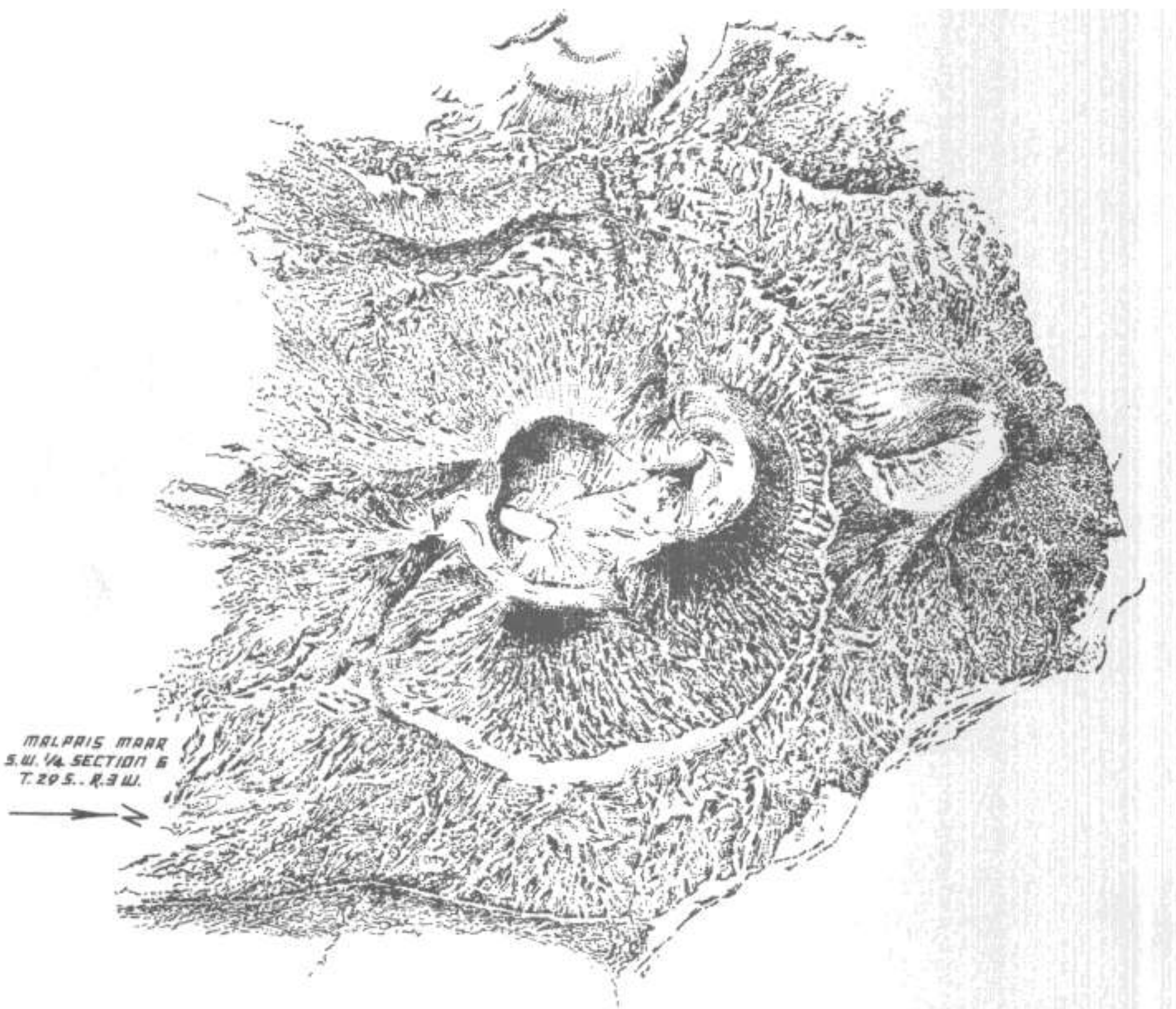
Geology of Potrillo Basalt Field, South- central New Mexico

by Jerry M. Hoffer



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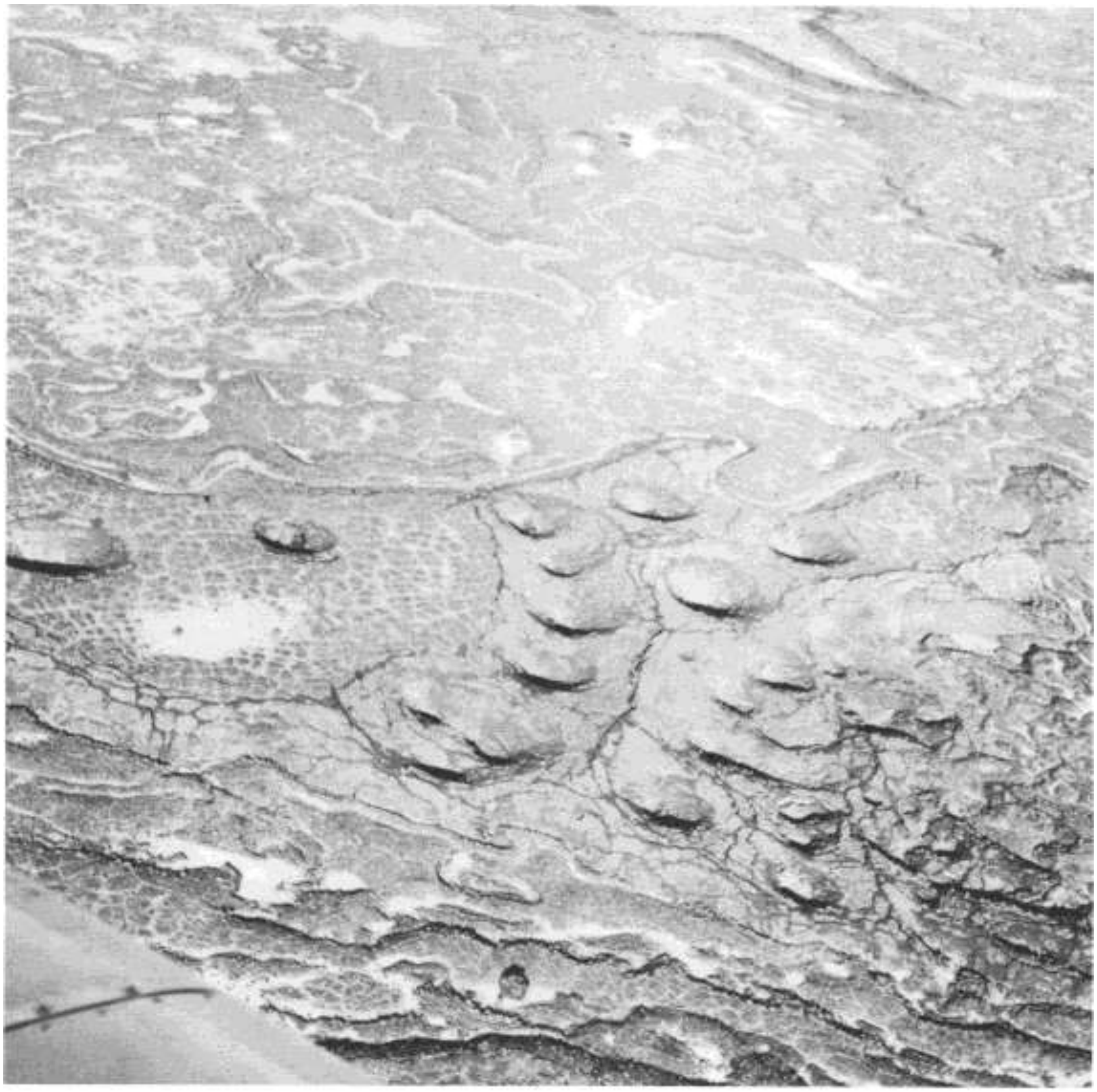

FRONTISPIECE

NORTHWESTERLY VIEW OF COLLAPSE DEPRESSIONS IN POTRILLO BASALT, SEC. 2, T. 26 S., R. 2 W., EAST OF ADEN CRATER. DEPRESSIONS ARE 100 FT TO 150 FT IN DIAMETER. NOTE TREE IN FOREGROUND FOR SCALE.

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REAR POCKET

Abstract

The Potrillo Basalt field is situated principally in southwestern Dona Ana County, New Mexico. Strata ranging from Paleozoic to Holocene are exposed in the area. Marine sediments, chiefly carbonates, were deposited during repeated advances and withdrawals of late Paleozoic and early Mesozoic seas. Throughout the Cenozoic the area was above sea level and experienced periods of volcanism, erosion, and deposition of continental material. Folding and faulting of Lower Cretaceous strata occurred during the Laramide disturbance in the East Potrillo Mountains. In the early to middle Tertiary a large andesitic pluton, Mt. Riley-Mt. Cox, was emplaced northwest of the East Potrillo Mountains. Closely associated with this activity was the intrusion of the andesite and quartz latite dikes of the East Potrillo Mountains, and small intrusive plugs adjacent to Mt. Riley. During middle Tertiary, high-angle faulting and uplift occurred in the East Potrillo Mountains and initiated the formation of intermontane basins such as the Mesilla bolson. Basin-fill deposits of late Tertiary to early Quaternary are termed the Santa Fe Group. These include a stream channel and flood-plain facies (Camp Rice) and a lacustrine-playa facies (Fort Hancock). During middle to late Quaternary, alkali olivine basalt (Potrillo Basalt) was extruded. The basalt was erupted from fissures associated with Fitzgerald, Robledo, and Aden faults. The basalt of the Aden-Afton region is situated in a graben, whereas those of the West Potrillo Mountains are on a horst. Numerous volcanoes occur in the volcanic field; they include such types as cinder, explosive, maar, and shield. Late Pleistocene to Holocene movement is evident along many of the major faults such as the Robledo and Fitzgerald faults. Holocene deposits, which cover large areas of basalt and the Santa Fe sediments, consist mainly of fine blown sand and minor playa deposits.

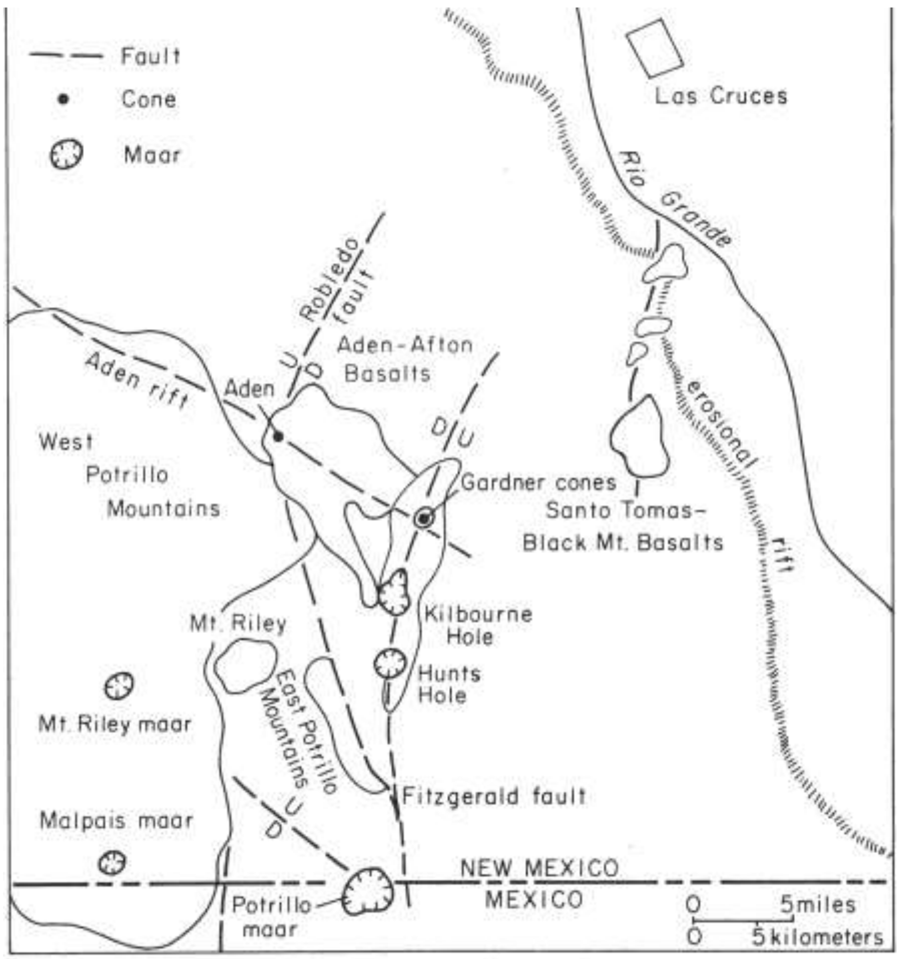

FIGURE 1—INDEX MAP OF THE POTRILLO BASALT FIELD.

Introduction

PHYSIOGRAPHY

The region of investigation covers over 500 square miles in southwestern Dona Ana County and a part of eastern Luna County, New Mexico, located about 40 miles west and northwest of El Paso, Texas and 20 miles southwest of Las Cruces, New Mexico (fig. 1). The study area is bounded on the north by the Southern Pacific Railroad tracks, on the east by the New Mexico meridian, on the west by a line 7 miles west of the West Potrillo Mountains, and on the south by the international boundary between the United States and Mexico.

Physiographically, this region is located in a major intermontane basin, the Mesilla bolson, which is part of the Mexico Highland section of the Basin and Range province (Thornbury, 1965). The basin surface of middle Pleistocene age has been designated the La Mesa surface (Ruhe, 1964, 1967; Hawley and Kottlowski, 1969). Major features of the region consist of Quaternary volcanoes and associated lava flows (Potrillo Basalt), a westward dipping fault-block mountain range (East Potrillo Mountains), and a number of small hills of intrusive igneous rock (Mt. Riley-Mt. Cox).

PURPOSE AND SCOPE

This report was prepared from geological studies of the area completed by J. M. Hoffer, C. J. Callahan, R. 0. Page, and R. S. Millican from 1970 to 1974.

During June and July 1970 Millican mapped and studied the petrography of the intrusive masses of the Mt. Riley region in conjunction with a master's thesis in the Department of Geological Sciences, University of Texas at El Paso. Callahan, also a geology graduate student at the same institution, investigated the geology of the East Potrillo Mountains during the months of August, September, and October 1970. During the summer of 1971, Callahan studied the surface features of the basalt near Aden as part of a master's thesis at the University of Texas at El Paso. The geology of Malpais volcano in the West Potrillo Mountains was studied by Page as a University of Texas at El Paso master's thesis. Hoffer mapped and studied the petrography of the volcanic rocks, investigated economic geology of the area, and directed the project.

The purpose of the investigation was to prepare a more detailed geological map than was previously available for the area with special emphasis on determining the major volcanic units and their relationships, reexamining the sedimentary units of the East Potrillo Mountains, determining the nature and composition of the igneous rocks in and around the Mt. Riley-Mt. Cox hills, and evaluating the economic resources of the area.

Mapping was done on Army Map Service aerial photographs at scales of 1:55,500 and 1:18,500. Data were transferred to U.S. Geological Survey topographic maps for preparation of the geologic map. Classification of rock types, both igneous and sedimentary, was determined by examination of over 300 thin sections.

PREVIOUS INVESTIGATIONS

No detailed geologic investigation has been completed of the entire area to date, although descriptions of specific features have been published. Part of the area is included in a reconnaissance geologic map by Kottlowski (1960), and the area is included in a geologic map of southwestern New Mexico, scale of 1:380,160, prepared by Dane and Bachman (1961).

Studies of several of the volcanic craters, especially the maar volcanoes, have been reported by DeHon (1965a, b, c), Reeves and DeHon (1965), Lee (1907), Darton (1911), Dunham (1935), Reiche (1940), Shoemaker (1957), and Page (1973). The major element geochemistry of the Potrillo Basalt was discussed by Renault (1970).

Information concerning the geomorphology and Cenozoic stratigraphy is included in reports of Hawley (1965), Hawley and Kottlowski (1969), Sayre and Livingstone (1945), Conover (1954), and King, Hawley, Taylor and Wilson (1969).

A geologic study of the structure and general stratigraphy of the East Potrillo Mountains was completed by Bowers (1960) as a master's thesis at the University of New Mexico.

ACKNOWLEDGMENTS

Thanks are due to all ranchers in the area for their cooperation and for furnishing information concerning local rocks. Particular acknowledgment is due Jay Gardner for access across his land and use of his front yard as a field camp during June and July 1970.

John W. Hawley, U.S. Soil Conservation Service, and William S. Strain, Department of Geological Sciences, University of Texas at El Paso, contributed information concerning the geomorphology and Cenozoic stratigraphy of the area. The expense of field work and preparation of thin sections was defrayed under arrangements of Don H. Baker, Jr., former director of the New Mexico Bureau of Mines and Mineral Resources, and the National Aeronautics and Space Administration grant (NASA 44-012-147). Frank Kottlowski, Senior Geologist and Director of the Bureau, suggested the project and was helpful in its definition. Four complete rock chemical analyses were obtained with funds from a University Research Grant, University of Texas at El Paso, 1969-70, to the author. The manuscript was reviewed and greatly improved by J. W. Hawley, J. R. Renault, and R. E. Clemons.

Paleozoic and Mesozoic Geology

PALEOZOIC ROCKS

The oldest rocks that crop out in the area are in small hills surrounded by sand dunes west of the West Potrillo Mountains (geologic map, in pocket). Coyote Hill (T. 29 S., R. 5 W.) includes a section of unfossiliferous, light-gray, cherty, dolomitic limestone of probable Paleozoic age. Kottlowski, Foster and Wengerd (1969) indicated that the rock appears to be Fusselman Dolomite (Silurian), but may be Hueco Limestone. On George Hill, located 2 miles east of the area, there is a section of fossiliferous Hueco Formation (Permian) overlain by Cretaceous strata. The Hueco there is a light- to dark-gray, cherty limestone containing numerous gastropods and brachiopods.

The Hueco crops out along the base on the eastern side of the East Potrillo Mountains and on the northwest end of the range. A 218-ft section of the Hueco Formation was measured just north of the marble quarry (sec. 1, T. 28 S., R. 2 W.). The section consists of medium- to dark-gray to black, fine- to medium-grained limestone, dolomite, and silicified marble; interbedded lenses of limestone conglomerate are also common.

Bowers (1960) reported that no fossils were found in these rocks, but local zones contain light-colored irregular spots that might be relics of shells almost completely destroyed by subsequent silicification and low-grade metamorphism. Based on similar lithology these beds are thought to be equivalent to the Hueco Limestone exposed near Las Cruces and east of Anthony.

Callahan collected several types of fossils from the Hueco Formation, and these have been identified as being Permian by E. L. Yochelson (Kottlowski, 1971, personal communication). The Permian fossils consist mainly of bellerophontid gastropods.

MESOZOIC ROCKS

Lower Cretaceous sedimentary rocks crop out in the East Potrillo Mountains, on the north flank of Mt. Riley, and at Eagles Nest west of the West Potrillo Mountains (geologic map, in pocket). The sedimentary units consist primarily of limestone and minor clastic rocks.

The Cretaceous rocks in the East Potrillos have been divided into 3 major units by Bowers (1960) on the basis of different lithologies, each unit separated by an unconformity or disconformity. Because of the uncertainty in correlation with known formations in nearby areas, the Cretaceous units outlined by Bowers (1960) were named after local geographic features. The units are informally called (oldest to youngest) Noria, Little Horse, and Restless formations and will be referred to in this report as Cretaceous units 1, 2, and 3, respectively.

Units 2 and 3 contain Lower Cretaceous fossils of Comanchean age belonging to the Fredericksburg Group or older; fossils from these Cretaceous units resemble both Fredericksburg and Trinity forms (Bowers, 1960, Darton, 1928). Craig (1972) indicates that unit 2 (Little Horse), based on lithologic and fossil evidence, correlates with the upper Cuchillo and Benigno Formations of Sierra de Juarez.

The oldest Cretaceous unit in the East Potrillos, unit 1, lies unconformably on the Hueco and ranges from 270 to 600 ft thick. It consists of basal conglomerate of limestone and cherty pebbles and cobbles in a calcareous matrix. This is overlain by a sequence of silty to sandy limestone and dense claystone. A soft, thin-bedded shale marks the top of this unit. The shale is white to light green; locally it is silicified, bleached, and stained red with iron oxides from hydrothermal solutions.

Lying unconformably on unit 1 is unit 2. It ranges from 219 ft in the south to over 300 ft at the north end of the range. At the base of this unit is a massive, gray, fine-grained limestone which can be traced the entire length of the range. The upper part of this unit is fossiliferous, containing pelecypods, corals, and large gastropods. Above this sequence are fine- to coarse-grained sandy limestone and a light-gray bioclastic limestone; the formation is fossiliferous near the top, containing fragments and shells of gastropods and pelecypods.

Unit 3 is locally disconformable on unit 2. It ranges from 150 to 470 ft thick and consists of massive, fine-grained, fossiliferous limestone at the base and grades upward into a silty and sandy limestone.

A 200-ft sequence of reddish-brown shale, brown to greenish siltstone overlain by brownish sandstone, and a quartz-lithic conglomerate crop out on the northeast side of Mt. Riley. The beds display erratic dips ranging from 14 to 65 degrees toward the northeast. A fossiliferous limestone boulder within the conglomerate contains Mesozoic pelecypods indicating a probable Cretaceous age for the strata (Strain, 1971, personal communication).

Early Cretaceous strata crop out at Eagles Nest and in several small hills to the north and east (T. 27 S., R. 5 W.). At Eagles Nest over 1,000 ft of both clastic and chemical rocks are exposed (fig. 2). The section includes (from top to bottom) the following major units: 1) massive, cliff-forming, light-gray limestone; 2) limestone conglomerate; 3) arkosic sandstone; 4) limestone-chert conglomerate; 5) fossiliferous gray limestone reef with abundant rudistids, brachiopods and pelecypods; 6) alternating thin-bedded shale, siltstone, and limestone; and 7) brownish-gray, thin-bedded limestone. This section is almost identical lithologically to the Lower Cretaceous in the Tres Hermanas Mountains, 24 miles to the west (Kottlowski and Foster, 1962).

FIGURE 2—EAGLES NEST (T. 27 S., R. 5 W.) SHOWING MASSIVE CLIFF-FORMING LIMESTONE; VIEW LOOKING NORTHWEST.

Tertiary Geology

Except for the Santa Fe, the only exposed rocks of probable Tertiary age are igneous and volcaniclastic. These include the stocklike bodies of Mt. Riley and Mt. Cox, the small plugs surrounding Mt. Riley-Mt. Cox, dike rocks in the East Potrillo Mountains, and volcanic flows, breccia, tuffs, and intrusives in isolated outcrops on the west and north flank of the West Potrillo Mountains (geologic map). The exact age of these igneous bodies is not known, but many show intrusive contacts with Cretaceous strata and are therefore thought to be at least Tertiary.

MT. RILEY-MT. COX AREA

Mt. Riley and Mt. Cox are the names of 2 high peaks on a stocklike intrusive mass located approximately 2 miles northwest of the East Potrillo Mountains (fig. 3 and geologic map). The intrusive mass rises abruptly some 1,600 ft above the La Mesa surface reaching an elevation of almost 6,000 ft.

The base of the pluton is buried by talus and alluvium, preventing a direct view of the relationships with the surrounding rocks. A small outcrop of andesite located about one-half mile north of the main mass is

FIGURE 3—MT. RILEY-MT. COX PLUTON; VIEWED FROM SOUTHEAST.

thought to represent an almost buried apophysis of the main pluton.

Small outcrops of dark-colored, fine-grained limestone which is probably Early Cretaceous occur in steep arroyos on the south, east, and northeast part of the stock (Millican, 1971). The contacts are relatively sharp and locally fragments of the andesite are included in a matrix of recrystallized limestone. The limestone is broken and fractured and appears to dip into the intrusion.

A 300-ft sequence of volcanic tuffs and sediments crops out on the northwest flank of Mt. Riley. At the base of the sequence is a dark-purple to reddish-purple flow(?) of latitic composition. This unit is exposed for one-half mile along arroyos on the northeast side. The contacts with the andesite pluton are generally sharp with minor brecciation and silicification of the latite flow. The contacts with the uppermost unit in the sequence (a brecciated, silicious to calcareous siltstone and conglomerate) are gradational.

The volcanic rocks have tentatively been assigned a Tertiary age; a similar sequence of probable Tertiary volcanic rocks has been penetrated in deep oil tests drilled approximately 16 miles east and southwest of Mt. Riley (Sunray No. 1 in Luna County and Texaco No. 1 Weaver-Federal in Dona Ana County; Kottlowski, Foster, and Wengerd, 1969).

A small basaltic cone and associated flow of the Potrillo Basalt (Quaternary) crop out in contact with the andesite pluton on the west flank of Mt. Cox. The basalt is separated from the main volcanic area to the west by alluvium and talus. However, fragments of andesite included in the basalt indicate that the intrusive mass is pre -Q uaternary.

STRUCTURE

The steep-sided intrusive mass is cut by 2 prominent sets of joints; one set strikes northwest and the other northeast (Millican, 1971). In most areas the jointing is closely spaced and produces sheety or tabular fragments. Downslope movement of these fragments has produced prominent talus cones and alluvial fans around the base of the mountain.

One major fault zone traverses the intrusive mass; it trends approximately N. 30° W. The fault can be traced intermittently from the west side of the pluton southeast across the pluton. The fault zone, which is brecciated and recemented by calcite and siderite, reaches a maximum width of about 100 ft.

PETROGRAPHY

The Mt. Riley-Mt. Cox pluton is a fine-grained, light-colored, microporphyritic andesite to rhyodacite (Millican, 1971). Texturally, the rock averages approximately 7 percent subhedral phenocrysts of altered mafic and feldspar crystals. The tabular phenocrysts display generally subparallel orientation. The groundmass, averaging less than 0.01 mm, is trachytic to pilotaxitic. The lath-shaped plagioclase displays subparallel orientations with interstitial anhedral crystals of K-feldspar and quartz.

The intrusive mass is composed of predominantly andesine. Plagioclase occurs as both phenocrysts and groundmass; small masses of granoblastic quartz grains indicate that at least some of the quartz is xenolithic. Small disseminated grains of anhedral magnetite are scattered throughout the groundmass.

Alteration ranges from moderate to high. The andesite, especially on joint surfaces, is reddish to reddish brown. The reddish colors are due to abundant hematite stain derived through almost complete alteration of biotite crystals. Chlorite is also present as an alteration product of the mafic minerals. The feldspars are altered to sericite and clay. Secondary replacements of calcite and silica occur locally.

CHEMISTRY AND MINERALOGY

The mineralogy and chemistry of the Mt. Riley-Mt. Cox pluton are presented in table 1. Also included are the normative mineralogy and chemical analyses of similar andesite masses from the nearby Rio Grande valley (herein referred to as valley andesites).

Chemically, the Mt. Riley-Mt. Cox mass is high in alkalis, a feature shared by most other igneous rocks of the area (Hoffer, 1970). The analysis is very similar to

TABLE 1—CHEMISTRY AND MINERALOGY OF THE RIO GRANDE VALLEY ANDESITES AND THE MT. RILEY INTRUSIVE (The Rio Grande valley andesites include the Vado, Westerner, and Campus Andesite. Analysis of Campus Andesites by Booth, Garrett and Blair, Inc., Ambler, PA, and analysis of Vado, Westerner, and Mt. Riley by Tadashi Asari, Japan Analytical Laboratory.)

Oxides	Valley andesites	Mt. Riley-Mt. Cox intrusive
SiO_2	63.43%	65.16%
Al_2O_3	16.42	15.86
Fe_2O_3	1.59	2.95
FeO	2.68	0.72
MnO	0.17	0.09
MgO	1.43	1.31
CaO	3.02	2.59
Na_2O	5.08	4.12
K_2O	3.45	3.74
TiO_2	0.42	0.23
P_2O_5	0.29	0.15
H_2O (±)	1.86	3.12
Totals	99.84%	100.04%
Apatite	0.7%	0.4%
Ilmenite	0.8	0.5
Orthoclase	20.6	22.9
Albite	44.1	35.9
Anorthite	11.4	12.3
Magnetite	2.0	2.0
Diopside	1.5	—
Hypersthene	6.4	3.4
Chromite	0.2	0.6
Hematite	0.3	1.6
Quartz	12.0	20.4
Totals	100.0%	100.0%

those of other andesite plugs located near El Paso. However, the Mt. Riley-Mt. Cox intrusive is notably higher in water and Fe_2O_3/FeO, reflecting a higher degree of weathering; nearly all of the mafic crystals are altered to iron oxides and clay. The high water content is from the abundance of clays derived from weathering of the feldspars. In addition, the Mt. Riley-Mt. Cox pluton is lower in total alkali content (Na_2O + K_20, 7.5 to 8.8 percent) and higher in total silica than the valley andesites although it shows more alteration.

Based upon chemistry and mineralogy the Mt. Riley-Mt. Cox intrusive mass is possibly related to the valley andesites. Both groups of andesite show intrusive contacts with Cretaceous strata and are in contact with undisturbed Quaternary sediments; all are thought to be Tertiary. One of these andesite plugs, the Campus Andesite, has been radiometrically dated at 47 ± 2.3 m.y. (Hoffer, 1970). The greater degree of weathering of the Mt. Riley-Mt. Cox body might reflect a greater age compared to the valley andesites. However, the exact temporal relationship between the Mt. Riley-Mt. Cox pluton and the valley intrusives cannot be definitely established until a radiometric age date is obtained on Mt. Riley.

Several small intrusive plugs, completely surrounded by late Quaternary blown sand and alluvium, crop out south of Mt. Cox. The plugs form small hills that rise 25 to 100 ft above the surface and are partially covered with Holocene blown sand (Millican, 1971).

The small plugs are andesites, similar to the Mt. Riley-Mt. Cox mass, or dark-colored basaltic andesites. The andesite masses are probably apophyses of the main pluton, but the basaltic andesites do not appear to be related to it. One of these basaltic plugs contains inclusions of dark-gray, fine-grained limestone and a quartz pebble conglomerate. The sedimentary rocks are similar to those exposed on the flanks of Mt. Riley and have tentatively been assigned to the Lower Cretaceous. The exact age of the basaltic plugs is not known, but they are possibly Tertiary.

EAST POTRILLO MOUNTAINS AREA

Andesite to latite dikes intrude all sedimentary rocks of the East Potrillo Mountains. The dikes, generally northeast-trending, average less than 10 ft thick and extend from 200 to over 3,000 ft. They are generally aphanitic, displaying sharp contacts with the surrounding sedimentary strata. Bowers (1960) reported that the dikes are younger than the overturned folds and thrust faults in the range, but have been cut by high-angle faulting.

The dikes can be divided into 3 types. These include light-colored porphyritic andesite, dark-colored andesite, and microporphyritic quartz latite.

The light-colored andesite dikes are the most abundant and occur predominantly in the northern part of the range within secs. 11 and 14, T. 28 S., R. 2 W. The dikes consist primarily of andesine with minor amounts of K-feldspar and quartz. Mafics that were formerly biotite and/or hornblende are completely altered to chlorite and iron oxides. The feldspars show moderate alteration to sericite, clay and calcite. The subhedral to anhedral groundmass crystals, with subparallel orientation, average 0.3 mm. There are occasional phenocrysts of plagioclase.

The dark-colored andesite dikes, resembling basalt, occur within the middle part of the range in secs. 14 and 25, T. 28 S., R. 2 W. These dikes are distinctly porphyritic with small subhedral to anhedral calcic andesine and minor K-feldspar phenocrysts set in a very fine grained groundmass; the phenocrysts average 0.5 mm. Parallel alignment of the lath-shaped phenocrysts is well developed. The finer-grained groundmass is composed of anhedral plagioclase, iron oxides, biotite(?), and magnetite. Alteration is moderate to light.

A light-colored dike of latitic composition is exposed at the south end of the range, sec. 21, T. 28 S. R. 2 W. The dike averages approximately 50 ft in width and can be traced within the Cretaceous rocks foi over 3,000 ft in a north-northeast direction. The dike rock is microporphyritic with occasional small pheno. crysts of plagioclase and K-feldspar set in a fine-grainec anhedral groundmass, averaging 0.05 mm of feldspar and quartz. The rock shows only minor alteration and is classed as a quartz latite.

Most of the dikes in the range are locally cut by thir veinlets of calcite and/or quartz. The more highly altered dikes are less resistant to erosion than them recrystallized and silicified bordering limestone anc therefore form narrow drainage channels on steepe slopes.

PROVIDENCE AREA

Mount Aden is a circular igneous plug cropping out over an area of approximately one-eighth square mile; it rises approximately 300 ft above the surface of the desert with the lower slopes mantled with talus.

Mount Aden is composed of rhyolite; the rock is very fine grained, averaging less than 0.02 mm in grain size

It is composed primarily of K-feldspar and is highly silicified. Most of the mafics, mainly biotite, are altered to iron oxides giving the rock a yellow-brown stain.

PROSPECT HILL—EAGLES NEST AREA

A complex intrusive mass of granite and andesite is located approximately a mile east of Eagles Nest (T. 27 S., R. 5 W.). The andesite pluton is in intrusive contact with Cretaceous strata; numerous andesite dikes cut the Cretaceous rocks. An irregular mass of granite crops out at the southern end of the hill. The granite, brecciated locally, is cut by andesite dikes that can be traced north into the Cretaceous carbonate rocks.

The granite averages approximately 1.5 mm in grain size. It is composed of perthitic K-feldspar and anhedral quartz. The andesite is porphyritic with phenocrysts of plagioclase in a groundmass of plagioclase, augite, and hornblende. Most of the minerals are highly altered with plagioclase showing abundant sericite and calcite and the mafics altered to hematite-limonite and magnetite.

The Prospect Hills (T. 29 S., R. 5 W.), located approximately a mile north of the international boundary, consist of a series of small andesite hills with a total outcrop of about half a square mile. The andesite plug is cut by several northwest-trending silicic dikes.

CAMEL MOUNTAIN AREA

A section of tuffs, breccias, and flows of silicic to mafic composition crop out in 3 major areas west and north of the West Potrillo Mountains (geologic map). The areas are located northwest of Mount Aden, the Butte area, and the region surrounding Camel Mountain.

Camel Mountain, located on the boundary of T. 29 S., R. 4 W. to R. 5 W., is an elongate hill rising over 500 ft above the surrounding desert. It is composed of tuffs and breccias of rhyolite to latite composition. Most of the outcrops are highly stained with iron oxides and the rocks are locally silicified. Camel Mountain is cut by several shear or brecciated zones, striking N. 15° E. to N. 45° W. In many of these zones the fragments are recemented by quartz and manganese oxides.

West and north of Camel Mountain are a group of small hills composed of volcanic rocks. The rocks are microporphyritic to porphyritic tuffs with a very fine grained groundmass. These volcanic rocks generally show good flow banding and range in composition from rhyolite to andesite; latite is the most abundant rock type; andesite to quartz latite breccias also occur.

BUTTE AREA

Small hills (T. 27 S., R. 4 and 5 W.) just west of the Black Hills (geologic map) are composed of fine-grained, silicic intermediate volcanic tuffs overlain by basalt; they represent units of the Bell Top Formation and Uvas Basaltic Andesite, respectively (Seager and Clemons, 1973, personal communication). At Butte and the hills to the southwest, only volcanic tuffs are present.

The tuffs are predominantly andesite and are generally porphyritic with a very fine grained groundmass. Phenocrysts are of plagioclase with small amounts of augite and biotite. Groundmass is of small subhedral plagioclase laths in subparallel orientation. Locally the rocks are silicified and iron stained.

Overlying the tuffs are thin flows of Uvas Basaltic Andesite. The basalts are porphyritic with phenocrysts of plagioclase (labradorite) and minor olivine. The groundmass is medium to fine grained and composed of predominantly plagioclase (andesine to labradorite), accessory pyroxene and glass, and minor olivine and magnetite. Most of the olivine is highly altered to iddingsite, thus giving the rock a brown to brownish-gray appearance on the outcrop.

MOUNT ADEN AREA

West and southwest of Mount Aden are a series of northwest-trending fault block hills. These hills consist of silicic tuffs and breccias generally overlain by basalt. The volcanic rocks are exposed along a series of faults that are upthrown on the south side and tuffs and units dip from 10 to 20 degrees southwest.

The tuffs are porphyritic rhyolites with phenocrysts of sanidine, plagioclase, quartz, biotite, and hornblende. The groundmass is predominantly glass shards showing a moderate degree of welding. The rocks are highly silicified locally. The tuffs resemble volcanic units of the Bell Top Formation (Seager, 1972, personal communication).

In most of the fault block hills, basalt overlies the tuffs. It resembles the basalt of the Butte area, being plagioclase-rich with the majority of the olivine altered to iddingsite. The basalt is thought to be Tertiary because it is mineralogically and texturally similar to the Uvas Basaltic Andesite.

The mode and 3 chemical analyses of the Tertiary basalt from the Mount Aden and Butte area are included in table 2. These lavas are much richer in plagioclase and poorer in olivine and pyroxene than the Quaternary basalts. These differences are also reflected in the chemical analyses.

TABLE 2—A) Chemical data and B) mode of basalt from the Mount Aden and Butte areas

A. Chemical analysis

	Sample 1	Sample 2	Sample 3
SiO_2	50.50%	49.49%	49.49%
TiO_2	2.08	2.16	2.03
Al_2O_3	16.00	15.92	16.05
Fe_2O_3	4.46	6.12	6.40
FeO	6.75	5.94	5.67
MnO	0.15	0.14	0.15
MgO	4.37	5.13	4.81
CaO	8.27	7.98	8.12
Na_2O	3.69	3.44	3.64
K_2O	1.76	1.64	1.59
P_2O_5	0.62	0.67	0.64
H_2O	1.66	1.08	1.31
	100.31%	99.71%	99.90%

B. Mode

Olivine	7.2%
Iddingsite	6.9
Plagioclase	51.9
Pyroxene	9.0
Opaque	15.4
Glass	9.6
	100.0%

Quaternary Geology

SANTA FE GROUP

The Santa Fe Group includes basin-fill deposits of Tertiary and Quaternary age associated with the Rio Grande trough (Hawley and others, 1969). The only significant outcrops of the Santa Fe in the study area are located in the walls of Kilbourne and Hunts Holes, Potrillo maar, and along a fault scarp (Mt. Riley fault) west of the East Potrillo Mountains. In all other areas the Pleistocene sediments are covered by basaltic flows or Holocene unconsolidated sediments.

In the Santa Fe Group of the Hueco and Mesilla bolsons, Strain (1966, 1969) has proposed 2 lithic units, the Fort Hancock and Camp Rice Formations. The Fort Hancock is composed of horizontal bentonitic claystone, siltstone, and silt; it is generally brown, evenly bedded, but crossbedded lenses of silt occur occasionally (Strain, 1969). Strain (1969) attributes the even bedding and fine texture as indicating deposition in lacustrine (Lake Cabeza de Vaca) and playa environments. Bones of vertebrate animals of the Blancan fauna indicate that at least the upper part of the Fort Hancock is early Pleistocene or early Kansan (Strain, 1966).

The Camp Rice Formation is composed of gravel, sand, silt, volcanic ash, and caliche and rests unconformably on the Fort Hancock. The Camp Rice is evenly bedded, poorly sorted, and light colored. These sediments represent mainly stream-channel and flood-plain deposits. Vertebrate fossils indicate a late early to middle Pleistocene age (Strain, 1966, 1969).

In both Kilbourne and Hunts Hole an approximately 70-ft section of the Santa Fe Group is exposed. The section is composed of primarily even-bedded clay, silt, and caliche assigned by Strain (1974, personal communication) to the Fort Hancock Formation. Several wedge- or lens-shaped layers of pebble conglomerate, to 5 ft thick, occur near the top of the section in Kilbourne Hole; these poorly sorted, coarse-grained layers represent the Camp Rice Formation (Strain, 1970, personal communication). A strong soil profile in the upper part of the section marks the buried La Mesa surface (Hawley and Kottlowski, 1969).

The eastern flank of the East Potrillo Mountains is covered by a coarse bajada deposit of fanglomerate mantled with talus. The deposit, consisting of poorly sorted, caliche-cemented, subrounded to angular fragments of Cretaceous and Permian(?) limestones, extends nearly 3,000 ft eastward from the base of the range (geologic map). The coarse fanglomerate ends abruptly against the finer sands and silts of the bolson along the east Robledo fault (Bowers, 1960). Bowers (1960) states that the fanglomerate, in part, is probably equivalent to the upper Santa Fe beds. Hawley (1974, personal communication) correlates the bulk of the deposit with the younger piedmont facies of the middle Pleistocene Camp Rice Formation described in the Las CrucesRincon area (Gile and others, 1970; Seager and Hawley, 1973).

POTRILLO BASALT

The term Potrillo Basalt refers to the Quaternary basaltic lava flows and associated cones that crop out between the Rio Grande valley and the Mimbres valley. These include the volcanic rocks of the West Potrillo Mountains, Santo Tomas-Black Mountain area, and Aden Crater-Kilbourne Hole region (Hoffer, 1971). Within the region of the current investigation at least 3 separate periods of volcanic activity can be differentiated. The lavas representing these periods, from oldest to youngest, are termed the West Potrillo Basalt, Afton Basalt, and Aden Basalt. The relationships of the latter 2 volcanic units are shown in table 3.

WEST POTRILLO BASALT

The West Potrillo Basalt is defined as the Quaternary basalt that crops out in the West Potrillo Mountains. The West Potrillo Mountains consist of a broad topographic high composed almost entirely of volcanic materials. The range rises 400 to 800 ft above the surrounding desert floor and is capped by numerous cinder cones that reach elevations of over 5,000 ft (Hoffer, 1973b).

The cover of late Quaternary alluvium and lack of sufficient erosion prevented the determination of total thickness of the lava pile. Individual flows, where measured, average approximately 10 ft in thickness. A well located 5 miles south of Mt. Riley penetrated 285 ft of basalt and interbedded sand and gravel; these flows average about 17 ft in thickness (King and others, 1969).

Mineralogy and Texture

The lava flows of the West Potrillo Mountains are hypocrystalline with microphenocrysts of olivine, minor plagioclase, and pyroxene. The groundmass, 0.01 to 0.07 mm, is mostly pyroxene and plagioclase with lesser amounts of opaques, glass, and minor olivine (table 4).

TABLE 3—MODAL MINERALOGY OF THE ADEN-AFTON BASALTS (Qad_1—oldest Aden flow; Qad_2—youngest Aden flow; Qaf_1—oldest Afton flow; Qaf_2—middle Afton flow; Qaf_3—youngest Afton flow.)

	Aden Member 1 Qad_1 Percent	Aden Member 2 Qad_2 Percent	Afton Member 1 Qaf_1 Percent	Afton Member 2 Qaf_2 Percent	Afton Member 3 Qaf_3 Percent
Plagioclase	22.2	23.2	23.4	16.1	15.5
Olivine	16.7	11.5	15.1	13.1	11.5
Pyroxene	37.5	41.9	33.8	46.0	48.5
Glass	13.7	13.2	18.5	14.5	12.5
Opaques	9.9	10.2	9.2	10.3	12.0
	100.0	100.0	100.0	100.0	100.0

TABLE 4—MODAL MINERALOGY OF WEST POTRILLO BASALT (8 samples of member 1 and 20 samples of member 2)

	Member 1 vol. %	Member 2 vol. %
Plagioclase	26	19
Olivine	11	18
Iddingsite	2	—
Pyroxene	27	39
Glass	20	12
Opaques	14	12
	100	100

On the basis of petrography and field relationships, the West Potrillo Basalt can be divided into 2 members, older flows termed member 1 and younger flows, member 2. The older flows are exposed in the southeast part of the range.

Pyroxene, the most abundant mineral, occurs as light-to dark-brown subhedral to euhedral grains. Most of the larger crystals are zoned.

Subhedral to euhedral olivine has a high 2V and negative sign. Olivine is most abundant and generally unaltered in the younger lavas, member 1, whereas it is commonly rimmed by iddingsite in flows of member 2.

Plagioclase, almost all of which occurs in the groundmass, is calcic labradorite (An_{60} to An_{70}). The plagioclase is present as subhedral laths in parallel to subparallel orientation.

Opaques are scattered throughout the groundmass as anhedral crystals and masses associated with the glass. Small grains of feldspathoid (analcime?) occur in the groundmass. In addition, occasional exotic crystals of anorthoclase, plagioclase, pyroxene, amphibole, and olivine-pyroxene-spinel masses are present as inclusions in the basalt flows (Hoffer and Hoffer, 1973).

Chemistry

Sixteen chemical analyses have been made of the lavas; 13 analyses are from Renault (1970) and 3 from this study (table 5).

The basalts of the West Potrillo Mountains are classified as alkaline olivine basalts on the ratio of total alkali to silica (Kuno, 1968; Renault, 1970). The average of the analyses shows low silica (44.54 percent), moderate Al_2O_3 (15.40 percent), high total alkali ($Na_2O + K_2O$ = 4.96 percent), and moderately high TiO_2 (2.29 percent).

One distinct chemical difference between the 2 members is the higher MgO content of the member 2 flows. The extent of differentiation of the lavas can be estimated by the use of the Solidification Index, S. I. The S. I. values of member 1 average 43 whereas those of member 2 average 37. This would indicate both lavas are relatively undifferentiated with member 2 showing some accumulation of early formed olivine.

Volcanic Features

Cinder cones are the most abundant volcanoes in the West Potrillo region; over 150 cones have been mapped. They range from 200 to 500 ft in height and 1,000 to 3,000 ft in diameter. Typically, the cones are composed predominantly of basal agglutinated cinder, bedded cinder, bombs, and a partial to complete spatter rim at the top. Most are horseshoe-shaped in plan view, with one or more vents.

Not all of the cones appear to be the same age. Based upon shape and degree of dissection, 2 types, young and old, have been differentiated. The characteristic features

TABLE 5—CHEMICAL ANALYSES OF WEST POTRILLO BASALT (POT by J. Renault, 1970, New Mexico Bureau of Mines and Mineral Resources; WP by T. Asari, Japan Analytical Laboratory. *represents total Fe reported as FeO; nd represents not determined.)

	Member 1					Member 2										
Oxide	WP-1	WP-2	POT 13	POT 15	POT 19	WP-3	POT 2	POT 10	POT 11	POT 12	POT 16	POT 17	POT 18	POT 20	POT 21	POT 22
SiO_2	44.63	44.37	43.50	44.98	45.16	44.21	43.92	43.13	44.06	46.08	45.48	44.24	44.70	44.47	43.87	44.42
TiO_2	2.60	2.37	2.51	2.15	2.20	2.21	2.25	2.37	2.29	1.97	2.23	2.35	2.28	2.34	2.18	2.34
Al_2O_3	15.92	15.98	15.65	15.29	15.67	15.01	15.13	15.70	14.32	14.23	16.22	14.49	15.30	15.49	15.48	15.44
Fe_2O_3	3.66	4.13	—	—	—	4.82	—	—	—	—	—	—	—	—	—	—
FeO	6.56	6.82	*10.06	*9.82	*9.95	6.07	*9.44	*9.47	*10.29	*8.84	*9.45	*9.93	*9.47	*10.29	*9.41	*9.93
MnO	0.14	0.16	0.19	0.20	0.19	0.14	0.17	0.17	0.22	0.18	0.17	0.19	0.18	0.18	0.17	0.18
MgO	9.17	7.30	9.10	9.09	8.97	10.34	11.35	10.17	10.39	11.10	10.17	10.84	10.98	10.38	10.81	10.92
CaO	10.36	10.09	11.16	10.12	9.84	10.94	10.98	10.63	10.25	10.57	9.66	9.75	10.73	10.56	10.82	10.72
Na_2O	4.70	4.48	2.93	2.23	3.40	3.67	2.70	3.36	3.11	3.82	3.60	3.29	3.41	3.05	2.86	3.38
K_2O	0.90	2.27	1.55	1.18	1.74	1.65	1.66	1.53	1.39	0.78	1.44	1.49	0.98	1.51	1.58	1.54
H_2O	1.60	1.90	nd	nd	nd	nd	nd	nd	nd	nd	nd	nd	nd	nd	nd	nd
P_2O_5	0.64	0.74	nd	nd	nd	0.48	nd	nd	nd	nd	nd	nd	nd	nd	nd	nd
Totals	100.88	100.61	96.65	95.06	97.12	99.54	97.60	96.53	96.32	97.57	98.42	96.57	98.03	98.27	97.18	98.87

of each type are summarized in table 6. The younger cones are generally large and steep-sided with slopes from 20 to 25 degrees. Most are relatively undissected by erosion with their slopes possessing shallow, closely spaced arroyos. The cinder cones usually contain a single vent with a breached rim through which the lava flow has been extruded. The older cinder cones are much more subdued with slopes from 10 to 20 degrees; deep arroyos cut the slopes. In addition, these cones occur in complexes with multiple vents. Within these complexes 3 to 6 individual cones with abundant spatter are arranged in an irregular or linear pattern. Those displaying a linear outline trend north and extend up to 11/2 miles. With these older cones xenoliths of feldspar and pyroxene occur as loose crystals or in the interior of bombs and cinders.

TABLE 6—CHARACTERISTIC FEATURES OF WEST POTRILLO CINDER CONES

	Young cones	Old cones
Height	200 to 500 ft	50 to 300 ft
Slopes	20 to 25 degrees, cut by shallow arroyos	10 to 20 degrees, cut by deep arroyos
Spatter	rare	abundant
Vents	single	multiple
Xenoliths	rare	abundant
Shape	horseshoe in plan	horseshoe to irregular in plan

Maar Volcanoes

Two maar volcanoes occur in the West Potrillo Mountains. These explosive volcanoes are Mt. Riley maar and Malpais maar located 5 miles west of Mt. Riley and 3 miles east of Malpais, respectively.

The Mt. Riley maar is nearly circular in outline with an interior diameter of approximately 3,000 ft. The rim is composed of thin parallel layers dipping 30 to 50 degrees away from the crater. The rim deposits are composed of poorly sorted, subangular to subrounded basalt, scoria, mineral, and lithic fragments. Mineral fragments include large crystals of feldspar, pyroxene, and olivine-enstatite aggregates to 3 inches in size. Similar olivine-enstatite masses occur as bomb cores and inclusions at Kilbourne Hole and Potrillo maar, respectively. Large fragments of dense basalt to 6 ft in diameter have been found in the rim deposits (fig. 4). The east and northeast floor of the crater is covered by a thin basalt flow that appears to have emerged from a vent within the crater. The age of the maar is unknown, but it appears to be one of the older features in this section of the volcanic field. Lavas from cones to the north and west have buried parts of the bedded rim deposits.

Malpais maar is classed as a tuff ring formed by phreatomagmatic eruption of basaltic magma among cinder cones and lava flows (Page, 1973). The crater measures 4,100 ft in diameter, approximately 1,400 ft in depth, and is outlined by a low rim of bedded ejecta which thins away from the crest (fig. 5). Bedded tuffs included ash, lapilli tuff, and tuff-breccia which were deposited by air-fall and base-surge currents. Sedimentary structures reported in the tuffs include dunes,

FIGURE 4—LARGE EJECTA FRAGMENT OF DENSE BASALT, MT. RILEY MAAR.

ripples, current crossbedding, plane parallel laminae, and bomb sag structures (Page, 1973).

On the northwest side maar ejecta are covered by younger lava flows, whereas to the north, west, and east these beds occur on the flanks of several small cinder cones. This indicates that the maar formed after development of most of the cinder cones in this area, but before the extrusion of the younger flows. Basaltic rocks, which nearly bury the maar crater, consist of flows, dikes, cinder-spatter cones, and vent agglomerate (Page, 1973). Within the maar occurs a large cinder-spatter cone complex with 2 to 3 associated vents. Several basaltic dikes crop out on the east side of the maar. Page (1973) has outlined the following series of events in the development of Malpais maar:

1) initial steam eruptions quarrying a conical crater, producing air-fall and base-surge tuff deposits,
2) building of the central cinder-spatter cones and eruption of basaltic lava flows,
3) intrusion of basaltic dikes toward the end of the period in which lava flows were erupted, and
4) post-maar cones and lava flows.

Xenoliths

Exotic crystals of feldspar, pyroxene, amphibole, and olivine-pyroxene-spinel masses occur abundantly in the volcanic rocks of the West Potrillo Mountains; they are found as isolated crystals, within volcanic bombs associated with the older cinder and maar cones, or as inclusions in basalt flows. Similar xenoliths, although not as abundant, are found at Kilbourne and Hunts Holes and Potrillo maar. To date, only the olivine-pyroxene-spinel nodules at Kilbourne have been studied. Carter (1970) reported that the mafic nodules represent a part of the upper mantle derived by partial fusion-partial crystallization and brought to the surface during volcanic eruption.

The most abundant crystals are feldspars; they occur commonly as loose crystals or as inclusions in bombs associated with the cinder cones. The crystals are anhedral to euhedral, white to colorless, and range from several millimeters to nearly 5 centimeters in diameter.

The feldspar inclusions were selected for chemical analysis of K_20, CaO, and Na_2O and the results calculated to mole percent Ab, An, and Or. The results show a variety of compositions which include anorthoclase, lime anorthoclase, potash andesine, and plagio-

FIGURE 5—Geologic map of Malpais maar: 1) colluvium, 2) tuff, 3) basalt, and 4) cinder cone.

clase (Hoffer and Hoffer, 1973). The plagioclase crystals occur as inclusions in volcanic bombs whereas the alkali feldspar crystals are found as loose crystals.

The structural state (degree of disorder) of the alkali feldspars is high. The plagioclases range from high to low structural state. The degree of plagioclase disorder correlates with increasing Or content, indicating that the ordered states are only apparent.

The occurrence of anorthoclase inclusions associated with basaltic rocks has been reported from 2 other locations, Mongolia and Antarctica. The specimen from Mongolia is a monoclinic form of anorthoclase formed at high temperature (Vlodavetz and Shavrova, 1953). Loose crystals of feldspar collected on the slopes of Mt. Erebus are lime-anorthoclase (Mountain, 1925).

The occurrence and texture of the West Potrillo anorthoclase and plagioclase crystals indicate that they are inclusions and were carried to the surface in an undifferentiated magma. A preliminary analysis of the alkali feldspar crystals indicates an origin in a high temperature environment, probably at great depth. This is indicated by 3 facts: 1) the alkali feldspars are associated with high temperature mantle derived olivine-pyroxene-spinel nodules, 2) the feldspar crystals are of high structural state, and 3) no known anorthoclase occurs in the pre-basalt rocks at shallow depth through which the magma passed.

AFTON BASALT

The Afton Basalt is defined as the flows that crop out south and southeast of Afton (T. 26 S., R. 1 W.). The Afton flows are spacially distinct from the Aden flows, and represent a single formation. Three periods of basalt extrusion can be identified within this area. Kottlowski (1960) designated 2 basalt formations, Qb_1 and Qb_2, but detailed mapping indicates that 3 periods of basalt extrusion have occurred here and all are from related vents. Therefore, the 3 basalt members are placed in the same formation, the Afton Basalt.

Mineralogy and Texture

The basalt flows of the Afton Basalt are hypocrystalline, microporphyritic, and vesicular. Microphenocrysts average approximately 15 percent and are composed of olivine and minor plagioclase. The groundmass displays an intergranular to intersertal texture and consists of small plagioclase laths and interstitial granules of pyroxene and irregular patches of glass and minor feldspathoid.

Labradorite (An_{50} to An_{65}) occurs as sparse subhedral to euhedral phenocrysts. These phenocrysts show both normal and reverse zoning. Groundmass plagioclase averages 0.08 mm and shows trachytic texture.

Olivine occurs almost exclusively as phenocrysts in glomeroporphyritic masses. The composition is magnesium-rich as indicated by a high 2V and negative sign.

Clinopyroxene, the most abundant mineral, occurs in small granules and as short tabular crystals; it ranges from light brown to a deep reddish brown. Micropheno-crysts have a low 2V, less than 40 degrees, and are probably pigeonite.

Glass, which ranges from less than 5 percent to over 30 percent of the rock, occurs as irregular patches and masses in the groundmass. The glass is light to dark brown; its opacity is a function of the amount of included iron oxides.

Minor alteration products consist of thin rims of iddingsite around olivine crystals and staining by iron oxide. Secondary minerals, which occur as vesicle fillings, consist predominantly of clay and calcite.

Flow Sequence

The oldest flow of the Afton Basalt is designated Qaf_i, corresponding to Kottlowski's (1960) Qb_1. This flow is exposed in the rim of both Kilbourne and Hunts Holes where it obtains a maximum thickness of 25 ft. Generally the flow is blanketed by Holocene blown sand except in the area south of Hunts Hole. The lava flow (Qaf_1) covers approximately 13 square miles, measuring 9 miles in length and averaging slightly less than 2 miles in width, but the flow narrows to less than one-fourth mile at its southern end. To the north the flow disappears beneath the middle basalt flow, Qaf_2, which is covered by blown sand.

Characteristic features of the Qaf_i lava include a generally dense interior with vesicular top and bottom zones and abundant pipe vesicles. Small pressure ridges are abundant along the margins at the southern end of the flow. Two K-Ar whole rock determinations from a lava sample (Qaf_1) at Kilbourne Hole by R. E. Denison (Mobil Research Corp.) give dates of 141,000 ± 75,000 years and 103,000 ± 84,000 years (Kottlowski, 1970, written communication).

Qaf_2 lava, the middle basalt flow, crops out over an area of 9 square miles; this flow was designated Qb_2 by Kottlowski (1960). The most prominent features of the Qaf_2 basalt are small marginal pressure ridges, shallow collapse depressions, and a major lineament located about a mile northeast of the Gardner cones. The lineament, which trends north-northeast for a distance of 1 1/2 miles, is a trough-shaped depression; it ranges from 10 to 16 ft deep and 50 to 100 ft wide. To the north of the basalt field, the lineament is expressed as a series of fault scarps and elongated depressions termed the Fitzgerald fault; the fault is downthrown on the west (DeHon, 1965b). The lineament is very similar to features described in the Aden Basalt.

The exact relationship between Qaf_2 and Qaf_1, lava is obscured by the cover of Holocene blown sand; however, the Qaf_2 flow, because of its higher topographic position, appears to overlie Qaf_1, and represents a separate extrusive episode.

Two features of the Qaf_2 basalt make it possible to distinguish it in the field from the Aden Basalt on the west and the Kilbourne-Hunts Hole basalt (Qaf_1) to the south; these include the nature of the vesicles and the color of the basalt. The Qaf_2 basalt contains 2 sets of vesicles, one averaging one-fourth to one-half inch in diameter and the other set 2 to 3 inches in diameter. The smaller vesicles are nearly equidimensional, whereas the larger ones are highly elongated. This gives a ridge and valley appearance to the top of the flow. The Qaf_2 flow has a distinct dark-bluish-black color in contrast to the dark-gray to black color of the Qaf_i basalt.

Approximately one-half mile southwest of the Gardner cones are 2 prominent elongate domal struc-tures; these ridges extend 10 to 17 ft above the lava surface and resemble pressure ridges. The 2 features are located at the crest of a broad northeast-southwesttrending ridge, in line with a trend from Kilbourne Hole to the Gardner cones and on to the northeast where the lineament is expressed as an elongated trough in the basalt. The location of the lineament is undoubtedly structurally controlled and has been identified as the trace of the Fitzgerald fault (DeHon, 1965b). The lineament may represent the surface trace of the fissure zone from which the Qaf_i or Qaf_2 lavas (or both) were extruded.

The youngest flows of the Afton Basalt are designated Qaf_i. They consist of 3 to 4 local flows averaging 10 ft thick and covering an area of approximately one-fourth square mile on the south and east flanks of the Gardner cones. The flows were probably small central eruptions, which crop out to the east and south of the cones.

The basalt is typically vesicular with development of crude columns near the top of the flow; the interior of the flow is dense. The upper surface of the flows is smooth to ropy.

Two major types of craters are associated with the Afton basalts; these include cinder-spatter cones and maar volcanoes. The cluster of 4 cinder and cinder-spatter cones termed the Gardner cones are from 50 to 100 ft high and are composed of predominantly cinder base and a spatter rim. Local flows, covering approx-imately one-half square mile around the craters, appear to have originated from one or more of the cones as flank eruptions. In addition, a small 50-ft-high spatter cone is located just north of Hunts Hole.

The most spectacular craters of the Aden-Afton Basalts are the maar volcanoes, Kilbourne and Hunts Holes. A similar crater, called Potrillo maar, is located approximately 9 miles south of Hunts Hole astride the international boundary (Reeves and DeHon, 1965). Kilbourne and Hunts Holes have been formerly called the Afton craters (Lee, 1907). Their origin has been variously attributed to subsidence due to the removal of volcanic material (Reiche, 1940), or volcanic explosion

(DeHon, 1965b; Darton, 1911; Shoemaker, 1954; Lee, 1907).

Kilbourne Hole, the largest of the 2 northern maar craters, is a depression 2 miles long and 1 1/2 miles wide. The floor of the depression is 250 to 300 ft below the surface of the surrounding desert and is bordered on the north, south, and east sides by a 10 to 170-ft-high rim (Reiche, 1940). From the bottom of the crater to the top of the rim the following major units are exposed: sand, silt, and clay of the Santa Fe Group; dense porphyritic olivine basalt; bedded tuffs; ejecta and loose sand on the rim and outer flanks (fig. 6).

The Santa Fe beds consist of red to buff bedded silt and clay, and interstratified caliche and soil horizons. The caliche and clay zones show nearly vertical slopes whereas the silt and clay-silt display more gentle slopes. These even-bedded units represent the Fort Hancock Formation (Strain, 1970, personal communication). Near the top of the section, lenses of a pebble conglomerate to 5 ft thick occur; this conglomerate represents the Camp Rice Formation (Strain, 1970, personal communication). Total thickness of the exposed Santa Fe Group is approximately 65 ft.

A 20-ft-thick olivine basalt flow is exposed above the Santa Fe Group. The flow is the oldest of the Afton basalts (Qaf_i). The same basalt crops out on the rim of the Hunts Hole and on the La Mesa surface south and east of Hunts Hole. In the vicinity of Kilbourne Hole it is covered by Holocene blown sand and fine-grained explosive ejecta. The basalt is porphyritic with phenocrysts of predominantly olivine. The rock is dense, but locally contains pockets and lenses of vesicles. They are most abundant near the base of the flow and are described as pipe vesicles.

Bedded tuffs lie directly on the basalt, or where the basalt is absent, as on the southeast and eastern margin of the rim, they rest on sediments of the Santa Fe Group. The lower slopes of the tuffs (on the east and north sides of the Hole) are covered with large angular blocks of basalt, to 4 ft in diameter. Fragments that have been reported include limestone, felsite, sandstone, micaceous siltstone, gneiss, pumice, and granite (Reiche, 1940). Also, large angular blocks of basalt are found in the upper parts of the tuff nearly 120 ft above its base. This fragment material is termed a vent breccia (Lee, 1907; Reiche, 1940) and Reiche (1940) describes the vent area as follows:

> A vent below one of the breccia accumulations is exposed in a section in the north wall of the Hole. At this place the continuity of the basalt and of the lower sands is broken for a distance of 530 feet. The basalt preserves its normal thickness quite to the break, but is slumped downward to it for about 50 feet on either side. The vent is filled with explosion debris, which is well exposed in sharp gulches. The material consists of whitish, dusty, sand matrix, basaltic, or granule and pebble dimension.

The ejecta fragments form an accumulation of blocky rubble on the lower slopes of the tuffs. In a re-entrant in the middle of the eastern rim of Kilbourne Hole the coarse ejecta mantles 87 ft of the 160 ft tuff sections; the bedded tuffs can be traced, under the ejecta blanket, to within 2 ft of the underlying basalt flow.

The bedded tuffs, which Reiche (1940) called fluvial sands, rest directly on the basalt or where the basalt is absent, on Santa Fe Group sediments. The tuffs are crossbedded and thin bedded with alternating layers of silt-sized and lapilli-sized particles of dark basalt. Interbedded with the sequence are layers of accretionary lapilli-sized particles of dark basalt and occasional basalt fragments to 2 ft across, producing bedding sags in the underlying tuffs (fig. 7).

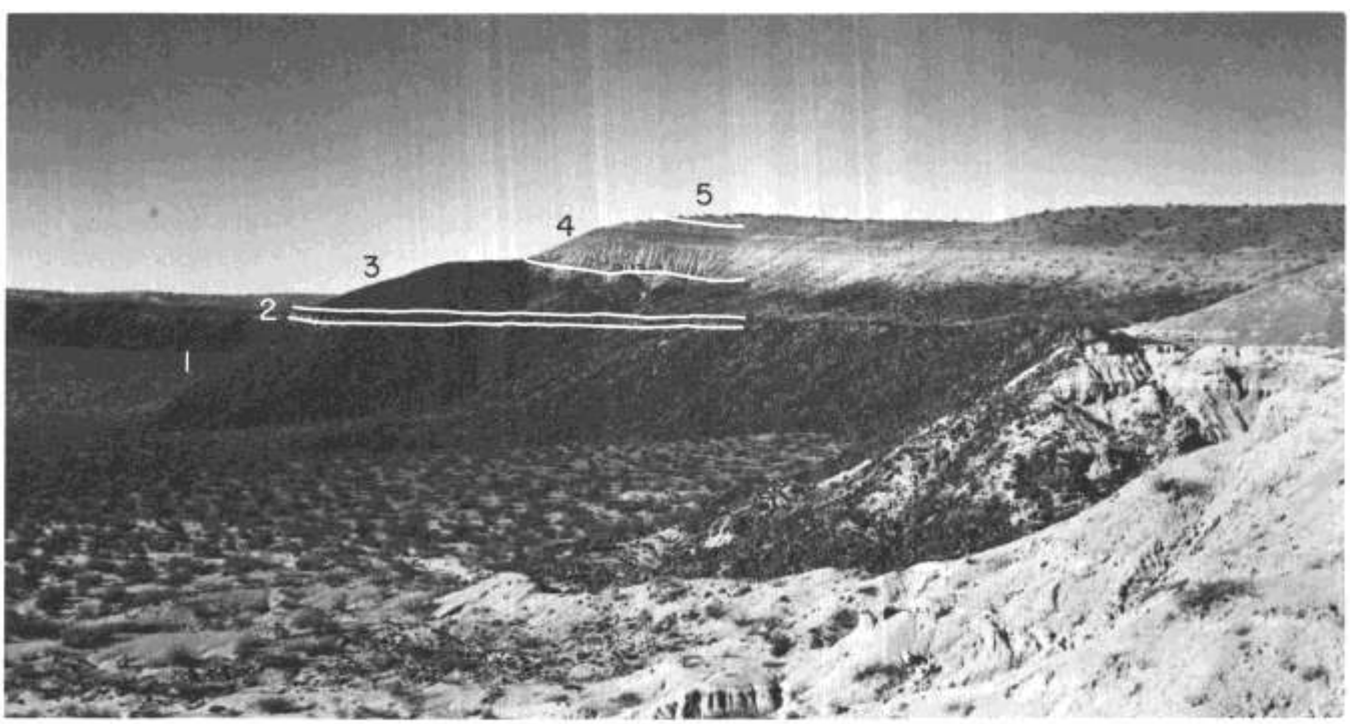

FIGURE 6—KILBOURNE HOLE, VIEW TO THE NORTH SHOWING MAJOR UNITS EXPOSED. THE SECTION CONSISTS OF 1) SANTA FE GROUP, COVERED BY BASALT TALUS, 2) BASALT FLOW, 3) COARSE EJECTA MANTLING RIM TUFFS, 4) RIM VOLCANICS OF AIR-FALL AND BASE-SURGE ORIGIN, AND 5) HOLOCENE BLOWN SAND.

FIGURE 7—BEDDING SAG STRUCTURE IN TUFFS AT KILBOURNE HOLE, SOUTHEAST CORNER.

The tuff sequence is divided into 3 major units on the basis of structure and size of particles:

Basal unit—alternating layers of silt- and coarse sand-sized particles; individual layers are a fraction of an inch to 40 inches thick. Bed forms are mainly plane parallel but also included are low-angle, cross laminae as described by Fisher and Waters (1970) at Zuni Salt Lake, New Mexico. Accretionary lapilli, averaging 2 to 3 mm, are common. This sequence represents predominantly base-surge deposits formed by high velocity density currents which spread outward from the base of a vertically rising ejecta column (Fisher and Water, 1970). Such base-surge currents have been observed as a result of phreatomagmatic volcanic eruptions (Moore, 1967). Air-fall blocks of angular basalt, distorting the underlying laminae and producing bedding sags, also occur in this tuff.

Middle unit—predominantly sand- to silt-sized particles in thin beds displaying rhythmic wave forms from a few inches to several feet across. Because such bed forms and resulting internal laminae, both stoss and lee sides, are situated at angles less than that of repose, they have been called antidune forms or antidune laminae (Fisher and Waters, 1970). Typically, laminae of the stoss side tend to become steeper than those of the lee side, indicating the direction of movement of the base-surge current (Fisher and Waters, 1970). Bedding sag blocks also occur in this sequence.

Upper unit—poorly sorted and bedded, silt- to lapilli-sized fragments of basalt and lithics cemented by silt. A characteristic feature of this unit is the abundance of lobe-shaped cumulations or concentric wrinkles 1 to 2 inches across. DeHon (1965b) has described similar features from Hunts Hole and attributed their origin to a lahar.

Holocene blown sand, containing mostly clear, rounded, quartz grains, covers the crest of the rim and outer slopes. In addition, sand- to lapilli-sized fragments of angular basalt and lithics are mixed with the blown sand. The basaltic fragments occur in a blanket around the crater in a pattern elongate to the north-northwest and east; the size of the ejecta decreases outward from the rim. If the primary vent is located in the north rim of the hole as indicated by Reiche (1940), then the cover fragmental material is distributed in a nearly circular pattern around the vent.

Hunts Hole, located about 2 miles south of Kilbourne Hole, is roughly circular in outline and a mile in diameter (geologic map). The floor is 150 ft below the level of the La Mesa surface, and a raised rim stands to 100 ft above the plain; the rim is best developed along the north and east edges of the hole. From the bottom to the top of Hunts Hole the same section seen at Kilbourne Hole is exposed; fine-grained, buff to reddish silt, sand, and clay and interbedded stringers of gravel and caliche of the Santa Fe Group; a porphyritic olivine basalt flow, stratified tuffs and breccia; and Holocene blown sand mantling the crest of the rim.

DeHon (1965b) divides the rim deposits into 4 units: unit I—eruptive breccia, unit 2—stratified tuffaceous sand, unit 3—fine-grained tuff with a granulated texture, and unit 4—Holocene blown sand.

The eruptive breccia lies above the basalt flow along the northern and eastern walls. The breccia, reaching a maximum thickness of 20 ft, consists of dense basalt, basaltic bombs, dacite, limestone, pumice, sandstone, caliche, and basaltic bombs with mudstone cores, in order of decreasing abundance. As at Kilbourne Hole, the breccia is not a continuous layer but merely mantles the lower slopes of the tuffs in the northern rim of the hole. The tuffs can be traced to within less than 2 ft of the underlying basalt. The eruptive breccia at both Hunts and Kilbourne Holes appears to represent an event of coarse fragment production occurring simultaneously with the formation of the fine-grained tuffs. Large angular blocks of basalt (to a foot in diameter) are found over 30 ft above the base of the stratified tuffs. Deformation of thin laminae below the block indicates its air-fall emplacement during accumulation of the tuff. The decrease in abundance of the large ejected fragments upward in the section is expected as the larger fragments should be located nearest the source.

DeHon's unit 2 represents both air-fall and base-surge deposits similar to those described at Kilbourne Hole. This unit contains 2 distinct aspects. The first is a lower zone, ranging in thickness from 2 inches to 15 ft of alternating nearly parallel layers of coarse- and fine-grained tuff. The fine-grained layers, with particles less than 0.1 mm, are well sorted and show massive to graded bedding. Several of the fine-grained tuff layers display a constant thickness over surface irregularities in the underlying Santa Fe sediments, thus indicating an air-fall origin for at least part of this unit (fig. 8). Bedding sags, produced by air fall of angular basalt blocks to 10 inches in diameter, are frequent. The second aspect is an upper zone, 10 to 30 ft thick, composed of predominantly fine-sand-sized particles in thin antidune lamellae of base-surge origin. In addition, thin seams of sand- and lapilli-sized fragments and layers of accretioning lapilli occur in the section. A few bomb sag structures are also present.

Above the stratified tuffs occurs a 10-ft layer of fine-grained material that displays a crenulated or lobate texture (unit 3). This unit is poorly sorted, friable, and of similar composition to the underlying tuffs; it is thought to represent a lahar (DeHon, 1965b).

The upper part of the rim is composed of loose, fine-to medium-grained quartz blown sand. The sand blankets the rim crest and outer slopes of the ridge. Mixed with the blown sand are sand- and lapilli-sized fragments of mostly basalt emplaced by air fall. The ejecta fragments are deposited concentrically around the northeast wall of the hole in the area where the eruptive breccia is most abundant; this is the most likely location of the primary vent.

DeHon (1965b) has outlined 4 stages in the development of Hunts Hole: I) separation of volatiles, 2) initial perforation, 3) gas venting, and 4) crater enlargement. The initial stage, separation of volatiles from the magma, has been attributed to either a reduction of confining pressure or changes in composition due to crystallization and reduction of pressure. However, Fisher and Waters (1970) state that maar volcanoes occur in environments where an available source of ground water is abundant or could have been present in the past. From their study of over 30 maar volcanoes,

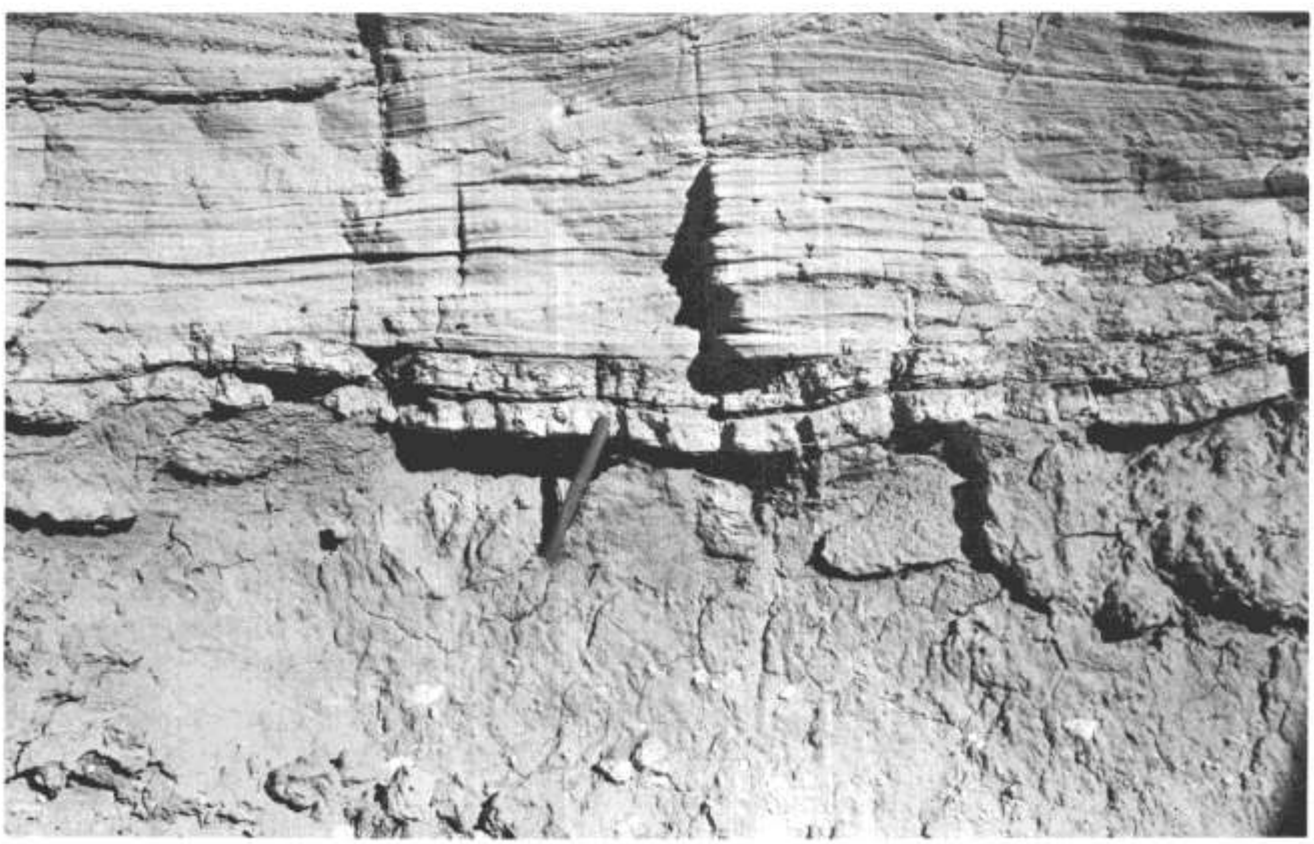

FIGURE 8—FINE-GRAINED, EVEN-BEDDED AIR-FALL LAYERS (TOP OF PEN) UNDERLYING CROSSBEDDED BASE-SURGE DEPOSITS, HUNTS HOLE.

Fisher and Waters (1970) conclude on the basis of morphological and geological evidence, together with the presence of abundant sideromelane within the ejecta layers, that steam explosions are an important factor in the development of maars. Sideromelane, a hydrated basaltic glass, has been identified within the ejecta layers in Kilbourne Hole.

During the initial stage large blocks, of angular basalt from the overlying flow, were thrown outward from the vent area along with bombs, scoria, and other rock fragments derived from the vent at depth. Contemporaneous with the emplacement of the larger fragments, which concentrated near the vent area, horizontally moving base-surge density currents spread outward from the vent. These turbulent density clouds of steam and solid ejecta along with air-fall debris constructed a rampart of stratified tuffs displaying antidune bedforms and cross laminae. The activity probably occurred as staccatolike eruptions of progressively lesser intensity as the overall grain size decreases upward in the section. Periodically, a large block was ejected from the vent and accumulated with the finer-grained tuffs; bedding sags under large basalt blocks high in the tuff section testify to this activity.

Crater enlargement was initiated during the first phases of venting and continued during the eruptive sequence. After final quiescence, normal backwasting and slumpage enlarged the crater to its present shape and size.

Potrillo maar, astride the international boundary between Mexico and New Mexico, is elliptical in plan with an east-west diameter of 2 miles and a north-south diameter of approximately 3 miles (Reeves and DeHon, 1965).

The maar deposits consist of a central basaltic cinder cone and flow complex; at the north end of the maar a small cinder-spatter cone and lava flow occur, and a rim of 90 to 100 ft of crossbedded ejecta containing accretionary lapilli and larger blocks of essential and accidental bombs and scoria. Some of the bombs contain granular olivine and glassy enstatite. Accidental fragments include igneous, metamorphic, and sedimentary rocks (Reeves and DeHon, 1965). A count of over 1,000 ejecta fragments larger than 2 mm indicates basalt scoria and cinder are the most abundant (table 7; Hoffer, 1973a).

Phillips Hole, 2 miles east of Hunts Hole, is an elliptical depression approximately 2 miles long, 1 mile wide, and 70 ft deep (geologic map). It does not have a raised rim or any outcrops, but its gentle slopes are covered with Holocene blown sand. Reiche (1940) considered it to be closely related to Kilbourne and Hunts Holes, but greatly modified by wind erosion. Possibly Phillips Hole is a maar, but because of the lack of underlying resistant basalt layer the hole has become filled in with Holocene blown sand. Other shallow depressions of irregular shape occur in the immediate vicinity; their origin is either structurally controlled or due to wind erosion or both (DeHon, 1965b).

ADEN BASALT

The Aden Basalt is defined as the lavas that crop out in Aden cone and the adjacent areas north, east, and southeast of the crater (Kottlowski, 1953). The Aden flows cover approximately 30 square miles and consist of thin vesicular flows with associated shield, spatter, and explosion-collapse craters and depressions. On the basis of petrography and field relationships the Aden Basalt can be divided into 2 members, older flows termed member 1 (Qad_1,) and a younger unit, member 2 (Qad_2).

TABLE 7—MINERALOGY OF EJECTED FRAGMENTS, LARGER THAN 2 MM, POTRILLO MAAR

Rock	Number of samples	Percent of total
Basalt	620	61.6
Sandstone and quartzite	91	9.0
Limestone and dolomite	45	4.4
Volcanic tuffs, flows, and breccias	63	6.2
Olivine	23	2.2
Gneiss	59	5.9
Granite-diorite	42	4.2
Pyroxene	9	0.9
Conglomerate	16	1.6
Chert	8	0.8
Caliche	1	0.1
Feldspar	2	0.2
Quartz	1	0.1
Marble	14	1.4
Schist	13	1.4
	1007	100.0

Mineralogy and Texture

The lavas of the Aden Basalt are hypocrystalline and microporphyritic with subhedral to euhedral microphenocrysts of plagioclase, olivine and pyroxene set in a fine-grained groundmass of subhedral plagioclase, euhedral pyroxene, very minor feldspathoid, and glass. The microphenocrysts, averaging less than 15 percent, are less than 1 mm in diameter and commonly glomeroporphyritic. The groundmass is subophitic to intersertal with lath-shaped plagioclase crystals in parallel to subparallel fabric with interstitial grains of pyroxene and patches of glass.

Plagioclase feldspar occurs in microphenocrysts as labradorite whereas that in the groundmass is more sodic, ranging from calcic andesine to sodic labradorite (AN, to An_{55}). Plagioclase phenocrysts show pronounced normal and reverse zoning; the groundmass plagioclase is unzoned. Olivine occurs as subhedral to euhedral microphenocrysts and comprises over half of the total phenocrysts. Minor amounts of olivine occur as small anhedral groundmass crystals.

Older flows of the Aden Basalt (Qad_1) contain more olivine and less pyroxene than the younger (Qad_2) flows (table 3). Preliminary studies indicate a higher pyroxene/olivine ratio for the Qad_2 flows. Pyroxene is sparse as microphenocrysts but abundant in the groundmass and is subhedral to anhedral, moderate to dark brown, with a moderate (less than 50 degrees) 2V.

Subhedral to anhedral magnetite-ilmenite, ranging in size from 0.1 mm to 0.05 mm, occurs as inclusions within olivine and pyroxene and as scattered subhedral crystals and needles in glass. Minor amounts of feldspathoid (analcime?) are present in the groundmass.

All samples appear to be essentially unaltered; minor alterations consist of narrow brownish rims (iddingsite) around some of the olivine crystals and iron oxide stains from weathering of opaques. Minor calcite and opal occur as vesicle fillings.

Flow Sequence

At least 2 major periods of extrusion can be identified within the Aden Basalt. The first period is represented by lavas located north and east of Aden Crater at the lower topographic levels; these are designated the oldest member Qad_1. Lying above the Qad_1 flows are younger flows designated Qad_2. The Qad_1 flows are associated with north-south lineaments (collapse pits and troughs) or as isolated outliers.

The Aden flows are interpreted as younger than the Afton flows because where the two lavas are in contact the Aden flows appear to onlap the Afton Basalt. In addition, a thicker eolian sand cover on the Afton flows indicates an older age.

Volcanic Forms

Volcanic forms in the Aden Basalt consist of a shield volcano, spatter cones, and a series of depressions formed by inward collapse and/or outward explosion.

Aden Crater is the most prominent feature in the area; it is classified as a shield cone (DeHon, 1965c). The base of the crater is approximately 3 to 4 miles in diameter and is made up of thin basaltic flows sloping outward from the cone with dips from 3 to 5 degrees. The rim is composed of spatter layers dipping from 30 to 45 degrees inward toward the center of the crater. Within the center crater is a series of nearly horizontal lava flows representing a former lava lake. A spatter and collapse crater are located in the southeast part of the crater (fig. 9).

The formation of Aden Crater involved the following events. Initially, lava flows issued from a central vent and built up a gently sloping shield cone. This period of activity was followed by a more explosive phase in which spatter was ejected, constructing a nearly circular rim around the orifice. About the same time, a rift opened on the southern flank of the crater and ejection of spatter produced several small spatter cones. A less explosive phase followed in the main crater in which lava rose to the surface, was dammed by the spatter rim, and formed a lava lake. Individual flows in the crater interior average 1 to 2 ft thick. At several low places along the spatter rim lava overflowed, producing thin tongues and lava tubes along the flanks.

FIGURE 9—Oblique aerial view of Aden Crater; view looking south.

Late activity in the crater consisted of minor explosive action, producing a small spatter cone in the center of the crater, and a withdrawal of the lava down the primary vent, resulting in a collapse pit near the center of the main crater. Solidification of the lava lake produced tension cracks parallel to the spatter rim. The final activity was confined to a fumarole located on the east rim. A ground sloth *(Nothrotherium shastense)* was recovered from the fumarole and described by Lull. The ground sloth was dated at 11,000 years (Simons and Alexander, 1964).

Spatter cones, or mounds, are rare in the Aden Basalt; their occurrence is restricted mainly to the flank and interior of Aden Crater. Four to five spatter cones are located along a fissure on the south flank of Aden Crater; the mounds range in height from 4 to 8 ft and are 30 to 40 ft in diameter. Two small spatter cones within Aden Crater itself are located north of the large collapse area. A small spatter mound, approximately 5 ft high and 20 ft in diameter, can be seen on the floor of one of the explosion craters in the central part of the field.

Negative topographic features, which are numerous in the Aden flows, are divided into 2 main types based on shape. The predominantly circular areas are termed collapse depressions; those displaying an elongate or linear outline are called troughs (fig. 10).

The collapse depressions occur in the younger flows (Qad_2) of the Aden Basalt and represent collapse over lava tubes or possibly collapse over vent areas. These depressions are of 2 general types. One has steep to nearly vertical interior slopes resembling a pit crater (Wentworth and MacDonald, 1953), and the other has more gentle slopes.

The steep slope depressions are generally composed of concentric slump blocks dipping at high angles away from the crater interior. They are nearly circular and range in depth from 20 to 55 ft and in diameter from 100 to 500 ft. Interior slopes range from 60 degrees to nearly vertical. One such depression, located approximately 4,000 ft southeast of Aden Crater, has overhanging walls; the diameter at the surface is about 8 ft but widens to 75 ft at the base.

The depressions of more gentle interior slopes, 15 to 45 degrees, range in depth from 15 to 40 ft and in diameter from 125 to 200 ft (fig. 10). The deeper ones show features of both crater types from one side of the depression to the other, indicating that differences in the crater probably are not due entirely to different origins.

The origin of similar pit craters, or collapse craters of nearly vertical walls, has been attributed to collapsed lava tubes (Callahan, 1973; Wilkes, 1845), sinking of a single block (Stearns and Clark, 1930), or sinking of several small blocks (Stone, 1926). In Hawaii, Wentworth and MacDonald (1953) concluded that large pit craters (several thousand feet in diameter) are formed

FIGURE 10—OBLIQUE AERIAL VIEW OF CIRCULAR COLLAPSE DEPRESSIONS, ADEN BASALT.

by collapse resulting from withdrawal of underlying magma; this would include sinking en masse or piecemeal of a cylinder bounded by ring fractures. The smaller pit craters in the Aden flows are attributed to the above processes or by collapse into lava tubes. Based on the fact that most of the Aden pit craters and other collapse craters contain variously oriented slabs of lava on the floor of the craters and are of relatively small diameter, their origin is attributed to collapse into lava tubes or piecemeal collapse over or near vent areas (Callahan, 1973).

Linear depressions are also common in the basalt field (fig. 11). Two such areas exist 2 and 4 miles east of Aden Crater. The depressions are not entirely continuous but extend for several miles with a north to south trend. The western depression area is in secs. 26 and 35, T. 25 S., R. 2 W., and can be traced for a distance of nearly 7 miles (geologic map). The eastern depression area (although not as distinct as the other depression area) parallels the eastern margin of the northeast lobe of the Qad_1-$_2$ flows in secs. 31 and 6, T. 25-26 S., R. 2 W. Both areas appear to be related to structural trends that can be traced northward into the Quaternary sediments where the lineament is expressed as a fault. Associated with these linear depression trends is the occurrence of the major circular collapse craters. The margins of the depression areas are usually topographically high representing the upper surface of the youngest flows. The majority of the pit craters and circular depressions occur in these youngest flows.

FIGURE 11—LINEAR COLLAPSE DEPRESSION, ADEN BASALT; WIDTH OF DEPRESSION APPROXIMATELY 30 FT.

These elongated depression areas are best described as troughs. The troughs can be traced continuously for over a mile and range in depth from 15 to 30 ft with dips on the sides from 20 to 50 degrees inward. The width of the floor is generally from 10 to 150 ft, but in one area southeast of Aden Crater, the floor of a shallow trough zone is 1,500 ft across. In several areas flows showing curved pahoehoe ropes can be traced across the troughs and indicate local flowage into the trough after or during their formation.

Craters which show the effects of explosive activity are located approximately 2 miles southeast of Aden Crater (fig. 12). They are irregular and are located on the crest of a broad ridge that can be traced southeastward from the flank of Aden Crater. This broad ridge is composed of thin lava flows and, in addition to the explosive craters, several collapse depressions are located along the crest. The ridge undoubtedly represents a major fracture of rift zone along which lava was extruded during the formation of the Aden Basalt; it is referred to as the Aden rift.

FIGURE 12—OBLIQUE AERIAL VIEW OF COARSE EJECTA RIM SURROUNDING EXPLOSION CRATER, 2 MILES SOUTHEAST OF ADEN CRATER; LONG DIAMETER APPROXIMATELY ONE-HALF MILE.

Characteristic features of these explosive craters include a broad rim, 13 to 30 ft high, composed of large angular fragments of dense basalt and an interior region of thin lava flows form central vents along a rift zone. An explosive period followed extrusion in which the flows near the vents were fragmented and accumulated in a rampart encircling the vent. Renewed extrusion of basalt filled the crater with thin flows forming a lava lake. In several craters, this period was followed by central collapse, producing a gentle sloping interior depression. In other craters, the lava lake simply cooled without subsequent collapse. Final activity concluded with the building of small spatter cones on the floor of several of the craters.

CHEMISTRY OF THE ADEN-AFTON FLOWS

Three new chemical analyses of the Aden-Afton flows have been made, one from the Aden Basalt and two from the Afton Basalt. The analyses, along with those reported by Renault (1970), are given in table 8.

TABLE 8—CHEMICAL ANALYSES OF THE ADEN-AFTON BASALT (Ad-1, Af-1, and Af-2 by T. Asari, Japan Analytical Laboratory; POT by J. Renault, New Mexico Bureau of Mines and Mineral Resources. *represents total Fe reported as FeO; nd represents not determined.)

Oxide	Ad-1	Af-1	Af-2	POT-4	POT-5	POT-6	POT-7
SiO_2	45.03	43.91	44.89	44.15	43.50	45.35	43.23
TiO_2	2.35	2.37	2.12	2.24	2.07	2.17	2.05
Al_2O_3	15.67	15.64	14.81	15.98	14.68	16.14	14.41
Fe_2O_3	1.86	2.47	3.55	nd	nd	nd	nd
FeO	9.22	8.42	7.98	*9.95	*10.14	*9.83	*10.34
MnO	0.17	0.17	0.18	0.18	0.19	0.18	0.19
MgO	9.74	9.34	10.58	9.26	10.10	9.51	9.81
CaO	10.08	11.44	10.74	10.27	11.00	9.79	11.00
Na_2O	3.29	2.86	2.56	2.69	2.75	2.75	2.11
K_2O	1.85	1.63	1.35	1.43	1.47	1.57	1.18
H_2O	0.52	0.98	0.97	nd	nd	nd	nd
P_2O_5	0.51	0.52	0.43	nd	nd	nd	nd
Totals	100.29	99.75	100.16	96.15	95.99	97.29	94.32

The basalts of the Aden-Afton field are classified as alkaline olivine basalts based on the ratio of total alkali to silica (Kuno, 1968). The analyses show low silica (44.61 percent), moderate $A1_20_3$ (15.27 percent), high total alkali ($Na_20 + K_20 = 4.51$ percent), and moderately high TiO_2 (2.29 percent).

The analyses compare favorably with those of normal alkali basalt, but are somewhat higher in total alkali, especially K_20 (Nockolds, 1954). Compared to the basalts in the eastern part of the Potrillo field, the Santo Tomas-Black Mountain basalt field, these basalts are lower in SiO_2, K_20, Na_2O, and higher in TiO_2 and MgO (Hoffer, 1971).

LATE QUATERNARY SEDIMENTS

The youngest sediments on the La Mesa surface are clay, silt, and sand of lacustrine and eolian origin. Clay occurs predominantly in the low topographic depressions both within the basalt field and on the La Mesa surface. Within the volcanic field fine-grained sediment is common on the floors of most of the collapse craters and depressions having accumulated from eolian and lacustrine sources. In both Kilbourne and Hunts Holes fine-grained playa deposits occur on the floor near the center of the crater.

Fine- to medium-grained loose sand forms a dune cover on the entire La Mesa surface. In addition, this eolian derived material covers a significant area of the Afton flows, especially in the region between the Gardner cones and Kilbourne Hole. Blown sand is also common on the crest and outer slopes of the maar craters where it obtains a thickness of 10 to 15 ft.

Two size analyses of the blown sand are given in table 9. They show that over 80 percent of the grains are less than 0.5 mm in diameter. The sample collected north of the Gardner cones is notably coarser with over 60 percent of the sample falling in the range of 0.5 to 0.25 mm.

Mineralogically, the blown sand is composed primarily of subrounded, clear to iron-coated, quartz grains averaging over 70 percent of the sand. Other minerals identified include (in approximate order of abundance) feldspar, opaques, zircon, tourmaline, and pyroxene.

TABLE 9—SIZE DISTRIBUTION OF LA MESA BLOWN SAND; 1) 1 MILE SOUTHWEST OF HUNTS HOLE, 2) 3 MILES NORTHEAST OF THE GARDNER CONES

Size range	Sample 1	Sample 2
1.9 mm	0.0%	0.0%
1.9 mm to 0.99 mm	0.1	0.6
0.99 mm to 0.71 mm	0.5	2.3
0.71 mm to 0.50 mm	0.7	14.9
0.50 mm to 0.25 mm	33.0	63.8
0.25 mm	65.7	18.4
	100.0%	100.0%

Principal Structures

The La Mesa surface id the area of the Potrillo Basalt field is structurally deformed by a series of high-angle faults; the faults strike generally north or northwest. North-striking faults include, from east to west, Fitzgerald, east Robledo, and an unnamed fault west of the West Potrillo Mountains (geologic map). In addition, a number of smaller north-striking faults are exposed north of the volcanic rocks between the Robledo and Fitzgerald faults. The northwest-striking faults include Aden and Potrillo faults, at the north and south end of the basalt field (geologic map).

NORTH-STRIKING FAULTS

The Fitzgerald fault, east and south of Afton, is downthrown on the west side. The fault is recognized in the field by a series of elongate shallow depressions north and south of the basalt flows. The fault cannot be traced within the basalt field, but there does occur an alignment of trough depressions, spatter-cinder cones, collapse craters, and maar volcanoes (Hunts and Kilbourne Holes). Alignment of these volcanic features suggests the location of a rift or fracture zone through which the Afton lavas were emplaced. Reeves and DeHon (1965) have suggested further extension of the Fitzgerald fault south of Kilbourne Hole to join the Robledo fault at the southern tip of the East Potrillo Mountains. The southern extension of the fault from this junction, which is marked by the Potrillo maar, is termed the Potrillo fault (Reeves and DeHon, 1965).

The east Robledo fault (downthrown on the east side) can be traced north of the Aden flows as an eroded fault scarp and a series of elongate depressions. South of the Aden flows the fault cuts several of the West Potrillo Basalt flows, and a small spatter cone covers the fault scarp approximately 2 miles west of Kilbourne Hole. The fault cannot be traced directly into the lava field, but within the Aden flows an area of elongate or trough-like depressions and abundant collapse craters align with the east Robledo fault (geologic map). A similar area of trough depressions and elongate zones of abundant collapse craters occurs approximately 2 miles east of Aden Crater. This alignment of volcanic features parallels the eastern margin of the southern tongue of the Aden flows, west and northwest of Kilbourne Hole. The lineament within the Aden field is thought to represent the position of the fault trace which is buried by Aden Basalt flows.

Three minor fault scarps crop out north of the basalt field between the east Robledo and Fitzgerald faults. The 3 faults cannot be traced into the basalt, but all are aligned with numerous elongate depressions and circular collapse features in the basalts.

A north-striking fault occurs on the border of the map area just west of the West Potrillo Mountains. The fault (upthrown on the east side) displays a prominent scarp near Indian Basin but northward the height of scarp decreases.

NORTHWEST-STRIKING FAULTS

At the north end of the West Potrillo Mountains occur a series of fault block hills exposing Tertiary volcanic units of Uvas Basaltic Andesite and Bell Top Formation (Seager, 1973, personal communication). The volcanic units dip to the southwest, and the faults strike generally northwest in a belt about 3 miles wide; the fault zone is referred to as the Aden fault or rift zone. To the southeast the fault zone is covered by the Aden-Afton Basalts. However, its extension is inferred because of the alignment of a shield cone (Aden), several collapse and explosion craters, and a series of cinder-spatter cones (Gardner cones; geologic map).

The Mt. Riley fault extends from Potrillo maar to a point about 2 miles south of Mt. Riley where it disappears under the flows of the West Potrillo Mountains. The fault (upthrown on the east side) displaces sediments of middle to late Quaternary.

In summary, the Potrillo Basalt field displays 2 structural trends. First, the major north-striking faults have produced a horst (West Potrillo Mountains) and graben (Aden-Afton area) structure. Movement along these faults has continued into the late Quaternary as indicated by displacement of middle to late Quaternary caliche layers. Second, this structure is cut by 2 northwest-striking faults, the Mt. Riley and Aden faults. At points of intersection of the northwest- and north-striking faults are located the major volcanic cones of the Aden-Afton Basalts.

RIO GRANDE RIFT

The Rio Grande rift is characterized by a series of grabens bounded on one or both sides by fault block mountains (Kelley, 1952). The bounding faults are mostly covered by pediment or alluvial fan deposits, but where exposed are steep to nearly vertical (Kelley, 1952).

Typically, the grabens are filled with a thick Santa Fe Group section derived from adjoining highlands. Associated with these sediments are intercalated basalt lava flows (Kelley, 1952).

From central Colorado to central New Mexico the rift is pronounced. However, south of Truth or Consequences, New Mexico, it merges with the Basin and Range province. Here because of more subdued topography and smaller gravity anomalies its exact boundaries are unclear (Sanford, 1968). Chapin (1971) suggested on the basis of alignment, age, sedimentation, and tectonic style of basins that south of Albuquerque the Rio Grande rift broadens into a series of parallel basins separated by intrarift horsts. Near the Mexican border the rift zone attains a width of approximately 100 miles. Postulation is that the western edge of the rift extends along the east side of the Cookes and Florida Mountains and that the Sierra de las Uvas-Potrillo Mountains represent a portion of an intrarift horst (Chapin, 1971). Lovejoy (1972) postulated that the rift may pass near the juncture of New Mexico, Texas, and Chihuahua (Mexico).

Basaltic lavas erupted within and adjacent to the Rio Grande rift during its formation. At the northern end of the rift Lipman (1969) correlated basalt types with structural setting. He concluded that basalts of alkali affinities, commonly showing evidence of crystal contamination, were erupted east and west of the rift during and after its formation. Basalts that were erupted within the rift are tholeiitic, lower in alkalies and little contaminated. The rift basalts differ both chemically and texturally from those extruded outside the rift; the former are much coarser grained, lack xenoliths, and are lower in K_20, P_20_5, Na_20, and TiO_2 than the latter. The chemical differences are attributed to differences in the conditions of magma generation at depth. Experimental studies suggest that tholeiites can be generated by partial melting at depths of less than 15 km and alkali basalts at depths of 35 to 70 km (Green and Ringwood, 1967; O'Hara and Yoder, 1967). These results suggest that the alkali basalts were generated at great depths whereas the tholeiites were fractionated at relatively shallow depths (Lipman, 1969). Lipman (1969) further stated that a similar relationship between rift structures and type of volcanism has been noted in the East African rift system, Ethiopian rift system, and Mid-Atlantic Ridge (Wright, 1963; McBirney and Gass, 1967; and Aumento, 1968).

In summary, the main structural features of the area include a central depression bounded by the Fitzgerald and east Robledo faults. The depression is cut at the north and south ends by northwest-striking faults. The faulting began in middle to late Tertiary and has continued into late Quaternary. Volcanic features are associated with all the faults, thereby suggesting that these faults served as the passageway through which magma made its way to the surface.

The Potrillo Basalt is alkali olivine, typical of the type that occurs on the flanks of the Rio Grande rift to the north. Preliminary analyses of the lavas indicate that chemical and mineralogical variations correlate with tectonic setting across the field.

Renault (1970) reported that the Potrillo Basalt is undifferentiated and the differences in TiO_2 correlate with structural setting; basalts on structurally higher rocks possess higher mean titanium concentrations than those on structurally lower rocks. This suggests that upthrown blocks have deep penetrating fractures, are under low compressive stress, and based upon the experimental system, $MgO\text{-}SiO_2\text{-}TiO_2$, would therefore allow higher concentrations of titanium in the associated basalts than in those associated with adjacent downthrown blocks (Renault, 1970). In addition to variations in titanium, the basalts show differences in sodium, potassium, and phosphorous (table 10).

Table 10 summarizes the relevant chemical differences of the Potrillo Basalt, and for comparison, the chemical data presented by Lipman (1969) for the basalts associated with the Rio Grande rift to the north. Lipman's data show good correlation between composition and structural setting. Basalts erupted within the rift are noticeably lower in Na_2O, K_20, P_2O_5 and TiO_2 than those associated with the upthrown blocks bordering the trench.

In the Potrillo Basalt, the West Potrillo Basalt and Santo Tomas-Black Mountains basalts are associated with upthrown blocks whereas the Aden-Afton Basalts lie in a graben. The basalts erupted in the depression are lower in total alkalis and P_20_5 than those on the outside

TABLE 10—CHEMISTRY OF BASALTS ASSOCIATED WITH THE RIO GRANDE DEPRESSION (Numbers in parentheses refer to number of samples averaged. [1]Basalts from northern New Mexico-southern Colorado, Lipman, 1969. [2]Major portion of chemical data from Renault, 1970, New Mexico Bureau of Mines and Mineral Resources.)

Oxide	Alkali basalt[1] west of rift	Tholeiite in the rift	Alkali basalt[1] east of rift
Na_2O	3.4	3.0	3.6
K_2O	1.6	0.6	1.5
$Na_2O + K_2O$	5.0	3.6	5.1
TiO_2	1.8	1.2	1.4
P_2O_5	0.4	0.1	0.6
	West Potrillo Basalt	**Aden-Afton Basalts**	**Santo Tomas-Black Mountain basalt**
Na_2O	3.3 (14)[2]	2.71 (7)[2]	3.70 (5)[2]
K_2O	1.43 (14)	1.49 (7)	1.90 (2)
$Na_2O + K_2O$	4.74 (14)	4.20 (7)	5.60 (5)
TiO_2	2.28 (14)	2.19 (7)	1.97 (5)
P_2O_5	0.62 (3)	0.48 (3)	0.54 (3)
Solidification Index	41.0 (14)[2]	42.0 (5)[2]	35 (5)[2]

of the graben. TiO_2 concentration correlates from the west side into the rift, but not across the east side. The reason for these variations from the typical sequence appears to be due to differentiation of the Santo Tomas-Black Mountain basalts. The Solidification Index of each group of lavas indicates that the West Potrillo Basalt and Aden-Afton Basalts are undifferentiated. The mineralogy of these two basalts is similar, and differences in chemistry correlate with structural setting across the rift. However, the much lower Solidification Index and much higher total alkalis of the Black Mountain-Santo Tomas basalts indicate some differentiation before eruption at the surface.

Regardless of these inconsistencies, it appears that variations in chemistry of the Potrillo Basalt correlates moderately well with tectonic environment and are typical of other rift valleys (Hoffer, 1975).

EAST POTRILLO MOUNTAINS

The East Potrillo Mountains can be divided into 2 structural regions. The northern part of the range is an asymmetrical breached anticline with a steeper dipping western limb. The axis of the anticline trends north-northwest and plunges to the north. East of the crest near the center of the range, Cretaceous units 2 and 3 have been compressed into a series of tight anticlines and synclines overturned to the east. Further north (secs. 2 and 3, T. 28 S., R. 2 W.) folding has produced a synclinal structure within units 1 and 2; the western limb of the structure is overturned and has been thrust eastward along a low-angle fault.

A major eastern boundary fault, expressed as a low fault scarp, parallels the crest line east of the range. Bowers (1960) indicated that it is a high-angle normal fault. The fault cuts the coarse bajada deposits on the east flank of the Potrillos, abruptly terminating these rocks against the sand and silt of the bolson. This fault can be traced from the southern end of the range northward over 13 miles where it is covered by Aden Basalt. The scarp ranges in height from 5 to 35 ft and can be seen to displace caliche horizons and a flow from the Potrillo Basalt in the bolson north of the range. These displacements indicate that there has been renewed or continued movement along the post-Cretaceous boundary fault during middle to late Q uaternary.

The northern end of the range is intensely faulted. Within the northern end of the range 2 predominant fault sets exist, one trending northwest and the other approximately northeast. The northwest-striking faults consist of both low and high-angle reverse faults and high-angle normal faults.

Northwest-striking thrust faults occur predominantly at the northern end of the range in secs. 2, 3, 10, and 11, T. 28 S., R. 2 W. These faults have produced eastward thrusting along both high- and low-angle faults. A small klippe (sec. 11, T. 28 S., R. 2 W.) of Cretaceous unit 1 rests on Cretaceous unit 3 along one of the high-angle thrusts. This fault can be traced for over 2 miles northward from NE^1/4 sec. 10, T. 28 S., R. 2 W. where it is covered by Holocene alluvium north of the range.

In the northwest part of the range, Bowers (1960) inferred northwest-striking, high-angle faults based on the presence of shear zones and bands of metamorphosed limestone which are silicified, iron stained, and locally contain fault breccia. On many of these faults the direction of movement cannot be differentiated because of the homogeneity of the limestone and the lack of a marker bed; many may be reverse faults.

The central part of the range (sec. 14, T. 28 S., R. 2 W.) is cut by 2 sets of high-angle oblique faults; one set strikes east and the other northeast. The northeast-striking faults are nearly parallel to the andesite dikes. Stratigraphic throw of unit 1, from 100 to 400 ft, and the slight displacement of higher beds along the same faults suggest renewed movement along faults that were active before deposition of unit 2 (Bowers, 1960). A low-angle thrust is associated with the closed folds in the Lower Cretaceous units 2 and 3.

The southern end of the range is relatively undisturbed. It represents a simple homocline dipping from 15 to 30 degrees to the west, bounded by a high-angle fault on the east.

Resources

The primary economic resources in the area consist of ground water and volcanic cinder. Minor amounts of marble and hydrothermal replacement deposits of barite, galena, sphalerite, and supergene malachite and azurite occur in the East Potrillo Mountains. Minor manganese occurs at Camel Mountain.

GROUND WATER

The water table occurs on the average about 300 to 400 ft below the La Mesa surface within the sand, clay, and silt of the Santa Fe Group basin fill (King and others, 1969). Most of the production comes from shallow wells and is utilized for domestic or stock use. Thermal ground water has been reported in a well drilled in the bottom of Kilbourne Hole (Reiche, 1940).

CINDER

Volcanic cinder is quarried from a number of cinder cones in the Potrillo Basalt for use in the manufacturing of cinder building blocks. Spatter and dense flow rock are undesirable in the production of the cinder blocks. The only cinder available in the Aden-Afton region occurs in the Gardner cones of the Afton Basalt. However, the presence of abundant spatter and dense lava, plus difficult access to the cones, would make the cinder uneconomical. Numerous cinder cones occur in the West Potrillo Mountains.

MARBLE

An abandoned quarry is located on the eastern edge of the East Potrillo Mountains in sec. 24, T. 28 S., R. 2 W. The marble represents recrystallized limestone of the Hueco Formation. The marble is of irregular occurrence and is locally highly silicified, making it generally undesirable except possibly for road metal.

HYDROTHERMAL DEPOSITS

Scattered mineralized zones occur throughout the north end of the East Potrillo Mountains as discontinuous pods, lenses, and veins filling fissures or replacing wall rock along fractures and fault zones (Bowers, 1960). In addition, numerous prospect pits can be found along unconformities and clay horizons. Especially prominent is the iron-stained, bleached, and silicified clay beds at the top of the Cretaceous unit 1. Stringers of malachite and azurite have been seen in these horizons, but the most abundant minerals consist of limonite (replacing pyrite), quartz, and calcite.

Dunham (1935) mentioned a pocket of rich gold ore that was said to have been mined from a quartzite bed on the east side of the East Potrillo Mountains by John Graham around the year 1900.

At the north end of the range, associated with the northeast-trending, high-angle faults, are replacement horizons of abundant barite with small disseminated crystals of pyrite, galena, sphalerite, and malachite. The limestone is highly silicified in the immediate area. The degree of silicification and accompanying barite mineralization increases toward the northwest. Although abundant barite is available, its close association with silica would make it undesirable.

The highly silicified northeast-trending faults and shear zones seem to have been channels for the introduction of low temperature hydrothermal solutions. The northeast-trending andesite dikes are not mineralized but show the effect of some hydrothermal alteration which include sericitization. Other hydrothermal solutions, depositing primarily silica, moved along northwest-trending, older faults and unconformities. Replacement and cavity fillings have both been formed along the fault zones.

MANGANESE

Several small prospect pits are located on quartz-manganese veins at Camel Mountain. Several shear or breccia zones cut the mountain, and the fragments are recemented by silica and manganese; the manganese is disseminated and appears to be uneconomical.

Summary of Petrology and Geologic History

During Paleozoic and Mesozoic time most of the Potrillo area experienced alternating periods of emergence and shallow submergence as indicated by scattered outcrops of lower Paleozoic, Permian, and Lower Cretaceous strata.

The clastics and impure limestone that characterize the lower part of the Cretaceous section indicate deposition near shore. Bowers (1960) suggested deposition probably continued in the East Potrillo area into Late Cretaceous, but the record has been removed by erosion.

Near the end of the Cretaceous the seas retreated, and the area was involved in the Laramide disturbance. In the East Potrillos, this activity is evidenced by folding and thrusting of the Lower Cretaceous units.

During the Tertiary volcanic flows and tuffs such as those exposed near Mt. Riley and north of the West Potrillo Mountains were deposited. During this period of time, the intrusion of the Mt. Riley-Mt. Cox pluton and associated plugs and the andesite to rhyolite dikes of the East Potrillo Mountains took place. Emplacement of the large Riley-Cox pluton might be responsible for some of the complex structure at the north end of the East Potrillos. Much of the high-angle faulting in the East Potrillos is probably related to the Basin and Range differential uplift which started about early to middle Tertiary (Bowers, 1960). During this period of time low temperature hydrothermal solutions were intruded along the high-angle faults.

Santa Fe Group sediments were deposited in the Mesilla bolson that was formed by middle Tertiary faulting associated with the Rio Grande rift of central New Mexico. Exposed basin-fill units of early to middle Quaternary age consist of stream-channel and flood-plain deposits (Camp Rice Formation) underlain by lacustrine and playa deposits (Fort Hancock Formation).

Formation of the Aden graben bounded by the east Robledo and Fitzgerald faults probably initiated in middle Tertiary as a part of the Rio Grande rift. In middle to late Quaternary magma rose first along fractures in the horst block west of the Aden graben (West Potrillo Mountains). These fractures were deep seated and tapped a magma producing a basalt high in TiO_2, P_20_5, Na_20, and K_20 (Renault, 1970). The chemistry of these lavas correlates with those of other horst blocks (Lipman, 1969). Field mapping and petrology indicates 2 episodes of extrusion occurred in the West Potrillos. Flows of the first eruption (member 1) are poorer in olivine and pyroxene than those of the second eruption (member 2). These differences in mineralogy can be explained by assuming crystal settling in the magma before eruption. Olivine, pyroxene, and plagioclase comprise the bulk of the mineralogy in a basalt. Both olivine and pyroxene have densities greater than that of the basalt magma, whereas the density of plagioclase is less. Therefore, if gravitational settling and floating did occur, the plagioclase would be enriched near the top of the magma chamber with olivine and pyroxene near the base. If eruption occurred at or near the top of the magma source, the initial flows would be depleted in olivine and pyroxene, and enriched in plagioclase (member 1). The final eruption would then tap the remaining magma which is enriched in olivine and pyroxene (member 2).

Member 1 lavas are thought to have been erupted through fissures; they are exposed today only at the southeastern part of the range. The younger flows (member 2) are associated with the cinder cones and are thought to represent central eruptions at localized centers along the fractures.

Shortly following the eruption of the West Potrillo Basalt, lava rose along faults bordering the Aden graben, producing the Aden-Afton Basalts. These lavas are poorer in Na_2O, K_2O, TiO_2, and P_2O_5 than those of West Potrillos and are typical of those associated with graben structures (Renault, 1970; Hoffer, 1975).

The oldest flow of the Afton group is exposed in the walls of Kilbourne and Hunts Holes; this flow is approximately 140,000 ± 75,000 years old. The middle flow crops out north of Kilbourne Hole, and the youngest flow is in the immediate vicinity of the Gardner cones. Emplacement of these lavas was probably associated with the Fitzgerald fault. The 2 older members (Qaf_1 and Qaf_2) of the Afton Basalt were probably emplaced along fissures associated with the Fitzgerald fault; the youngest member (Qaf_3) resulted from a central eruption associated with the Gardner cones. Sometime after extrusion of the youngest Afton flow (Qaf_3) magma at depth encountered a confined aquifer at depth in the vicinity of Hunts and Kilbourne Holes, and resulting explosions produced the maar volcanoes.

At approximately the same time the Aden Basalt rose along the east Robledo fault. Zones of collapse depressions mark the trace of the former fissures. The final phase in the volcanic cycle consisted of central eruptions along the Aden rift, building Aden Crater and the Gardner cones. These major volcanoes are located at points of intersection of the Aden rift and the Fitzgerald and east Robledo faults. The major volcanic events in the region are summarized in table 11.

Middle to late Quaternary movement along the east Robledo and Fitzgerald faults is evidenced by displacements in the West Potrillo Mountains and caliche zones at the top of the La Mesa surface.

Late Quaternary deposits, which blanket the La Mesa surface and cover a large part of the basalts, consist of mostly fine blown sand and minor lacustrine sediments.

TABLE 11—QUATERNARY EVENTS IN THE POTRILLO BASALT FIELD

	WEST POTRILLO MOUNTAINS	ADEN-AFTON AREA	
1.1×10^4 yrs			
		Aden Basalt member Qad_2 (Aden Crater)	Afton Basalt member Qaf_3 (Gardner cones)
		Aden Basalt member Qad_1	Afton Basalt member Qaf_2
1.4×10^5 yrs	West Potrillo Basalt member Qwp_2		Afton Basalt member Qaf_1
2.0×10^5 yrs	West Potrillo Basalt member Qwp_1		
9×10^6 yrs	Selden Basalt		
2.0×10^7 yrs	SANTA FE GROUP		

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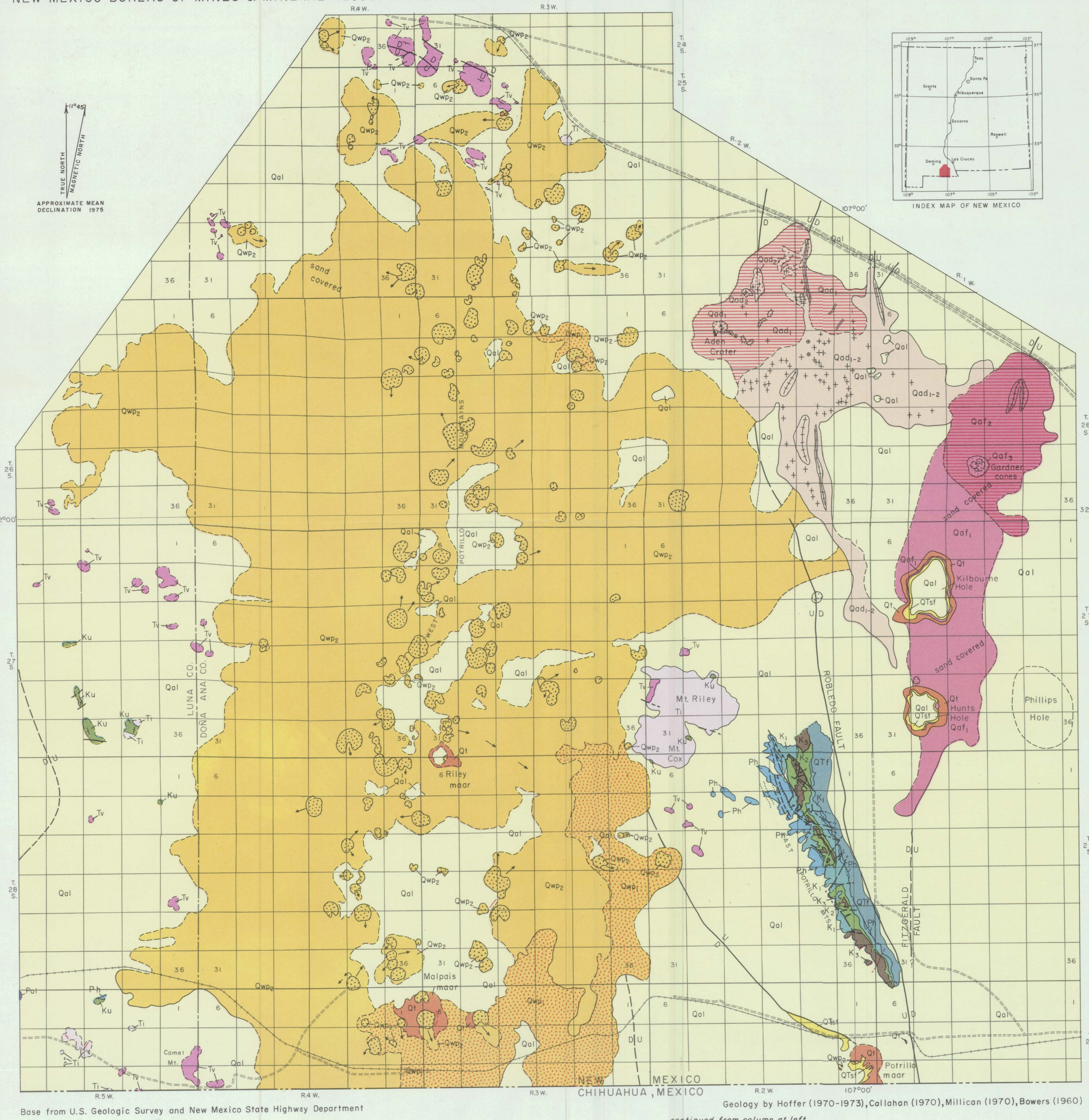

Base from U.S. Geologic Survey and New Mexico State Highway Department

Geology by Hoffer (1970-1973), Callahan (1970), Millican (1970), Bowers (1960)

QUATERNARY

Qal — Alluvium
Calichified gravel, silt, and sand underlying La Mesa surface, includes recent playa and eolian sand deposits

Qad₂ / Qad₁ / Qad₁₋₂ — Aden Basalt
Thin flows and cones of olivine basalt; Qad_2: youngest member, Qad_1: oldest member, Qad_{1-2}: undifferentiated

Qaf₃ / Qaf₂ / Qaf₁ — Afton Basalt
Thin flows and cones of olivine basalt; Qaf_3: youngest member, Qaf_2: intermediate member, and Qaf_1: oldest member

Qwp₂ / Qwp₁ — West Potrillo Basalt
Thin flows and cones of olivine basalt; Qwp_1: older flows, generally olivine-poor; Qwp_2: younger flows, olivine-rich

Qt — Volcanic tuff and ash
Air-fall deposits associated with the maar volcanoes, Kilbourne Hole, Hunts Hole, and Potrillo maar, to 150 ft thick

QTf — Fanglomerate and talus
Bajada deposits associated with East Potrillo Mountains

QTsf — Santa Fe Group
Alluvial facies of gravels, sands, silts, and caliche; exposed in walls of the maar volcanoes, to 70 ft exposed

TERTIARY

Ti — Tertiary intrusives
Rhyodacite to andesite stocklike plugs, consists chiefly of the Mt. Riley-Cox pluton

Tv — Tertiary volcanics
Consists of scattered outcrops of dacite, latite, and basaltic andesite, mainly south of the Mt. Riley-Cox pluton and west of West Potrillo Mountains

LOWER CRETACEOUS

Ku — Cretaceous, undifferentiated
Consists of limestones, limestone conglomerates, arkosic sandstones, and rudistid reefs, to 1,000 ft thick at the Eagles Nest

K₃ — Cretaceous, unit 3
Locally called Restless limestone by Bowers, 1960. Limestone, fine-grained, thin-bedded to massive, 150 to 450 ft

continued to column at right

continued from column at left

LOWER CRETACEOUS

K₂ — Cretaceous, unit 2
Locally called Little Horse formation by Bowers, 1960. Limestone, fine-to coarse-grained, and calcareous sandstone, 75 to 175 ft

UNCONFORMITY

K₁ — Cretaceous, unit 1
Locally called Noria formation by Bowers, 1960. Limestone conglomerate, calcareous shale, and silty limestone, 270 to 600 ft

UNCONFORMITY

PERMIAN

Ph — Hueco Limestone
Fine- to coarse-grained limestone, recrystallized and silicified, 200 to 225 ft

LOWER SILURIAN(?)

Pal — Paleozoic, undifferentiated
Unfossiliferous, light-gray, cherty dolomitic limestone, possibly Fusselman Dolomite (Silurian)

Volcano, generally cinder or cinder-spatter cone; only major cones shown

Direction of lava flow

Contact, dashed where inferred

Normal fault, dashed where inferred

Reverse fault, dip <50°

Reverse fault, dip >50°

Anticline

Strike and dip symbol

Dike

Volcano, shield cone rim

Volcano, spatter cone

Depression, elongate

Depression, circular

Depression, explosive

Lava tubes

Pit craters

Fumerole

GEOLOGIC MAP OF POTRILLO BASALT FIELD, SOUTH-CENTRAL NEW MEXICO

by Jerry M. Hoffer 1976

Scale 1:125,000

0 1 2 3 4 5 miles