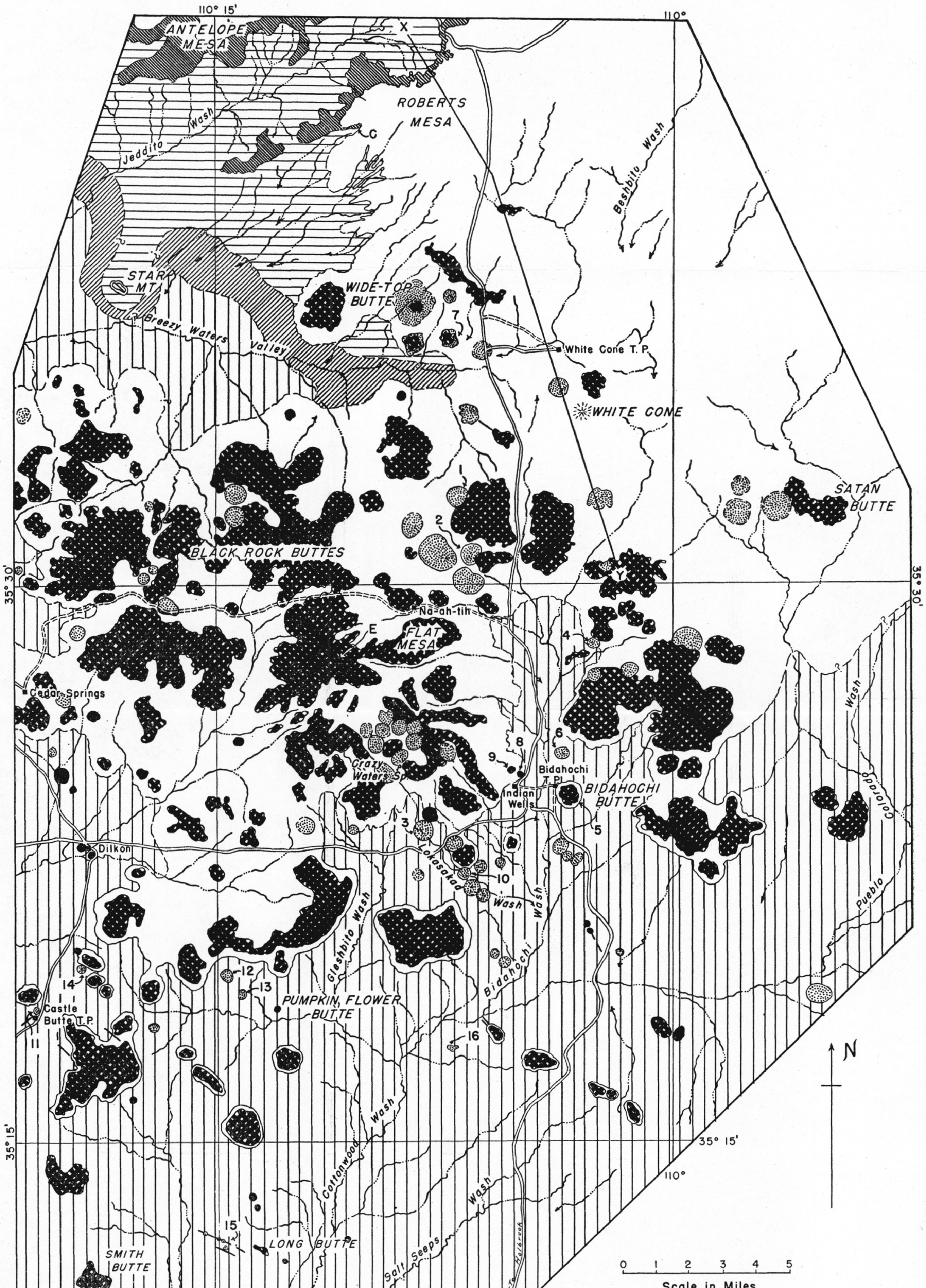

TERTIARY ROCKS
(BIDAHOCHI FORMATION)

Dikes

Diatremes filled with pyroclastic rocks

Volcanic necks (basalt-filled)

Basalt interbedded with Bidahochi formation

Sedimentary rocks of Bidahochi formation

MESOZOIC ROCKS

Mesaverde sandstone (Upper Cretaceous)

Mancos shale (Upper Cretaceous)

Dakota sandstone (Upper Cretaceous)

Triassic and Jurassic rocks (Chinle, Navajo, and Morrison formations)

GEOLOGIC MAP OF MAJOR PORTION OF HOPI BUTTES AREA

(Based on photoengravings of U. S. Soil Conservation Service)

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SEDIMENTATION AND VOLCANISM IN THE HOPI BUTTES, ARIZONA

BY JOHN T. HACK

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ILLUSTRATIONS

ABSTRACT

The Hopi Buttes area in the southern Navajo Country, Arizona, lies in a Pliocene basin of sedimentation and volcanism. The thin Pliocene sediments, known as the Bidahochi formation, are interbedded calcareous sand, clay, marl, tuff and other pyroclastic material. These sediments extend southeastward as far as the Zuni area, New Mexico. They overlie the Hopi Buttes erosion surface of low relief, a portion of which is now exhumed on the southern edge of Black Mesa. This surface may be widespread in northern Arizona. The Bidahochi formation and the erosion surface have evidently been deformed in Pliocene or post-Pliocene time.

The Hopi Buttes area, which lies at the lowest point of the structural basin of deformation, contains Pliocene volcanic rocks of alkalic composition greater in volume than the sediments, and over 200 closely spaced volcanic necks or diatremes ranging from 500 to 4000 feet in diameter, and arranged along a complex pattern of fractures.

Flows are few in number, for the volcanism produced pyroclastic débris and lava domes. Deep erosion reveals that explosions produced funnel-shaped pipes which were rapidly filled with explosion débris, with material poured in by streams or with lava and viscous agglomerate erupted from below. Small rims protected many diatremes for a time from filling by river-borne sediments so that fine ash, gypsum, and calcium carbonate collected in their crater lakes to be later buried by coarser material as stream aggradation continued. The structure of the diatreme fillings indicates that subsidence occurred after eruption.

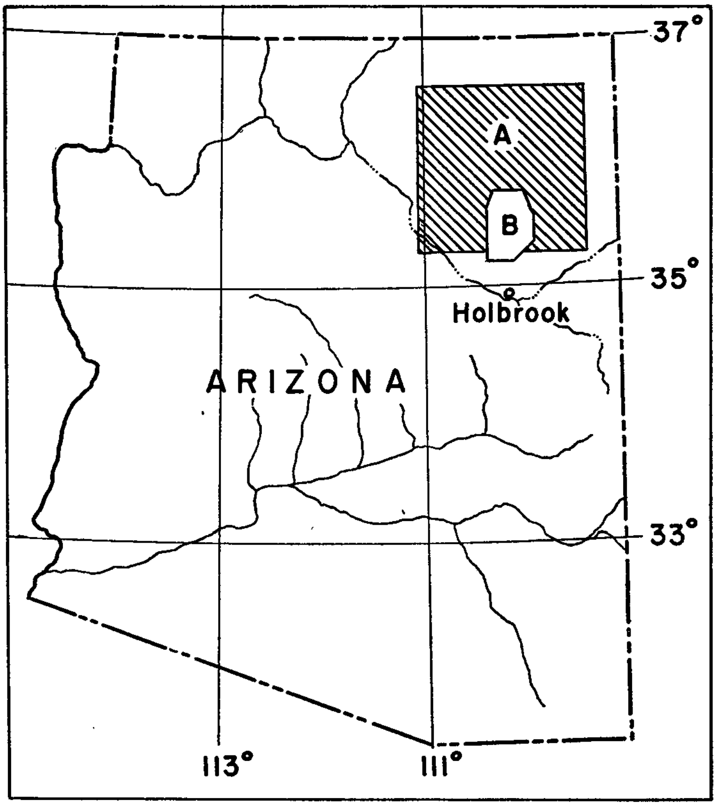

FIGURE 1.—*Index map*

A—area of reconnaissance studies, shown in Figure 2.
B—Hopi Buttes area, shown in Plate 1.

INTRODUCTION

The portion of the Navajo Country known as the Hopi Buttes is dominated by eroded and dissected lava-capped buttes, and volcanic necks filled with basalt and pyroclastic debris. The volcanic necks, or diatremes, are over 200 in number and closely spaced.

Several factors make this area favorable for observation of the structure and origin of diatremes. The volcanism in the Hopi Buttes occurred in the Pliocene when the area was receiving a thin cover of sediments derived from highlands on the north and east. These sediments and the interbedded volcanic debris overlie an erosion surface of low to moderate relief, known as the Hopi Buttes surface. At the present time the Pliocene rocks and the erosion surface under them are dissected in places to depths of over 700 feet, so that structures of typical diatremes can be observed at the level of their uppermost extremities as well as at depths far below the original level of extrusion.

The Hopi Buttes surface thus serves as a reference plane from which to measure the depth of erosion of the various diatremes. This erosion surface and the sediments which overlie it are widespread in northeastern Arizona. Evidence of deformation of these sediments and the underlying surface is revealed, which is important both for correlation and for an understanding of the nature of the volcanism.

PREVIOUS WORK

Geologic work in the Hopi Buttes has been limited to reconnaissance studies. Gregory (1917) describes the general geology and petrography in his comprehensive work on the Navajo Country. Williams (1936) has published an account of the Hopi Buttes volcanic field in a report on the petrography of the volcanic rocks of the whole Navajo Country. Reagan (1932) named the Pliocene sediments of the Hopi Buttes the Bidahochi formation. The most important features of the region have thus been briefly treated, but the ideal conditions for the study of volcanic structures and geomorphic history have not been fully interpreted and discussed.

ACKNOWLEDGMENTS

The present study began while the writer acted as geologist for the Awatovi Expedition of the Peabody Museum of Harvard University. Mr. William H. Claflin IIIrd, a member of the expedition staff, ably assisted the writer in the field for several weeks. Kirk Bryan, E. S. Larsen, Jr., and M. P. Billings visited the writer in the field and offered many valuable suggestions. The field work was completed under a generous grant from the Penrose Bequest of the Geological Society of America and greatly aided by the generous hospitality of Mr. and Mrs. Clarence N. Halderman of Indian Wells, and Mr. and Mrs. Wilmer C. Roberts of Jeddito Trading Post.

The mapping was based on photoengravings of aerial mozaics and base maps furnished by the U. S. Soil Conservation Service.

TOPOGRAPHY

The Hopi Buttes form a highland mass rising above the barren plains of the southern Navajo Country to an average altitude between 5500 and 6500 feet. The average relief is only about 500 to 700 feet, but their rise from the flat, alluvium-filled valleys gives the buttes an august appearance. This region may be divided into: (1) The high, central area which includes the rolling surface of the Black Rock Buttes,—an area of unexcavated diatremes, lava domes, and small lava flows which give a false appearance of a continuous but irregular lava-capped plateau; and (2) the surrounding lower area which is more deeply dissected and consists of scattered volcanic necks or high lava domes perched on rocky buttes.

Extensive highlands lie to the north and east of the volcanic area. Black Mesa, a dissected plateau 100 miles in diameter, overlooks the Hopi Buttes from the north. On the east a less conspicuous highland underlain by the Pliocene Bidahochi formation stretches eastward to the Defiance Plateau.

PRE-TERTIARY ROCKS

The Pliocene lavas and sediments rest unconformably on Mesozoic sedimentary rocks which include the Cretaceous Mesaverde sandstone, Mancos shale, and Dakota sandstone; the Jurassic Morrison formation and Navajo sandstone; and the Triassic Chinle shale. These rocks dip slightly to the north so that the oldest rocks crop out in the southern portion of the area. In general the region rises to the north in a series of broad but low benches or escarpments where each resistant bed crops out, culminating in the plateau of Black Mesa. This more or less irregular ascent is broken by the mass of volcanic rocks which forms a highland in the Hopi Buttes. The major portion of the Hopi Buttes area is shown in Plate 1.

PLIOCENE BIDAHOCHI FORMATION

GENERAL DESCRIPTION

The volcanic rocks are interbedded with water-laid marl, calcareous tuff, calcareous clay, and calcareous sand which on Roberts Mesa are about 400 feet thick. These sediments have been named the Bidahochi formation by Reagan (1932); Wilmarth (1938) accepted this name. According to Williams (1936) and Wood (1941) the formation is Pliocene.

AREAL EXTENT

The Bidahochi formation is apparently thickest on Roberts Mesa. It extends a short distance to the north in small outliers on the flat surface of Black Mesa (Fig. 2), and extends southward into the Hopi Buttes where it is made up mostly of pyroclastic debris interbedded with lava domes. Sedimentary material is absent in the Buttes at the southwestern margin of the area. The formation extends continuously eastward from the Hopi Buttes beyond Ganado where it overlaps the westward dipping

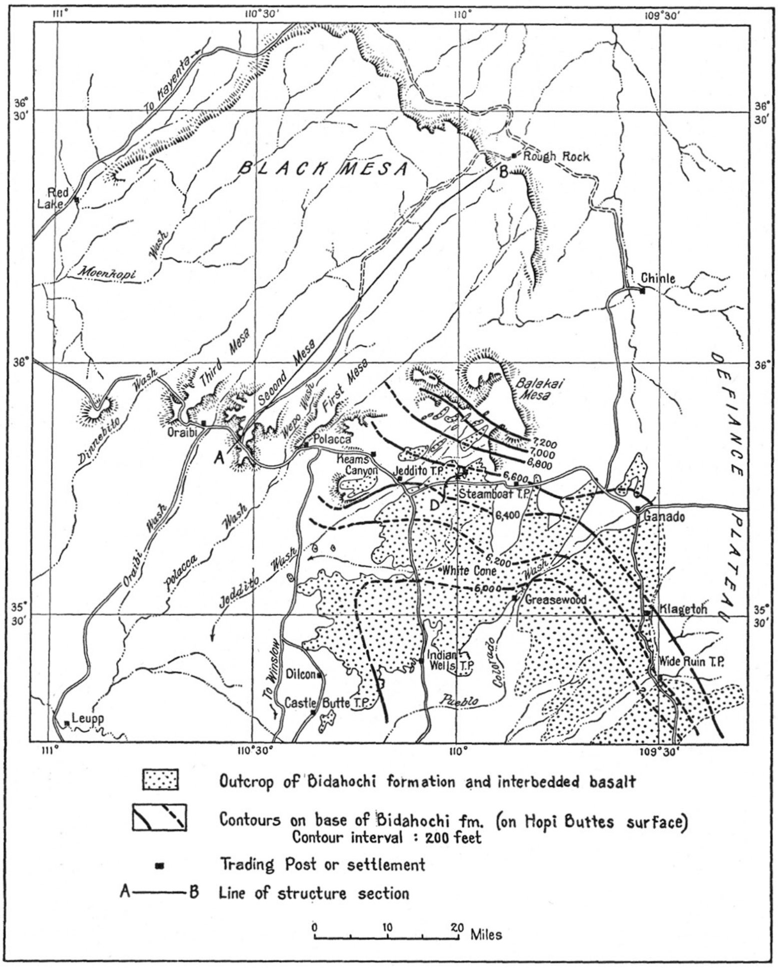

FIGURE 2.—*Map of part of western Navajo Country*

Showing outcrop of Bidahochi formation and Hopi Buttes surface. Based on map of Navajo Country of Office of Indian Affairs.

Permian rocks of the Defiance Plateau and is found southeastward beyond the limits of the Navajo Country. The Bidahochi is apparently continuous with the late Tertiary rocks of the Zuni area of New Mexico, described by McCann (1939).

LITHOLOGY

General statement.—Volcanic rocks comprise the major portion of the Bidahochi formation among the volcanoes of the Buttes. To the north and east, however, sediments predominate, although fine-grained tuffs are apparently universally present. The lithology varies considerably depending on the source of the material.

Sediments.—On Black Mesa the Bidahochi formation is confined to small outliers less than 100 feet thick. It is composed chiefly of calcareous sand with thin concretionary layers of coarse, crystalline calcium carbonate. The most abundant sand grains of this facies are subangular quartz resembling closely the sand of the Mesaverde sandstone. Plagioclase and grains of microgranular quartz, both minor constituents of the Mesaverde sandstone, occur also. However, even where the proportion of sand is over 80 per cent, the rock looks like a sandy limestone. It is almost certain that in the northern area of outcrop on Black Mesa and on Roberts Mesa the Bidahochi formation is composed largely of erosion products from the Mesaverde sandstone.

South of Black Mesa, on Roberts Mesa and near White Cone, the Bidahochi formation is about 350 to 400 feet thick. The white calcareous sand constitutes only the upper 100 to 200 feet of the formation. It overlies much finer-grained pink and green calcareous clay, as shown in the following section:

Section of Bidahochi Formation on Roberts Mesa

North of White Cone

(Elevation of top of section is 6530 feet)

		Feet
(1)	Thin layer of white, chalky marl or limestone caps Roberts Mesa	2
(2)	White calcareous sand with some clay or bentonite and containing hard concretionary layers	64
(3)	Interbedded greenish-gray and pink sandy clay	12
(4)	White calcareous sand with numerous calcareous concretionary layers	53
(5)	Interbedded greenish-gray and pink or red sandy clay	24
(6)	White calcareous sand	11
(7)	Interbedded greenish-gray and pink sandy clay	24
(8)	Greenish-pink calcareous sand with concretionary layers	10
(9)	Dark greenish-gray, coarse basaltic tuff or sand, well stratified	3
(10)	Interbedded greenish-gray and red sandy clay, calcareous	64
(11)	Covered	10
(12)	White, rhyolite tuff, quarried by natives	3
	Total	280

Base of formation is covered.

On Bidahochi Butte, the type locality, the calcareous sand is entirely absent, and the lower beds of the formation are composed of brown, greenish-gray, or reddish, calcareous clay, in places containing gypsum crystals (Pl. 1). This facies is overlain by coarse pyroclastic rocks or lava flows.

Section of Bidahochi Formation

On the north side of Bidahochi Butte

	Feet
(1) Dense monchiquite with phenocrysts of olivine	50
(2) Pinkish-gray, tuffaceous sandy clay, interbedded with grayish-green, tuffaceous clay which weathers to a gray-white powder	196
(3) Brown, sandy clay containing abundant rounded pebbles of gray and yellow quartz, especially at base	34
Total	280

At the southern margin of the Hopi Buttes area the sediments thin, and at Long Butte they are absent. The white calcareous sand present on the south side of Black Mesa is probably the most characteristic facies of the Bidahochi formation, for it is found as far eastward as Ganado and southeastward at Chambers.

At Greasewood the basal beds are apparently similar to the calcareous clay found at White Cone. At Ganado the basal beds are composed of soft brown sandy conglomerate or gravel. At Wide Ruin Trading Post, where the Bidahochi formation rests against the Defiance Plateau, yellowish sand and gravel are dominant.

Volcanic rocks.—Volcanic rocks are present almost everywhere in the Bidahochi formation although they are abundant and predominant only near the lava domes and diatremes which are their source.

The volcanic activity was violently explosive, and extrusion of lava was limited to small mushroom-shaped domes around the numerous diatremes. Few flows are continuous. There is little difference, if any, in the composition of the lava of the flows, domes, and diatremes. It is dense, black basalt, in most places limburgite or monchiquite, as described by Williams (1936). The typical monchiquite, probably the most common rock, has a groundmass of microlithic augite and iron ores with interstitial analcite, although some basalts contain interstitial orthoclase, rather than analcite. Phenocrysts are augite, and in some rocks, olivine. In many places, especially in the volcanic vents, the lava is vesicular and the open spaces are filled with zeolites or analcite, which may be replaced by calcite. Chlorite and iddingsite are common secondary minerals.

Pyroclastic rocks are greater in volume than the lavas, and in places make up the entire Bidahochi formation. They range from fine ash to coarse agglomerate containing bombs or blocks of country rock several feet in diameter.

Petrographic study of these rocks has shown that their igneous constituents are similar. The highly variable appearance is due largely to great differences in texture, varying content of country rock, or to admixture of sedimentary materials. The coarser pyroclastic rocks show bedding only vaguely, or not at all. The finer rocks, however, are well bedded almost everywhere, apparently reworked by streams, and thus are water-laid. The various grades of pyroclastic material can be summarized as follows:

FINE WHITE RHYOLITE TUFF: Occurs over a very large area in one thin bed near the base of the Bidahochi formation,—south of Ganado, at Greasewood, on Roberts Mesa, and in the Bidahochi Valley north of Indian Wells. This tuff was probably derived from a distant source and may be in part water-laid.

CALCAREOUS TUFF: White, thinly laminated, fine-grained ash (in places finer than .005 mm.) altered to calcium carbonate. It occurs as filling in diatremes, probably in part deposited in standing water.

COARSE BASALTIC TUFF: Coarse, sandy greenish-gray tuff. Widespread in Bidahochi formation interbedded with sediments. It is the dominant facies in central area of Hopi Buttes. Almost everywhere this material is well stratified (Pl. 2, fig. 3). Typically it is composed of fragments of basalt glass (limburgite), augite, olivine, and iron ore which range from .10 to 3.0 mm. Fragments of quartz, plagioclase, and microgranular quartz are almost always present, proving the presence of some sedimentary material. In some cases the larger fragments are rounded lapilli, often showing prominent rims. This basaltic tuff is most common as a water-laid pyroclastic sediment interbedded with calcareous clay, but it also fills many diatremes, especially those which are relatively little dissected by erosion.

TUFF-BRECCIA: Coarse, dark-green breccia and basaltic tuff of varying size containing mostly fragments of basalt or minerals of basalt ranging from .1 mm. to several cms. in diameter. This material is nowhere stratified. It fills numerous diatremes.

BASALTIC AGGLOMERATE: Many of the diatremes, especially those now deeply eroded, contain very coarse agglomerate composed of large bombs and irregular masses of vesicular basalt of monchiquitic composition. In many places this agglomerate contains fragments of tuff, clay, and blocks of country rock and is permeated by stringers of dense basalt. It contains crude bedding or what is more probably flow banding.

The basaltic agglomerate was derived by violent explosion which threw out bombs and lapilli or comminuted a solid mass of basalt. This material fell back into the open explosion hole, probably while still hot and viscous, and was later welded by more quiescent intrusion of dense basalt. Often the agglomerate was pushed out in large flat domes beyond the limits of the source vent.

EXPLOSION BRECCIA: Many of the deeply dissected diatremes contain a filling of coarse angular blocks (5 feet in diameter) of Mesozoic rocks mixed with minor amounts of basaltic tuff, tuff-breccia, and sedimentary materials. The most common of the angular blocks are Jurassic sandstone.

Large blocks of Mesozoic and older rocks are also found in the finer pyroclastic rocks near and inside diatremes. In an area near Crazy Waters Spring many large bombs of graphic granite were found, apparently derived from deep-seated pre-Cambrian rocks.

SOURCE OF MATERIAL AND CONDITIONS OF DEPOSITION

The Bidahochi formation thickens and becomes coarser to the north and northeast. On Black Mesa and immediately to the north it contains material derived from the Mesaverde sandstone, which is present on Black Mesa and which once occurred farther east in the Chinle Valley. Undoubtedly, the sediments of the Bidahochi formation were deposited by streams flowing from the north and east. The pyroclastic material was derived from the diatremes of the Hopi Buttes.

Fresh-water shells occur in the clays of White Cone, a fact which led Williams (1936) to refer to the formation as the Hopi Lake Beds. Ripple-marked and mud-cracked sand and clay do not commonly occur but have been found. The formation contains numerous remains of camel, horse, and mastodon, and a few plants.

During the field work, the writer conferred with Mr. Howard Scott Gentry, a collector employed by Dr. Childs Frick. Among other finds Mr. Gentry showed the writer a skeleton of a small camel which rested on its belly on a thin layer of sand. Its fore feet projected down through the sand into soft greenish clay beneath. This animal had certainly perished because it had broken through a thin layer of sand into wet clay, too soggy to support its weight.

Thus the lithology and biota of the formation suggest deposition by southwestward-flowing streams, on a low, wet, swampy plain. Damming of the streams may have been caused in part by the growth of numerous small volcanoes rising in little hillocks above low marshes and lakes. The bedded nature of the pyroclastic rocks suggests that much of the volcanic material was spread over this low plain by streams in flood. The abundant animal life indicates that vegetation was lush and the climate warm and moist for at least part of the year.

DEFORMATION OF BIDAHOCHI FORMATION

The base of the Bidahochi formation has been contoured (Figs. 2, 14) with a Paulin altimeter checked two or three times daily when possible at bench marks of the U. S. Coast and Geodetic Survey. The maximum error may in a few places be as great as 50 feet. On the southeastern edge of Black Mesa on Balakai Mesa and Antelope Mesa, the base of the Bidahochi formation slopes to the southwest at an average of 100 feet per mile. In the White Cone area where the base of the formation is composed of clay, it slopes at about 20 feet per mile. Evidently the slope was imposed after deposition, for the material is too fine to have been deposited on the existing gradient.

Deformation is particularly evident between latitudes 35° 30′ and 35° 45′ at the longitude of White Cone (Pl. 1; Fig. 3, section). The Bidahochi formation slopes to the south at a gradient of over 20 feet per mile. At the base it consists of clay beds deposited in ephemeral lakes or swamps. The modern Beshbito Wash which traverses this area from north to south has the same average gradient as the Bidahochi formation, for it crosses the base of the formation at two places, and its alluvium contains coarse gravel, coarser than any material found in the Bidahochi formation in this area.

A thin bed of coarse, water-laid tuff furnished further evidence of deformation. This horizon may be traced all the way from White Cone to the north end of Roberts Mesa (Fig. 3).

It now slopes southward 10 feet per mile. Its source obviously lay to the south, and it must have been deposited on a surface which sloped to the north or was nearly flat. Therefore, the Bidahochi formation in

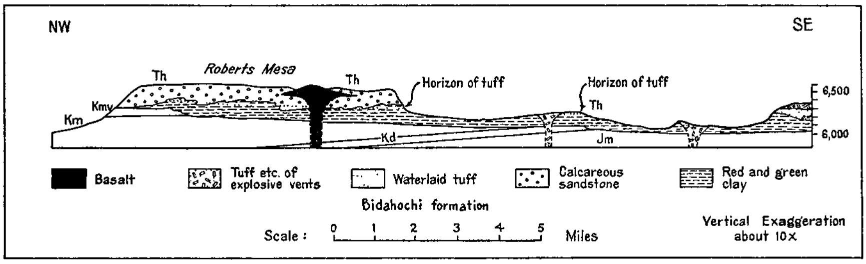

FIGURE 3.—*Structure section X — Y (Pl. 1) across part of Hopi Buttes area*

this region probably has been tilted to the south at least 10 feet per mile, and at least half of the present gradient resulted from Pliocene or post-Pliocene deformation.

HOPI BUTTES EROSION SURFACE

GENERAL DESCRIPTION

The Bidahochi formation overlies an erosion surface of low relief which truncates rocks ranging from Triassic to Upper Cretaceous. Gregory (1917, p. 121) recognized this surface calling it the Hopi Buttes peneplain.

In the Hopi Buttes area this erosion surface became the site of sedimentation and intense volcanic activity. At least the southern tip of Black Mesa was also the site of Pliocene sedimentation. The largest part of the mesa, however, rose above the Pliocene lowlands. Apparently only a small part was ever reduced to an erosion surface of low relief. The extent and nature of the erosion surface is a problem of importance to the Tertiary geology of the region, for many volcanic areas in the Plateau region are thought to rest on a supposedly Pliocene erosion surface, or peneplain, and the region about the Hopi Buttes is one of the few having Tertiary fossils.

HOPI BUTTES SURFACE ON BLACK MESA

General considerations.—Black Mesa is a dissected highland about 60 miles in diameter. It is drained by the Tusayan Washes which rise at its northern edge and flow southwestward through steep-walled valleys to the fingering southern escarpment. The north and northeast sides of the mesa rise to altitudes of over 8000 feet and support stands of scattered yellow pine. A bold and towering escarpment borders Chinle Valley on the east. The southern side has elevations from 6200 to 6500 feet and lies at the lower edge of the zone of juniper and pinyon.

The mesa, viewed from the south and east, presents a wide and even skyline which appears to truncate its structure, and at first inspection

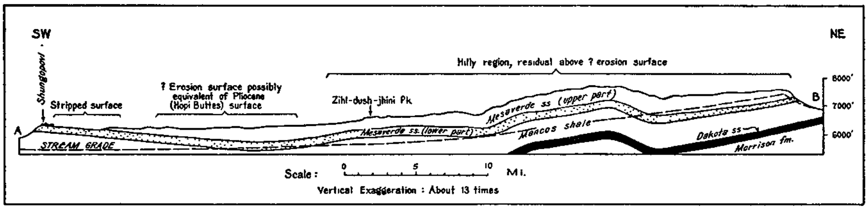

FIGURE 4.—*Structure section A — B (Fig. 2) across Black Mesa*

Elevations determined with Paulin altimeter, controlled from bench mark near Shungopovi and subsidiary barometric control points.

the divides between the southwestward trending canyons appear to be remnants of the Hopi Buttes surface. A traverse across the mesa from Oraibi to Rough Rock (Fig. 2), however, shows that only a small portion of the mesa was ever eroded to a plain of low relief.

Stratigraphy.—The soft Mancos shale is exposed on the lower slopes of the escarpment of Black Mesa on all sides. The Mancos is overlain by the Mesaverde sandstone which caps the entire mesa surface, except in the deep interior valleys.

At the southern edge of the mesa, the mesaverde consists of about 50 feet of white, massive sandstone at the top, underlain by about 130 feet of interbedded shale, soft sandstone, and coal, underlain in turn by about 70 feet of buff, massive sandstone. These three divisions, about 250 feet in total thickness, are recognizable throughout the Black Mesa area, and form a recognizable lithologic unit of the Mesaverde, resting on the Mancos shale. To the north the sandstone of this lower part of the Mesaverde increases at the expense of the shale, and at the northern edge of the mesa, the lower part of the Mesaverde is dominantly sandstone.

Except for scattered patches of higher beds, the lower part of the Mesaverde holds up the southern portion of Black Mesa. Northward on Second Mesa, however, (Fig. 4, line A-B) a higher part crops out on the divide between the Oraibi and Wepo Washes. This part is less reduced by erosion northward. North of Zihl-dush-jhini Peak it is over 600 feet thick. This part of the Mesaverde is composed mostly of shale, with thin sandstone and coal beds. The proportion of sandstone in the upper part increases northward, and at the north end of the mesa the highest beds of the upper part are predominantly massive sandstone, which forms a high and bold escarpment. The contact between the top white sandstone of the lower part of the Mesaverde and the basal shale of the upper part forms a horizon marker which probably can be recognized anywhere on Black Mesa.

Structure.—The strata of Black Mesa form a structural basin known as the Tusayan downwarp, whose axis lies near the settlement of Pinyon. At the south end of the mesa (First, Second, Third, and Antelope Mesas) the rocks dip slightly northward and at the north end they dip more steeply southward.

North of Zihl-dush-jhini Peak (Fig. 4) is a flat-topped anticline or double monocline, whose axis trends northwest-southeast. In Figure 4 this anticline is drawn with a large vertical exaggeration. The southern limb strikes N. 20° W. and dips 10° SW. The northern limb strikes N. 65° W. and dips 6° NE. The existence of this anticline had previously been recognized by Dr. Parry Reiche and Dr. Frank Johnson.

The anticline raises the base of the Mesaverde high above stream grade and exposes the Mancos shale in the valley walls. The massive white sandstone at the top of the lower part of the Mesaverde supports a prominent wide rock bench flanking the inner valleys. The same anticline may be traced southeastward to Balakai Mesa where it is truncated by the Hopi Buttes surface.

Erosion surface.—Measurement of altitudes at intervals at the top of the Oraibi-Wepo divide along the traverse A-B (Fig. 2) reveals the extent to which the structure has affected the topography. The topography of the northern two-thirds of this mesa is controlled by rock structure, and the profile of the stream divide parallels the rock strata (Fig. 4). South of Zihl-dush-jhini Peak, however, the strata are truncated, and this region probably represents an erosion surface which may be the Hopi Buttes surface or which may be a younger surface below it. At the end of Second Mesa, near the village of Shungopovi, as on Antelope Mesa, only the lower part of the Mesaverde remains. This may represent a stripped surface corresponding to the surface on Antelope Mesa to the east on which are found patches of the Bidahochi formation.

Thus during the Pliocene the southern edge of Black Mesa was an erosion surface and may have become buried by the Bidahochi formation. The greater portion of the mesa, however, was not eroded to a surface of low relief and was probably never buried but rose above the swampy lowlands to the south.

HOPI BUTTES SURFACE IN THE HOPI BUTTES

General statement.—The marked unconformity between the Bidahochi formation and the underlying Mesozoic rocks is visible south of Black Mesa in the Hopi Buttes area, and in most places shows no evidence of relief during the Pliocene. At several localities, however, the Bidahochi formation evidently buried low escarpments held up by resistant Mesozoic strata.

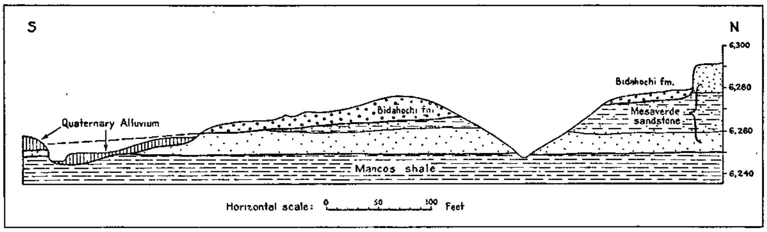

FIGURE 5.—*Cross section at locality C (Pl. 1)*
Showing relief on Hopi Buttes erosion surface.

Escarpments formed by Mesaverde sandstone.—At locality C (Pl. 1) the Hopi formation overlaps the Mesaverde sandstone, and where this overlap is exposed in a stream valley the Mesaverde forms a buried cliff about 10 feet high and in a distance of about 600 feet the total relief was about 40 feet (Fig. 5). The 10-foot cliff thus rose above a gentle shale slope. The sandstone at this locality forms the base of the Mesaverde and caps the mesa north of locality C (Fig. 2). North of the Jeddito Valley the whole lower part of the Mesaverde sandstone, 250 feet thick, is preserved. Thus another escarpment or series of escarpments once existed in between, at the site of the present Jeddito Valley.

In the headwaters of the Beshbito Wash, at locality D (Fig. 2), the basal sandstone of the Mesaverde forms a buried cliff over 50 feet high, as shown in Figure 6. This section is well exposed in a canyon wall and is probably the same escarpment as the one shown at locality C, farther west.

Escarpment formed by Dakota sandstone.—The resistant Dakota sandstone may also have formed a low escarpment before the Bidahochi formation was deposited. The outcrop of the Dakota sandstone occupies a large area near Steamboat Trading Post (*see* Gregory, 1917, Pl. 2) where the Bidahochi formation has been eroded off. It is evident that a wide rock bench underlain by the Dakota sandstone once existed. Such benches usually cap low escarpments and are associated with a steplike topography. Thus in the Pliocene the Dakota sandstone probably formed a low escarpment.

PLIOCENE TOPOGRAPHY

During the Pliocene, before the Bidahochi formation was deposited, the region of Black Mesa and the Hopi Buttes area had little relief, but there were low escarpments, some 50 feet high which encircled the Tusa-

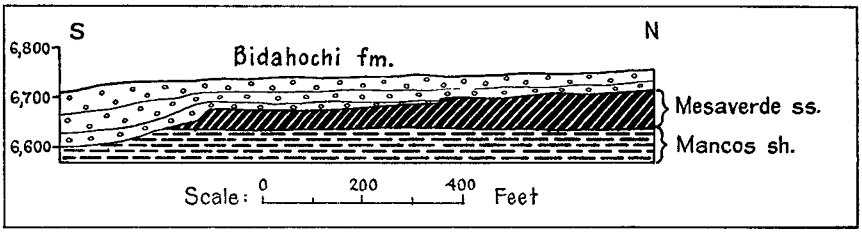

FIGURE 6.—*Cross section at locality D (Fig. 2)*
Showing relief of Hopi Buttes erosion surface.

yan downwarp as do the escarpments today. This contrasts greatly, however, with the relief of the present land surface, for valleys with walls 400 to 1000 feet high are characteristic.

Black Mesa in the early Pliocene was a highland area overlooking the lower country to the south. During this period aggradation by streams occurred and the southern edge of Black Mesa and the Hopi Buttes area were buried by sediments. Most of Black Mesa rose above this aggrading plain, however, and probably furnished material to be deposited on it.

In either Pliocene or post-Pliocene time, the Hopi Buttes surface and the overlying Hopi formation were deformed, and the gradients of the southwestward flowing streams were steepened. This warping may have accompanied the volcanic activity of the Hopi Buttes area.

CORRELATION WITH OTHER EROSION SURFACES

In the Zuni area of west-central New Mexico, McCann (1938) showed that Tertiary sedimentary rocks believed to be Pliocene overlie a deformed erosion surface of low relief called the Zuni erosion surface. His argument for deformation is the same as that presented here for the deformation of the Bidahochi formation, that is, that the material which rests on the Zuni erosion surface is too fine-grained to have been deposited on the existing gradient. The Tertiary rocks of the Zuni area are apparently correlative with the Bidahochi formation in the Hopi Buttes for the same rocks crop out over a wide area between the two regions. Thus the Zuni erosion surface is evidently correlative with the Hopi Buttes surface.

The late Tertiary lavas of the San Francisco volcanic field and the Coconino Plateau are believed by Robinson (1907) to rest on a Pliocene erosion surface. This may be correlative with the Hopi Buttes and Zuni erosion surfaces. The Chuska sandstone of the Chuska Mountains rests on an erosion surface of low relief. According to Reiche (1941) the Chuska sandstone is similar to the sediments which rest on the Zuni erosion surface, and is probably correlative with them. It is therefore probable that the erosion surface beneath the Chuska sandstone is correlative with the Hopi Buttes surface.

VOLCANISM

GENERAL CONSIDERATIONS

The diatremes or explosion pipes of the Hopi Buttes occur in a dense cluster covering about 800 square miles. A few are far removed from this cluster, as in the Jeddito and Oraibi valleys. The larger part of the main volcanic area has been mapped and the various diatremes located (Pl. 1). Detailed studies were made of several of the best exposed diatremes, which are numbered on the geologic map.

The central and northern portions of the Hopi Buttes have probably been relatively little dissected since completion of the volcanic activity and deposition of the Bidahochi formation. This area consists of a dense group of diatremes, many of which have poured forth dome-shaped or mushroom-shaped masses of lava. These have coalesced to give the appearance of a continuous sheet. To the south and west, where erosion has been more effective, only the feeding pipes of the diatremes are exposed, except here and there where a large lava dome or cluster of domes holds up a high mesa or butte. In both areas the nature of the filling of the volcanic vents ranges from basalt to the finest pyroclastic material. Extremely coarse explosion breccia occurs only in the deeply eroded diatremes.

In general the diameter of the vents decreases as erosion increases. In areas where dissection has been slight, at levels above the Hopi Buttes surface, explosion pits are generally 3000 to 4000 feet in diameter. In many places the initial explosion pit is overlain by domes of lava which have pushed outward, spilling over the sides, crumpling and pushing out the underlying and bordering tuffs and sediments. In a few places these lava eruptions were of sufficient duration to form rather continuous flows. The more deeply dissected diatremes range in diameter from 500 feet to 2000 or 3000 feet. In general the material in them is less well bedded, and, if pyroclastic, is coarser.

FIGURE 1. VIEW DOWN THE VALLEY OF COTTONWOOD WASH
From Bidahochi Butte, showing deeply eroded area.

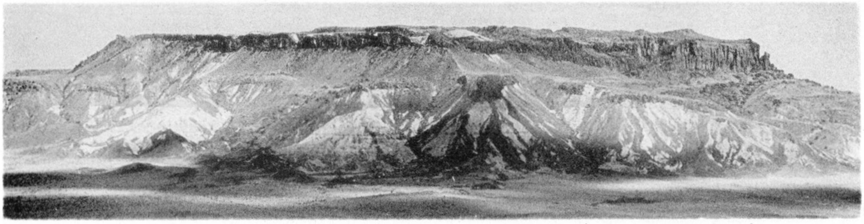

FIGURE 2. BIDAHOCHI BUTTE VIEWED FROM INDIAN WELLS

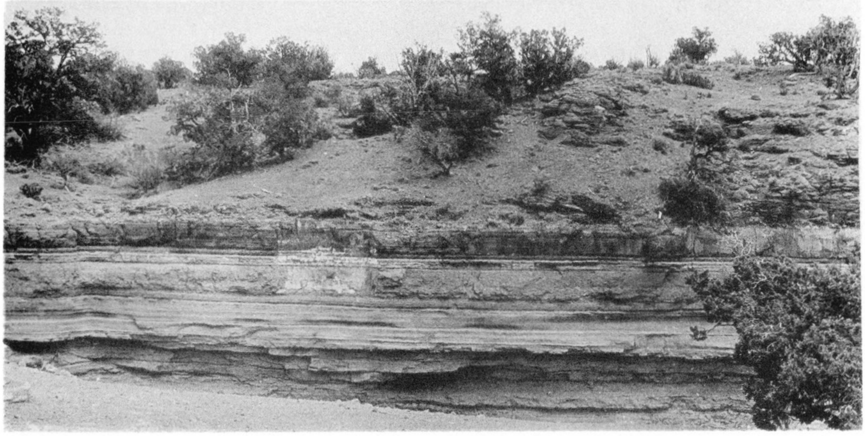

FIGURE 3. STRATIFIED BASALTIC TUFF
Overlain by a lava flow on north side of Flat Mesa.

BUTTES AND STRATIFIED BASALTIC TUFF

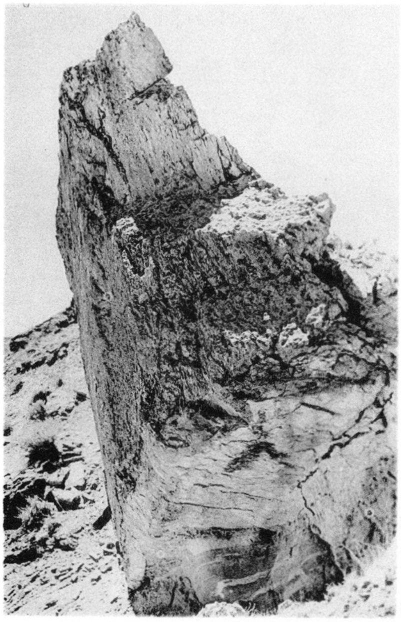

FIGURE 1. SLICKENED SURFACE OF UPTURNED TRAVERTINE
At eastern margin of diatreme No. 6.

FIGURE 2. AGGLOMERATE AND LARGE BLOCKS OF NAVAJO SANDSTONE
At the contact of a diatreme with the Navajo sandstone.

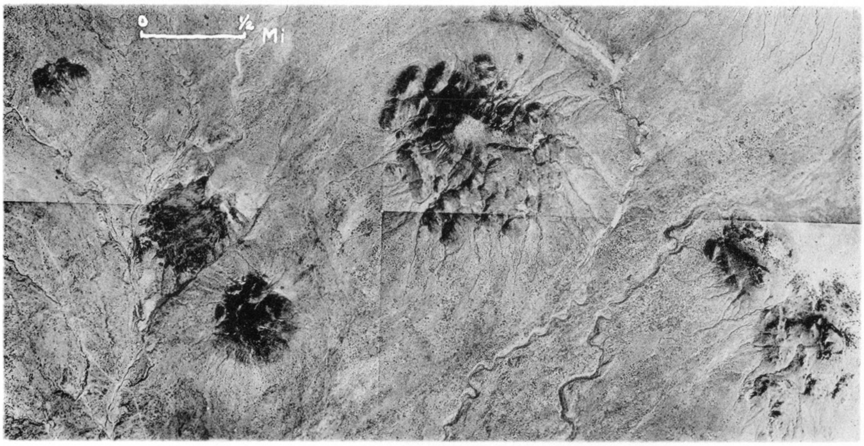

FIGURE 3. AIRPLANE PHOTOGRAPH OF DEEPLY ERODED VOLCANIC NECKS
(Basalt-filled) near Dilcon (U. S. Soil Conservation Service).

UPTURNED TRAVERTINE, AGGLOMERATE, AND VOLCANIC NECKS

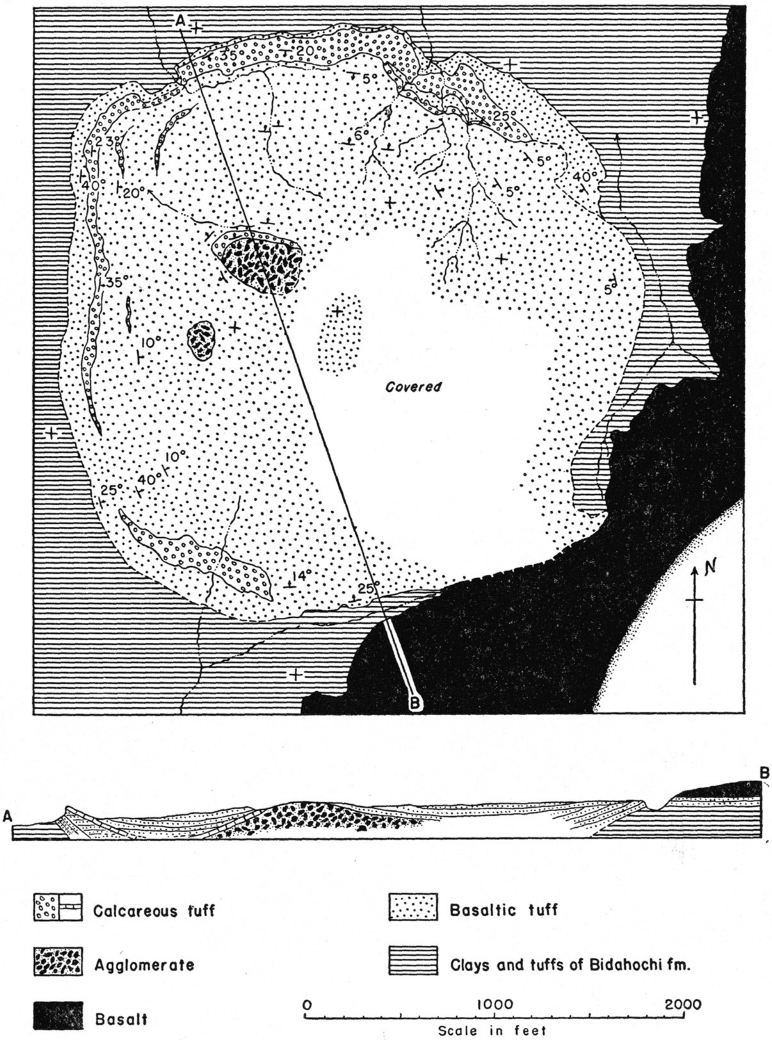

FIGURE 7.—*Map and structure section of diatreme number 1*

(Plane table survey, 1940.)

DIATREMES

NUMBER 1 (FIG. 7): This diatreme is one of the best exposed in the Hopi Buttes. It occurs in the north central portion of the Black Rock Buttes in an area underlain by water-laid, flat-lying basaltic tuff of the Bidahochi formation. The hard bed of tuff, altered to calcium carbonate which occurs near the periphery of the diatreme, is resistant and forms a nearly circular ridge, about 3000 feet in diameter; it can be clearly

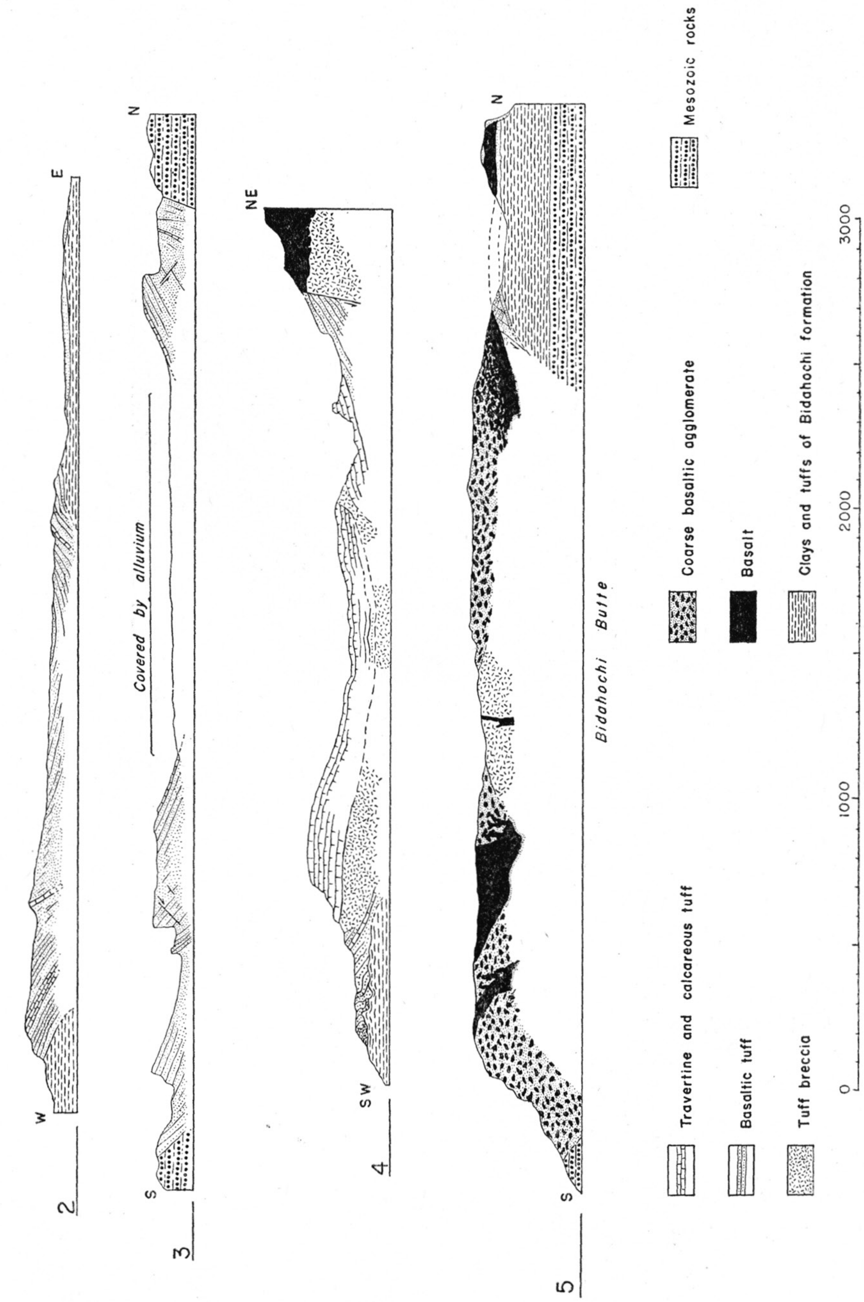

FIGURE 8.—*Cross sections of four diatremes*

Above or near level of Hopi Buttes erosion surface (Traverse with Paulin altimeter, 1940).

seen on an aerial photograph (Pl. 4, Fig. 1). The filling is mostly basaltic tuff ranging from coarse sand to fine ash. The only exception is the bed of altered white tuff which forms the ridge mentioned above.

The central outcrops of agglomerate are amygdaloidal limburgite with phenocrysts of augite. This rock is so vesicular that in this section the limburgite forms only a thin network around the cavities, which are filled with calcite. The white calcareous tuff at the periphery resembles travertine and is composed almost entirely of calcite with a grain size of less than .005 mm. A few coarse grains of quartz, augite, and limburgite are scattered throughout. The basaltic tuff forming much of the filling is indistinguishable from the tuff of the surrounding Bidahochi formation, except that it contains many layers of interbedded fine tuff, not as common in the rocks outside the vent. All the tuff is well stratified and appears to be water-laid. The grains consist of monchiquite, vesicular limburgite, augite, and quartz.

The structure is complex. At several places on the rim the outer wall of the diatreme can be observed. As indicated in the structure section the wall flares widely outward, dipping at an angle of from 5° to 40° toward the center. Inward from the outer wall several pronounced unconformities are observed in the tuffs. They suggest a complex history of formation which involves more than one explosion, or inward sliding of the filling. Toward the center, and around the inner core of basalt the tuffs dip outward almost as steeply as they dip inward at the periphery. A bed of fine, white calcareous tuff or travertine rests on the central outcrop of agglomerate. It may be the same bed as the similar tuff near the margin of the vent.

The structure of the diatreme must be explained by a complex history involving inward collapse of debris along the walls of the explosion pipe, later welling up of lava, and deposition of water-laid tuff, and partial subsidence. Part of the filling, especially the fine-grained material, may have been deposited while the small crater contained a shallow lake, and was supplied from outside the diatreme.

NUMBER 2 (FIG. 8): This diatreme lies a short distance southeast of number 1 and is about the same size. Like number 1 the Bidahochi sediments surround it. Its walls flare widely. The filling is mostly well stratified basaltic tuff. One bed of calcium carbonate which resembles travertine forms a resistant circular ridge. The strata dip inward, most steeply about 500 feet from the rim with dips as high as 65°, indicating subsidence of the filling. To the east of the diatreme, tuff beds dip outward, away from it. These may represent part of the rim of the original explosion crater.

Number 3 (Fig. 8): This diatreme lies a few miles west of Indian Wells in the Lokasakad Valley. It is now exposed at a lower stratigraphic level than the diatremes described above and is larger than most of the diatremes exposed at this level. Williams (1936, p. 120) has described this diatreme as a cauldron subsidence. It contains over 1000 feet of basaltic tuff and interbedded calcareous tuff. The walls are very steep and a few hundred feet from the outer rim the tuff beds dip inward as much as 85° at one place. Lokasakad Wash has cut directly through the diatreme, cutting canyons in both sides of the rim, which disclose well-developed, but small faults, probably formed during the subsidence of the filling. The diatreme is surrounded by the Jurassic Navajo sandstone and probably is now exposed at least 100 feet below the level of its original crater.

Number 4 (Fig. 8): Five miles north of Indian Wells on the east side of Bidahochi Wash is a diatreme which reveals more details of the manner of eruption. In the main portion of this well-exposed vent about 200 feet of fine, stratified, gray and buff-colored, calcareous tuff rests on coarse tuff-breccia which shows no evidence of bedding. At the western margin of the vent, coarse stratified basaltic tuff dips inward beneath the tuff-breccia. This is much contorted and rests on the soft clay of the Bidahochi formation. It apparently represents the tuff surrounding the original crater which was pushed outward or contorted by later eruptions, or by compression caused by the subsidence of the filling. At the northern margin the material of the diatreme rests against tuff-breccia and basalt of a high mesa. The contact is clearly a fault contact for the beds adjacent to the fault are curved upward, showing a downward movement of the material of the vent.

The basal tuff-breccia of the vent is interpreted as the filling of the crater, derived from an explosion in the diatreme itself. The fine-grained material above was probably washed or blown in from outside and may have been deposited in a crater lake. Subsidence of at least a portion of the diatreme occurred at some time during its formation. The original land surface must have been near the level of the basalt to the north, so that erosion has been considerable.

Bidahochi Butte, number 5 (Fig. 8): Bidahochi Butte rises more than 600 feet above the surrounding low valleys. On first inspection this butte appears to be capped by a remnant of a sheet of lava. Its nearly circular plan, however, suggests a central core for the lava. Furthermore, as can be seen on airplane photographs, the system of gullies on top of the butte has a roughly circular outline indicating that the drainage has become adjusted to a basinlike rock structure. The detailed pace and compass traverse of the butte from south to north reveals a complex diatreme. The fill is largely a coarse agglomerate composed of large, rounded, vesicular bombs. This material which shows no good stratification is penetrated here and there by dikes of coarse, olivine-rich basalt with orthoclase in the ground mass. At the northern end of the butte this material rests on stratified basaltic tuff which is faulted as though it had slid inward after becoming partially cemented. At the very northern edge of the butte some of the olivine basalt apparently spilled over the edge of the diatreme and is flat-lying or dips slightly outward. This butte is typical of many of the high, lava- and agglomerate-capped buttes of the region.

NUMBER 6 (FIG. 9): This diatreme lies a short distance north of Bidahochi Butte in the flat floor of the low Bidahochi Valley. Its form is regularly elliptical and is unusually well exposed. Its walls dip more steeply on the northeast rim than on the southwest rim. The travertine which rims the diatreme on east and north stands up as a prominent, resistant ridge. In several places it shows a slickened surface on its outer wall indicating subsidence of the filling (Pl. 3, Fig. 1). The contact with the Navajo sandstone is clean cut, and the sandstone is undisturbed, except that it is slightly altered for a distance of about half an inch away from the travertine. The travertine appears to have replaced the basaltic tuff which lies adjacent to it. The two materials merge into each other. The pure travertine is from 1 to 3 feet thick and contains abundant fragments of basalt and euhedral crystals of augite. Inward for a distance of several feet the proportion of basalt and augite grains increases. The pure basaltic tuff is conformable with the travertine, and is cemented by calcium carbonate.

The gypsum in the center of the diatreme is the highest deposit of the well-stratified filling. It is composed of swallow-tail crystals and coarse grains of gypsum. The strata are highly contorted. Beneath the gypsum is a considerable thickness of stratified gypsum interbedded with basaltic tuff. This material may have been deposited in a crater lake. Both the calcium carbonate of the travertine and the calcium sulfate of the gypsum may be in part hydrothermal in origin.

NUMBER 7 (FIG. 10): This diatreme forms a low, lava-capped butte on the north side of the Breezy Waters Valley. It is surrounded by the clays and tuffs of the Bidahochi formation and is probably exposed at the horizon at which eruption occurred. This butte shows part of the outward-dipping rim of the original crater on its southeast margin. This outer rim was apparently destroyed by a second explosion forming an unconformity. The second explosion was succeeded by deposition of stratified basaltic tuff, and extrusion of a thin cap of lava. Eruption of lava

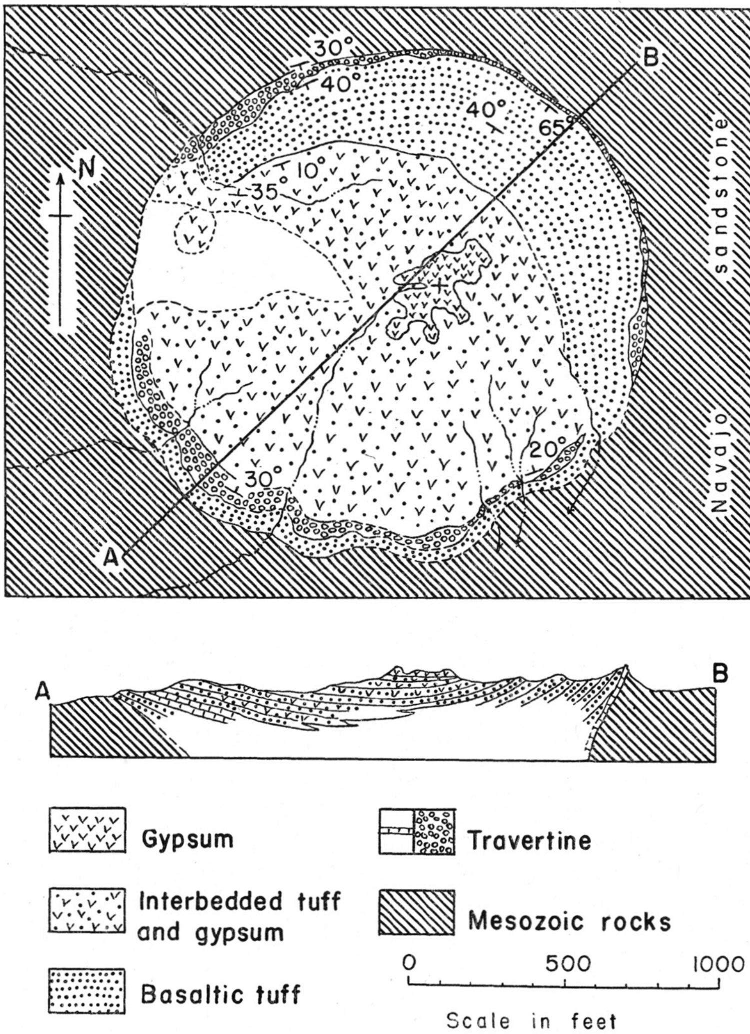

FIGURE 9.—*Map and cross section of diatreme number 6, Bidahochi Valley*
(Plane table survey, 1940.)

was followed by more explosions, forming two smaller vents. The eastern vent may have erupted the lava.

NUMBER 8 (FIG. 11): This is a small, deeply eroded vent at Indian Wells, surrounded by the Navajo sandstone. The exposed southern wall is vertical. The first eruption was explosive, choking the vent at this depth with coarse tuff-breccia and agglomerate. It was followed by a quieter eruption of monchiquite.

NUMBER 9 (FIG. 11): This diatreme lies about 500 feet northwest of number 8. As in number 8, the first eruption was explosive. It was followed by the eruption of coarse agglomerate which shows well-developed nearly vertical flow layers. Note that the basaltic tuff which forms the eastern rim dips steeply inward.

NUMBER 10 (FIG. 11): South of Black Rock Buttes on the north side of Lokasakad Valley is a diatreme which shows unmistakable evidence of subsidence. Only the northern half is exposed, the southern portion being eroded and buried by alluvium. A dike of vesicular, glassy limburgite extends northwestward from the diatreme.

The lowest beds of the filling consist of coarse breccia composed of blocks of stratified fine-grained tuff, basaltic tuff containing many boulders of glassy limburgite, and red Navajo sandstone. This coarse material probably represents the material which fell into the vent after the initial explosion. The coarse breccia is overlain by well-stratified and fissile, fine-grained, white, calcareous tuff. This in turn is overlain by inward-dipping, interbedded basaltic and fine-grained tuff. The coarser layers contain lenses of gravel with angular pebbles of Navajo sandstone and limburgite. The inward-dipping material perhaps fell in on top of the more fine-grained material during or after the subsidence. A fact of importance is that the boulders in the diatreme are composed of glassy limburgite similar to the dike which juts to the northwest from the diatreme. The lava flow on top of the mesa to the north is composed of coarse monchiquite and probably came from another vent.

The fault surface along the northern periphery is well exposed, showing a smooth, slickened surface. The lowest part of the fill has clearly subsided into the original vent, not by progressive slumping, but as a single unit.

NUMBER 11 (FIG. 11): This diatreme lies near Castle Butte Trading Post (Pl. 5, Fig. 2). Extending southwestward from it is a dike of dense agglomerate. The diatreme is exposed several hundred feet below the Hopi Buttes erosion surface and is thus deeply eroded. Like number 10 it contains both coarse explosion breccia and fine-grained calcareous tuff. There is no evidence of subsidence.

NUMBER 12 (FIG. 11): This deeply eroded diatreme lies near Pumpkin Flower Butte at Cottonwood Spring. Most of the fill is coarse, scoriaceous agglomerate which contains clearly exposed flow layers, showing evidence of subsidence at the periphery. At the south and west margins the agglomerate is underlain by stratified explosion breccia containing a high percentage of boulders of scoria and Mesozoic sandstone.

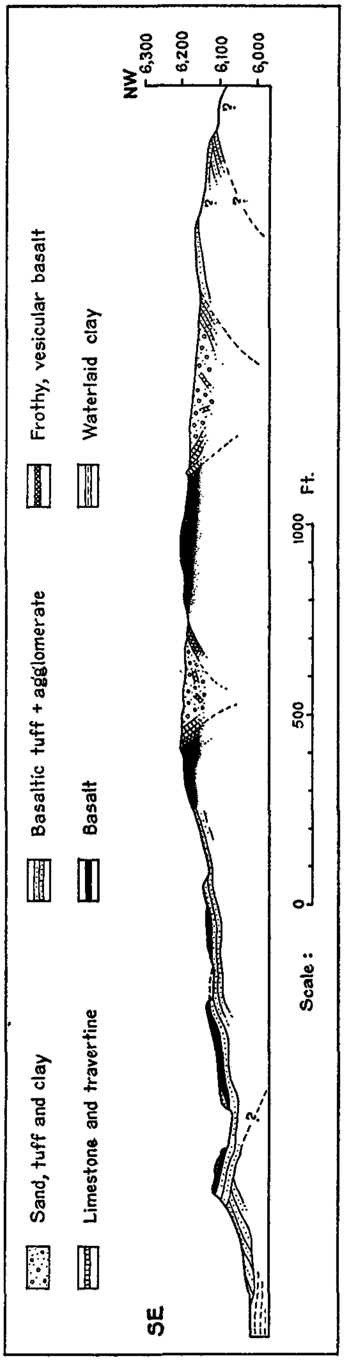

FIGURE 10.—*Cross section of diatreme number 7, Breezy Waters Valley*

(Traverse with Paulin altimeter, 1939.)

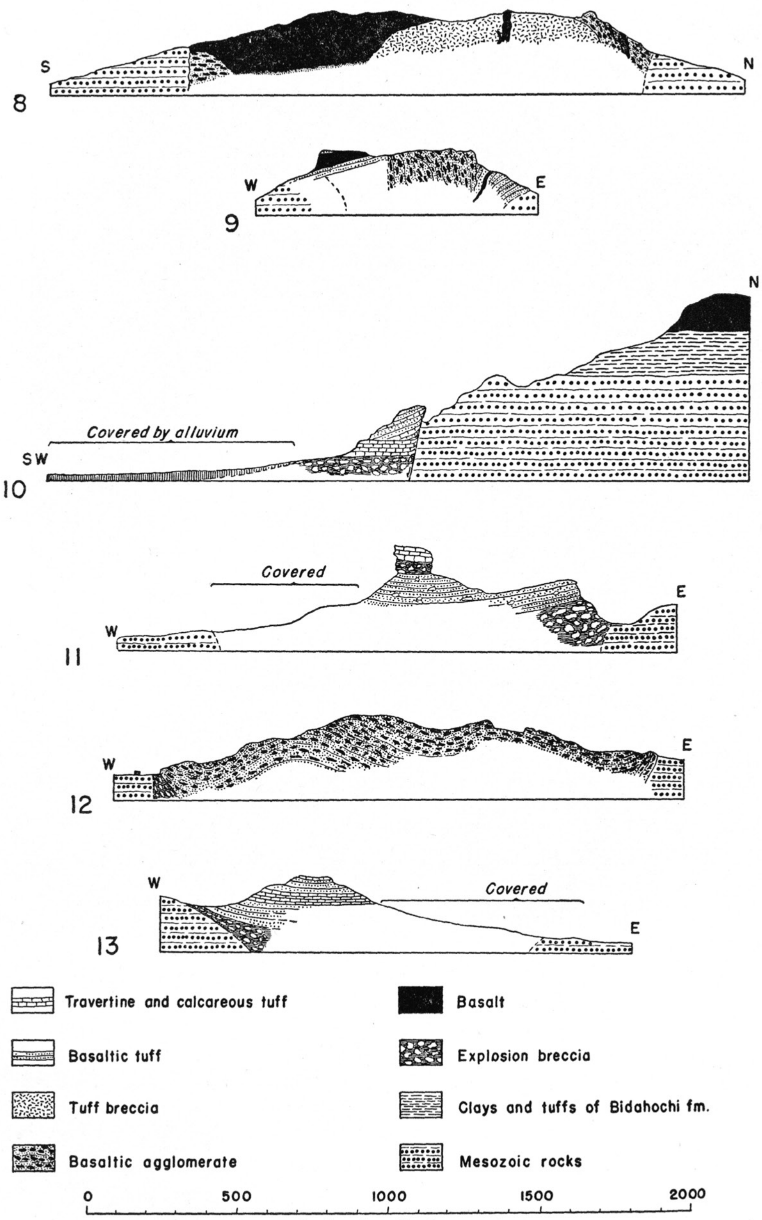

FIGURE 11.—*Cross sections of six diatremes eroded below Hopi Buttes surface*

(Traverses with Paulin altimeter.)

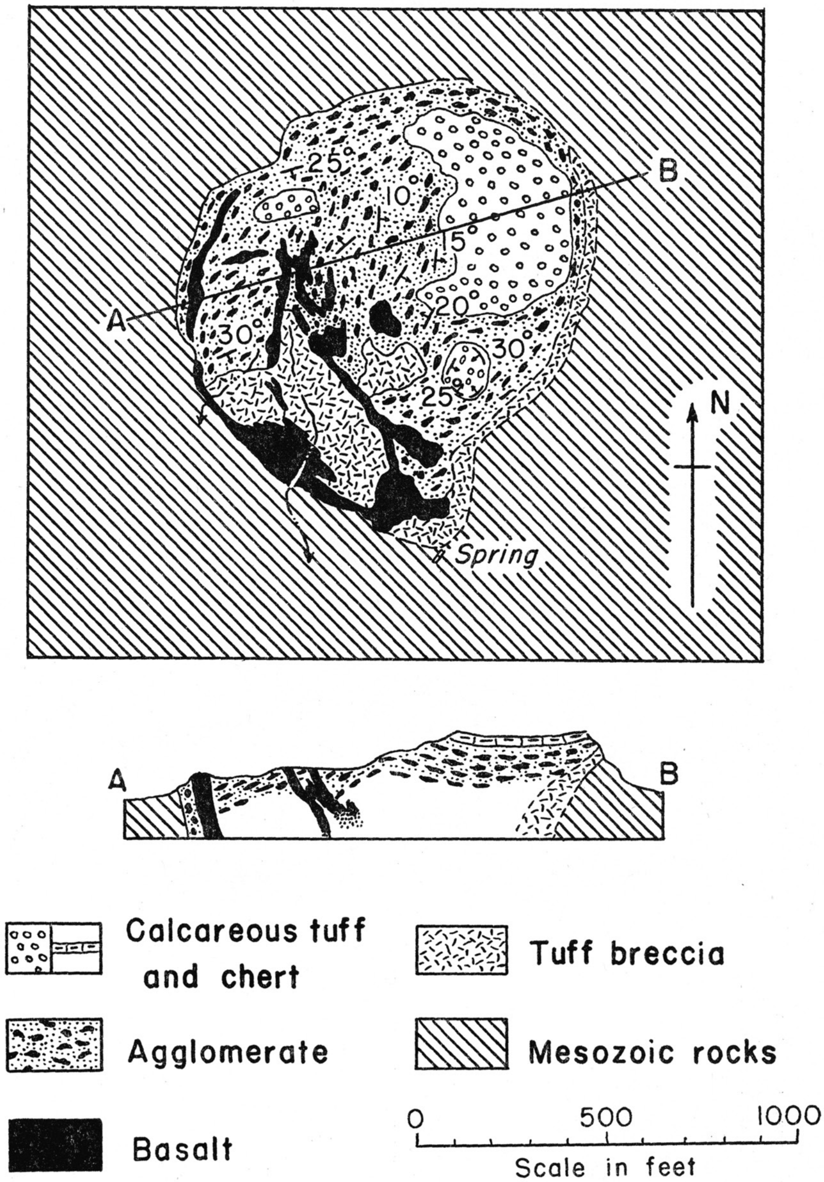

FIGURE 12.—*Map and cross section of diatreme number 14*
Near Castle Butte Trading Post (Plane table survey, 1940).

Number 13 (Fig. 12): Near number 12 and at the same deep horizon is a small diatreme filled completely with clastic debris. Like number 11 it contains coarse explosion breccia as well as extremely fine-grained and stratified tuff.

Number 14 (Fig. 12): Diatreme number 14 is eroded to a depth of 100 to 200 feet below the Hopi Buttes surface. It is a relatively small vest filled with a great variety of materials. The lower part of the filling consists of coarse agglomerate and tuff-breccia, penetrated by irregular dikes and stringers of monchiquite. The flow-banding of the agglomerate has a rough basin-shaped structure. The agglomerate is overlain by thin-bedded calcareous tuff, which is silicified at the top, and is hard. On the western periphery inward-dipping tuff-breccia and basaltic tuff underlie the agglomerate.

Number 15 (Fig. 13 and Pl. 5, Fig. 1): This group or line of diatremes occurs at the southern margin of the area mapped. It forms the most deeply eroded group of diatremes observed, lying 700 or 800 feet below the Hopi Buttes surface. Three diatremes occur in a northwest-southeast line, two of them connected by a dike of agglomerate. The northwesterly and southeasterly vents are filled completely with structureless tuff-breccia. The middle one contains three materials; its center is composed of coarse tuff-breccia penetrated and welded by small apophyses of glassy limburgite. This material is resistant and stands up as a small castellated butte. The central core is surrounded by a less resistant fill of large blocks of Navajo sandstone, tuff, and tuff-breccia. The dike connecting the two vents is composed of limburgite with a large fragmental admixture of quartz and tuff. The central diatreme shows a simple history, an initial gaseous explosion, blowing out the explosion pipe, followed by more quiescent eruption of lava.

Number 16 (not illustrated): A well-exposed, tuff-filled diatreme occurs south of Cottonwood Wash, 3½ miles west of the Holbrook-Indian Wells highway. The borders of the vent are covered, but small canyons have exposed about 50 feet of the filling. In the center of the vent, the top bed is coarse-grained gypsum which is severely contorted, but more or less flat-lying. This is underlain by a grayish rock composed of fine-grained gypsum, calcareous tuff, and clay; a network of seams filled with gypsum so fine and clear that it might be called alabaster penetrates this rock. This is underlain by 20 feet of tuff-breccia, clay, fragments of Mesozoic sandstone, and fragments of cemented basaltic tuff. The tuff-breccia is permeated by gypsum which fills the pores between the grains. It appears that gypsum may have been deposited in a lake on top of the vent filling. Solutions percolating either upward or downward have deposited gypsum in pores and cracks in the underlying material.

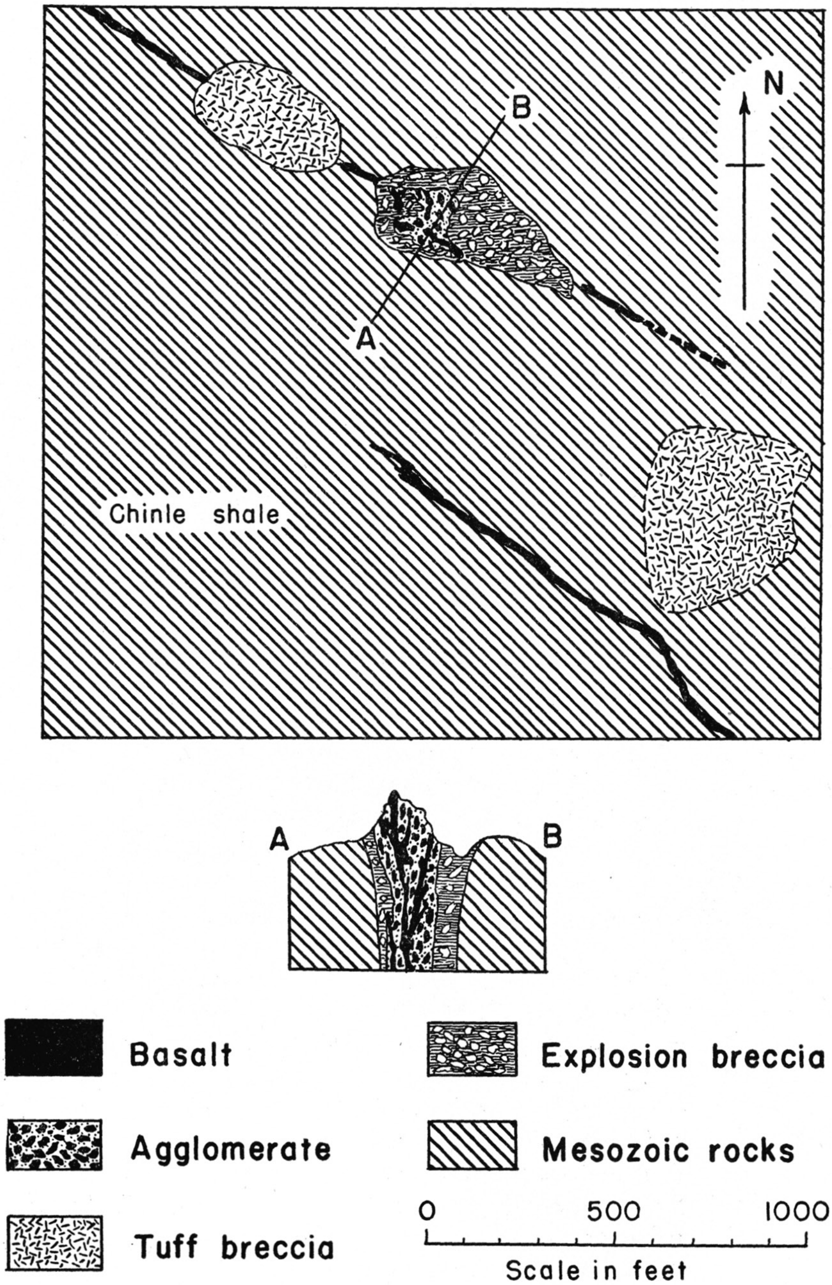

FIGURE 13.—*Map and cross section of three diatremes near Long Butte*

(Plane table survey, 1940.)

DIKES

Dikes are more numerous in the areas where the Bidahochi formation has been eroded than at higher stratigraphic levels. However, they are surprisingly scarce anywhere. Most dikes are connected to at least one diatreme, and with one exception they trend northwest. At Castle Butte Trading Post is a dike which trends northeast.

The material which fills the dikes may be tuff-breccia, agglomerate, or basalt. A dike in the Breezy Waters Valley contains basaltic tuff.

LAVA FLOWS

In general the lava erupted from the diatremes did not extend far from its source. Most of the eruptions formed flat, mushroom-shaped lava domes, which spilled only a short distance, if at all, over the crater rims. There are, however, a few lava flows. The largest of these forms a high mesa in the Black Rock Buttes, known as Flat Mesa. It has a maximum thickness of about 20 feet, and overlies nearly flat, stratified basaltic tuff of the Bidahochi formation. That this lava is a flow and not a series of lava domes is suggested by the fact that the mesa has an irregular outline, is flat on top, sloping with an eastward gradient of less than 2°, and its drainage pattern is dendritic (Pl. 5, Fig. 3). The lava was probably derived from a vent lying on the high point of the Black Rock Buttes to the west (Pl. 1, loc. E). There are a few other small areas apparently remnants of independent lava flows.

COMPLEX STRUCTURE OF BLACK ROCK BUTTES

Northwest of Indian Wells, east of Cedar Springs and south of Breezy Waters Valley is a large highland area underlain mostly by basalt and agglomerate. This highland has been called Hauke Mesa by Gregory (1917). The Indian name for the area is "Tsejhin-deshgishih" which means Black Rock Buttes. This highland mass is underlain by the Bidahochi formation, which at this place contains a high proportion of lava and agglomerate. In nearly all places where erosion has cut canyons and valleys exposing the rocks beneath the highland, the structure is complex.

The most striking area is at Crazy Waters Spring, northwest of Indian Wells (Pl. 4, Fig. 2). This area is underlain by pyroclastic material and basalt. Excellent exposures reveal more than five diatremes. They are so close together that some overlap, and one truncates another. In one of them are several red graphic granite bombs more than a foot in diameter. The granite is composed of crystals of quartz, feldspar, and biotite which average over 2 mm. in diameter. Granite bombs of smaller size are reported by Williams (1936, p. 128) to occur at diatreme number 3 which lies nearby at Lokasakad Spring. No other localities have been found. Williams believes that this granite must have been blown up from the pre-Cambrian basement, which in the Hopi Buttes probably lies at a depth of over 4000 feet. Perhaps the occurrence of these boulders in the area around Crazy Waters Spring is related to the great number of diatremes there as explosions may have been more violent and more frequent.

The group of diatremes at Crazy Waters Spring lies at the southern margin of the lava plateau of the Black Rock Buttes. This plateau has a rolling surface, consisting of rounded knobs of black, alkalic basalt or brownish agglomerate. Gullies in many places on the plateau show circular or radial patterns as on Bidahochi Butte. This suggests that they are subsequent streams adjusted to a complex underlying structure of closely spaced circular basins of tuff, agglomerate, and basalt or are consequent streams on lava domes. The only exception is the smooth lava flow of Flat Mesa. It is believed, therefore, that the Black Rock Buttes are a plateau consisting of closely spaced diatremes; the plateau has as yet been dissected only at the margin. Smaller basalt-capped mesas occur around the Black Rock Buttes, as for instance the mesa north of Pumpkin Flower Butte. These have a similar origin.

SUMMARY OF DATA

The various diatremes apparently have many features in common and the pattern of the various eruptions was similar in every case.

(1) The diatremes not deeply eroded are in general larger in diameter than the deeply eroded ones. Furthermore, their walls flare widely, indicating that most of the diatremes are funnel-shaped and narrow downward. At depth their walls are perhaps more nearly vertical.

(2) The diatremes which are not deeply eroded are preponderantly filled with basaltic tuff, or with lava and agglomerate. Those which are deeply eroded are filled with lava, agglomerate, or very coarse explosion breccia and tuff-breccia showing little or no stratification. At depth, therefore, the diatremes contain mostly debris blown out by the initial explosion which has slumped into the opening, or they contain viscous erupted material which has displaced the explosion debris. At and near the surface the filling is stratified basaltic tuff, or fine calcareous tuff which has been blown or washed in from outside, or has been deposited in standing water.

(3) A few diatremes contain gypsum, travertine, or silica, minerals which may be of hydrothermal origin. Most diatremes contain tuff, which is altered to or cemented with calcium carbonate. These minerals must indicate that the vents contained circulating waters, which in part may have been juvenile.

(4) None of the diatremes disturbs the bedding of the intruded rocks.

(5) The material of many of the diatremes has subsided. In those diatremes which are not deeply eroded this is shown by steep inward dips of the filling, forming a structural basin (superbly illustrated by diatreme number 2). At greater depth the subsidence produced faults at the walls of the diatremes, and the filling moved downward more or less as a unit (as in diatremes 4 and 10). This difference in the manner of collapse is probably due to the flare of the diatremes near the surface. Material lying above the flare cannot move downward without slumping toward the center, and dragging along the walls.

(6) Most diatremes had a complex history. It is necessary to postulate more than one eruption to explain their structure.

(7) Many diatremes connect with dikes, or are with other diatremes aligned in long rows.

SURFACE CONDITIONS DURING ERUPTION

Origin of stratified tuff.—The dominant material of the diatreme fillings near the surface is well-stratified tuff. This material is indistinguishable from the water-laid tuff which is widespread in the Bidahochi formation, interbedded with fluviatile sands and lacustrine clays. Stratified materials in explosion vents rarely occur. Bedding is not common at well-known explosion pipes such as Cripple Creek (Lindgren and Ransome, 1906), the Braden Crater, Chile (Lindgren and Bastin, 1922) or the diamond pipes of South Africa (Wagner, 1914). Walker (1928) in a paper summarizing the literature on explosion pipes makes no mention of bedding. Daly (1925, p. 26), however, has described a vent filled with inward-dipping stratified tuff on Ascension Island, and the Pretoria salt pan is a volcanic explosion pipe or diatreme filled with explosion debris interbedded with lake clays (Wagner, 1922). Daly and Wagner consider the bedding to be of fluviatile or lacustrine origin and the source of the material to be outside of the original crater. In the case of the Hopi diatremes the similarity between the tuffs in the vents, and the obviously water-laid ones of the Bidahochi formation, leads to the same conclusion.

Origin of gypsum, travertine, and silica.—Diatreme number 6 contains beds of gypsum and gypsiferous tuff in its center. At its eastern margin is a dike or vein of calcium carbonate which rests against the outer wall. This dike or vein is clearly secondary. Inward from the wall it becomes richer in basalt fragments, and at a distance of from 10 to 15 feet it is entirely basaltic tuff. This vein dips 65° and could not have been deposited in that position as a lacustrine marl. Apparently, therefore, it is a vein of travertine intruded between the wall rock and the filling of the vent. It has altered part of the fill.

In diatreme number 14 the top layers of the filling are capped by chert which appears to be secondary, derived by the alteration of calcareous tuff to silica. The pure silica or chert is underlain by calcareous tuff which contains stringers and layers of silica and looks like a cherty limestone.

Gypsum occurs in the filling of diatreme 16. It forms cementing material in tuff-breccia and forms contorted beds of large, swallow-tail crystals.

The rocks of the Bidahochi formation are rich in calcium carbonate over a wide area, and the clay beds at its base contain gypsum crystals at many places. Chert, however, has not been found outside the diatremes.

The explanation for the occurrence of these three minerals is probably related to the high water table during the time of eruption. If the diatremes formed craters which held small lakes fed by ground water they must have become the site of deposition of compounds in the ground water. If the lakes had no outlets the water might have become supersaturated with these salts, depositing them on the crater floors. The diatremes themselves were certainly excellent channel-ways for percolating ground water, for many were filled with porous material. The ground water was hot and may have been added to by juvenile waters and by hot gases charged with calcium sulfate, or silica.

Large deposits of travertine, some with inward-dipping structure, occur in the Tertiary rocks south of the Navajo Country (Harrell and Eckel, 1939).

Conclusion.—During the period of eruption, the area of the Hopi Buttes was the center of an aggrading basin dotted with swamps and lakes. During times of flood, powerful streams carried large quantities of debris across the region, brought from highlands to the north and east. When eruptions occurred small craters were produced and large supplies of tuff were added to the aggrading streams. Inasmuch as the region had a high water table for at least parts of the year these craters probably at times contained standing water which allowed fine-grained tuff, calcium carbonate, and calcium sulfate to accumulate undisturbed. After a time aggradation and change of stream courses allowed the powerful streams to erode or spill over the crater rims and fill them with coarse material.

Many of the diatremes underlie flattish lava domes which welled outward, pushing the wet clayey material of the crater rim and the sur-

FIGURE 1. AIRPLANE PHOTOGRAPH OF DIATREME NO. 1
Showing basalt-capped mesa on right (U. S. Soil Conservation Service).

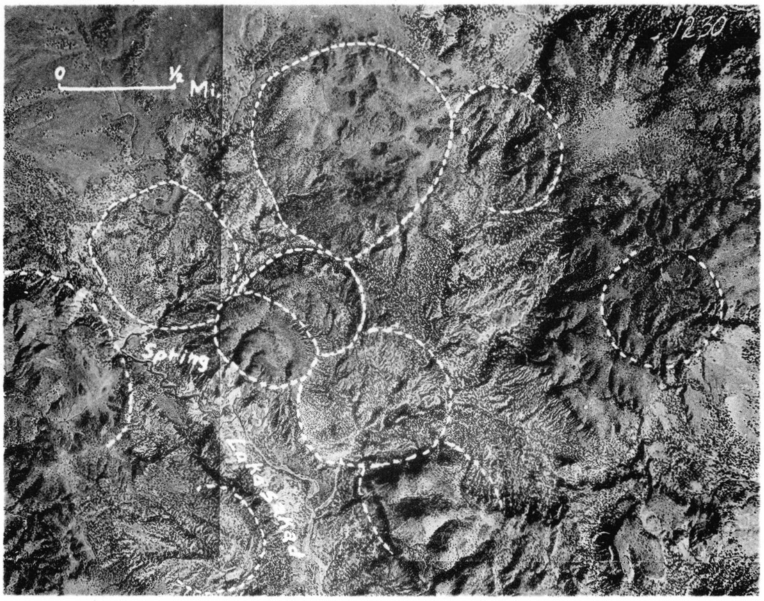

FIGURE 2. GROUP OF CLOSELY SPACED DIATREMES
On south margin of Black Rock Buttes at Crazy Waters Spring. The best exposed diatremes are outlined in white.

DIATREMES

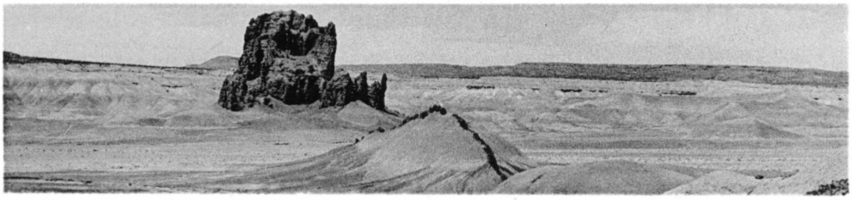

FIGURE 1. DIKE AND DIATREME AT DIATREME GROUP NO. 15

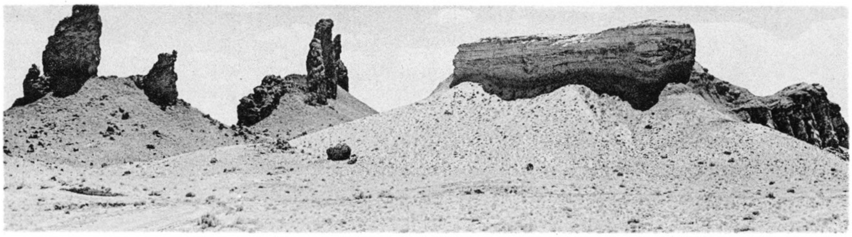

FIGURE 2. AGGLOMERATE-FILLED DIKE ON LEFT
Diatreme No. 11 in right center.

FIGURE 3. AIRPLANE PHOTOGRAPH OF FLAT MESA, A LARGE LAVA FLOW, AND THE PROBABLE SOURCE VENT
Vent outlined in white (U. S. Soil Conservation Service).

DIKES AND VIEW OF FLAT MESA

rounding plain ahead of them. Exposures of contorted clay and tuff at the borders of steep-faced lava domes are common.

CONDITIONS OF ERUPTION AT DEPTH

General statement.—The material which makes up the fill of the Hopi diatremes at depth is not unusual. Other areas of diatremes show a similar structure and eruptive history, as for instance, the large group in Missouri (Rust, 1937), the Scottish diatremes (Geikie, 1897), and the numerous pipes described by Walker (1928). However, three features of the Hopi diatremes, which are probably not unique, are so well exposed that they are significant—the presence of connecting dikes and fissures, the pronounced funnel shape, and the evidence of subsidence of the filling.

Alignment along fissures.—In Figure 14 all the diatremes discovered are shown, whether they are exposed at the surface or are covered by basalt domes, and merely indicated by the presence of subsequent streams with circular courses. Many of them are arranged in long lines. Careful examination shows that a northwest-southeast alignment is most prominent. That this arrangement is not accidental is shown by the perfect alignment of several groups which are detached from the main volcanic area. Furthermore, some of the diatremes are attached to dikes filled either with clastic debris or with monchiquite and agglomerate, as in the case of diatreme group number 15 (Fig. 13). Thus, apparently, the diatremes are related to a system of fractures and dikes in the earth's crust. This relationship has been suggested by Dutton (1885) and Johnson (1907) for the volcanic necks of the Mount Taylor region, New Mexico.

Funnel shape.—Daubrée (1891), first to use the term "diatreme," produced artificial explosion pipes which were funnel-shaped at both ends. The Hopi diatremes appear to narrow downward and may even merge with a system of narrow fractures. Near the surface, however, they have a funnel shape approximating the funnel illustrated by Daubrée. Some of them flare widely at angles as low as 25° in the first 100 feet beneath the surface.

The origin of the flare may be related in part to the fact that near the surface the explosions penetrated soft, unconsolidated sediments, and in part to decrease in static pressure.

Subsidence of filling.—The subsidence, or inward collapse observed in most diatremes is observed in many volcanic areas. Many volcanoes have subsided by faulting after the original eruption. Obviously in the Hopi Buttes, subsidence occurred long after the first explosion, for in

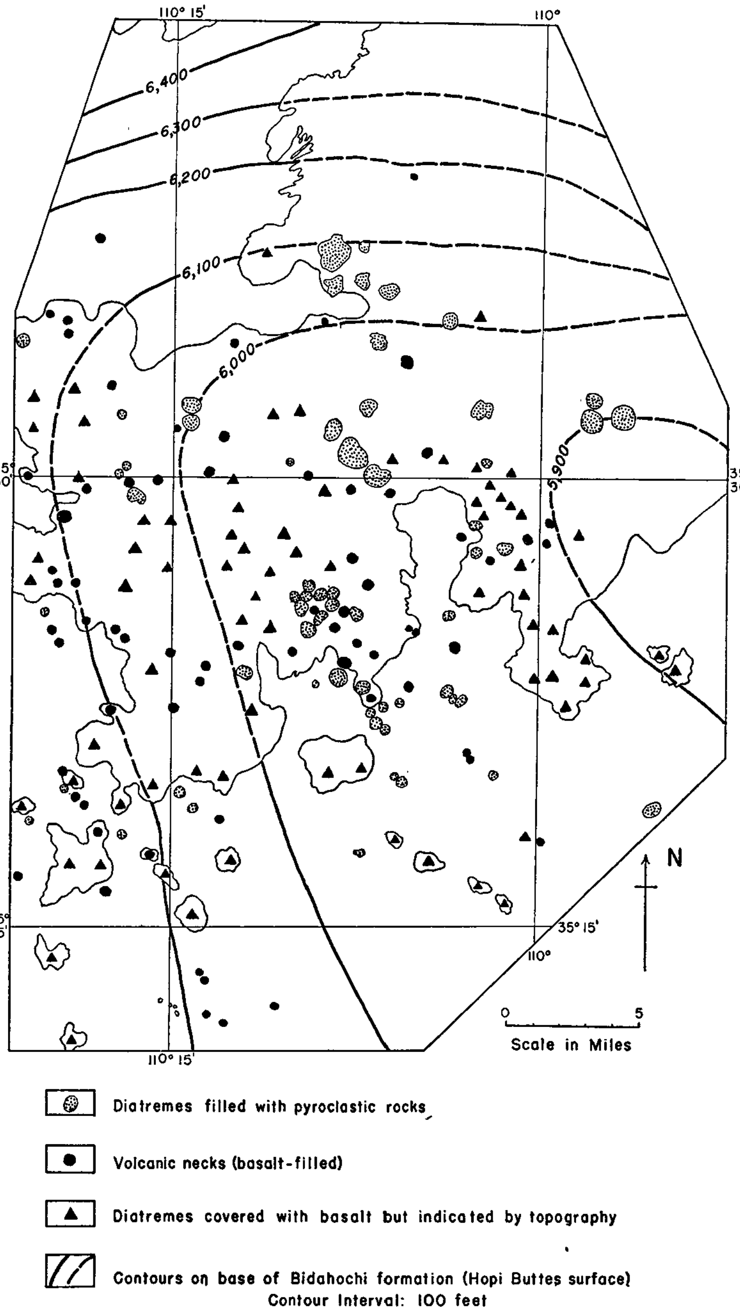

FIGURE 14.—*Map of Hopi Buttes*

Showing location of diatremes (tuff-filled vents drawn to scale) and contours on Hopi Buttes surface. Based on photoengravings of U. S. Soil Conservation Service.

most vents a considerable thickness of water-laid debris had accumulated. As shown by the flow layers of diatremes number 12 and 14, this subsidence occurred while the agglomerate filling was still plastic. In number 14, not only does the tuff have a basin structure, but also the agglomerate beneath it has a basin structure. This suggests that subsidence may have occurred because of the removal of molten material, or the contraction of molten material at depth.

Probably the filling of the diatremes was supported for a considerable time by a plug of cooling but hot and viscous material which, unless it was blown out by a subsequent eruption, subsided when the pressure of gas or molten magma was transferred to another diatreme or to another fracture.

THEORETICAL CONSIDERATIONS

Nature of volcanism.—Williams (1936, p. 171) considers the eruptions in the Hopi Buttes to have occurred at relatively low temperature, and to have been of the phreatic type. The author agrees with this conclusion. Very little evidence of metamorphism around diatremes is observed in the Hopi Buttes. Diatreme 6, in the Bidahochi Valley is walled on the east side by a vein of travertine which has altered the Mesozoic sandstone adjacent to it, for a distance of about half an inch outward. This alteration is probably a result of hydrothermal activity, and deposition of calcium carbonate in the pores of the sandstone. Many xenoliths of sandstone are observed in other diatremes which appear to be completely unaltered.

During the period of volcanism the Hopi Buttes area was an aggrading basin of sedimentation, and was in part wet and swampy. The high content of calcium carbonate and gypsum in many of the vents is evidence that the water table was at times high, and that ground water circulated through the rocks beneath, using the diatremes as channelways. Conditions were therefore suitable for the generation of steam by contact with rising magma and the conclusion that the volcanism was phreatic is justified by *a priori* evidence.

Magma reservoir.—There is little positive evidence in the Hopi Buttes concerning the nature of the magma source. The field relationships indicate only that within a distance of about 1000 feet from the surface the diatremes narrow downward and are associated with a system of fractures in the earth's crust. The occurrence of numerous and closely spaced phreatic eruptions, however, is a phenomenon interpreted by many authors as associated with the occurrence of a laccolithic or sill-like magma reservoir at shallow depth. (For a concise discussion of this problem, and bibliography, *see* Daly, 1933.) The most famous example is the large area of diatremes or embryonic volcanoes in Swabia (Branco, 1894).

The geomorphic history of the Hopi Buttes negates this hypothesis. It has been shown that before volcanism occurred, the Hopi Buttes area was an erosion surface of low relief. Contemporaneously with the volcanism it became an aggrading basin of sedimentation and the earliest sediments were deposited on a gradient less than the one existing today. During or after the volcanism the region was downwarped.

If the Hopi Buttes were underlain by a shallow, more or less horizontal and concordant magma reservoir, one would expect it to be domed, at least a perceptible amount. The opposite is true. A preferred conclusion is that the magma reservoir lies at greater depth and may even be the reservoir which furnished magma to the other Tertiary volcanic areas of the Navajo Country.

Several other areas in the Navajo Country contain Tertiary igneous rocks. Two of them, Navajo Mountain and Carrizo Mountain, are laccoliths, with no evidence of explosive volcanism. Others, although containing rocks of different composition, are similar to the Hopi Buttes area in that they contain diatremes which have not deformed or altered the rocks which they intrude. Rough calculation of the volume of the lava and other extruded debris of the Hopi Buttes indicates that it has a volume of about 50 to 100 cubic miles. Relatively little loss by dissection has occurred. The cross sections and map of Gregory (1917) indicate that both the Navajo Mountain and Carrizo Mountain laccoliths contain a similar volume of igneous rock.

In the Hopi Buttes the magma reached the surface by penetrating a widespread system of fractures. In the laccoliths the same volume of magma was confined to a domal reservoir at shallow depth.

SUMMARY

In the Pliocene the Hopi Buttes area was reduced to an erosion surface of low relief, called the Hopi Buttes surface. This surface, whether or not it can be called a peneplain, must have been reduced nearly to base level. At present it has an average gradient of 50 feet per mile. Inasmuch as the surface has been deformed the Pliocene gradient must have been less. Low escarpments rose above the plain, however, and the central part of Black Mesa formed a residual highland mass.

Pliocene sediments were deposited in a broad lowland, extending from the Hopi Buttes to a point far to the southeast, probably to the Zuni Mountains. In the Hopi Buttes the first sediments were clays, deposited in ephemeral lakes and swamps. At a later time coarse materials were spread out by aggrading streams.

This period of sedimentation was accompanied by volcanic activity. Magma penetrated the earth's crust beneath the area in a complicated system of fissures. As the rising magma neared or reached the surface its extrusion was accompanied by violent explosions which produced numerous, funnel-shaped diatremes. The craters of the diatremes were partially filled soon after the explosions by the rising magma or by a mass of explosion debris and viscous agglomerate, penetrated by apophyses of basalt. Many of them had a crater rim at the surface and contained pools of water which allowed fine ash, gypsum, and other materials to collect. Eventually many of the craters which had not overflowed with lava or agglomerate were filled and buried by coarse sandy basaltic tuff, carried by aggrading streams.

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