbr, breccia; Tfsr, sodic rhyolite

MITCHELL MESA TUFF

Tmm, ash-flow tuff

CHISOS FORMATION

Tc, undifferentiated tuff and sedimentary rock; Tctm, Tule Mountain Trachyandesite Porphyry; Tcb, basalt; Tcm, Mule Ear Spring Tuff; Tcbm, Bee Mountain Basalt; Tcac, Alamo Creek Basalt; Tcls, limestone

JEFF CONGLOMERATE

Tj

Fig. 3. Tertiary strata mapped in Bofecillos Mountains area.

Probably the Jeff was the deposit of planing streams on a giant, gently sloping pediment surface that developed by prolonged erosion of streams at or near base level. Stokes (1950) invoked this mechanism to explain similarly thin and extensive Mesozoic conglomerates on the Colorado Plateau.

Igneous rock fragments are reported in the conglomerate at the base of the Pruett in the Buck Hill quadrangle (Goldich and Elms, 1949), but they are not reported in similar conglomerates in the Barrilla Mountains, the northern Davis Mountains, or the Rim Rock Country; perhaps extrusive activity in these areas began after the Jeff was buried by pyroclastic detritus blown from distant sources.

Goldich and Elms (1949), Eifler (1951), and other workers to the northwest of the Bofecillos Mountains reported quartzite pebbles in the Jeff or its equivalent in their respective areas. Absence of quartzite in the Jeff of the Bofecillos Mountains area suggests a different source area.

Chisos Formation

The type locality of the Chisos Formation as redefined by Maxwell et al. (1967) is in the Big Bend National Park, where it includes undifferentiated tuff and sedimentary rock and five formally named members:

- Tule Mountain Trachyandesite
- Mule Ear Spring Tuff
- Bee Mountain Basalt
- Ash Spring Basalt
- Alamo Creek Basalt

Of these, all but the Ash Spring Basalt were extended into the Bofecillos Mountains by Dietrich and Maxwell (in preparation). In this report, two local units of nonmarine limestone, several basalt flows, and an unmapped silicified microcrystal tuff are discussed separately but not given formal member status.

Most of the area underlain by Chisos Formation in the Bofecillos Mountains is in erosional lowlands in the southeastern part of the map area; the upper part is also exposed in several intrusive domes. Thickness is difficult to determine at most places because the formation is extensively slumped. The thickest section in the map area is at the east end of Lajitas Mesa, where Dietrich and Maxwell (in preparation) measured 1,060 feet. The formation thins over domes of the Contrabando Lowland as a result of uplift during deposition; it is about 650 feet thick in a cliff on the southeast flank (MS 2).[2] To the north, in Fresno Canyon, the Chisos thins and in some places pinches out against the flanks of the Solitario Dome and Terlingua Monocline, probably in part because of nondeposition and in part because of erosion prior to the deposition of overlying rock. Although a complete section is not exposed to the west, one exposure within the breached Tapado Dome has more than 500 feet of Chisos strata; probably the Chisos Formation is about 500 to 800 feet thick over most of the western part of the map area.

Age

The only fossil collected in this study from the Chisos Formation is a poorly preserved gastropod, useless for significant age determination. According to Maxwell et al. (1967), fossils collected from the Chisos Formation in the Big Bend National Park are insufficient to date the beds precisely. They inferred, however, that the beds beneath the Bee Mountain Basalt are most likely Middle Eocene and those above the basalt, Upper Eocene. They reported radiometric ages ranging from 44.3 m.y. for the Alamo Creek Basalt to 28.4 m.y. for the Tule Mountain Trachyandesite.

Chisos Formation Undifferentiated (Tc)

Rock designated in this report as undifferentiated Chisos consists of variegated and laterally discontinuous slightly to moderately indurated volcanic conglomerate and sandstone, tuffaceous mudstone, and tuff.

The thickest single deposits are conglomerate beds, which range from less than a foot to about 10 feet thick; several superposed conglomerate beds may total 30 feet, although lenses of sandstone or mudstone, less than a foot thick and as much as 10 feet in outcrop length, are commonly included. The matrix is buff, gray, or gray-green calcareous tuffaceous sandstone. In the conglomerate the largest fragments are boulders of volcanic rock which are angular or rounded with a maximum diameter of about 2 feet. Most conglomerate beds, however, contain 40 to 95 percent well-rounded cobbles and boulders of limestone and cherty limestone with a maximum diameter of 15 inches; the rock resembles Cretaceous limestone in areas adjacent to the Bofecillos Mountains, but it may be from more distant sources.

Sandstone occurs in beds and lenses up to 5 feet thick, and superposed beds may form units up to 35 feet thick; cross-bedding is common. Colors are mostly white, gray, gray green, or buff, but some sandstone is pink or red. The rock is poorly sorted volcanic arkose of variable composition. Major constituents are angular, slightly to thoroughly weathered feldspar and angular unaltered quartz cemented by hematite-limonite, clay minerals, and calcite. Minor mineral constituents include slightly hematitic flakes of biotite, opaque mineral grains, and celadonitic and hematitic crystals of pyroxene and amphibole. Lithic fragments are common in coarse-grained sandstone; most are rounded limestone fragments, but a few are angular to rounded fragments of aphanitic igneous rock, now weathered to hematite, celadonite, and clay minerals.

Mudrock beds are mostly less than a foot thick, but sedimentary layers consisting dominantly of mudrock are commonly 50 to 70 feet thick and in some places up to 120 feet thick. Bedding of mudrock tends to be more continuous laterally than that of sandstone or conglomerate. Colors are commonly red or gray green but may be buff, gray, white, black, purple, or pale green. Silt-size grains are mostly quartz and kaolinized feldspar; the matrix is hematitic and limonitic clay minerals and calcite. Hematitic biotite flakes and opaque mineral grains in small percentages are common.

The sequence of conglomerate, sandstone, and mudrock probably represents a fluvial environment of deposition: conglomerate and sandstone represent channel deposits, whereas the mudrock is a flood-plain or overbank deposit.

Variegated red, gray-green, gray, white, buff, or yellow tuff is present throughout the Chisos; the upper half of the formation is mostly tuff. Most is either nonbedded or faintly bedded. A few zones up to 30 feet thick are well bedded and commonly have mud-cracked beds less than 2 inches thick; these zones were probably deposited in local ponds or lakes. Hollow tubes less than 1/16 inch in diameter, abundant in some parts of the section, are probably relict root holes.

The rock is mostly dull, but where cemented by silica it is porcellaneous. The grain size is generally fine to medium; except for sparsely distributed pumice fragments up to 5 cm in diameter, the coarsest grains are mostly less than 0.5 mm across. In a few places all grains are less than 0.05 mm in diameter; perhaps the source of the fine tuff beds in the map area was so distant that all but the finest particles had previously settled out.

Most of the rock is vitric or vitric-crystal tuff; crystal constituents, including vacuolized K-feldspar and plagioclase, quartz, hematitic and celadonitic basaltic hornblende, celadonitic augite and aegirine-augite, hematitic biotite, and opaque minerals, generally make up less than 20 percent of the rock. Lithic fragments, mostly limonitic, hematitic, and celadonitic fragments of aphanitic igneous rock, make up less than 5 percent of most of the rock. Devitrified axiolitic glass shards are commonly obliterated by recrystallization. Interstitial material is probably the devitrification products of glass dust; it is now altered to pale-green zeolites or clay minerals and some anhedral or vermicular celadonite crystals up to 0.01 mm in diameter. Hematite and limonite are commonly disseminated as a fine dust throughout the rock; concentration is greatest around devitrified shards and around altered dark minerals from which they were probably derived. Calcite partly or totally fills pore space and commonly replaces all but the quartz grains of the tuff, maintaining minute details of the parent structure.

[2] The measured sections mentioned by number in this text are detailed in McKnight (1968, pp. 149–192).

A zone up to 8 feet thick of distinctive microcrystal tuff, here included in the undifferentiated Chisos Formation, lies near the base of the Tule Mountain Trachyandesite and may be underlain or overlain by basalt (Tcb). It crops out along the southern edge of the map area between Lajitas Mesa and Tapado Dome. In most places this stratigraphic interval is covered by talus from the overlying Tule Mountain Trachyandesite Porphyry.

Three thin-sectioned samples of the rock are well-sorted microcrystal tuff. Partly vacuolized laths of sanidine (8 to 25 percent) and plagioclase (0 to 5 percent), each up to 1 mm long, are commonly embayed and broken. Quartz (0 to 3 percent) occurs in partly embayed commonly broken bipyramids about 1 mm in diameter. Partly broken stubby needles of augite (up to 1 percent) as much as 0.5 mm long are fresh or partly altered to hematite and celadonite. Basaltic hornblende (0 to 5 percent) occurs mostly as unaltered or slightly celadonitic needles up to 5 mm long, but about 1/10 is thoroughly altered with pseudomorphic celadonite and chalcedony and a corona of hematite. Celadonitic flakes of biotite (up to 2 percent) are as much as 4 mm in diameter. Opaque minerals (up to 2 percent) are in blocky crystals up to 0.5 mm across and in clots around altered dark minerals. Accidental fragments of aphanitic igneous rock (2 to 10 percent) as much as 1 mm in diameter are partly altered to celadonite and hematite. Pumice fragments (0 to 1 percent) are filled with zeolites, celadonite, and chalcedony. The matrix is mostly altered to zeolites, clay minerals, and celadonite, although a few devitrified axiolitic glass shards remain; most of the rock is porcellaneous as a result of chalcedonic cement.

In general, stream-laid sedimentary rock—conglomerate, sandstone, and mudrock—predominates in the lower part of the Chisos Formation; the upper half is predominantly tuff. This upward gradation is probably the result of continued or increased deposition of pyroclastic material which increasingly disrupted streams by choking them with more pyroclastic material than they could carry.

Nonmarine Limestone (Tcls)

Two beds of white, cream, or gray mottled and burrowed nonmarine limestone crop out in the lower 70 feet of the Chisos Formation in a breached dome about 2 miles southeast of Rincon Mountain in Fresno Canyon. The lowest is up to 4 feet thick and massive and lies immediately above 20 feet of Jeff Conglomerate. The upper bed, up to 25 feet thick, overlies 25 feet of undifferentiated Chisos tuff, sandstone, and mudrock above the Jeff. It contains layers from less than an inch to several feet thick. The rock is mostly structureless micrite, but patches of sparry calcite fill in voids, probably where the semi-consolidated ooze was disturbed by burrowing animals or plant roots. Broken calcite shell fragments, some recognizable as gastropod forms, are abundant in some zones. Several layers in the rock are mudcracked and filled in by sparry calcite. These limestone beds were probably deposited in intermittent ponds or small lakes.

Alamo Creek Basalt (Tcac)

Dietrich and Maxwell (in preparation) extended the Alamo Creek Basalt into the Bofecillos Mountains from its type locality along Alamo Creek in the Big Bend National Park, where it was named and described by Maxwell et al. (1967). It crops out on the south and southeast faces of Lajitas Mesa where the maximum thickness is about 95 feet. If it is present on the north face, it does not crop out because the slope is extensively slumped and largely covered by colluvium; it thins markedly to the west along the south slope and is absent from the west face. The westernmost exposure in the map area is a small outcrop in the southeastern part of the Contrabando Lowlands, near the mouth of Contrabando Creek, where the member is less than 5 feet thick.

On the south face of Lajitas Mesa at MS 1 the Alamo Creek Basalt is a single flow about 90 feet thick. A basal flow breccia about 2 feet thick includes fragments of sandy clay and tuff up to 10 inches across. Both inclusions and basalt contain abundant calcite amygdules. The basalt is thoroughly altered to a gray-green granular rock that weathers red brown. A cliff-forming basal colonnade 30 feet thick overlies the flow breccia; in most places the columns do not extend to the base of the flow. Rock in the lower 3 feet of the colonnade is yellow brown to gray green and granular from intense alteration; it grades through a 2-foot zone to fresh basalt above. The relatively nonresistant entablature is about 40 feet thick; the upper 10 feet is altered and contains abundant amygdules of chalcedony and moss agate. A false colonnade is 13 feet thick but columns are poorly defined because of intense alteration which has made the rock dark gray or black; the lower 8 feet supports a nearly vertical cliff, and cliffs are steep in the upper 5 feet, although the rock is distinctly less resistant. Amygdules are abundant in the false colonnade; most are composed of calcite and celadonite, but a few contain silica. Above the false colonnade the upper 8 feet of the flow is a black to dark gray crumbly, sand- to gravel-size rubble of thoroughly altered highly amygdaloidal basalt, with calcite-filled interstices and vesicles.

Fresh rock is black; exposed surfaces weather red brown or yellow brown. Green to yellow-brown limonitic celadonite is common along fractures, as mottling in the groundmass, around vesicles, and in amygdules; where abundant, it colors the rock olive green.

One thin-sectioned sample of the fresh rock collected in MS 1 is subequigranular, felted to subophitic, aegirine-augite basalt. Slightly vacuolized laths of plagioclase less than 0.15 mm long comprise 60 percent of the rock. Aegirine-augite (15%) is mostly in pale-green subhedral to anhedral grains less than 0.2 mm long. Clusters of anhedral aegirine-augite (3%), iddingsite (1%), and opaque minerals (3%) about 0.1 mm in diameter are probably relict olivine grains. Limonitic celadonite (12%) occurs as mottling and along fractures, probably as an alteration product of interstitial glass. Limonite (1%) is a microcrystalline weathering product on exposed surfaces. Apatite (5%) needles are less than 0.15 mm long.

Bee Mountain Basalt (Tcbm)

The type locality of the Bee Mountain Basalt Member is on the west side of Bee Mountain in the Big Bend National Park, where Maxwell et al. (1967) named and described it. Dietrich and Maxwell (in preparation) extended it into the Bofecillos Mountains. It crops out in Lajitas Mesa, South Lajitas Mesa, and in the hills within a mile north of the Rio Grande between Fresno Creek and Madera Canyon. It is almost continuously exposed along the Rio Grande in Mexico between Lajitas and Madera Canyon. It does not crop out north or west of the Contrabando Lowland, although a complete section of Chisos is exposed there. It probably pinches out within a few miles north of the Rio Grande and less than a mile west of Madera Canyon.

The Bee Mountain Basalt generally thins westward, but the thickness ranges locally by as much as 100 feet because of relief on the surface over which it spread. North of Lajitas it is a maximum of 250 feet thick. The westernmost exposures which occur about 2 miles east of Santana Mesa are sporadic; probably the flow followed pre-existing stream valleys but did not cover the interfluves.

A representative section of the Bee Mountain Basalt is immediately north of State Ranch Road 170 near Lajitas. At this place the unit crops out continuously for several hundred feet across the southeast face of South Lajitas Mesa; it is between 150 and 220 feet thick as a result of relief on the base. An intensely altered red-brown weathering basal flow breccia less than a foot thick consists of fragments of scoriaceous basalt, limestone pebbles, sandstone, and tuff in a matrix of amygdaloidal basalt. The next 1 to 3 feet of the basalt is highly vesicular and amygdaloidal in moss agate (chalcedonic celadonite), celadonite, chalcedony, and calcite; the lower part weathers red brown, but the upper part is black to gray with yellow-brown to olive-green alteration products (limonitic celadonite?) in fractures and as mottling in the matrix. Above the highly amygdaloidal zone, the rock grades in a few inches to sparsely amygdaloidal black to gray basalt that composes the thick middle part of the flow. About 80 percent of this basalt is altered nonresistant rock that weathers to a granule- to pebble-size rubble; the remaining 20 percent is less altered, relatively more resistant rock that forms lenses up to 10 feet thick and as much as 100 feet across—perhaps the more fluid parts of the lava were subject to greater alteration before complete solidification. In the relatively unaltered rock, felted plagioclase laths up to 0.1 inch long are readily visible to the naked eye together with yellow and red-brown specks that are probably relicts of altered dark minerals. More vesicles and amygdules occur in the upper 5 to 15 feet; the upper few feet is nonresistant gray-green sand- to gravel-size rubble made up of altered basalt, and fragments containing moss agate, celadonite, chalcedony, and calcite that previously filled amygdules.

At the northeastern end of South Lajitas Mesa, the Bee Mountain Basalt is 190 feet thick; the character of the upper 113 feet resembles the basalt in the representative section, but the lower 77 feet is highly vesicular and amygdaloidal—far thicker than the 1- to 3-foot amygdaloidal zone present elsewhere at the base of the basalt. This amygdaloidal zone was probably deposited as a lobe of more fluid lava that broke through the viscous front of the flow and was later overridden by the more slowly advancing main flow. Nichols (1936) described similar "flow-units" in basalt flows in the San Jose Valley, Valentia County, New Mexico. Ross A. Maxwell (oral communication, March 1966) found similar zones—and lack of zones—in the Bee Mountain Basalt in the Big Bend National Park, but in some places he found nonzoned amygdaloidal basalt made up of two distinct flows separated by sedimentary rock. Thus, the Bee Mountain Basalt of the Park is made up of two flows; one, or perhaps both, is here and there broken into flow units.

One thin-sectioned sample of the unaltered rock is aphanitic to very fine-grained, equigranular, subophitic to ophitic iddingsite-augite basalt. Plagioclase forms 55% of the rock; it occurs in euhedral zoned andesine-labradorite laths as much as 2 mm long, in more sodic overgrowths, and as interstitial albite-oligoclase. Pale red-brown, anhedral to subhedral grains of augite (17%) partly enclose plagioclase laths. Olivine (1%) is mostly altered to iddingsite (19%). Interstitial celadonite and limonitic celadonite (2%) are probably alteration products of groundmass glass. Blocky opaque mineral (3%) grains about 0.3 mm long are included in other mineral species. Calcite (1%) fills sparse amygdules.

Mule Ear Spring Tuff (Tcm)

The type locality of the Mule Ear Spring Tuff Member is at Mule Ear Spring in the Big Bend National Park, where Maxwell et al. (1967) named and described it. Dietrich and Maxwell (in preparation) extended it into the Bofecillos Mountains. Except in middle and upper Fresno Canyon where it is sporadically present, the Mule Ear Spring crops out as a single ash flow of nonwelded to thoroughly welded tuff wherever its place in the section is exposed. Outcrops are scarce because slopes are generally covered by slump blocks and landslide material from the stratigraphically higher Tule Mountain Member, but a sufficient number of outcrops are distributed throughout the map area to suggest that the Mule Ear Spring was deposited as a more or less continuous sheet over all but the northeasternmost part. Its great areal extent is remarkable because it is only 3 to 10 feet thick, except in Tapado and Fresno Canyons where it is a maximum of 30 and 40 feet thick. The surface of ash-fall tuff over which this member spread must have had slight relief.

Ten thin-sectioned samples of the Mule Ear Spring are vitric to vitric-crystal tuff. Laths of sanidine (2 to 10%) and plagioclase (0 to 3%) and bipyramids of quartz

(< 1%) all up to 3 mm long are a useful criterion for distinguishing this ash flow from others in the section. Fresh aegirine-augite prisms as much as 1 mm long comprise about 1% of the rock; hematite-magnetite-rimmed needles of basaltic hornblende (less than 1%) are up to 0.7 mm long. Clots of hematite, limonite, celadonite, zeolites, and clay minerals are probably completely altered dark minerals. Opaque minerals (1%) occur as equant grains about 1 mm across. Fragments of aphanitic igneous rock (0 to 5%) are mostly altered to hematite-limonite, celadonite, and zeolites or clay minerals. The matrix of the rock consists of glass shards—mostly devitrified and axiolitic—and celadonite, zeolites, clay minerals, chalcedony, opal, and finely disseminated hematite-limonite. Devitrified pumice fragments as much as 5 cm long comprise up to 10% of the rock. Calcite (0 to 5%) fills voids or replaces matrix material.

In a typical exposure, the contact with the underlying strata is abrupt. At several places, a few inches to several feet of light gray bentonite is present at the base. Above the bentonite or the underlying strata the rock grades in a few inches to rock that differs in appearance from place to place because of variations in welding, devitrification, vapor phase crystallization, alteration, and coarse crystallization. In the top few feet, the rock grades to friable, nonwelded, slightly indurated brown to gray tuff.

In a general way, welding increases with thickness, but exceptions are numerous—the tuff is slightly welded in some places where the member is less than 10 feet thick, but elsewhere it lacks welding even though it is 20 feet thick. Welding is greatest a few feet above the base. At no place is the tuff welded to a basal obsidian, but at several places, the welded zone is highly eutaxitic and shard structure is eliminated by compaction and subsequent crystallization. In these thoroughly welded zones, white miarolitic lenses up to several centimeters long parallel and accentuate the eutaxitic structure. They are made up of crystals of chalcedony or cristobalite-feldspar intergrowths similar in form to the axiolitic structure seen in devitrified shards of other samples. Some lenses are replaced pumice fragments and others are filled void spaces; others are probably the result of crystallization of the matrix. Their present shape is due to flattening during welding.

The appearance of the rock is greatly changed by devitrification, vapor phase crystallization, and alteration. In many places the rock is porcellaneous as a result of extensive silicification of the matrix; radiating fibrous and colloform aggregates of chalcedony, opal, or cristobalite-feldspar intergrowths have partly filled interstices between fragments, crystals, and axiolitic devitrified shards. Zeolites or clay minerals fill the centers of many interstices, and minute grains of opaque minerals and celadonite speckle the matrix. Hematite-limonite forms rims around devitrified shards, is concentrated in and around altered dark minerals or accidental fragments, and is disseminated as a fine dust throughout the matrix; the red, red-brown, brown, pink, or orange color of the rock is dependent on type, concentration, and distribution of these iron oxides.

Coarse crystallization of the Mule Ear Spring Tuff occurred near the base where the member is especially thick and thoroughly welded. In Tapado Canyon, southeast of Tapado Dome, the matrix of the rock in the lower few feet of a 17-foot section is coarsely crystallized to equigranular interlocking anhedral feldspar grains up to 0.5 mm long with undulose, composite extinction. The crystallization probably occurred during or soon after devitrification while the rock was still hot; the relatively thick section of the ash flow above probably supplied heat and insulation, which promoted the annealing process. Similarly crystallized tuff on the east face of Santana Mesa has up to 18 percent of subhedral to anhedral albite-oligoclase grains up to 0.2 mm long. This rock is gray and has a stony aspect not found elsewhere, probably as a result of the coarse crystallization.

Basalt (Tcb)

Several flows of basalt crop out in the map area either within the few feet below the Tule Mountain Member or, in the absence of the Tule, bracketed between the Mule Ear Spring Tuff (below) and the Mitchell Mesa Tuff (above). These flows covered small areas; they are in South Lajitas Mesa and in Carrasco, Tapado, Llano, and Saucita Domes.

The thickest flow is in Tapado Canyon where a flow of seriate trachytic and ophitic olivine augite basalt in MS 9 is 109 feet thick. It consists of a lower 18-foot zone of slightly vesicular and amygdaloidal basalt, a 78-foot nonvesicular middle zone, and a 13-foot nonresistant scoriaceous zone of thorough alteration, now mostly weathered to a pebble-size rubble partly cemented with calcite.

A flow of red-brown to dark-gray altered and weathered limonitic and calcitic trachytic iddingsite augite basalt, up to 30 feet thick, crops out immediately under the Tule Mountain Trachyandesite Porphyry on the west and south faces of South Lajitas Mesa. In the Carrasco Dome, an altered and weathered augite basalt flow crops out sporadically between the Mule Ear Spring Tuff and the Mitchell Mesa Tuff; its thickness is less than 10 feet. Altered and weathered dark lava flows are exposed in the same stratigraphic position in the Llano and Saucita Domes. Thickness in the Llano Dome is less than 10 feet; in the Saucita Dome it is more than 30 feet, and the base is not exposed.

Tule Mountain Trachyandesite Porphyry (Tetm)

The type section of the Tule Mountain Member is at Tule Mountain in the Big Bend National Park where Maxwell et al. (1967) named and described it. Dietrich and Maxwell (in preparation) extended it into the Bofecillos Mountains. It crops out in the southeastern part of the map area and in several breached domes where its stratigraphic interval is exposed. The member does not crop out in Fresno Canyon north of its pinch-out near Rincon Mountain or in the Llano, Saucita, and Carrasco Domes. It is present to the southeast in the Big Bend National Park and crops out in the Rio Grande Valley in Mexico at least as far west as the Santana Bolson and probably as far west as Redford. It does not crop out in quadrangles north of the Bofecillos Mountains area. Thus, it probably pinches out south of a line due west from Rincon Mountain and against the Solitario Dome and Terlingua Monocline from the south and east.

The Tule Mountain Trachyandesite Porphyry is a cliff-forming lava flow that is normally 200 to 300 feet thick; it is thickest in the northeast slope of Santana Mesa, where Dietrich and Maxwell (in preparation) measured 350 feet. A poorly defined orange-weathering scoriaceous basal flow breccia less than a foot thick is overlain by a vesicular zone a few feet thick. It grades upward to green, brown, or black, nonvesicular, trachyandesite porphyry typical of most of the unit. The trachyandesite, particularly the upper half, exhibits a marked swirled flow structure; it tends to split along the flow foliation producing abundant spalls, which litter the slopes below the outcrop. The spalls are mostly 4 inches to 2 feet across, but some are as large as slump blocks. The upper 10 feet is vesicular or scoriaceous and weathers orange to red brown. The Tule Mountain Member is probably a single flow.

One thin-sectioned sample is celadonitic aegirine-augite trachyandesite porphyry. Zoned to nonzoned plagioclase phenocrysts (21%) are as much as 6 mm long and have rhombic outlines. Pale-green stubby needles of aegirine-augite (7%) are up to 3 mm long; most are fresh, but some crystals or parts of crystals are completely altered and filled in by celadonite, hematite, or chalcedonic celadonite. Blocky opaque mineral grains 1 mm across are commonly surrounded by hydrated iron oxides. The groundmass is felted feldspar laths up to 0.1 mm long with finely divided interstitial opaque minerals and hematite, celadonite, zeolites, and clay minerals. Prisms of apatite as much as 0.5 mm long comprise less than 1% of the rock.

Mitchell Mesa Tuff

The top of the Mitchell Mesa Tuff is one of the most useful horizons for stratigraphic correlation in the Big Bend region of Texas. From its type locality in the northern part of the Buck Hill quadrangle, where it was named and described by Goldich and Elms (1949), it has been traced over a large area to the north and west of the Bofecillos Mountains. It is present as a nearly continuous sheet extending about 50 miles north-northeast to the Cathedral Mountain quadrangle (McAnulty, 1955). It occurs in some places in the Davis Mountains north of Alpine, Texas (D. E. Gorski, oral communication, July 1966). DeFord (1958) correlated it with the Brite Ignimbrite in the Rim Rock Country. Dietrich (1965) estimated a minimum areal extent of 2,500 square miles in the United States, and Haenggi (1966) added a minimum of 700 square miles in Mexico.

In the map area, the Mitchell Mesa is a cliff-forming ash flow that lies either directly above the Tule Mountain Member or above as much as 20 feet of Chisos tuff that separates the two units; it is present nearly everywhere that its stratigraphic interval is exposed. Except on the flanks of the Solitario and Contrabando Domes—areas that were probably high topographically at the time of deposition—it was probably a more or less continuous sheet over the entire map area.

The tuff is mostly between 20 and 35 feet thick; maximum thickness is about 50 feet. It thins markedly in the southeastern part of the map area; at two outcrops on South Lajitas Mesa it is 5 feet and 2 feet thick; on the northeastern end of Santana Mesa it is less than 10 feet thick.

Within the lower few feet, the rock grades upward from friable, white to buff tuff to the well-indurated resistant rock characteristic of most of the formation. Most of the rock is generally nonwelded to slightly welded, but in some places where the formation is more than 30 feet thick, the rock is foliated with pronounced eutaxitic structure in a broad zone about midway between the base and the center. The upper part is a zone of nonresistant friable tuff that may be only a few feet thick or that may comprise more than half of the ash flow; the thickness differs with degree of welding, devitrification, vapor phase crystallization, and alteration. Spherical caves up to 5 feet in diameter abound in this zone, developed on cliffs and particularly on the rolling surface that commonly forms on the upper part of the ash flow. Similar caves in the Valles Mountains, New Mexico, were formed by wind erosion, according to Ross and Smith (1961).

Five thin-sectioned samples of the rock are vitric-crystal tuff. An excellent criterion for field identification is 5 to 20% chatoyant, euhedral crystals of sanidine as much as 4 mm long; they are unaltered to slightly vacuolized and many are broken or fragmented. Bipyramids of quartz up to 4 mm long are commonly embayed and broken; they are about 1/5 as abundant as the sanidine crystals. Pale-green stubby needles of aegirine-augite (less than 1%) up to 4 mm long are fresh to slightly celadonitic. Needles of basaltic hornblende (less than 1%) up to 1 mm long are fresh to intensely altered to celadonite, hematite, and magnetite. Clots of fine-grained celadonite, clay minerals, zeolites, chalcedony or opal, hematite-limonite, and opaque minerals comprise up to 5% of the rock; they are probably completely altered dark minerals. Blocky grains of opaque minerals (1%) are as much as 0.5 mm across. Fragments of hematitic and celadonitic, aphanitic igneous rock range from 0 to 10% of the tuff; they were probably incorporated into the rock from the substrate over which the ash flowed. The matrix consists of devitrified, axiolitic glass shards that are commonly obliterated by interstitial celadonite, zeolites, clay minerals, opal, and chalcedony. The matrix of some samples contains alkali feldspar in interlocking, seriate, elongate grains up to 0.2 mm long that probably formed either during devitrification or through later recrystallization. Devitrified pumice fragments as much as 10 cm long make up 1 to 10% of the rock. Apatite needles up to 0.3 mm long are a trace constituent.

Fresno Formation

The Chisos and Mitchell Mesa Formations include regional volcanic units, probably from sources outside of the map area. At about the same time as the effusion of the Mitchell Mesa, however, the Bofecillos Volcano began erupting ash and latitic lava; tuff and lava flows from this source were interbedded with minor amounts of regional tuff and with local conglomerate and sandstone. Extrusive activity was accompanied by intrusions; concordant intrusions domed the overlying strata, and strata deposited concurrently or subsequently were thinned or pinched out against the flanks. The Solitario was breached by the time the upper Fresno flows were extruded; the flows are interbedded with conglomerate containing rock fragments derived from within the uplift. Strata that were deposited under this complex, predominantly local regimen, are exhibited in the Fresno Formation.

As defined by Dietrich and Maxwell (in preparation) at its type locality in the Bofecillos Mountains, the Fresno Formation consists of strata above the Mitchell Mesa Tuff and below the Santana Tuff; where the Santana is absent the contact is placed at the base of the lowest lava or tuff of the overlying Rawls Formation. Near the center of the Bofecillos Volcano the Fresno Formation is almost entirely lava flows; several miles from the center, the formation is predominantly tuff or sedimentary rock, containing only a few flows near the top. A valley-fill sequence and a sodic rhyolite are exposed only in the northern part of Fresno Canyon; they comprise much less than 1 percent of the total volume of the Fresno Formation in the map area.

The maximum thickness of the Fresno Formation in the vent area may be inferred from a 1,000-foot section in upper Tapado Canyon 6 miles southwest of the main vent. Allowing for the depositional slope of the lava flows away from the cone, the Fresno Formation in the volcanic center was probably 1,200 to 1,500 feet thick before erosion. Away from the vent, the Fresno was probably about 500 to 800 feet thick where not thinned over intrusive domes.

Fresno Formation Undifferentiated (Tf)

Rock mapped as undifferentiated Fresno Formation includes ash-fall tuff, eolian tuff, eolian tuffaceous sandstone, fluvial tuffaceous sandstone, and near the top, conglomerate and conglomeratic sandstone. It makes up the lower part of the Fresno Formation at most places and is interbedded with some of the flows in the upper part.

Fresno tuff is mostly friable, bedded, cross-bedded, massive, and sandy. "Root holes" like those in Chisos tuff are common. Eolian cross-beds with 4-foot amplitude occur in zones up to 100 feet thick. In most places there is no sharp break between bedded, massive and cross-bedded zones, and there is a continuous gradation in rock type from ash-fall tuff through eolian cross-bedded tuff to eolian tuffaceous sandstone; grains, including pumice and autoclasts of tuff, are progressively better defined and many—even some of the larger crystals of feldspar and quartz—are rounded in the eolian sandstone.

The tuff is white, buff, gray, or green; pale-green to yellow-green (2 G 7/2 to 7 GY 6/4 and lighter values of Goddard et al., 1951) cross-bedded tuff is characteristic of the Fresno Formation and its stratigraphic equivalent, the Tascotal Formation. The color is imparted by finely crystalline celadonite; it is brightest green where it is surrounded by chalcedony probably because the silica protected it from oxidation in the weathering environment.

Four thin-sectioned samples of the rock are vitric-crystal tuff and tuffaceous sandstone. Crystals of sanidine (10 to 20%) and plagioclase (2 to 10%) up to 2 mm long are unaltered to thoroughly vacuolized and commonly embayed or broken. Fragments of bipyramids of quartz (1 to 4%) are mostly less than 1 mm across. Needles of basaltic hornblende (0 to 2%) and stubby needles of aegirine-augite (0 to 1%), each up to 1 mm long, are fresh to thoroughly altered and grade to clots of celadonite, opaque minerals, and hematite-limonite that comprises up to 15% of the rock. Fragments (1 to 15%) of aphanitic igneous rock are thoroughly altered to hematite, celadonite, zeolites, and clay minerals. The matrix consists of devitrified, axiolitic glass shards, celadonite, zeolites, clay minerals, chalcedony, and opal. Pumice fragments as much as 3 inches in diameter are mostly sparse, but the rock in a few exposures is up to 10% pumice. In the tuffaceous sandstone the matrix contains rounded autoclastic fragments as much as 2 mm in diameter.

Most of the fluvial sandstone interbedded with the tuff is only slightly reworked tuff or eolian sandstone. It was perhaps deposited during storms by sheet wash or rill wash off the volcano; rapid deposition of ash probably choked through-flowing streams that might have thoroughly reworked the tuff. Most of the fluvial sandstone contains a greater percentage of accidental fragments; framework grains, including poorly cemented grains of tuff, are well defined and easily distinguished in thin section from the matrix.

Gradual upward transition from ash-fall tuff, in the upper Chisos and lower Fresno, to eolian sandy tuff in the Fresno Formation, probably reflects more rapid deposition of volcanic ash that smothered or poisoned soil-holding vegetation and was then free to drift when not wet from recent rain.

The upper part of the Fresno Formation contains abundant conglomerate and sandstone in some places interbedded with flows. Individual beds range from a few inches to 20 feet thick, and zones composed dominantly of conglomerate and sandstone are up to 130 feet thick.

The conglomerate is derived from two major source areas:

(1) Most eroded from the Bofecillos Volcano; conglomerate is interbedded with the flows and commonly extends farther from the vent area than the flows. Included rock fragments are mostly angular to rounded boulders and cobbles of volcanic rock eroded from Fresno flows.

(2) Conglomerate eroded from the Solitario is present

northeast of the Bofecillos Volcano in the upper part of Fresno Canyon. It consists mostly of rounded cobbles and pebbles of cherty Cretaceous limestone, but in the upper part of the section it also contains abundant recognizable fragments of Maravillas (Ordovician) black chert; Caballos (Devonian-Mississippian) white, green, and red-brown chert; Tesnus (Carboniferous) red-brown siliceous shale; and "shut-up" (basal Cretaceous) conglomerate. These units are described in detail by Powers (1921), J. L. Wilson (1954), Herrin (1958), and Irvin (1957).

Lava Flows of Bofecillos Eruptive Center

The sequence of Fresno flows of the Bofecillos Volcano grades upward from latite (Tfl) to latite porphyry (Tflp); the contact between the two rock types is more or less arbitrary. Trachyandesite (Tfa) and a single flow of olivine basalt (Tfb) probably issued from fissures on or near the volcano.

Latite (Tfl).—The lower flows are mostly nonporphyritic or slightly porphyritic latite. Few flows extend far from the eruptive center; thick exposures in breached domes and in deeply incised canyons belong to the lower part of the Fresno Formation near the vent.

Most flows range from 20 to 75 feet thick. In general, a red-brown to black-weathering, highly scoriaceous basal flow breccia less than 2 feet thick is overlain by a vesicular or amygdaloidal zone less than 5 feet thick. Most of each flow is dark-gray to light-gray, nonvesicular aegirine-augite, iddingsite latite; in places olive-green limonitic celadonite mottles the rock or colors the entire groundmass. Some flows have a prominent layered or swirled flow structure and the rock weathers in curved slabs or spalls along flow laminae. A vesicular or scoriaceous zone from 5 to 35 feet thick occurs at the top. Acetate peels of samples collected in upper Tapado Canyon and Rancherias Canyon (MS 7) indicate that the latite resembles the matrix of latite porphyries from the Bofecillos Volcano.

Trachyandesite (Tfa).—A single distinctive flow of mafic trachyandesite as much as 350 feet thick is present southeast of the vent area between the east end of Santana Mesa and Primero Canyon; probably the same flow, or one from the same pulse of eruption, is exposed east and northeast of the vent, north of Rincon Mountain in Fresno Canyon, and in Llano and Saucita Domes. In the lower part of Fresno Canyon (MS 4), it is 115 feet thick. At the base is a laterally discontinous 1-foot zone of red-brown and black banded, perhaps flow layered, obsidian that is either a chilled basal flow breccia or, more probably, fused tuff beneath the flow. Above the obsidian is a 5-foot zone that grades from highly vesicular rock near the base to nonvesicular trachyandesite at the top. Most of the flow is cliff-forming unaltered gray trachyandesite. The upper 20 feet grades through vesicular trachyandesite to black scoriaceous rubble in the upper few feet, consisting mostly of gravel-size fragments with a few blocks nearly a foot across.

Four thin-sectioned samples are mafic, celadonitic, hornblende-aegirine-augite trachyandesite. Zoned plagioclase phenocrysts up to 2 mm long comprise 0 to 5% of the rock; they are commonly corroded and embayed and partly overgrown by alkali feldspar. The groundmass feldspar is trachytic or subtrachytic, interlocking, strongly seriate plagioclase laths up to 1 mm long; rims are thoroughly vacuolized alkali feldspar. Olivine (0 to 5%) is mostly altered to pseudomorphic iddingsite. Intergranular, fresh to slightly celadonitic aegirine-augite comprises a few percent of most samples but ranges as high as 20 percent. Intergranular hornblende (0 to 20%) is mostly thoroughly celadonitized. Blocky crystals of opaque minerals (ca. 1%) are about 1 mm across. Hydrated iron oxides cluster with celadonite and opaque minerals around relicts of dark mineral grains. Apatite needles (less than 1%) are up to 0.4 mm long.

Latite porphyry (Tflp).—Most of the Fresno lava extruded from the Bofecillos center of eruption is latite porphyry (Tflp); the thickest flows are about 250 feet thick, but most are less than 100 feet thick; average thickness is 20 to 80 feet; they may lie directly on other flows or on thin (unmapped) zones of tuff, sandstone, conglomerate, or volcanic mudflows. The flows are highly varied: they may erode to steep unscalable cliffs or relatively gentle vegetated slopes; they may be thoroughly vesicular or scoriaceous or the vesicles may be restricted to thin zones near the top and base; jointing may be columnar, irregular, or follow laminar or swirled flow structure—spacing between joints may be a few inches or several feet; alteration or weathering may be intense or slight and differs with position in the flow; angular or rounded weathered fragments range in size from gravelly rubble to slump blocks.

In general, the rock is intergranular or hypidiomorphic granular, felted or subtrachytic, aegirine-augite or augite, iddingsite porphyry. Texture and composition range widely between flows. Although the average rock is latite, it ranges from trachyandesite to trachyte. Most rock is dark or light gray, but much is weathered or altered red brown from hematite-limonite staining and some is gray green from interstitial celadonite present either as mottling or distributed throughout the groundmass. Feldspar phenocrysts are cloudy white or pink.

Nineteen thin-sectioned samples of Fresno and Rawls latite porphyry reflect the variability of the different lavas of the volcano. Plagioclase phenocrysts, which comprise 5 to 40% of the rock, are from a few millimeters to 1 cm long; most are corroded, embayed, and slightly vacuolized; they range from albite to andesine and most are zoned and contain alkali feldspar overgrowths; they may be Carlsbad-, albite-, or pericline-twinned or may be nontwinned; many form glomerocrystic clusters with pyroxene that resemble syenodiorite intrusions near the vent area. K-feldspar phenocrysts (0 to 30%) are microcline, microcline-perthite, or sanidine laths up to 1 cm long; most are corroded, embayed, and slightly vacuolized and many have rhombic outlines; Carlsbad twins abound. Iddingsite (0 to

12%) pseudomorphically fills clustered relicts of olivine crystals. Stubby needles of aegirine-augite or augite (0 to 7%) as much as 2 mm long and needles of basaltic hornblende (less than 1%) up to 5 mm long are fresh or weakly to thoroughly altered to opaque minerals and celadonite. Blocky phenocrysts of opaque minerals (1 to 2%) are up to 1 mm across. Groundmass feldspar is felted to subtrachytic subequigranular to strongly seriate laths of plagioclase and alkali feldspar as much as 0.3 mm long. Intergranular to the feldspar is aegirine-augite, augite, hornblende, or basaltic hornblende. Celadonite, hydrated iron oxides, and disseminated opaque minerals are interstitial to the feldspars and dark minerals. Apatite (1 to 2%) occurs as thin needles up to 0.5 mm long and as prisms up to 2 mm long.

Basalt (Tfb)

A single flow of Fresno basalt, in places about 100 feet thick, crops out below the Santana south of the vent area in a small canyon north of the Santana Bolson between Rancherias and Panther Canyons. Both in outcrop appearance and in petrography, the rock resembles basalt in the lowest member of the Rawls Formation (Trlb); it probably represents an early pulse in the phase of eruption recorded by Rawls member 1. The black rock which weathers red brown is strongly seriate, intergranular deuterically or post-magmatically altered, slightly porphyritic, augite or aegirine-augite basalt.

Sodic Rhyolite (Tfsr)

In the middle part of Fresno Canyon, a layer of sodic rhyolite up to 10 feet thick is exposed at or near the base of the Fresno; it contains sparse, broken, and partly fragmented phenocrysts of quartz, sanidine, and less commonly of hornblende. It is overlain with sharp contact by massive tuff, and it rests on massive tuff, on Comanche limestone, or on flaggy Boquillas limestone. In some places the rhyolite is brecciated, either by flowage during emplacement or by subsequent jointing. In one thin-sectioned sample of the rock, the original groundmass texture is everywhere obliterated. The rock is mostly horizontally streaked or layered with undulose discontinuous zones of fibrous chalcedony, and perhaps zeolites in sheaf-like colloform bundles; some of the layers are disrupted by stylolites. Interstitial microscopic opaque minerals, hydrated iron oxides, and aegirine-augite or riebeckite color the normally white silica gray to black, red, brown or orange, and gray green or blue gray.

The origin is uncertain. The rock is probably not intrusive because it rests on a structurally varied stratigraphic horizon that in some places, particularly in massive tuff, is unsuited for the emplacement of a concordant sill. It was probably not a lava flow either, because so silicic a lava would probably be too viscous to spread so thin and extensive a sheet. It is probably pyroclastic; if it were originally a volatile- and alkali-rich vitric tuff, devitrification and extensive alteration could have produced a unit with the observed composition and field relationships. Additional silica and perhaps alkalies were probably added in places by ground water; large bodies of silica mapped about a mile to the north are perhaps completely silicified sodic rhyolite.

Valley-Fill Sequence

Where the present road ascends the upper part of Fresno Canyon, a valley 400 feet deep was eroded into undifferentiated Fresno tuff (Tf) and the underlying Boquillas Formation. Thereafter, it was filled before effusion of the Santana Tuff by:

Tfvm, volcanic mudflow
Tfat, ash-flow tuff
Tf, undifferentiated conglomeratic sandstone
Tfbr, volcanic breccia

Volcanic breccia (Tfbr).—The massive volcanic breccia is as much as 100 feet thick. It is made up of closely spaced, but not self-supporting, angular to slightly rounded fragments of white to light-gray flow-banded rhyolite. Most fragments are 3 to 12 inches in diameter, but some range up to 6 feet. The matrix consists of gradational patches of red-brown to orange and gray to white tuff-like altered rhyolite. Pumice fragments are sparse, but common lens-shaped cavities up to 10 inches long are probably pumice relicts. At several places the breccia is made up of as many as 6 subunits; they are vaguely defined lenses up to 60 feet thick and several hundred feet across whose outlines are distinguished by changes in matrix color and induration over a vertical distance of a few inches. Contacts between the subunits are undulose, with as much as 20 feet of relief in exposures about 100 feet across.

The breccia is probably a single flow-brecciated lava flow (R. L. Smith, oral communication, November 1966); the subunits were perhaps formed through differences in fluidity of the lava, which permitted some zones in the rhyolite to flow faster than other parts.

Conglomeratic sandstone (Tf).—Here and there, well-bedded conglomeratic sandstone, mapped as undifferentiated Fresno Formation, is present between the breccia (Tfbr) and ash-flow tuff (Tfat); it is up to 60 feet thick. In most beds, the coarsest clasts are about 3 inches in diameter, but some beds contain boulders up to 2 feet across. The matrix is tuffaceous sandstone; constituent clasts are mostly blue-gray to white rhyolite like that in the breccia below. Micritic limestone clasts are also present, and some contain abundant fossil gastropods; black chert clasts are sparse.

Ash-flow tuff (Tfat).—The ash-flow tuff is up to 30 feet thick, and except for about 6 inches of dull gray friable tuff at the base and a few feet of similar rock sporadically present at the top, it looks the same from base to top; it is gray to white, porous, porcellaneous, nonwelded, vitric or vitric-crystal tuff with partly fragmented crystals of sanidine and quartz a few millimeters across, and with 5 to 10 percent lensoidal pumice fragments up to 15 cm long. It weathers orange or buff. It closely resembles the Santana Tuff; the two units may be genetically related.

Volcanic mudflows (Tfvm).—The uppermost unit of the valley-fill sequence is about 200 feet thick, consisting of four or more massive volcanic mudflows up to 100 feet thick with interlayered volcanic conglomerate and conglomeratic sandstone; toward the top it includes a few zones of tuff up to 8 feet thick and ash-flow tuff sheets up to 5 feet thick laden with fragments of nonwelded pumice and flow-banded rhyolite.

The volcanic mudflows consist of angular to rounded fragments of biotite-bearing latite; they are mostly cobble size and the largest are about 2 feet across. The matrix is white to gray tuff and tuffaceous sandstone. A gradation in the upper part of some of the flows from massive breccia below to bedded conglomerate above indicates that the material was water-charged and that the upper parts were probably reworked by the runoff.

The latite of the mudflows closely resembles latite of the Bogles Domes immediately to the west and southwest. This resemblance suggests that some of the Bogles intrusions were deroofed soon after they were emplaced and thereby supplied the blocks to the mudflows.

Santana Tuff

Dietrich and Maxwell (in preparation) named and described the Santana Tuff. The type locality is in Santana Mesa and nearby cliffs in the south-central part of the map area. It is ash-flow tuff composed of one to at least four partly welded ash flows. West of Santana Mesa at the mouth of Panther Canyon it is about 550 feet thick. The Santana thins gradually to the northwest and pinches out across Tapado Canyon. It thins abruptly to the north and northeast, probably because of faulting before or during effusion; it pinches out over Fresno flows on the flanks of the Bofecillos volcanic cone but extends almost to the head of Fresno Canyon as a layer mostly less than 5 feet thick. Maxwell and Dietrich (1965) reported the northernmost known outcrop of Santana at the southern end of Tascotal Mesa, about 5 miles north of the map area. During air reconnaissance south of the map area, W. R. Muehlberger (oral communication, April 1966) noted that a tuff that looks like the Santana at Santana Mesa extends at least 10 miles into Mexico.

The Santana forms distinctive orange cliffs; stream valleys cut into it are narrow gorges with near-vertical walls. Normally, the longitudinal profiles are uneven because zones within the Santana differ in resistance to erosion; relatively level stretches are interrupted by commonly insurmountable, fall zones up to 100 feet high.

The rock is nonwelded to thoroughly welded vitric-crystal tuff; the high percentage of glassy sanidine crystals and generally low percentage of lithic fragments are, in general, sufficient to distinguish it from similar tuff in the map area. Pumice fragments up to 1 or 2 inches across are abundant; however, some range up to a foot in diameter. Where nonwelded it is friable, dull, porous, gray, buff, or white devitrified tuff with interstitial zeolites and clay minerals. The nonwelded material grades to well-indurated porcellaneous pink or dark red-brown rock. The induration is probably the result of a complex interaction of devitrification, vapor phase crystallization, and deuteric alteration of dark minerals, characteristic of the nonwelded zone of vapor phase crystallization of Smith (1960), although secondary chalcedony, opal, zeolites, and clay minerals commonly predominate in the rock over vapor phase minerals. Most of the welded tuff is thoroughly indurated, porcellaneous rock that is slightly to intensely eutaxitic; it probably corresponds to Smith's partly welded zone of vapor-phase crystallization, although some may be devitrified vitrophyre of his zone of dense welding.

Where the Santana is less than 100 feet thick, it is mostly a single cooling unit and probably a single ash flow. A friable nonwelded zone at the base, a few inches to several feet thick, grades upward to the vapor-phase zone of nonwelded tuff. Where the Santana is more than 50 to 70 feet thick eutaxitic structure indicative of slight to moderate welding is common in a zone beginning 10 to 20 feet above its base; the structure grades from faint at the top and bottom of the zone to moderate or intense near the center. The thickness of this zone increases with thickness of the unit as a whole; it is overlain by the 20- to 50-foot upper nonwelded zone of vapor-phase crystallization. The upper 5 to 50 feet of the Santana is friable nonwelded tuff like that at the base.

The Santana is more than 100 feet thick only in the south-central part of the map area. There it is mostly one or two compound cooling units consisting of alternating gradational layers of nonwelded, slightly, moderately, or intensely welded tuff; in fact one to six or more ash flows and two cooling units may be inferred in some places.

Twelve thin-sectioned samples of the Santana are vitric-crystal tuff. Sanidine mostly makes up about 5% of the rock, but it ranges from 1 to 13%; it occurs in glassy, commonly broken stubby laths up to 4 mm long that are commonly corroded and embayed; some is perthitic and a few have graphic intergrowths with quartz; Carlsbad twins abound. Plagioclase (0 to 1%) is in corroded and embayed commonly broken stubby Carlsbad- and albite-twinned laths up to 4 mm long. Quartz (0 to 4%) occurs in partly corroded, embayed, fragmented, and strained glassy bipyramids up to 3 mm across; liquid inclusions abound and some crystals have chalcedonic overgrowths. Augite (0 to 1%) is in stubby needles up to 3 mm long with hematite and opaque minerals filling fractures and forming coronas; some is aegiritic. Needles of basaltic hornblende (0 to 1%) up to 0.1 mm long are mostly thoroughly altered to celadonite and opaque minerals. Clots of celadonite, opaque minerals, and hematite are probably relicts of altered dark minerals (0 to 4%). Blocky crystals of opaque minerals (1%) are up to 1 mm across. Fragments of aphanitic igneous rock and welded tuff (0 to 5%) are altered to celadonite, hematite, zeolites, and clay minerals; most are a few millimeters or less in diameter, but some are several centimeters long. The matrix is devitrified axiolitic glass shards with interstitial celadonite, zeolites, clay minerals, and chalcedony; in some samples the matrix consists of anhedral interlocking grains of quartz and alkali feldspar up to 0.2 mm in diameter with interstitial celadonite—such a matrix may have resulted from recrystallization or coarse crystallization during or soon after devitrification. Devitrified pumice fragments (mostly less than 10%) are filled by the same suite of alteration minerals as the matrix.

The source of the Santana Tuff is probably in Mexico south or southwest of Santana Mesa. The Santana thickens and the number of ash flows increases in that direction, probably because contemporaneous faulting or folding formed a topographic basin there. Perhaps the roof collapsed into its own magma chamber and the magma was displaced upward as pyroclastic material filled the depression thus formed. The body of rhyolite porphyry (Tirp) at the southeastern end of Santana Mesa is similar in composition to the Santana; it may be an intrusion associated with the Santana vent area.

Rawls Formation

At about the same time that the Santana Tuff was spread, volcanic eruption in the Bofecillos Mountains became more complex. In addition to latite porphyry and latite from the Bofecillos Volcano, trachyandesite, basalt, and basalt porphyry flowed out, probably from fissures in and around the eruptive center. Moreover, ash-fall and ash-flow tuff layers were spread over the area, probably from vents within or nearby the map area. Block faulting began before extrusion of the uppermost basalts which are interbedded with graben-filling sedimentary rock. A maximum of about 1,200 feet of volcanic and associated strata were deposited, but the section is thinner over topographically high areas —for example, over intrusive domes and over the Fresno flows of the Bofecillos Volcano. The Rawls Formation is the stratigraphic record of the interfingering of units of these diverse volcanic rock types.

Goldich and Seward (1948) named the Rawls Formation to comprise the lava flows capping Tascotal Mesa which overlie sedimentary and pyroclastic rock of the Fresno equivalent, Tascotal Formation. As redefined by Dietrich and Maxwell (in preparation) and as used in this report, the Rawls includes volcanic and associated sedimentary strata in the Bofecillos Mountains that lie above the Santana Tuff. In the absence of Santana, the base of the Rawls is the lowest lava or tuff unit that overlies the Santana.

In the map area, this report modifies and extends Dietrich's (1965) nomenclature of units within the Rawls to reflect the increasing complication of the Rawls Formation in the Bofecillos Mountains area. Thus, this report divides the Rawls into 9 numbered members. Except for member 8, each member represents a major pulse of eruption characterized by an index rock type; member 8 is characterized by two such index rock types.

Numbers of members are used *ordinally*; ascending stratigraphic position is indicated by higher numbers. It is possible, however, to move *laterally* in the stratigraphic section from a higher to a lower number (fig. 3). Subdivisions of members indicate *only* the rock type—no stratigraphic position is implied, and indeed, the same rock type may be found at several stratigraphic positions within a member.

Member 1

The lowest member of the Rawls Formation consists of as many as six basalt flows, and interbedded volcanic conglomerate sandstone and tuff. A few flows of trachybasalt porphyry (Trlbp), like that of member 4, and thick sequences of undifferentiated sedimentary rock and tuff (Trl) are mapped separately. Most flows are 10 to 30 feet thick; maximum thickness is about 50 feet. The maximum thickness of basalt flows and interbedded sedimentary rock is about 160 feet near the mouth of Rancherias Canyon (MS 7), but in most places it is less than 75 feet thick. The member thins toward the northeastern boundary of the map area and pinches out against Fresno flows both on the Bofecillos volcanic cone and on the flanks of the Solitario.

At the mouth of Bofecillos Canyon, member 1 (MS 13) is a single flow about 50 feet thick. The upper 3 to 6 feet of pale buff tuff over which it spread is altered pink probably by the hot lava. A sporadically present basal flow breccia up to a foot thick is composed of a matrix of tuff with scoriaceous black basalt fragments up to 5 inches across. Above the breccia is a red-brown to pink weathered zone up to a foot thick that grades upward to black unweathered basalt. Most of the flow is black homogeneous to slightly amygdaloidal or vesicular basalt with prominent horizonal and vertical jointing. It erodes to a blocky talus with angular fragments up to a foot across. In the upper 10 feet of the flow the member grades from solid basalt to a breccia of scoriaceous basalt fragments in tuff similar to, but thicker than, the basal flow breccia.

Ten thin-sectioned samples of the rock are trachytic to subtrachytic, intergranular aegirine-augite to augite-olivine basalt. Most samples have less than a few percent of plagioclase phenocrysts, but some of the rock contains as much as 40% phenocrysts; where present, they are corroded and commonly embayed, zoned stubby laths up to 5 mm long. Before alteration, the rock contained 5 to 20% strongly seriate grains of olivine that ranged from 0.1 mm to 2 mm in diameter; almost all olivine is altered to pseudomorphic iddingsite or antigorite. Stubby needles of augite (up to 10%) are as much as 2 mm long. Blocky phenocrysts of opaque minerals (1 to 5%) are up to 0.5 mm across. The groundmass plagioclase is narrow seriate, trachytic or subtrachytic, partly vacuolized laths up to 0.1 mm long; Carlsbad and albite twins may be abundant or absent. Intergranular or subophitic grains of aegirine-augite (10 to 30%) are up to 0.1 mm long; in some samples the aegirine-augite is in disseminated saccharoidal grains about 0.02 mm in diameter. Feldspars are vacuolized and partly altered to zeolites and clay minerals; celadonite and opaque minerals formed by alteration of dark minerals or interstitial glass. Anhedral, interlocking groundmass feldspars in some of the intensely altered rock suggest recrystallization. Calcite (0 to 5%) fills amygdules, fractures, and interstitial voids.

Source of most basalt flows in member 1 is uncertain. Basalt dikes in the map area are thin and sparsely distributed, although feeder dikes may be buried under later Rawls flows. A gabbro intrusion in Rancherias Dome was probably the source of a thick wedge-like succession of basalt flows in Rawls member 1 to the east. Petrographically the basalt in this area resembles that elsewhere, but the rock is generally more vesicular and weathers gray rather than brown. The lava was probably more viscous than that of other Trlb flows because the probable initial dip of the tops of flows is as much as 3 degrees; no other Trlb flow dips as steeply.

Member 2

Tuff (Tr2t).—Tuff, the index rock type of member 2, interfingers with lava flows of the Bofecillos volcanic cone; it is absent in the southeastern part of the map area south of Primero and east of Panther Canyons and is only sporadically present in upper Fresno Canyon along the flanks of the Solitario. Elsewhere in the map area, it is mostly between 50 and 200 feet thick; the maximum thickness of about 300 feet is exposed to the southwest of the vent in a cliff prominently visible from State Ranch Road 170 between Burro and Tapado Canyons northwest of Three-Dike Hill. The member consists of ten or more superposed ash falls; the thickest is about 100 feet and thickness generally decreases upward. Tuffaceous sandstone and volcanic conglomerate are interbedded throughout the member but are relatively more abundant in the upper part where in some places they predominate, almost to the total exclusion of tuff (MS 10 and 12). The member is distinctive: it is mostly yellow, buff, or gray tuff in a section made up mostly of dark lava flows. Each ash fall is a massive cliff-forming unit: induration is greatest in the middle part where the rock is porous and dull but not friable; a few feet of rock at the base and a thicker zone at the top, comprising up to half the ash fall, are distinctly softer and slightly to moderately friable. Erosion accentuates these variations: in many places the base is undermined and the upper part slopes gently back from nearly vertical cliffs of the middle part; elaborate erosional forms, including lensoidal caves up to 6 feet high and 10 feet across, are common in the upper part. Cave drawings, smoky roofs, and grinding holes under overhangs and in caves are records of Indians who previously inhabited the area.

Pumice fragments abound in the tuff, commonly making up almost all of the matrix; fragment size ranges from microscopic to 2 feet in diameter, and the modal size differs in different parts of the section. Altered gray fragments of latite and latite porphyry like that extruded from the Bofecillos Volcano are abundant; they are a useful criterion for distinguishing this member from other tuffs—most notably nonwelded Santana Tuff—in the map area. A few latite fragments are included in pumice fragments, a fact suggesting that at least part of the latite was included in the magma before eruption.

Fourteen thin-sectioned samples of the rock are vitric to vitric-lithic tuff or lapilli tuff. Broken K-feldspar (mostly anorthoclase but partly sanidine) laths up to 5 mm long comprise 2 to 25% of the tuff and are commonly corroded and embayed; they are fresh to partly vacuolized and altered to zeolites and clay minerals. Twinned to nontwinned plagioclase resembles K-feldspar in habit and alteration. Broken and fragmented bipyramids of quartz (0 to 4%) 4 mm across contain abundant fluid inclusions. Stubby needles of aegirine-augite (0 to 1%) as much as 2 mm long and needles of basaltic hornblende (less than 1%) up to 0.2 mm long are mostly completely altered to celadonite, opaque minerals, and hydrated iron oxides. Blocky crystals of opaque minerals (less than 1%) are as much as 2 mm across. Clots (0 to 5%) of celadonite, opaque minerals, and hydrated iron oxides are probably relicts of altered dark minerals. Fragments of latite and latite porphyry like that extruded from the Bofecillos Volcano make up as much as 15% of the rock, but most samples contain 3 to 8%; the fragments are fresh to thoroughly altered to hydrated iron oxides, aegirine-augite, celadonite, zeolites, and clay minerals. Many samples contain sparse hematitic and celadonitized fragments of aphanitic mafic igneous rock and welded tuff, and one sample contained 12% of such fragments. The matrix is devitrified axiolitic glass shards and interstitial chalcedony, opal, celadonite, zeolites, clay minerals, opaque minerals, and hydrated iron oxides. Pumice fragments are devitrified and altered and grade from a maximum of 2 feet in diameter to microscopic fragments that are commonly indistinguishable from the matrix constituents. Calcite fills pore space, and in some samples it patchily replaces the matrix.

After touring the area in November 1966, R. L. Smith thought that faint stratification and sorting, and in places cross-bedding, together with lack of welding, suggest an ash-fall origin. He regarded the large size of many of the included fragments as evidence that the rock originated nearby. The fact that almost all accidental fragments resemble fragments of rock from the Bofecillos Volcano suggests that much of the tuff originated from the Bofecillos vents, probably during a relatively explosive phase. The ash that erupted was probably relatively more silicic than the latite of the flows, because the tuff contains quartz crystals which are not present in the flows. A possible additional source for some of the tuff on the east side of the map area is a vent in the Solitario, described by Lonsdale (1940); the vent agglomerate is strikingly similar to Tr2t tuff, both in hand specimen and in thin sections of samples collected by Dietrich and Maxwell (in preparation).

Other mapped units.—Latite porphyry (Tr2lp) and volcanic mudflow (Tr2vm) are included between or interfingered with ash flows of the index Tr2t. A few flows of latite (Tr2l) are exposed on the south and east sides of the vent; maximum thickness is about 100 feet. The rock is similar in outcrop and petrography to latite of the Fresno (Tfl).

Rock mapped as latite porphyry (Tr2lp) also includes thin flows of slightly porphyritic latite and beds of tuff. Maximum thickness is about 300 feet; at the present stage of erosion, it is the most extensive unit exposed on the site of the Bofecillos Volcano. Elongate lobes of lava dip from 1° to 15° away from the vent area.

Festooned flow structure is well developed on many of these flows and is accentuated by differential erosion of nonresistant zones between pressure ridges; festoons are convex away from the source vent of the Bofecillos Volcano. The rock looks essentially the same, both in outcrop and under the petrographic microscope, as the latite porphyry suite of the Fresno Formation (Tflp).

A rock unit interpreted as several volcanic mudflows (Tr2vm) crops out between flows on the north side of the Bofecillos cone. Maximum thickness is about 50 feet; it is mostly massive breccia of gray to white latite porphyry and latite fragments in a gray to green celadonitic tuffaceous matrix with interbeds of volcanic conglomerate and tuffaceous sandstone. It is in all respects similar to laharic breccias described by Fisher (1960).

Member 3, Latite Porphyry (Tr3lp)

Member 3 (Tr3lp) consists predominantly of latite porphyry but contains some porphyritic latite. It is made up of essentially the same type of lava flows as Tr2lp and Tflp; it is distinguished from Tr2lp because it overlies, rather than interfingers with, the index tuff (Tr2t) of member 2.

Member 3 has been stripped away from the high-standing central part of the Bofecillos Volcano, but it is exposed in an interrupted ring around the cone. Maximum thickness, south of the vent in the upper part of Tapado Canyon, is about 300 feet.

Member 4

Trachybasalt porphyry (Tr4bp).—The index rock type of member 4 is trachybasalt porphyry that contains up to 40 percent tabular plagioclase phenocrysts as much as 6 cm long; even the largest crystals are only a few millimeters thick. In a few of the upper flows the crystals have rounded rhombic outlines (*see* member 8—Tr8bp—(p. 21) for discussion). On slightly weathered surfaces the white- to gray-weathering feldspar phenocrysts are conspicuous in a red-brown, gray, or black groundmass sparsely speckled with red-brown grains of iddingsite.

The trachybasalt porphyry forms a discontinuous ring around the Bofecillos eruptive center. Dietrich (1965) estimated that it is about 500 feet thick north of the map area. It thins southward against latite porphyry (Tr3lp) flows on the flanks of the Bofecillos Volcano; the cone was partly, but not totally, inundated. East of the volcano, the maximum thickness is only about 200 feet, probably because of uplift of the Solitario before or during extrusion. Maximum thickness to the west is about 400 feet, and to the south, about 300 feet; it is thinner across the Rio Grande in Mexico.

The trachybasalt porphyry spread as flows ranging from a few feet to about 50 feet thick; some of the thinner flows are probably flow-units of a larger flow, as was described in the Bee Mountain Basalt (Tcbm). A nonresistant and commonly crumbly basal flow breccia, a few inches to several feet thick, consists of pebble- to boulder-size scoriaceous blocks of altered trachybasalt poryhyry weathering red brown; calcite, chalcedony, and celadonite partly or totally fill fractures and vesicles. Above the flow breccia, the rock is vesicular and amygdaloidal and weathers red brown. Fresh hand specimens are difficult to collect because alteration to celadonite and zeolites is common throughout the flow. The alteration, and the resultant susceptibility of weathering and erosion, generally increases with the percentage of vesicles. The middle part of the flow is the most resistant to erosion; it stands as a steep but rounded and generally scalable cliff. The upper part is highly scoriaceous and weathers red brown; the top few feet is a clinker-like rubble of boulder- to sand-size fragments that commonly grades into the basal flow breccia of the next higher flow.

Three thin-sectioned samples of the rock are subophitic to intergranular, titaniferous or aegiritic augite-iddingsite trachybasalt porphyry. Corroded and embayed partly vacuolized tabular phenocrysts of plagioclase, which constitute 15 to 40% of the rock, are commonly zoned; many are in glomerophyric clusters with augite and iddingsite. Subhedral to anhedral grains of augite or titanaugite (up to 2%) as much as 2 mm in diameter mostly adhere to or are included in plagioclase phenocrysts. Iddingsite, antigorite, and opaque minerals (up to 3%) are pseudomorphic after olivine grains that are mostly 0.2 mm to 1 mm across but range to as much as 3 mm long. Blocky phenocrysts of opaque minerals (up to 2%) are as much as 0.8 mm across. Groundmass plagioclase is felted, subequigranular to seriate laths mostly 0.1 to 0.5 mm long; they are rimmed either by alkali feldspar or by interstitial zeolites, which are probably alteration products of the alkali feldspar. Aegiritic augite (15 to 30%) occurs either as stubby needles up to 0.2 mm long or as intergranular grains less than 0.1 mm in diameter; much of it is altered to celadonite, opaque minerals, and hydrated iron oxides. Hornblende (0 to 5%) is sporadically present as intergranular grains that commonly have augite cores; it alters to the same mineral suite as the aegiritic augite. Subhedral to blocky grains of opaque minerals (5 to 15%) less than 0.1 mm across are disseminated in the groundmass. Apatite (up to 2%) occurs in thin needles up to 0.4 mm long and in stubby prisms up to 2 mm long. Calcite, chalcedony, and celadonite fill fractures and amygdules.

Dikes of trachybasalt porphyry, commonly 20 to 50 feet thick, in the Presidio area are the probable source of most of the flows of trachybasalt porphyry (Dietrich, 1965); thin dikes and relatively small intrusions of the trachybasalt porphyry in the central part of the Bofecillos Mountains area were probably also a source of some of the flows.

Other mapped units.—Mapped units included between or interfingered with the flows of trachybasalt porphyry (Tr4bp) are flows of trachyandesite (Tr4a) similar to Tr5a. Several flows of latite porphyry, resembling that described elsewhere in the Fresno and Rawls Formations, are not mapped separately but are included within mapped trachybasalt porphyry (Tr4bp).

Member 5

Rawls member 5 is indexed by a pulse of trachyandesite extrusion that began before cessation of trachybasalt porphyry extrusion characteristic of member 4. The resultant interlayering and interfingering of the two rock types make the contact between the two members more or less arbitrary; the contact was placed beneath the lowest trachyandesite flow that could be traced laterally to a part of the section consisting dominantly of trachyandesite (fig. 3).

Trachyandesite (Tr5a).—The trachyandesite of member 5 spread as flows a few feet to about 50 feet thick. Above a basal flow breccia, mostly less than a foot thick, the rock is brown to olive-green weathering, nonvesicular, gray trachyandesite, commonly with yellow-brown to gray-green celadonite or zeolite(?) mottling. In contrast to a scoriaceous upper surface common in lower flows, the top of the member 5 trachyandesite flows is mostly slightly vesicular. The flow tops may be festooned with pressure ridges several feet apart.

The rock is of essentially the same mineral composition as trachyandesite Tfa of the Fresno Formation. Some of the member 5 trachyandesite is, in fact, petrographically indistinguishable from it, but most has a pronounced trachytic texture, accentuated by plagioclase crystals 5 to 10 times longer than wide.

The member 5 flows were probably fed by trachyandesite dikes, which are common in the Bofecillos Mountains; an irregular intrusion of trachyandesite Tia on the west side of the eruptive center, about 1 mile south of triangulation station Burro, feeds Tr4a and Tr5a flows.

Other mapped units.—In addition to the index trachyandesite (Tr5a), mapped units in member 5 include trachybasalt porphyry (Tr5bp), latite porphyry (Tr5lp), and basalt (Tr5b). Trachybasalt porphyry (Tr5bp) and latite porphyry (Tr5lp) resemble rocks lower in the section and probably have the same source areas.

Basalt (Tr5b) is exposed at two widely separated localities. The rock at a 100-foot sequence of five or more basalt flows southwest of the central vent of the Bofecillos Volcano between Rancherias Dome and Panther Dome is like the vesicular gray-weathering variety of basalt in member 1 in the same general area and probably also originated from the basaltic intrusion in the Rancherias Dome. Northeast of the Bofecillos Volcano, in a mesa north of the present road out of Fresno Canyon, several flows of basalt (Tr5b) and interbedded tuff totaling about 100 feet rest on trachyandesite flows (Tr5a) and are overlain by ash-flow tuff (Tr7at). These flows, assigned to member 5 on the basis of stratigraphic position, are a southward extension of a sequence of basalt (Trb) flows that Erickson (1953) mapped and described.

Member 7

Ash-flow tuff (Tr7at).—Exposures of ash-flow tuff (Tr7at) are erosional remnants of a sheet that extended from southeastern Presidio area (Dietrich, 1965) and southern Tascotal Mesa quadrangle (Erickson, 1953) through all but the western part of the Bofecillos Mountains area and an undetermined distance into Mexico. It is as much as 205 feet thick in MS 12, near the north boundary of the map area; it thins southward and is discontinuous in most of the area, probably because of relief of the surface over which it spread. It did not cover the Bofecillos Volcano.

The rock is nonwelded to thoroughly welded, crystal-vitric to lithic-vitric tuff. Anorthoclase phenocrysts (5 to 20%) and abundant accidental fragments of latite and latite porphyry (3 to 10%) like that in flows from the Bofecillos Volcano are characteristic of the member.

The member is mostly a simple cooling unit 20 to 100 feet thick consisting of one or several ash flows. A few feet of bright orange or pink, friable, nonresistant, palagonitic nonwelded tuff at the base grades upward in a few inches to brownish-gray, slightly friable, nonwelded tuff that forms the lower part of a near-vertical cliff overhanging the nonresistant tuff below; the brownish-gray-colored rock here and higher in the section is probably characteristic of the zone of vapor-phase crystallization (Smith, 1960). A few feet higher in the cliff the rock grades to well-indurated, brownish-gray rock that is slightly to intensely eutaxitic; there is no vitrophyre. The welding and attendant foliation die out upward in the cliff. The upper part of the unit is slope-forming, light brownish-gray, friable, nonwelded tuff that may be a few feet thick or comprise the entire upper half of the cooling unit. Where the unit is nonwelded it commonly grades through similar zones except that the eutaxitic zone is absent.

The cooling unit is compound in many places, probably, as Smith (1960, p. 801) stated, "because the intervals between ash flows were too great for readjustment to a single-unit cooling gradient." The compound unit has alternating gradational zones of welded tuff, nonwelded but indurated brownish-gray tuff, and friable orange or pink palagonitic tuff described in simple cooling units. These zones may be parts of ash flows or include several ash flows; distinctly separate zones may grade laterally in a few hundred feet into a single zone (MS 11).

Four thin-sectioned samples of the rock are crystal-vitric to lithic-vitric tuff. Laths of Carlsbad- and fine-grid-twinned anorthoclase (5 to 20%) and Carlsbad- and albite-twinned plagioclase (0 to 1%) are up to 3 mm long; they are partly corroded and embayed and commonly broken. Iron-rich (optically +) grains of olivine (0 to 2%) up to 1 mm long are corroded, partly or totally altered to iddingsite, and rimmed by opaque minerals. Corroded stubby needles of augite (up to 3%) as much as 2 mm long are mostly aegiritic and slightly altered to celadonite; nonaegiritic augite, which is altered to uralite and celadonite, was probably incorporated into the ash flow from the substrate. Brown partly broken needles of hornblende and basaltic hornblende (up to 3%) are fresh to thoroughly altered to celadonite and opaque minerals; some needles are as much as 3 mm long but most are fragmented to angular grains less than 0.1 mm in diameter. A few flakes of iron-rich biotite (less than 1%) up to 0.2 mm in diameter are corroded and rimmed with opaque minerals. Blocky phenocrysts of opaque minerals are as much as 0.5 mm across. Fragments of latite and latite porphyry like that extruded from the Bofecillos Volcano (3 to 10%) are mostly altered to celadonite, zeolites, and clay minerals; other accidental fragments including basalt and welded tuff are mostly altered to hematite, celadonite, zeolites, and clay minerals. The matrix consists mostly of dark-red-brown axiolitic shards and pumice fragments with interstitial celadonite, zeolites, clay minerals, and opaque minerals, all of which are colored red brown by finely divided hematite-limonite; patches of the matrix, however, are relatively clear and are more coarsely crystallized to anhedral interlocking grains of alkali feldspar with discrete interstitial grains of celadonite, opaque minerals, and hematite. Calcite (0 to 2%) fills pores and interstices.

Latite porphyry (Tr7lp).—In a few places flows of latite porphyry (Tr7lp) from the Bofecillos Volcano are interbedded with ash flows of the index tuff (Tr7at). The rock resembles the latite porphyry described elsewhere in the Rawls and in the Fresno Formations.

Member 8

Trachybasalt porphyry (Tr8bp).—The lower part of member 8 consists of trachybasalt porphyry (Tr8bp) in flows that are as much as 50 feet thick. It is discontinuously exposed in high mesas in a 3-mile-wide belt extending three-quarters of the way around the Bofecillos Volcano from an eastward pinch-out in Panther Dome to the south, clockwise through the Presidio area (Dietrich, 1965) and Tascotal Mesa quadrangle (Erickson, 1953) to the north, and on to a pinch-out south of Arroyo Segundo to the east; it is absent and probably was not deposited southeast of the Bofecillos Volcano.

The lower flows are a continuation of the extrusive pulse that began with member 4 (Tr4bp), but they grade upward to flows with somewhat different outcrop form and lithology. The upper flows form steeper cliffs and are thicker than the lower flows, probably because they moved mostly as a single unit rather than as a number of flow-units. Intense deuteric or post-magmatic alteration, common throughout lower flows, is present only near the base and top of the upper flows. The fresh groundmass of the upper flow is gray, rather than black, and the rock weathers pale gray rather than red brown. Dull, not glassy, white plagioclase phenocrysts are mostly oligoclase-andesine rather than andesine-labradorite. They are embayed and thoroughly vacuolized; rounded corners are probably caused by partial resorption. Some have alkali feldspar rims formed either by replacement or by antirapikivi overgrowth; shapes tend to be rhombic rather than rectangular. The rock contains a lower percentage of dark minerals, and intergranular hornblende is relatively more abundant than aegiritic augite. Some of the rock is actually mafic trachyandesite porphyry, but it is all mapped as trachybasalt porphyry because the trachyandesite is interbedded with, gradational from, and probably genetically related to trachybasalt porphyry.

Trachyandesite (Tr8a).—The upper part of member 8 is trachyandesite similar to that of member 5. It was present in a ring around the Bofecillos Volcano, except possibly to the east; it has been extensively removed by erosion and is preserved only as the caprock on isolated mesas. Maximum thickness in the map area is about 100 feet. Festoon structure is common in the thicker flows. Erosion along pressure ridges and weathered flow laminae at the top of some of the flows emphasize the festoon structure to such an extent that it is easily visible on aerial photographs.

Dietrich (1965) located a probable major vent of member 8 trachyandesite eruption in the east-central part of the Presidio area. An additional source might be some of the many trachyandesite dikes on the Bofecillos Volcano, some of which may have extended to the surface at the time the member 8 trachyandesite flows were extruded.

Other mapped units.—Latite porphyry (Tr8lp) is interlayered with the two index rock types; it is similar to latite-porphyry units lower in the section. About 50 feet of gray sodic trachyte porphyry (Tr8tr) crops out above member 8 trachyandesite in a high-standing mesa northwest of Tapado Dome; it contains sanidine and aegirine phenocrysts in a groundmass of trachytic alkali feldspar with interstitial hematitic riebeckite. Thin beds of sedimentary rock and tuff between flows were not mapped but included within overlying or underlying units.

Member 9

In contrast to earlier Rawls flows, the basalt flows of member 9 (Tr9b) were extruded after appreciable faulting; as a consequence, they are interbedded with thick sequences of graben-filling sedimentary rock (Tr9). Northeast of Panther Dome, member 9 is more than 300 feet thick and consists dominantly of sedimentary rock; it may be thicker near Redford where the base is not exposed.

Basalt (Tr9b).—The index basalt of member 9 is conformably exposed above trachyandesite of member 8, capping mesas west and southwest of the Bofecillos Volcano and capping Rincon Mountain to the east. Individual basalt flows are mostly less than 50 feet thick; at least 4 superposed flows occur in the map area, and Dietrich (1965) reported at least 10 in the Presidio area.

Outcrops of the basalt in general resemble those of member 1, and in many places, stratigraphic position is the only criterion for distinguishing them. The rocks are also petrographically similar, except for generally lower percentages of plagioclase (0 to 5%) and augite (0 to 3%) phenocrysts. However, faint spherical white splotches 2 to 5 mm in diameter are common in member 9 basalt but were not found in lower members; they are strikingly accentuated on weathered surfaces. The origin is unknown but is perhaps related to alteration or devitrification of groundmass constituents that progressed outward from widely separated centers.

Sedimentary rock (Tr9).—Poorly sorted massive gray to white conglomerate and conglomeratic sandstone of member 9 (Tr9) partly fill the Redford Bolson, the Santana Bolson, and other block-faulted grabens in the map area; more than 200 feet accumulated at several places.

The unit is well exposed at the southeast end of the Redford Bolson about 200 yards north of Ranch Road 170, 2 miles west of the bridge across Tapado Creek, where it rests disconformably on trachybasalt porphyry of member 4 (Tr4bp). It is about 70 feet thick with the lower 20 feet covered; the upper 50 feet forms a rounded bluff with cavernous weathering. The rock grades from poorly sorted massive sandy volcanic conglomerate in layers 5 to 20 feet thick to faintly bedded conglomeratic sandstone in layers 1 to 5 feet thick. Rounded and subrounded clasts in the conglomerate average about 1 inch in diameter but range up to 10 inches; they include abundant trachyandesite, latite porphyry, and trachybasalt porphyry from the Rawls and Fresno Formations, and a few pebbles are the distinctive ash-flow tuff of Rawls member 7 (Tr7at). The matrix is pale buff to gray, moderately indurated calcite-cemented volcanic arenite with weathered grains of feldspar and volcanic rock and sparse fresh grains of quartz and opaque minerals.

In general, except for the few localities described in the following paragraphs and except for induration, the composition and lithology of the graben-filling Tr9 conglomerate is nearly the same as the modern side stream alluvium (Qals) and the pediment gravels (Qg1-Qg4) in the same area—a fact suggesting a similar source for the Tr9 conglomerate in the Bofecillos Mountains. The conglomerate was probably deposited mostly as alluvial fans.

Gray conglomerate, with rock fragments atypical of those elsewhere in Rawls member 9, is exposed in the western part of the map area along the north boundary where a graded dirt road parallels Palo Amarillo Creek. Adjacent to the north in the Presidio area, Dietrich (1965) mapped this exposure as sedimentary rock in the Fresno Formation (Tf); similar rock, however, overlies Tr9b basalt in the Bofecillos Mountains area about 1.5 miles to the east. All of this conglomerate in the map area is probably within Rawls member 9 and it is so mapped; much of Dietrich's mapped Tf to the north, on the south flank of Torneros Dome, is probably also within the Rawls.

Well-rounded cherty limestone pebbles and boulders up to 2 feet in diameter make up 60 percent of the coarse fragments in the atypical Tr9 conglomerate. The remaining 40 percent consists of well-rounded, commonly vesicular or scoriaceous, igneous rock fragments up to 3 feet in diameter; most is trachyandesite but a few boulders are trachybasalt porphyry and a very few weathered pebbles are possibly the ash-flow tuff of member 7.

Pediment gravel (Qg2) overlying the Tr9 conglomerate is of the same composition. The gravel-mantled pediment surface slopes gently upward to the northwest into the Presidio area (Dietrich, 1965); source area of most of this Tr9 conglomerate and the overlying pediment gravel was probably 10 or more miles northeast to northwest of this locality in an area where Dietrich (1965) mapped extensive exposures of Cretaceous limestone and Tertiary volcanic rock.

At a few places along the mountain front member 9 consists of breccia containing blocks as much as 6 feet across, probably representing talus and landslide debris from youthful fault scarps. Such deposits are strikingly exposed in the graben 1 mile north of the Redford Bolson along Burro Canyon, where partly dissected Tr9 talus cones extend toward the center from both sides.

An isolated exposure of volcanic conglomerate above undifferentiated Fresno Formation (Tf) on the south side of South Lajitas Mesa contains about 1 percent of cobbles and boulders of pumiceous rhyolite similar to, and probably originating from, that which intrudes Santana Tuff at the Big Hill on Santana Mesa. The conglomerate was therefore probably deposited after the Santana. Except for the rhyolite fragments, the conglomerate is similar in texture and composition to Tr9 conglomerate and, lacking criteria for precise correlation, it is arbitrarily mapped as Tr9. Although it may not have been deposited at the same time as Tr9 conglomerate elsewhere, its environment of deposition was probably similar.

Interbedded conglomerate and bolson fill (Tr9f).—In the Santana Bolson, typical "gray" Tr9 conglomerate is intercalated with "pink" conglomeratic sandstone typical of bolson fill (QTf) in alternating beds or groups of beds as much as 50 feet thick; this interfingered sequence is arbitrarily mapped as bolson fill in the Rawls Formation (Tr9f).

Intrusive Rock

Dikes and Sills

Dikes are abundant in and around the Bofecillos Volcano but are progressively less common away from the vent; only the larger ones are mapped. They are aligned radially about the volcano and are particularly abundant along the northwest trend followed by late-volcanic and post-volcanic block faults. Exposed sills are distinctly less numerous, probably because the well-layered Cretaceous strata favorable for concordant emplacement crop out only along the edges of the map area. Contact effects extend at most a few feet on either side of the dike or sill; normally, iron-oxide staining is the only noticeable difference in flows intruded by dikes, but tuff is commonly baked to red-brown, slightly porcellaneous rock that is more resistant to erosion than the unaltered tuff.

Dikes and sills of latite porphyry, trachyandesite, trachybasalt porphyry, and basalt are similar in composition to flows of the same rock type in the Fresno and Rawls Formations; most of the intrusive rock, however, is more intensely altered: intergranular pyroxene is saccharoidal or completely transformed to celadonite; plagioclase phenocrysts are more corroded, embayed, vacuolized, and partly altered to zeolites or clay minerals; olivine is altered to iddingsite, antigorite, and opaque minerals. By far the most abundant dike rock in the area is latite porphyry (Tilp); some dikes are as much as 20 feet thick and some are several miles long. Trachyandesite (Tia) is next most common in dikes ranging up to 10 feet thick and several thousand feet long. Generally, sparse latite (Til), basalt (Tib), and trachybasalt porphyry (Tibp) dikes are as much as 6 feet thick and traceable for 1,000 feet or less; trachybasalt porphyry dikes are most abundant in the general area of the Bofecillos vent and south of a large irregular trachybasalt porphyry pluton in Burro Canyon, but they are found throughout the map area. A few dikes in the map area are composed of light-gray to gray-green, trachytic, intergranular, hornblende sodic trachyte porphyry (Titr) consisting of glassy partly corroded phenocrysts of sanidine or anorthoclase and aegirine-augite in a groundmass of alkali feldspar with green interstitial sodic hornblende and disseminated opaque minerals; much of the pyroxene and amphibole alters to vermicular celadonite. Rhyolite (Tir) dikes and sills crop out in the eastern part of the map area. The rock is mostly altered with a porous chalky white matrix and iron oxides in fractures and in liesegang bands; sparse phenocrysts of glassy to dull feldspar and glassy quartz are a few millimeters long.

Laccoliths

Laccoliths are mostly intruded into the flaggy Boquillas Formation, but they are also emplaced beneath some of the thicker lava flows and probably also in strata beneath the Boquillas. Several are dated relative to volcanism by nearly horizontal volcanic strata which overlap the partly deroofed intrusive domes.

The form of intrusions in the Contrabando Lowland is typical of that elsewhere in the map area. The lowland is a compound dome bowed up by clustered laccoliths and sills that intrude flaggy Boquillas limestone; the intrusive rock is mapped as diorite and gabbro (Tidg). Similar concordant bodies probably exist at depth because the intrusions themselves are commonly domed; 8 holes drilled in Contrabando Dome in search of mercury deposits under the supervision of L. C. Whitaker (oral communication, January 1964) penetrated several layers of igneous rock similar to that at the surface. The exposed bodies are in all stages of dissection, and arroyos incised through the intrusions provide excellent cross sections exhibiting a diversity of forms and contact effects. Bases are generally not faulted, but they may arch or sag; tops may be symmetrical or asymmetrical and the arching may be uniform or the sides steep and the crown relatively flat. The roof is commonly faulted and dikes or intrusive wedges commonly extend upward into the overlying limestone; at least one body is a trap-door laccolith. Limestone is baked gray, recrystallized and partly silicified a few feet to several tens of feet from the contact.

Probably the largest exposed intrusion of the Contrabando Lowland is the Wax Factory Laccolith, a syenodiorite intrusion named and described by Lonsdale (1940). It is as much as 150 feet thick and at least 2 miles across. Smaller laccoliths to the southwest consist of medium- to fine-grained rock that is black to gray where fresh but altered to olive green or white in most places. Fractures are occupied by hematite-limonite. To the unaided eye, the rock is similar to that of the Wax Factory Laccolith, but three thin-sectioned samples are celadonitic augite syenodiorite; olivine, titanaugite, analcitic syenodiorite; and celadonitic syenogabbro.

Irregular Intrusions

Riebeckite rhyolite intrusions.—Two riebeckite rhyolite plutons, each about 2,000 feet across, are exposed in the northern part of the area. A generally discordant body north of the old road out of Fresno Canyon cross-cuts the upper part of the Fresno Formation and the Rawls Formation through member 5 on the northeast and northwest; faults truncate it on the southeast and southwest. The base is not exposed. A 200-foot section is exposed on the southwest side. Contact alteration is slight where it intrudes lava flows; Fresno tuff is porcellaneous and red brown in a contact zone a few feet thick. The metamorphosed zone forms a low cuesta between less resistant tuff and the intrusive rhyolite. The rhyolite is mostly altered to a rubble of white or gray silt- to pebble-size chalky or porcellaneous grains. About 10 percent of the intrusion is fresh rock which occurs as rounded blocks as much as 4 feet across in a matrix of the rubble; many of the blocks are brecciated and contain autolithic inclusions. This fresh rock is porcellaneous and blue gray to gray green with corroded 1-mm long anorthoclase and quartz phenocrysts; riebeckite is mostly in dendritic crystals up to 1 mm across that poikilitically include groundmass feldspar but about one-tenth is stubby 1-mm long needles. The groundmass is strongly seriate interlocking anhedral alkali feldspar and quartz with interstitial celadonite.

The second riebeckite rhyolite pluton is southwest of Saucita Dome and north of the Big Bend ranch road. It was intruded essentially concordantly between latite porphyry flows of Rawls members 2 and 3 and is at most 50 feet thick; the intrusion was probably laccolithic in form, but all of the roof except part of a nearly flat-lying lava flow on the crown is eroded away. The rock is brown-weathering, cream or yellow, and intergranular with flow structure accentuated in outcrop by dark riebeckite needles as much as 2 mm long and by brown splotches several millimeters long of hematite that is pseudomorphic after dendritic-poikilitic riebeckite. The groundmass is strongly seriate trachytic alkali feldspar with interstitial quartz and celadonite.

Bogles Domes.—Triangulation station Bogles, in the northeastern part of the map area, is approximately at the center of a roughly circular area 1.5 miles across that contains overlapping intrusions of latite emplaced into the middle and upper part of the Fresno Formation and as high as the lower trachybasalt porphyry flows of Rawls member 4. The intrusions are generally domical but several are irregular where they abut against, or were emplaced along, the steep sides of previously intruded domes; near the edges of the area of intrusion they are mostly concordant. This compound mass was emplaced near the surface and is perhaps extrusive in part; nondomed volcanic mudflows of the valley-fill sequence of the Fresno Formation (Tfvm) lap onto it from the northeast side and most of the mudflows contain blocks similar to rock of the Bogles intrusions. Beds and flows of Rawls members 1 and 4 also lap onto some of the domes, but elsewhere they are themselves tilted—a fact indicating that emplacement continued through extrusion of these units; the upper trachybasalt porphyry flows of member 4 buried the partly eroded complex and were not subsequently arched. The rock is blue-gray to white, flow-laminated, intergranular, aegiritic augite-hornblende latite with sparse biotite flakes 2 to 4 mm across.

Big Hill intrusion.—At the southeast end of Santana Mesa at the Big Hill of Ranch Road 170, a faulted dome-shaped slightly discordant body of rhyolite porphyry (Tirp) at least 6,000 feet across and about 800 feet thick is partly included within and partly immediately beneath Santana Tuff. It extends across the river into Mexico. The contact with the flanking Santana Tuff is poorly exposed or inaccessible, but as nearly as can be determined, the Santana, although distinctly upwarped, abuts into the intrusion with low angle discordance. Thus, for unknown reasons, the intrusion probably diverges somewhat from a true laccolith. While joints in the rock are mostly irregular, some in the upper part parallel the upper contact. Although these are probably partings paralleling flow laminae, no flow structure is visible.

The groundmass is red brown; about 50 percent of the rock is phenocrysts of cloudy white feldspar and clear quartz as much as 1 cm long. Two thin-sectioned samples collected by Dietrich and Maxwell (in preparation) contain abundant corroded, fractured, and embayed crystals of sanidine and quartz and a few percent of albite-oligoclase; sparse grains of celadonitic augite, opaque minerals, and opaque mineral-rimmed basaltic hornblende are mostly less than 2 mm long. The groundmass is hematite-dusted devitrified glass containing vermicular celadonite(?), disseminated opaque minerals, and clay minerals or zeolites. With nicols crossed, the groundmass commonly exhibits patchy extinction, which is the "snowflake" texture described by Snyder (1962) as poikilitic quartz inclosing minute feldspar grains; Anderson (1962) interpreted the "snowflakes" as a texture resulting from devitrification and subsequent recrystallization. Faint microscopic foliation is visible in the matrix of one of the samples.

Intrusions of Rancherias Dome.—Rancherias Dome is eroded to an elliptical valley about a mile long with gently outward-dipping upper Fresno and Rawls flows forming a discontinuous in-facing cuesta. The flows rest unconformably on undifferentiated Comanche, Pen, Boquillas, or Jeff strata which floor the valley. The Chisos, Mitchell Mesa, and the lower part of the Fresno Formation—totaling more than 800 feet elsewhere—are absent, either by nondeposition or erosion; from available exposures, it is impossible to state whether the uplift took place before, during, or after their accumulation. The uplift is probably intrusive because the axial area is cut by numerous dikes and irregular plutons, including a discordant gabbro (Tig) intrusion about 2,000 feet across at the west end. Abundant white colloform hydrothermal chalcedonic silica occurs in fissure veins as much as 20 feet thick in the gabbro, in the Pen, and between the Pen and overlying flows. Except around the gabbro intrusion, it is impossible to demonstrate outward dip of the Cretaceous and Jeff strata, because only the Pen is exposed away from the intrusion and bedding in the Pen is mostly imperceptible. If the gabbo intrusion caused the upwarping, it probably extends eastward beneath the surface about half a mile, because the exposed gabbro is located asymmetrically on the west side of the dome. On the other hand, the fact that many of the dikes and small plutons are not gabbro suggests that the dome was formed at least in part by an unexposed intrusion.

The medium- to fine-grained subophitic pyroxene (probably titanaugite) gabbro (Tig) grades to basalt. The rock is mostly altered and contains olive-green interstitial limonitic celadonite. The Comanche limestone about the gabbro is marbleized a few feet to several hundred feet outward from the contact; lenses of pale-green skarn—probably containing calcite, wollastonite, and vesuvianite—are sporadically present in the marble. Numerous altered titanaugite-olivine basalt dikes as much as 4 feet thick cut through the intrusion; some contain gabbro and basalt inclusions, and their boundaries with the wall rock are commonly vaguely defined—these dikes may have been emplaced before the gabbro was completely solid. They may have been the source of wedge-shaped sequences of Rawls members 1 and 5 basalt flows that extend to the east and southeast of the Rancherias Dome.

Almost all of the small dikes and irregular plutons are so intensely altered that the original rock type is unknown; a few, however, are recognizable latite porphyry. Near these intrusions, particularly the more irregularly and intensely altered ones, the Pen contains abundant silt-, sand-, and pebble-size fragments of the altered igneous rock; perhaps the Pen host rock behaved as a viscous fluid at the time of intrusion and incorporated and dispersed gobs of the intruding molten rock. Away from the intrusions, the Pen is typical gypsiferous clay.

Bofecillos Vents

The main source of lavas from the Bofecillos Volcano is near the center of the map area southeast of triangulation station Elephant; it consists of two vents partly surrounded by a breccia zone.

The east vent is 1.1 and the west vent 0.6 miles across; they are erosional lowlands developed on deuterically or hydrothermally altered, chalky, white, iron-oxide-stained vent rock (Tiv). Most of the vent material is poorly indurated breccia consisting of clay-, silt-, and sand-size fragments, but blocks range up to 10 feet across. In several places, the breccia grades to irregular intrusions as much as 100 feet across, in which ghosts of feldspar phenocrysts are preserved. Altered dikes of latite and latite porphyry stand as resistant ridges above the floor of the lowland.

Syenodiorite.—Two plutons, each about a mile across, of gray, medium- to fine-grained, hypidiomorphic-granular, aegiritic-titanaugite syenodiorite and syenodiorite porphyry intrude the Fresno and Rawls member 2 latite porphyry flows southwest and northeast of the east vent. The rock is mineralogically similar to trachyandesite porphyry end-member lava flows of the Bofecillos Volcano and resembles glomerocrystic inclusions in the lavas. The southwestern intrusion is half-cone shaped and is discordant; the surrounding flows dip outward as much as 50°. The rock is relatively unaltered and resistant to erosion—the intrusion forms the highest peak in the map area (elevation 5,111 feet), standing 500 feet above the vent. On the other hand, at least the top of the northeast intrusion is concordant, sloping outward at about 3° beneath the flows; the base is not exposed. The intrusion is about 100 feet thick where it abuts against the vent rock. The rock is moderately to intensely celadonitic; it is nonresistant and forms a valley where the overlying lava flows have been stripped away.

Breccia.—The rock mapped as breccia (Tibr) is a discontinuous shell as much as 50 feet thick around the vents. Either it formed as an intrusion breccia in the country rock along the contact of the vent material, or it is a chilled border phase of the vent rock; it differs markedly from the breccia mapped as vent rock (Tiv), and the contact with the vent rock is sharp. It weathers red brown; where freshly broken it is dark green or gray green and has a waxy luster. It is hydrothermally altered, aegirine-augite, latite porphyry with faintly defined angular to rounded autolithic fragments up to a few feet across. Feldspars are mostly altered to clay minerals or zeolites. Dark minerals, except for corroded opaque phenocrysts, are altered to saccharoidal aegirine-augite; 40 to 50 percent of this pyroxene is common in the rock and suggests hydrothermal addition of iron and perhaps sodium.

Siliceous Fissure Veins and Replacement Deposits

Milky-white to pale-gray chalcedonic silica occurs as hydrothermal deposits in several intrusive domes. It is most abundant and typically exhibited in Rancherias Dome, where steeply dipping fissure veins and lenses as much as several feet thick and a few hundred feet long cross-cut gabbro, Pen clay, and Fresno tuff; a discontinuous manto occurs along the contact of the lowest lava flow and the underlying Fresno tuff or Pen claystone at the east end of the uplift.

Elsewhere in the area, the silica replaces or fills pores and fractures in country rock and was probably derived from tuff and transported by ground water. It occurs in layers or discontinuous mantos. The chalcedony contains sparsely disseminated magnetite and hydrated iron oxides. Locally, it contains finely divided anhedral grains of aegirine-augite and riebeckite, probably alteration or recrystallization products of the host rock. Stylolites are common, particularly in the thicker, flat-lying masses of silica.

The largest exposed body of this type of replacement silica is in middle Fresno Canyon east of triangulation station Bogles; it is a layer several hundred feet in outcrop length and as much as 20 feet thick between Fresno tuff and the underlying Boquillas Formation. The original rock type is unknown because it is completely replaced, but vaguely to well-defined angular fragments suggest that it was originally a breccia. Perhaps it was talus formed on the flanks of the Solitario before deposition of the overlying Fresno tuff; alternatively it may be a thoroughly silicified part of the sodic rhyolite that crops out half a mile to the south.

TERTIARY AND QUATERNARY DEPOSITS

BOLSON FILL (QTf)

In addition to predominantly white or gray locally derived subangular volcanic conglomerate, fanglomerate, and talus breccia included in the Rawls as Tr9, bolsons along the Rio Grande contain predominantly pink, and probably far-traveled, conglomeratic sandstone with angular to rounded clasts of volcanic and sedimentary rock. This pink rock is similar in color and clast composition to a "bolson fill" facies mapped to the northwest over much of the Presidio and Redford bolsons by Amsbury (1959), Dietrich (1965), and many other workers. The term "bolson fill" as used in this report is restricted to deposits that contain beds of this "pink" facies, even though much of Rawls units Tr9 and Tr9b were also aggrading sequences in bolsons. Except in the Santana Bolson, where interfingered "gray" and "pink" facies are mapped as Tr9f, the "pink" overlies the "gray," and the bolson fill is mapped as a separate unit (bolson fill, QTf).

At least 150 feet of bolson fill (QTf) is exposed in the Redford Bolson; abundant normal faults, many of unknown throw, and lack of marker beds make it unfeasible to work out stratigraphic detail. In the Santana Bolson, bolson fill is exposed in the road cut at the top of the "Big Hill" on Santana Mesa about 700 feet above similar rock included in Rawls member 9 (Tr9f); probably 700 feet or more of the "pink" facies was present there, perhaps with interbedded "gray" conglomerate.

In the Redford Bolson, the contact between pink bolson fill and the underlying "gray" Tr9 conglomerate is sharp and commonly discordant at 0 to 3 degrees with the fill overlapping the Rawls toward the edge of the bolson. Although it may indicate faulting in the interval between deposition of the two units, the angular relationship is probably caused by a difference in original depositional dip of the "gray" fan conglomerate (Tr9) and the more nearly horizontal "pink" fill. From the discontinuous exposures, it is not clear whether the contact is a disconformity representing considerable time and erosion or a diastem; however, the sharp contact, difference in induration, and lack of interfingering in the Redford Bolson suggest a disconformity.

In the map area the rock is salmon pink, pebble-to-cobble conglomeratic sandstone in beds a few feet to 50 feet thick that differ mostly in percentage and size of constituent fragments and in degree and type of bedding. Angular to rounded pebbles and cobbles make up 10 to 50 percent of the rock and are generally supported by the interstitial sand, rather than neighboring pebbles; they are mostly latite and trachyandesite with minor basalt, some limestone pebbles, and a very few pebbles of chert. The matrix is coarse- to fine-grained, moderately indurated, calcite- and clay-cemented, volcanic arenite containing feldspar, quartz, volcanic rock fragments, and sparse opaque minerals; the salmon-pink color of the rock is probably imparted by finely divided iron oxides in the clay cement.

The unit commonly forms steep cliffs adjacent to laterally planing streams. Different induration from bed to bed is etched out by differential erosion. The top of a cliff cut in bolson fill commonly has small caves a foot or two across, perhaps where laterally seeping ground water has dissolved away the calcite cement.

Source of the pink bolson fill in the map area is probably not in the Bofecillos Mountains; rounding of some pebbles in the fill suggests a more distant source, and exposures of limestone and chert in the Bofecillos Mountains are far too scanty to supply even the small percentages present in the fill. The fact that the bolson fill of the map area is continuous with that of the Presidio Bolson suggests that it was transported in from the northwest, perhaps along the axis of the bolson.

If, as is proposed here, the bolsons were being simultaneously filled by locally derived conglomerate (Tr9) and by far-travelled bolson fill, an interfingering of the two rock types, like that in the Santana Bolson, would be expected. Lack of interfingering along the exposed contact in the Redford Bolson may have been caused by a number of circumstances. Perhaps the "pink" conglomeratic sandstone was deposited so rapidly that it overwhelmed the "gray" conglomerate entering the bolson across the fans; such an influx might occur with climatic change, or perhaps by invasion of the bolson by a larger stream system. Another possibility is that as the "pink" gravel was deposited, the "gray" facies was partly reworked and incorporated into the "pink" facies.

PEDIMENT AND TERRACE GRAVELS

After the period of filling, the bolsons were breached and the through-flowing Rio Grande—or its ancestor before it was integrated—provided a pulsationally lowering base level for the side streams. During periods of relative base-level stability, both main stream and side streams cut surfaces of lateral planation chiefly in the fill; during periods of quickened downcutting the streams incised the previously formed planation surfaces. The resultant step-like sequence of gravel-mantled pediments and terraces is strikingly exhibited in the map area.

The most extensive pediment and terrace deposits are in the Redford Bolson where four gravel sheets are numbered in order, in accordance with the system started by Amsbury (1959) and modified by Dietrich (1965, p. 168); the highest (oldest) is Qg1 and the lowest Qg4. Only a few remnants are preserved of the pediment gravel Qg1; mostly they are close to and sloping steeply from the high-standing parts of the Bofecillos Mountains. The gravel projects everywhere to about the same height above the Rio Grande, but the remnants are so widely separated and far-removed from the river that the correlation expressed by the symbol Qg1 is very loose and does not imply a single period of base-level stability. Gravels Qg2 and Qg3 are remnants of extensive sheets mapped by Dietrich (1966) in the Presidio Bolson and in the northwest part of the Redford Bolson. Gravel Qg4 includes all pediment and terrace deposits between gravel Qg3 and flood-plain alluvium of the Rio Grande and its tributaries.

In the Santana Bolson, two extensive gravel sheets are tentatively correlated with Qg1 and Qg2 of the Redford Bolson, because they resemble their counterparts in lithology, appearance on aerial photographs, and projected height above the Rio Grande. Similarly, three gravel sheets that extended across Contrabando Lowland and into Fresno Canyon are tentatively correlated with Qg2, Qg3, and Qg4 of the Redford Bolson. Elsewhere in the map area, pediment and terrace gravels are undifferentiated Qg.

The side-stream pediment gravel ranges from a few feet to 20 feet thick; it rests unconformably on bolson fill or Rawls member 9. It is mostly poorly sorted angular to subrounded volcanic boulder to cobble conglomeratic sandstone; boulders are as much as 4 feet in diameter. Volcanic rock types are like those in Rawls and Fresno flows in the adjacent mountains. Rounded limestone cobbles are abundant only in the western part of the area northwest of Bofecillos Creek; like the cobbles in the underlying Rawls member 9 conglomerate, the source was probably to the northwest of the Bofecillos Mountains, although some may have been reworked from the Tr9 conglomerate. The matrix is coarse- to fine-grained volcanic sand, locally cemented by caliche. In the Redford Bolson, cementation is greatest in the Qg2 and Qg3 gravels; it is not yet well developed in the

Qg4 gravel, and in the Qg1 gravels the cement has been partly removed by leaching. Pediment gravels elsewhere are moderately to slightly cemented.

In the southeastern part of the Santana Bolson and between Church and Buzzard Creeks in the Redford Bolson, terrace gravels of the Rio Grande underlie—and are mapped with—the Qg2 and Qg3 gravels. The exposed Rio Grande gravel is up to 30 feet thick; it rests on and abuts laterally against adjacent bolson fill. The gravel is dark gray; it is made up of poorly defined beds 2 to 15 feet thick and is cross-bedded in some places. Constituent fragments are poorly sorted rounded pebbles to boulders as much as 3 feet in diameter, mostly of igneous rock including latite, trachyandesite, riebeckite rhyolite, welded tuff, and basalt; less than 1 percent of the fragments are limestone and 5 percent of the pebble-size fragments are chert.

ALLUVIUM AND COLLUVIUM

In and adjacent to the Rio Grande Valley, alluvium deposited by the river is designated Qalr and that deposited by side streams Qals; elsewhere it is mapped as undifferentiated Qal.

Rio Grande alluvium is of two types. Channel gravel is made up of rounded pebbles, cobbles, and boulders, mostly volcanic, as much as 3 feet in diameter, with interstitial sand and silt; it resembles the Rio Grande terrace gravel included in Qg2 and Qg3. Flood-plain deposits are markedly different, consisting of medium- to fine-grained well-bedded buff clay-rich, silty sand with sparse large boulders that were probably floated to their present position while entangled in tree roots. Except in the present channel, the coarse gravels are covered almost everywhere by the flood-plain deposits; buried channels are marked by lines of cottonwood trees and salt cedar, both of which flourish over these aquifers.

Most side-stream channels are dry except during storms when flash flooding is common. The alluvium is sandy gravel and gravelly sand resembling that preserved on the pediments. In the mountains, slump or landslide blocks may clog the channel, moving downstream only during flash floods; in the bolson, however, the larger boulders are 4 feet or less in diameter. Composition of the gravel reflects the geology of the drainage basin.

Colluvium (Qc) is mapped only where the cover of talus and other locally derived material is so thick that an attempt to infer the underlying geology is not warranted.

STRUCTURAL GEOLOGY

PRE-VOLCANIC REGIONAL TECTONIC SETTING

Most or all of the map area is underlain at depth by folded and faulted Paleozoic strata of the northeast-trending frontal zone of the Ouachita structural belt (Flawn et al., 1961, p. 100); these strata are exposed in the Marathon region (King, 1937) and in the Solitario (Herrin, 1958). After a period of Mesozoic emergence, dominantly marine Cretaceous strata were deposited with angular unconformity on the Paleozoic rocks. During Laramide deformation, intense folding and faulting occurred along north-northwest trends about 35 miles southwest of the map area in the broad, but as yet poorly delimited, Chihuahua Tectonic Belt and about 40 miles to the northeast in a belt a few miles wide including the Del Norte-Santiago Mountains and the Sierra del Carmen (Maxwell et al., 1967). Between these two strongly deformed areas is a relatively stable block with generally broad folds and normal faults extending from the Coahuila Platform southeast of the map area to the Diablo Platform to the northwest; whether the two platforms were continuous or separate structural elements during Laramide deformation is not known (Dietrich, 1965, p. 200). Local Laramide structures extending into or adjacent to the map area are the Terlingua Monocline to the east, fault blocks at the north end of Mesa de Aguila to the southeast (Maxwell and Dietrich, 1965, p. 32), and relatively gentle deformation to the northwest (Dietrich, 1965, p. 207); in the erosional lowlands, an angular unconformity with as much as 10 degrees of dip between Upper Cretaceous strata and the Jeff Conglomerate indicates gentle Laramide folding.

After the development of Laramide structures, the map area and much of the region to the northwest were structurally stable while laterally planing streams eroded much of the region to a pediment mantled by the Jeff Conglomerate. Probably all of the map area was thus planed to base level except for the Laramide Terlingua Monocline which remained topographically high. Eruptive activity followed the deposition of most of the Jeff, and the conglomerate is, therefore, essentially post-orogenic but pre-volcanic.

POST-LARAMIDE STRUCTURES

GRAVITY SLIDES

Thrust faults exposed at four places in the eastern part of the map area are here interpreted as gravity slides.

Shelter Thrust.—The Shelter Thrust, named by Dietrich and Maxwell (in preparation), is a nearly horizontal fault beneath a klippe in the central part of Fresno Canyon; an overhang on the west side of the klippe has a smoky roof and hand prints typical of ancient Indian shelters in the Big Bend region. The klippe is about 200 feet across; it rests on the lower part of the Boquillas Formation about 30 feet above the base and consists of about 20 feet of Buda Limestone overlain by 5 feet or less of Boquillas Formation. The klippe probably slid to its present position from a hogback of Buda Limestone, about 2,000 feet to the east and several hundred feet higher, over clay-rich colluvium from the Del Rio and Boquillas Formations; it is not a remnant of a west-dipping tectonic thrust because the fault is not present in a cliff a few hundred feet to the west.

Fresno Canyon imbricate thrusts.—An imbricate thrust involving at least 15 repetitions of the Mule Ear Spring Tuff is strikingly exposed in south Fresno Canyon about one-half mile northeast of MS 4. In this area, the Mule Ear Spring rests on tuff a few feet above clay in the upper part of the Boquillas Formation; above the Mule Ear Spring is about 20 feet of tuff overlain by about 100 feet of Tule Mountain Trachyandesite Porphyry. The thrusting probably occurred when a block of Tule several hundred feet long broke loose from the rest of the unit and slid downslope over the Boquillas clay; Mule Ear Spring, dragged under the block, broke into imbricate slabs along the slide plane. The unstable slope that caused the sliding may have been created by intrusive uplift of the Solitario or Terlingua Monocline, or it may have been formed at a later time when Fresno Creek or its ancestral equivalent eroded away at the toe of the slope.

Llano Dome thrusts and folds.—Chisos, Mitchell Mesa, and the lower part of the Fresno Formations are intensely deformed in the east half of the Llano Dome. North-trending folds and imbricate thrust faults repeat the Mitchell Mesa at least eight times. Dips are steep and some of the Mitchell Mesa slabs are overturned at 50 degrees; bedding of most other strata, including tuff and sedimentary rock, is poorly preserved, largely because they were incompetent during thrusting. Similarity of these structures, though on a larger scale, to the imbricate thrusting of Mule Ear Spring in south Fresno Canyon suggests a similar mechanism of formation. Uplift of the Solitario may have caused gravity slides westward, uplift of smaller intrusive domes in the Bofecillos Volcano may have caused eastward slides, or perhaps incision of streams during volcanic activity created unstable slopes; the plane of failure was in Chisos, or lower, strata—perhaps the clay-rich upper part of the Boquillas Formation. A later intrusion, perhaps along the slide plane, probably domed the contorted strata to their present position. The thrusting was not caused by the intrusive doming because domed members 2 and 4 of the Rawls Formation truncate the faults.

Bench Mark Thrust.—A low-angle thrust is strikingly exposed in Fresno Canyon about a hundred yards south of the mouth of Primero Creek near bench mark R749 (elevation 3,013 feet); it is covered by younger strata to the west and it dies out along the crest of a chevron fold to the east. The thrust occurred during deposition of the lower part of the Chisos Formation because the Jeff Conglomerate is faulted and the fault is overlain unconformably by the Mule Ear Spring Tuff. It is probably not a regional Laramide structure because such thrusting is atypical of Laramide deformation in the block between the Coahuila and Diablo Platforms, and because it occurred after the Jeff was deposited—a conglomerate interpreted as following most of the Laramide activity. For these reasons, and because this mechanism is consistent with the interpreted mode of formation of other thrusts in the area, the structure is probably a gravity slide.

INTRUSIVE DOMES

Because laccoliths are exposed in the center of several breached domes (p. 23), similar partly breached domes are probably also laccolithic. Most domes formed above laccoliths emplaced in Cretaceous rocks, particularly the flaggy Boquillas limestone; exceptions are Segundo and Little Domes emplaced in lower Rawls strata and Saucita Dome emplaced in the stratigraphic interval from upper Chisos to lower Rawls.

Domes are both simple and compound. Simple domes are roughly circular in plan and were probably formed by uplift over one intrusion or several nested intrusions. Most simple domes range in diameter from 5,000 to the maximum 9,000 feet, with structural relief of 200 to 500 feet; smaller domes range to less than 100 feet in diameter with only a few feet of structural relief. Compound domes have cuspate outlines caused by interconnecting domes formed over clustered and overlapping intrusions. Compound domes include the Contrabando Lowland uplift, about 25,000 feet in diameter with 1,000 feet of structural relief; Saucita Dome, about 15,000 feet east-west by 3,000 feet north-south with 200 feet of structural relief; Bogles Domes, about 7,000 feet in diameter with 200 feet of structural relief.

The time of emplacement of many domes is dated relative to domed or on-lapping volcanic strata. For example, Tapado Dome formed largely during the deposition of the Fresno, because the Fresno thins over the dome between the bounding Mitchell Mesa and Santana ash flows. Llano Dome formed during the deposition of Rawls member 4, because the upper flows of member 4 pinch out by onlap against lower domed member 4 flows. Domed Fresno and Rawls strata thin or pinch out over Panther Dome, indicating continued uplift during deposition; flat-lying strata of member 9 on-lap the dome indicating the uplift had essentially ceased before the deposition of Rawls member 9 (section C-C').

Abundant small unmapped faults were caused by the doming; they are mostly less than 100 feet long with 4 feet or less of throw and they die out upward above the doming intrusion in a few tens of feet. Only where there are marked discordances—as above the trap-door structures of Segundo Dome and the central part of Saucita Dome—are the faults large enough to be mapped. Large faults of random orientation at the west end of Saucita Dome suggest a discordant intrusion at depth. Elsewhere in the area, concordant domes are probably concealed by overlapping strata.

NORMAL FAULTS

Fault zones.—Normal faults trend generally northwestward; they are aligned in the Redford-Lajitas (Dietrich, 1965, pp. 174–175) and Bofecillos fault zones. Faulting of the 5- to 15-mile-wide Redford-Lajitas fault zone is typical of that elsewhere in the Basin and Range Province; the faults form a compound, step-faulted graben centered along the southwest boundary of the map area. Structural relief of the graben ranges from 1,000 to 2,500 feet; it may be distributed more or less evenly over a broad belt of a dozen or more faults and tilted fault blocks or may be concentrated on a single fault with 2,000 feet or more of throw. The southwest side of some faults on the United States side of the graben is upthrown, producing horst blocks that interrupt the over-all down-to-the-southwest step-fault pattern; such horsts are relatively more common along the northeast edge of the graben complex than near the axis. The intersecting, complexly arcuate faults are as much as 12 miles long. Most are high-angle normal faults, but a few dip 45 degrees or less where they cut structurally anisotropic lava flows such as the Tule Mountain Trachyandesite Porphyry and latite lava flows of the Bofecillos Volcano. At no place was it possible to demonstrate reverse faulting. Several faults that cross Contrabando Lowland are scissors faults; perhaps intrusions at depth on the downthrown sides of previously formed faults caused sufficient uplift across the faults to reverse the relative upthrown and downthrown sides in the overlying strata.

The Redford-Lajitas fault zone curves from a trend of about N. 50° W. at the west end of the map area to about N. 70° W. at the east end. The change is most pronounced at Tapado Canyon where the faults bend southwestward around the approximate outline of the Bofecillos Volcano, perhaps because intrusions at depth in or under the Bofecillos Volcano created a massif that deflected the fault zone.

The 1- to 3-mile-wide Bofecillos fault zone cuts across the center of the map area at about N. 50° W. through the vent area of the Bofecillos Volcano; it extends about 5 miles both to the southeast and northwest of the two vents. In contrast to the faults of the Redford-Lajitas zone, those of the Bofecillos zone are straight high-angle structures, mostly less than 2 miles long, and mostly with less than 100 feet of throw; they produced jostled fault blocks but no step-faulted graben structure. These differences suggest genetic and perhaps temporal differences in the formation of the two zones. Perhaps faults of the Bofecillos zone are upward extensions of an early-formed fissure system that fed the volcano. Alternatively, the faults may be in a modified radial pattern caused by uplift of the volcanic center, as suggested by a few faults east and south of the vent area with radial trends; paucity of faults at trends other than northwest might be caused by a northeast-southwest regional stress acting at the time of eruption. Finally, a few faults within the zone might be caused by local stresses: the rather random fault pattern immediately northwest of the west vent may be caused by a small intrusive dome, and an arcuate fault on the north side of the two vents may be a collapse structure caused by cauldron subsidence.

Time of faulting.—Normal faults following regional trends were probably active throughout the period of Tertiary volcanism, but faulting that occurred before deposition of the upper part of the Rawls Formation is difficult to document because later movement along early-formed faults has obscured evidence of the early movement. In the Bofecillos fault zone, exposures are poor, but in the Redford-Lajitas fault zone, there is ample indirect evidence, in the form of abrupt thickening of stratigraphic sequences, to indicate early faulting. For example, in Carrasco Dome north of State Ranch Road 170, at least one fault occurred between the spreading of the Mule Ear Spring and Mitchell Mesa ash flows because the stratigraphic interval between them ranges from less than a foot on a knob to the southeast to more than 50 feet across arroyos to the north and west. Similarly, about a mile northeast of Santana Mesa faulting occurred before emplacement of the Santana, because its thickness across a fault ranges from 30 feet on the upthrown side to more than 100 feet on the downthrown side; renewed movement on the fault separated the top of the Santana several hundred feet, and the abrupt change in thickness is only demonstrable in Madera and Panther Canyons.

Field relationships, however, indicate that most of the block faulting occurred after the deposition of volcanic strata: (1) faults cut the youngest volcanic strata and the bolson fill; (2) faults are not perceptibly more abundant in older strata—fewer faults were mapped in the late- and post-volcanic bolson fill principally because exposures are poor, rather than because of an actual decrease in fault abundance; (3) at no place in the area was a fault found truncated by strata older than Quaternary gravel; (4) significant differences in thickness of given intervals of volcanic strata across faults—indicating early faulting—are relatively uncommon. Dietrich (1965, p. 216) reported faults displacing Quaternary pediment gravel in the Presidio area, a fact suggesting that faulting continued throughout the latter part of the Cenozoic era.

GEOMORPHOLOGY

PHYSIOGRAPHIC SUBDIVISIONS

The Bofecillos Mountains area is within the Basin and Range physiographic province, and it manifests desert landforms which are characteristic of the region as a whole. For purposes of orientation and description, it is useful to group these features according to origin into stripped structural surfaces, the Bofecillos Volcano, the fault block zone, breached bolsons, erosional lowlands, and dissected domes.

Stripped structural surfaces.—Highland surfaces of low relief are common, perhaps dominant, features of the landscape to the north and northwest of the Bofecillos Mountains. These are stripped structural surfaces formed by differential erosion of nonresident tuff and sedimentary rock from more resistant nearly horizontal lava flows and from the Mitchell Mesa ash flow. In the map area, surfaces of this type include (1) the Llano Flats, to the northeast, (2) the Primero Flats, to the east-center, and (3) numerous mesa tops. Highland flats did not form elsewhere in the area because of laterally heterogeneous stratigraphy, structural complexity, and active downcutting by Rio Grande tributaries.

Bofecillos Volcano.—West of the Llano flats, the Bofecillos Volcano is dissected to a rugged area of discontinuous ridges and steep-sided canyons. Lava flows dipping away from the vents at 1° to 15° form elongate topographic lobes which overlie pyroclastic material and lower flows. Discontinuous cuestas, developed across the flows, face toward nonresistant pyroclastic material of the main vents. Faults, joints, and dikes, which radiate from the center of the volcano, further accentuate a radial drainage pattern developed on the outward-dipping flows. The greatest elevation in the map area is near the center of the volcano, where the syenodiorite intrusion south of the east vent stands at an elevation of 5,111 feet; crests of several flow-supported ridges around the vents are at elevations of 4,900 to 5,000 feet.

Fault-block zone.—The present course of the Rio Grande adjacent to the map area is approximately located along the axis of the Redford-Lajitas fault zone. The lower grabens, which received sediments after faulting, are now breached bolsons. The remainder of the system of horsts and grabens constitutes the fault-block zone. It consists of an extensive broken area to the south and west of the Bofecillos Volcano that is made up of high-standing blocks with relatively resistant Tertiary volcanic rocks exposed at the surface. Relief is mostly the result of original movement on the faults, although scarps are modified by differential erosion. Major streams are deeply incised and poorly adjusted to fault trends. They are probably antecedent, maintaining consequent radial courses away from the Bofecillos Volcano. Smaller streams are better adjusted to the fault block structure and are probably subsequent. Rapid downcutting by streams in this area was controlled by incision of the Rio Grande, which served as a progressively lowering base level; the zone exhibits the greatest relief of all the subdivisions in the area. Many cliffs and canyon walls are 300 to 600 feet high, and several cliffs are more than 1,200 feet high.

Breached bolsons.—The map area contains two breached bolsons: the Santana Bolson in the south-central part of the area and the more extensive Redford Bolson to the northwest, which is a southeastern extension of the much larger Presidio Bolson. In contrast to the rugged topography of the fault-block zone, the bolson areas exhibit moderate relief carved on nonresistant fill; most present streams are incised less than 100 feet below interstream areas. Gravel-capped pediment surfaces slope toward the Rio Grande, which adjoins the lower part of the Santana Bolson and occupies the axial part of the Redford Bolson. Drainage is generally subparallel toward the Rio Grande.

Erosional lowlands.—The southeastern part of the map area is mostly a lowland developed on relatively nonresistant Upper Cretaceous and Tertiary sedimentary rock where resistant Tertiary lava flows higher in the section have been removed by erosion. Removal of the resistant rock has progressed to the greatest extent on or adjacent to structural highs: the Contrabando Lowland is developed on laccolithic domes including Contrabando Dome; the Lajitas Lowland is developed on homoclinally dipping beds south of the Terlingua Monocline.

Fresno Canyon is a lowland developed on the west-dipping flanks of the Solitario Dome and the Terlingua Monocline. Fresno Creek is probably a consequent stream in the topographic low between the highlands of the Bofecillos Volcano and the Solitario. Although most of the volcanic strata in this area have been eroded, even the poorly preserved remnants attest to a recurrent valley cutting and filling. The earliest such evidence is in upper Fresno Canyon, where the valley-fill sequence of the Fresno Formation occupied a broad valley cut in lower Fresno and Chisos strata.

A 20-foot basalt flow interpreted as Tr9b is exposed in Fresno Canyon on the southwest flank of the Solitario; it suggests a deep canyon before or during the deposition of Rawls member 9, because the flow rests unconformably on Boquillas and Chisos strata at least 800 feet lower than the Tr9b basalt above member 8 about a mile to the southwest at the top of Rincon Mountain. The basalt resembles member 9 basalt elsewhere in the area, and it differs from basalts lower in the section in that the groundmass contains the spherical white splotches commonly found in member 9 basalt but not found in lower flows.

Much of Fresno Canyon is occupied by valley fill, in places more than 100 feet thick, that probably indicates late Tertiary or Quaternary changes in gradient of the stream or aggradation downstream. In some places the fill consists of superposed deposits of different composition, texture, and sedimentary structure. Most of the deposits are alluvium, but some are colluvium and others, because they are nonsorted, massive, and lobe-shaped, are probably mudflows. Fresno Creek is now eroding downward through fill and bedrock; at least two terrace levels indicate pauses in downcutting.

Dissected domes.—Erosion of laccolithic domes in the map area has resulted in the formation of concentric cuestas with striking annular drainage. Such breached domes are found throughout the area and are included within the physiographic subdivisions described above.

COURSE OF THE RIO GRANDE

The Rio Grande valley along the southwest edge of the map area forms three sharply contrasted segments: (1) a southeast segment principally in nonresistant Gulf and Chisos strata, (2) a middle segment in faulted resistant

Tertiary volcanic strata and nonresistant bolson fill, and (3) a northwest segment in the nonresistant fill of the Redford Bolson.

Southeast segment.—In general, the course of the Rio Grande in the southeast segment is poorly adjusted to faulting and bedrock resistance. Presence of conglomerate interpreted as Tr9 on the south side of South Lajitas Mesa suggests that this part of the Rio Grande was superposed across structures in the Gulf and Chisos strata. The river is actively cutting downward—it has few terraces and the flood plain is narrow.

Middle segment.—In the middle segment, the relationship of the river to the raised fault blocks and bolsons is complex; at the Big Hill gorge and at Colorado Canyon, the course is seemingly anomalous. At the gorge the river is incised in resistant rhyolite porphyry across a fault block, rather than along either of the bounding faults. Therefore, the gorge was probably not formed by headward erosion of streams from the southeast, because such streams would probably have developed along the relatively nonresistant fault zones. Most likely, the course across the fault block formed by overflow of the Santana Bolson after it was filled by water or sediment; the Big Hill locality is on the lowest block on the southeast edge of the basin, and an exposure of fill at the crest of the Big Hill indicates a high level of filling.

Colorado Canyon is cut in the resistant Santana Tuff of the Colorado Horst, even though much of the canyon paralels and is close to the Santana Bolson, floored by nonresistant fill. This relationship might have occurred if the river were antecedent to the faulting and bolson filling—the river could have maintained an original course by incising itself into the horst as faulting occurred. However, a few feet of Tr9 conglomerate is preserved on the Colorado Horst just west of Closed Canyon; it is probably part of an aggrading sequence of fill, rather than a thin veneer left by a degrading stream. At least the west end of Colorado Canyon is therefore superposed through fill rather than antecedent. It is unlikely, however, that even the east end of the canyon is antecedent, because there is fill at each end of the canyon. The Santana Bolson would thus have been filled from either end by the same river, and a by-pass route through the Santana Bolson and north of Colorado Canyon would have been nearly inevitable.

An alternative explanation for the formation of Colorado Canyon requires a level of fill that completely buried the Colorado Horst after cessation of most of the faulting. Although the elevation necessary for such inundation to occur is about 700 feet above the top of the Big Hill—where the highest documented remnant of fill in the map area is preserved—examination of aerial photographs reveals probable exposures of fill at greater elevations in Mexico. If such a fill existed, the river could have been superposed through it onto the Colorado Horst.

Although the above arguments suggest that the major cause for the course of the Rio Grande through Colorado Canyon is superposition rather than antecedence, there is ample evidence—in the form of faulted bolson fill—to indicate that faulting continued after much of the bolson was filled, and perhaps also as the fill was dissected. Once the course was established by superposition the erosive power of the river was probably sufficient to maintain itself, and it was thus incidentally antecedent to the late faulting.

The creek in Closed Canyon, which crosses the Santana Bolson to join the Rio Grande in Colorado Canyon, was probably also superposed. Most other side streams, however, are well adjusted to rock resistance and structure; they reach the river by flowing along the Santana Bolson. Rancherias Creek swings abruptly west from its southward course and follows a nonresistant fault zone north of the Colorado Canyon Horst to the Rio Grande; because it is larger and probably had more erosive power than "Closed Canyon Creek," it should have been more likely to superpose across the block than the smaller creek. Perhaps it did, in fact, become superposed but was later captured by a subsequent stream eroding headward along the fault zone from the west.

Northwest segment.—The Rio Grande flows approximately along the axis of the Redford Bolson. The river may have assumed and maintained this course soon after the bolson was breached, or it may have shifted to the axial position at a later time, perhaps as a result of deposition of side-stream alluvial fans which forced the river away from the sides of the bolson.

SUMMARY OF GEOLOGIC HISTORY

With the exceptions of the Terlingua Monocline to the east and large fault blocks on the north side of Mesa de Anguila (Maxwell and Dietrich, 1965, p. 32) southeast of the area, Laramide deformation in and adjacent to the map area produced only gentle open folds. In an interval of relative quiescence following at least the main pulse of Laramide activity, laterally planing streams, recorded by the Jeff Conglomerate, reduced the area to a pediment that truncated all exposed Laramide structures except the Terlingua Monocline and probably also the Mesa de Anguila fault blocks.

The advent of volcanic activity—probably during the Late Eocene—caused a change from erosion to erosion and deposition. The Chisos Formation, which overlies the Jeff, is an accumulation of tuff, lava flows, volcanic conglomerate, sandstone and mudrock, essentially all of which originated outside of the Bofecillos Mountains area.

Uplift of the Solitario probably began before or during Chisos deposition because Chisos strata thin by nondeposition or erosion against its flanks. Thrust faults that occurred during and after Chisos deposition are probably the result of gravity slides; some were shed from unstable slopes along the flanks of the Solitario. Over most of the area, the Mitchell Mesa ash flow spread across a nearly featureless plain formed on Chisos strata; however, a few areas, including the Terlingua Monocline, the Solitario, and domes of the Contrabando Lowland, remained topographically high and were not covered by the Mitchell Mesa.

Soon after effusion of the Mitchell Mesa, the Bofecillos Volcano came into existence and began erupting a varied sequence of porphyritic and nonporphyritic lava flows ranging in composition from trachyandesite to trachyte. Intrusive domes are associated with the volcanic activity and some are dated relative to the lava flows which thin or pinch out on the flanks.

Flows of the Fresno Formation make up roughly the lower half of the Bofecillos Volcano; interbedded tuff and sedimentary rock predominate over the flows away from the Bofecillos vents. Festooned cross-bedding in the tuff suggests that ash blanketed the area and at times was drifted by wind. Breaching of the Solitario by the time the upper part of the Fresno was deposited is indicated by Paleozoic rock fragments—derived from the Solitario—in Fresno conglomerates.

The Santana ash flows probably originating from the south inundated much of the map area; thickening to the south suggests that part of the area subsided as the unit was deposited.

The Rawls Formation, overlying the Santana Tuff, makes up the upper half of the Bofecillos Volcano but in addition contains a complex suite of on-lapping lava flows, tuff, and ash flows, mostly derived from within or near the map area. The change to a more varied suite is signalled by the extensive basalt flows of Rawls member 1. They were followed by an interval when the Bofecillos Volcano decreased its outpourings of lava in favor of effusions of ash which formed much of member 2; a vent in the Solitario may also have contributed ash to this member. The vast majority of the trachybasalt prophyry flows of Rawls member 4 probably originated north of the Bofecillos Volcano in the Presidio area (Dietrich, 1965) or the Tascotal Mesa quadrangle (Erickson, 1953), but sparse trachybasalt porphyry intrusions throughout the Bofecillos Mountains area suggest minor additions from a few places in the map area as well; the thick sequence of these flows partially inundated the volcano, which became relatively inactive during and after deposition of member 4. Most trachyandesite lava flows of member 5 were probably fed from fissures within the area, but some may have entered the area from the north; the volcano, though generally quiescent—erupting occasional flows to be intercalated with fissure-fed lavas—probably stood as a topographic high above the trachybasalt porphyry-trachyandesite lava field.

Ash flows characteristic of member 7 and the trachybasalt porphyry and trachyandesite flows of member 8 thin generally southward; they probably entered the area from the north. The apex of the nearly extinct Bofecillos Volcano probably stood above the level of the highest member 8 flow.

It is uncertain whether Rawls flows ever spilled over the outer rim of the Solitario and into the center. Basalt porphyry flows of Rawls member 4 form a gangplank nearly up to the present rim on the north side, but at the time of extrusion the rim was probably higher. Furthermore, even some of the uppermost—member 9—Rawls flows on the flanks of the dome tilt outward, suggesting that uplift may have kept pace with accumulation. Any flows that may have extended into the central area have since been removed by erosion.

Although faulting began as early as the deposition of the Chisos Formation, the major episode of faulting followed deposition of Rawls member 8; most of the basalt flows that characterize member 9 are interbedded with thick sections of sedimentary rock that were probably deposited in alluvial fans formed along fault scarps. The largest displacements occurred along the Redford-Lajitas fault zone where structural relief is as much as 2,500 feet. Offsets in the Bofecillos fault zone are mostly less than 100 feet; faults in this zone probably formed through upward extension of, and perhaps collapse along, the fracture system that fed the Bofecillos Volcano.

Closed basins in the Redford-Lajitas fault zone accumulated thick sections of bolson fill. When the bolsons were breached, the exiting Rio Grande or its ancestor incised fill.

The present eccentric course of the Rio Grande between Tapado and Madera Creeks was probably caused chiefly by superposition of the river through the fill onto jostled fault blocks. The present physiography of the Bofecillos Mountains reflects the effects of erosion on the complex sequence of faulted volcanic strata.

ECONOMIC GEOLOGY

MERCURY

The Terlingua quicksilver district adjoins the east-central part of the map area and extends eastward about 20 miles. According to Ross (1941), the presence of quicksilver mineralization was known as early as 1850, but mining did not occur until 1894. Since then mines in the district have produced more than 150,000 flasks of mercury; the rate of production has fluctuated markedly with variations in the price of mercury. With the discovery in 1935 of the Fresno mine and low-grade metallization about a mile to the south on Contrabando Dome (Chester, 1965), the known belt of metallization was extended about 6 miles to the west and thereby overlapped the east-central part of the Bofecillos Mountains area.

The soaring price of quicksilver in the 1960s has increased interest in the Terlingua district. A few mines are now in limited production and exploration is being done throughout the district. L. C. Whitaker recently discovered and drilled out a blind contact replacement ore body about 250 feet west of the Fresno mine at a depth of about 250 feet; the deposit has been reached by shaft and is now in limited production.

Mercury mineralization.—Mercury occurs mostly as cinnabar, but the district contains a varied suite of uncommon or rare mercury minerals including native mercury (Hg), calomel (HgCl), kleinite (Hg, NH_3 chloride), mosesite (containing Hg, NH_3, Cl, SO_3, and HO), eglestonite (Hg_4Cl_2O), terlinguaite (Hg_2ClO), and montroydite (HgO). Associated with the mercury deposits are pyrite, marcasite, fluorite, quartz, chalcedony, hematite, limonite, calcite, aragonite, kaolinite, barite, anhydrite, gypsum, melanterite, epsomite, alunite, jarosite, and hydrocarbons (Yates and Thompson, 1959, p. 65).

The ore deposits mostly occur along northeast-trending fractures in a west-trending belt that generally parallels the Terlingua Monocline. Yates and Thompson (1959) described the ore deposits under four headings: (1) limestone-clay contact deposits, (2) deposits in breccia-filled pipes, (3) deposits in calcite veins, and (4) deposits in igneous rock. By far the most economically important of these classes is the first. Such deposits formed where the Santa Elena limestone underlying the Del Rio clay dissolved—perhaps by the action of hydrothermal fluids associated with the mineralization—and the clay collapsed into the cavity thus formed. The resultant cave-filling rubble of clay and limestone blocks then served as an excellent host material for deposition of mercury minerals. Solution of the Del Carmen or Santa Elena limestones, followed by collapse of roof material, formed breccia-filled pipes as much as several hundred feet across and perhaps thousands of feet deep; ore deposits were formed in clay-rich parts of the breccia and generally show a preference for the upper parts of the pipes. Veined ore deposits in the Boquillas Formation or in fractured igneous rock are generally commercially unimportant; a major exception is in the Study Butte mine—with the third largest production of the district—where the host rock is fractured syenite.

Mercury prospects in Bofecillos Mountains area.—Metallization of the Terlingua district may extend into the Bofecillos Mountains area along established trends in either of two directions from the Fresno mine: (1) westward—along the same trend as to the east—under Tertiary volcanic rocks or (2) northward—paralleling the trend of the Terlingua Monocline—along the east edge of the map area.

Westward, a 1,000-foot-thick section of Tertiary volcanic strata blankets the zones which are mineralized in Cretaceous rock in the district proper, and economic exploitation at these depths seems unlikely in the near future. Prospecting to the west might examine the possibilities of mercury deposits in northeast-trending fractures in the volcanic and intrusive rock; from what is known in the Terlingua district, however, such occurrences of mineralization would have relatively little chance of being minable ore bodies. Attention might better be focused on intrusive domes where Cretaceous strata are nearer the surface. Rancherias Dome is probably the most favorable of the known domes because there are Cretaceous strata at the surface, numerous siliceous fissure veins, and abundant iron oxide stains.

North of the Terlingua district, volcanic strata are mostly stripped off the strata known to be favorable host rocks in the district. The area of interest extends from the Fresno mine north to where the monocline abuts against the Solitario and perhaps along the west—and even east—side of the Solitario. Siliceous fissure veins and replacement mantos are common in parts of Fresno Canyon along this general trend. Furthermore, calcite veins are common in Cretaceous strata; although many were probably deposited by ground water hematite staining in some suggests hydrothermal activity.

BENTONITIC CLAY

Some of the tuff in the area, particularly that in the lower parts of ash flows, contains bentonitic clay that might be of economic value if it meets industry specifications and is present in sufficient volume. Dietrich (1965) reported prospect pits in the Fresno Formation at the west end of the map area northwest of Carrasco Dome, but they were of little economic interest. At the south end of Tapado Dome, a 3- to 6-foot bentonitic zone of unknown lateral extent at the base of the Mule Ear Spring Tuff is remote from good roads and has a thick overburden laced with lava flows. It would not be amenable to stripping without drilling and blasting. Bentonitic clay probably exists partly or totally covered elsewhere in the map area. The base of the Santana Tuff is probably the most likely stratigraphic interval for an economic deposit because it is part of a thick unit and therefore has at least the potential of containing a thick deposit; furthermore, this part of the Santana is mostly covered by talus from the steep slopes above —possible deposits near the base are therefore covered.

PERLITE

Increased need for lightweight aggregates in construction has created a demand for perlite, a hydrous volcanic glass that expands on heating. Perlite is now being mined about 30 miles northwest of Presidio in Pinto Canyon. The only perlite found in the Bofecillos Mountains area is a poorly exposed, foot-thick stringer about 50 feet in outcrop length that occurs in Rawls Tr2t tuff on the south side of the Bofecillos Volcano. This exposure is along the jeep track that extends southward from the road between the Bofecillos vents and Rancherias Dome; it is about half a mile south of the junction of the two roads. The rock contains less than 1 percent of feldspar phenocrysts and basaltic hornblende; the groundmass is green perlitic glass, about one-third of which is altered or weathered to yellow-green zeolites. Its origin is uncertain; it may have been tuff that was fused by an unexposed dike or sill, or the tuff may have been hot enough to weld after it settled. Because of the uncertainty of origin, it is impossible to assess the likelihood of more extensive deposits occurring elsewhere in the area. This stringer is not nearly big enough a deposit to be economically exploitable, and it was not tested for expansion characteristics.

WATER

Probably the most important mineral resource in the map area is water; it supports an agricultural economy on the Rio Grande flood plain and ranching elsewhere. The Rio Grande now has ample flow for irrigation of farms on the river's flood plain, but added cultivation upstream will probably require the most efficient use possible by all concerned. Much depends on eradication of phreatophytes—particularly the salt cedar—which transpire huge quantities of water into the air.

Ground water along the flood plain is readily available at depths of 30 feet or less in the alluvium. Dissolved salts attain concentrations sufficiently high to make the water unpalatable to nonresidents. Water from well UW-74–39–501 near Redford was analyzed by the U. S. Salinity Laboratory of the United States Department of Agriculture (Davis and Leggat, 1965, Table U 3); this analysis is reproduced in table 1, below. County Commissioner Enrique Madrid of Redford stated (oral communication, July 1964) that clay beds exist 10 or more feet below the present water table and tend to separate the alkaline water of the Rio Grande from fresher water below; the fresher water is perhaps uncontaminated rainwater that seeps into the basin from the sides.

Except during periods of rain, when arroyos flow, surface water is present only in the Rio Grande and its larger tributaries. Only Fresno Creek below the Fresno mine flows continuously, but the other large creeks commonly have springs somewhere along their lengths. Ranchers have made many stock tanks by damming the small arroyos with earth and catching the occasional runoff. Larger arroyos are difficult to dam because of torrential floods; earthen dams across the channel tend to fill up with bed-load or erode away when breached by overflow.

Ground water supplies almost all of the water used in the high-standing central part of the Bofecillos Mountains. Windmills dot the landscape and permit stock to range for great distances in search of forage. The Javelina pump, a gasoline-driven water pump located 5 miles south of the Big Bend ranch headquarters, is connected by pipeline to tanks several miles away. Most wells in the area are shallow and produce water from alluvium or bolson fill, although a few produce a trickle from the tuff beds between lava flows on the Bofecillos Volcano. No analyses are available from wells or springs in the uplands of the Bofecillos Mountains area, but an approximation of the water quality is afforded by analyses B and C of table 1 on samples collected from a spring and a well in the Presidio area, 5 and 2 miles north of the map area.

The distribution of springs in the map area indicates that two tuffs are excellent aquifers. The Tr2t tuff of Rawls member 2 is probably the aquifer for the three major springs along Bofecillos Creek and the spring at the head of Palo Amarillo Creek, just north of the map area. Probably the most prolific aquifer, however, is tuff of the Fresno Formation (Tf in part). Springs fed by this aquifer are most likely to occur at the contact with the underlying Mitchell Mesa Tuff, which is probably relatively impermeable; such springs include Tapado Spring, Panther Spring, and Trough Spring, and several seeps elsewhere in the area. If, in the future, deeper drilling becomes necessary, the base of the Fresno Formation will probably be one of the more favorable stratigraphic intervals for a plentiful supply of water.

Table 1. *Composition of well water from three wells in the Bofecillos Mountains and vicinity.* Modified from Davis and Leggat (1965, Table U 3).

	A	B	C	D
Well number	UN-74-39-501	UW-74-32-401		
Water-bearing unit	Rio Grande alluvium	Tertiary igneous rock	Tertiary igneous rock	
Depth of well (feet)	25	spring	?	
Date of collection	11/2/49	11/23/49		
Analysis (in ppm unless stated otherwise):				
Silica (SiO_2)	67	59		
Iron (Fe)	....	....		0.3
Manganese (Mn)				0.05
Calcium (Ca)	125	44		
Magnesium (Mg)	21	6		
Sodium (Na)	439	24		
Potassium (K)	5.1	2.0		
Bicarbonate (HCO_3)	252	151		
Sulfate (SO_4)	566	20	46	250
Chloride (Cl)	383	16	22	250
Fluoride (F)	4.0	1.1		1.7 max.
Nitrate (NO_3)	32	12		45
Boron (B)	0.5	0.13		
Dissolved solids	1,790	257	405	500
Hardness as $CaCO_3$	398	134		
Percent sodium (Na)	70	28		
Sodium adsorption ratio (SAR)	9.6	0.9		
Specific conductance (micromhos at 25°C)	2,650	359		
pH	7.6	7.8		

A. Well in Rio Grande alluvium at Redford, Texas.
B. Flowing spring in Tertiary igneous strata (Tr8 or Tr9 in Presidio area) (Dietrich, 1965), north of Torneras Creek, about 5 miles north of Bofecillos Mountains area from Cuevas Amarillas Spring.
C. Well in Presidio area about 2 miles north of Bofecillos Mountains area from Cuevas Amarillas Spring (probably at Rancho Viejo windmill).
D. U. S. Public Health Service standards for drinking water (1962, pp. 2152–2155). Analyses A, B, and C by U. S. Salinity Laboratory of U. S. Department of Agriculture.

PETROLEUM

The Bofecillos Mountains area has not been drilled for oil or gas. The profusion of intrusions and lava flows about the volcanic center probably destroyed any accumulation that occurred before the igneous activity. After volcanism, however, the area was perhaps amenable to accumulations of oil and gas.

Probably the best opportunity for shallow deposits in the Bofecillos Mountains area is in thick accumulations of bolson fill. Petroleum might accumulate in bolson sands confined beneath clay. Davis and Leggat (1965) reported artesian water thus confined near Presidio which rose 1,210 feet in a well. Drag along faults cross-cutting the fill might form structural traps, and stratigraphic traps might result from the interfingering of sand and clay.

Tertiary volcanic strata in most of the Bofecillos Mountains are unlikely to bear economic petroleum; they are too dissected to trap significant amounts. However, tuff and sandstone intercalated between flows are potential reservoir rock beneath impervious bolson deposits.

Cretaceous rocks are unlikely to yield petroleum because the map area is extensively faulted. Unlike bolson deposits which are potentially capable of forming an impervious clay-rich fault gouge, the Cretaceous rocks are mostly limestone. Fault zones in the Cretaceous rocks would probably be permeable enough to allow oil and gas to escape.

Paleozoic rocks lie beneath about 3,000 feet of Cretaceous strata. Paleozoic strata of the Ouachita fold belt contain numerous structural traps, and potential reservoirs might exist in Ordovician limestone of the Maravillas and Marathon Formations beneath impermeable shales of the Caballos (Devonian) and particularly the Tesnus (Carboniferous) Formations. A normal succession of Paleozoic rocks resembling oil-bearing strata elsewhere in West Texas may exist beneath a thrust sheet of the Ouachita facies (Dietrich, 1965, p. 229).

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