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PLIOCENE VOLCANOES OF THE NAVAJO-HOPI COUNTRY

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CONTENTS

ILLUSTRATIONS

INTRODUCTION

Scores of volcanic necks, dikes, and lava-capped mesas rise from the high plateau of northeast Arizona and the adjacent parts of Utah and New Mexico. These are the remnants of a volcanic field that formerly covered many thousands of square miles. Erosion has so far dissected this field that the original cones have disappeared, the sheets of lava have been dismembered, and the old volcanic conduits now rise as giant towers, revealing their inner structure with singular clarity. The objects of this paper are to discuss the features of these denuded volcanoes, the character of their ejecta, and the age of their eruptions. To petrologists, the region is one of unusual interest, because of the similarity of its igneous rocks to certain of those in the classic regions of alkaline rocks in Montana and Wyoming.

So extensive is the Navajo-Hopi volcanic province, that the present survey is to be considered as little more than a reconnaissance. When this study was made, only a few of the excellent, large scale aerial maps were available. The sheets of the United States Geological Survey, on the scale of 1 : 250,000, and the Indian Service maps, are inadequate for detailed mapping. Accordingly, the sketch maps included in this paper merely indicate the general distribution of the volcanic rocks. However, the salient features of the volcanism have been considered, and the rock-types discussed are representative. The large laccolith of

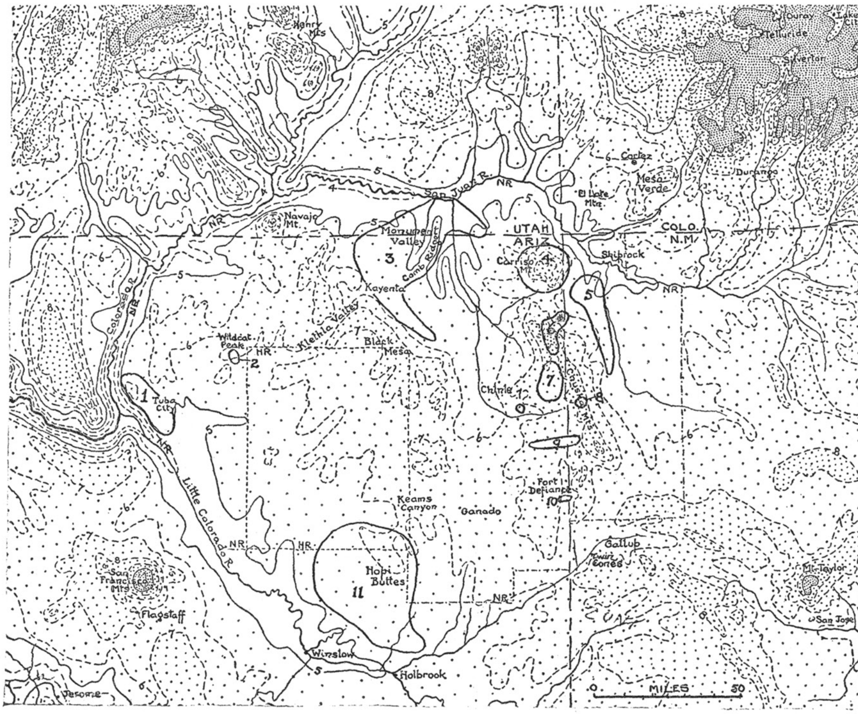

FIGURE 1.—*Sketch-map illustrating location of Navajo and Hopi reservations (NR and HR)*

Volcanic clusters are: (1) Tuba, (2) Wildcat Peak, (3) Monument Valley, (4) Carrizo laccolith, (5) Chuska and Redrock valleys, (6) Lukachukai Mountains, (7) Wheatfields, (8) Washington Pass, (9) Zilditloi, (10) Black Rock, (11) Hopi Buttes. Contour interval, 1000 feet.

the Carrizo Mountains, which lies in the northeast corner of the area, has already been described by Emery[1] and is, therefore, briefly mentioned.

For a history of previous work, the reader is referred to the report by Gregory.[2]

ACKNOWLEDGMENTS

For liberal grants from the Geological Society of America and from the Board of Research of the University of California, I am extremely grateful. I wish, also, to thank Mr. Childs Frick, of the American Museum of Natural History, for notes concerning fossil camels found by his parties in the Hopi country; Messrs. C. J. Hesse and R. A. Stirton,

[1] W. B. Emery: *The igneous geology of Carrizo Mountain,* Am. Jour. Sci., 4th ser., vol. 42 (1916) p. 349-363.

[2] H. E. Gregory: *The geology of the Navajo country,* U. S. Geol. Surv., Prof. Pap. 93 (1917) p. 9-10.

of the Museum of Palaeontology at the University of California, for their identification of certain vertebrate remains found at White Cone; Messrs. A. F. Hall, T. L. Mayes, and V. L. Vander Hoof and Drs. Parry Reiche and F. A. Johnson for aid in many ways; and Mr. Roberts, of the Jedito Trading Post, for his genial hospitality. My colleague, Professor C. A. Anderson, has kindly criticised the manuscript. In the notes that follow the reader will be aware that I owe a particular debt of gratitude to Dr. Herbert E. Gregory, whose splendid pioneer work in the Navajo country was the first incentive to the present study.

REGIONAL SETTING

The location and topography of the Navajo-Hopi region are roughly indicated in Figure 1. Other regions of Tertiary and later igneous activity are not far distant. To the southwest lies the volcanic field of the San Francisco peaks; to the southeast that of Mount Taylor and the Zuni Plateau and the floods of Quaternary basalt which cover wide stretches of New Mexico; to the north and northeast are the volcanic highlands of Colorado and the famous laccolithic groups of the Henry, Abajo, and Ute Mountains; while to the south are the volcanic fields of southern Arizona.

From pre-Cambrian time to the Pliocene, there seems to have been no volcanism in the Navajo-Hopi country, for the tuffs found in the Chinle (Triassic) shales doubtless came from a source far removed. The only marked folding movements that affected the region took place probably at the beginning of the Tertiary era; and the most recent marine deposits are of Cretaceous age.

HOPI BUTTES VOLCANIC FIELD

GENERAL STATEMENT

The largest volcanic cluster in the region to be considered is the southernmost, that of the Hopi Buttes, an isolated field, measuring from 35 to 40 miles on a side. Here the rolling badlands and plains are diversified by groups of castle- and chimney-like buttes, by wall-like dikes, and by lava-capped mesas that stand out all the more conspicuously among the delicately tinted sediments by reason of their somber colors. The sheets of basic lava and tuff that once covered the whole region may have reached a thickness of more than a thousand feet, but they are now reduced to remnants that vary from mere hillocks, a few yards across, to one, Hauke Mesa, 19 miles in length and 11 in breadth (Fig. 2).

PRE-LAVA SURFACE AND HOPI LAKE

The surface upon which these flows were erupted was carved from almost flat-lying Mesozoic sediments during the long interval between

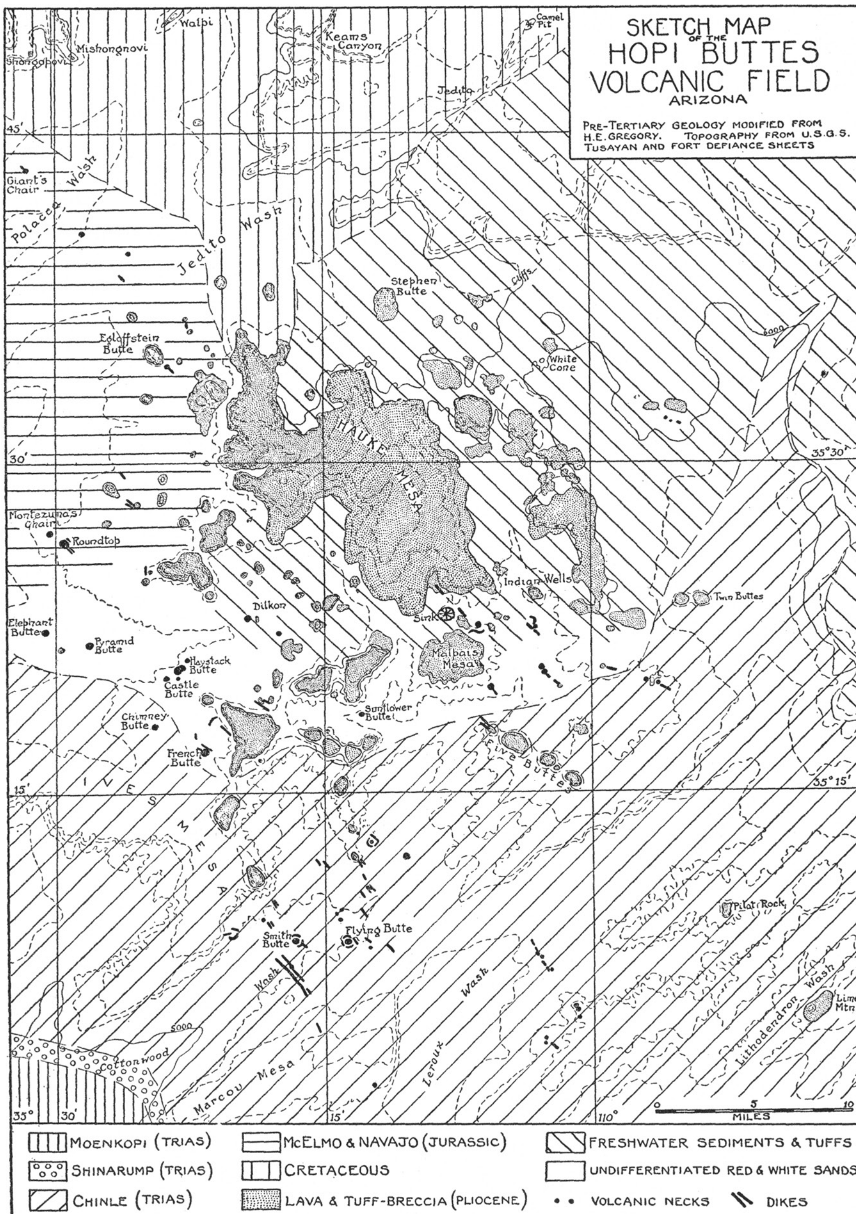

FIGURE 2.—*Sketch-map of the Hopi Buttes volcanic field*

Cretaceous and Pliocene times. That it was a surface of low relief is clear from the fact that the lava base is nowhere far from an elevation of 6,000 feet.

Such valleys as existed on this old surface must have been choked by showers of ash during the opening stages of volcanic activity. The streams were repeatedly dammed, forming playas and ponds, which seem to have been united ultimately into a lake of great extent. This may be spoken of as the Hopi Lake. Its deposits stretch as far north as Jedito Wash and south to the vicinity of the Five Buttes, a distance of almost 35 miles: in an east-west direction they are traceable for 50 miles, from near Ganado to Dilkon (Fig. 2). The northern shore of the lake was bordered by low mesas of cream and white Cretaceous sandstones; its other shores, by brilliant red and white Jurassic sandstones and delicately tinted Chinle shales. Correspondingly, the lake sediments show a general gradation from white calcareous sands near one shore through varicolored shales in the center of the basin to sands that are dominantly red on the opposite side. Near the southern shore, many low islands of red Jurassic sandstone, fringed with blocky talus, rose from the shallow water. As time passed, the water became increasingly shallow and the re-worked Cretaceous sediments spread continually farther south until the clays and silts in the middle of the lake, about White Cone, were largely buried by rain-pitted and ripple-marked sands (Pl. 4, fig. 1).

Most of the Hopi volcanoes rose along the southwestern shore of the lake, though many formed islands within it. Accordingly, the lake beds are intimately admixed with ashes and interbedded with countless flows of lava. Other volcanoes contributed ejecta. Thus, on the edge of the mesa south of Ganado, close to the base of the lake beds, there is a deposit of clean, white rhyolite pumice, 8 feet thick. Followed for 15 miles westward to Sunrise Springs, the same bed dwindles to 5 feet in thickness and is partly re-worked. Here it lies below the dark ashes of the Hopi vents. Its extremely fine grain and westward thinning indicate a source far to the east. Doubtless a more prolonged search will reveal that it persists throughout the Hopi Buttes, and it seems likely that future workers on the Tertiary deposits of Arizona and New Mexico will find it a valuable index for correlation.

HOPI VENTS

Although the original cones have long since been removed, there is no difficulty in recognising where they once existed. Erosion, acting rapidly on the surrounding sediments, has left the crater- and conduit-fillings as conspicuous towers, the summits of which cannot be more than a few hundred feet below the tops of the former cones. It is not surprising, therefore, that the intrusive rocks are indistinguishable from the surface flows.

At least 30 volcanic necks have been recognised. A few are isolated, but most occur in clusters or are aligned in a northwest-southeast direction, parallel to the adjacent dikes. The typical neck is circular in plan, though some are oval and merge gradually with dikes. Necks with such intricate outlines as those described by Geikie [3] from the Central Valley of Scotland are not to be found; on the contrary, the simple plans of the Hopi necks recall those of the diatremes of the Schwabian Alb and the necks of the Mount Taylor district, so vividly described by Dutton.[4]

The typical Hopi vent was opened by the explosive drilling of a cylindrical pipe, and doubtless a pyroclastic cone or maar-like depression was formed about the orifice. Subsequently, upwelling lava filled the crater and finally spilled over the rim in broad floods. The evidence for this history is abundant. There is hardly a neck without a jacket of inwardly dipping pyroclastic debris, made up of lava and sedimentary fragments that range in size from the finest dust to blocks many yards in diameter. Normally, the dip of these ejecta increases both upward and inward (Fig. 4A). Unbedded friction breccias bordering the necks are extremely rare, and, in general, the enclosing sandstones and shales remain undisturbed. An upward arching of the adjacent sediments, such as Gevers [5] noted around a neck in South Africa, or a downward deflection like that seen around many of the necks of Fife and the Rhöngebirge in South Germany,[6] has not been discovered in the Hopi region. The Hopi diatremes are of the Alb type.[7]

The peripheral bedded tuff-breccias are usually cut by irregular dikes, and the contact with the central pipe of lava, though mainly vertical, is in detail very intricate. Occasional pieces of shale and sandstone have suffered a slight induration and reddening, but most of them do not seem to have been affected either during the explosions or during the later uprise of lava.

In many of the Hopi necks, the central body of lava is strongly columnar, and, in general, the columns curve outward from the top so as to

[3] A. Geikie: *The geology of Eastern Fife,* Geol. Surv. Scotland, Mem. (1902) p. 200-283.

[4] C. E. Dutton: *Mount Taylor and the Zuni Plateau,* U. S. Geol. Surv., Sixth Ann. Rept. (1885) p. 165-182. *Also,* D. W. Johnson: *Volcanic necks of Mt. Taylor region,* Geol. Soc. Am. Bull., vol. 18 (1907) p. 303-324.

[5] T. W. Gevers: *The volcanic vents of the Western Stormberg,* Geol. Soc. South Africa, Pr., vol. 31 (1929) p. 43-62.

[6] H. Bücking: *Uber die vulkanischen Durchbrüche in der Rhön und am Rande des Vogelsberges,* Gerland's Beitrage, vol. 6 (1904) p. 267-308.

[7] R. Lachmann: *Die systematische Bedeutung eines neuen Vulkantypus (Hemidiatrema) aus dem Rezgebirge,* Deutsche geol. Gesell., vol. 61 (1909) p. 326.

be perpendicular to the inward-dipping tuff-breccias at the contact. In other necks, the columns are disposed at random. Auto-brecciated and scoriaceous lavas may be present along the margins, but normally the rocks are dense throughout and free from vesicles. Necks almost wholly composed of pyroclastic debris, which are characteristic of the Navajo country, are here the exception.

On some of the Hopi mesas, it is impossible to be sure whether one is dealing with an erosional remnant of a lava sheet or with a vertical neck; on others, horizontal flows may be traced into necks fringed with breccia (Fig. 4C).

Not all the lavas issued from central vents; some rose through fissures. An excellent example of such a feeder may be examined at the northern end of the Five Buttes. Here a dike, from 12 to 18 inches wide, can be followed upward into a lava sheet. Immediately above its source, the flow is about 150 feet thick, but on the neighboring buttes it thins away rapidly.

The succession and thickness of the flows and interbedded tuffs vary greatly even over short distances. On one mesa, from three to six flows may be counted, though on the next, less than a mile away, there may be only one or two. While some of the closely spaced vents were erupting piles of ash, others were pouring out tongues of lava.

BEDDED PYROCLASTIC ROCKS

Explosive ejecta from the Hopi vents probably exceed the lava flows in volume. Only a very small fraction of this pyroclastic debris makes up the volcanic necks; most of it is interbedded and admixed with lake and river deposits or is intercalated in lenses between the lava flows. Toward the west and south, tuffaceous deposits are thin and rare, but in the opposite direction, along the edge of Jedito Mesa and along the borders of Pueblo Colorado and Wide Ruin Washes they are extensively developed.

Typically, the ejecta consist of angular and subangular chips of black limburgite and monchiquite in a sedimentary matrix. True bombs and scoriaceous lapilli blown out while still viscous are exceptional. Cinder cones, made up of scoriaceous fragments, like those in the neighboring San Francisco volcanic field, can not have been present in the Hopi region. On the contrary, the activity must have been dominantly of vulcanian and ultra-vulcanian type, for the shapes of the ejecta indicate that the material was solid, or very nearly so, prior to explosion. With the fragments of lava were erupted great volumes of pulverised sandstone and shales, but debris of plutonic rocks, so common among the tuffs of the Navajo volcanoes to the north, is conspicuously rare.

The first products of eruption assumed dips in conformity with the pre-volcanic slopes, but the later ejecta were generally laid down horizontally between freshwater deposits of mud, limestone, limey mud, sand, and gravel. Locally, coarser tuffs and breccias seem to have spread out along irregular channels on the lake bottom, in the form of mud flows. The debris must be pictured as accumulating on an extremely varied surface, here becoming admixed with lake sediments, there falling into rivers to be water-worn and admixed with sands, and at another place infilling depressions on the hummocky top of a lava flow. Near some of the vents, tuff-breccias, including lava blocks up to 3 feet in diameter, are to be found, but compared with the fine detrital tuffs the breccias are rare.

CAULDRON SUBSIDENCE NEAR INDIAN WELLS

A cauldron subsidence occurred about 3 miles S. 65° W. of the trading post at Indian Wells, in the Hopi Buttes (Fig. 2). It lies near the southern margin of the old Hopi lake. Topographically, the subsidence has produced an oval basin, measuring approximately half a mile in an east-west direction and a third of a mile across. The floor of the basin is covered with recent river deposits, but the sides and surrounding region are formed of detrital limburgite and analcite basalt tuffs, and lapilli-tuffs, freshwater clays, sands, and limestones, in rapidly alternating beds. Some of the tuffs carry fragments of red granite and quartz diorite, which are noteworthy as the only plutonic ejecta found in the Hopi volcanic province. With these may be found sporadic crystal bombs made up of pyroxene, hornblende, and a little biotite.

These lake beds and pyroclastic deposits had accumulated to a thickness of at least 1,000 feet when they suffered local collapse. The structures produced by this disturbance are perfectly revealed in the gorges cut through the rim of the basin on its southwest and northeast sides. On the inner side of the basin, the beds dip inward at angles of approximately 40 degrees; near the rim they are, in general, vertical; whereas, on the outer side the dips flatten to horizontality within the space of a few hundred yards (Fig. 3). Innumerable, outwardly dipping reverse faults and recumbent folds cut the beds, particularly outside the rim, where the dips are high, though the maximum observed displacement is only 5 feet. There are indications also of a sliding in the vertical beds.

It is clear that the depression is not an explosion pit, since freshwater sediments are regularly interbedded with the pyroclastic rocks. Nor can it be related to orogenic movements, for nowhere else in the Hopi country is there any evidence of recent disturbance. Such a local structure can hardly be accounted for except as a result of the movement of magma at depth. The withdrawal of magma, either by the surface escape of lava or by the intrusion of dikes, might so weaken the crust as to form ring fractures. In more solid rocks, these would tend to be vertical, at least at depth, and clean cut, as at Buell Park (p. 139), but fractures transmitted upward into incoherent tuffs and sediments would tend to produce sliding and downward slumping. Moreover, if some of the fractures converged toward the surface, as they do in many

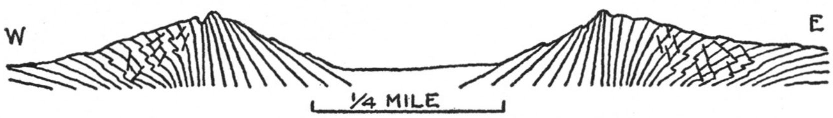

FIGURE 3.—*Diagrammatic section across the Indian Wells subsidence*

ring dikes, the collapse would tend to produce just such reverse faults and recumbent folds as are diagrammatically represented in Figure 3. There are no dikes within the basin itself, but perhaps the intrusion of lava into the necks beyond the rim of the basin and into the dikes to the east is responsible for the subsidence.

DIKES

Trend.—A glance at the map (Fig. 2) shows that most of the dikes and necks of the Hopi country are aligned approximately in a northwest-southeast direction, that is parallel to the axes of the very gentle post-Cretaceous folds. Faults are entirely absent.

No dike is straight for any great distance; in detail, all show many small rectangular offsets. Locally, the discontinuous outcrops of a dike may be arranged *en échélon,* and the branches, though usually only five to ten yards apart, may be separated by as much as fifty yards. Curved dikes are rare.

Width.—Except where they widen into volcanic necks, most of the Hopi dikes are only a foot or two across, though a few reach ten feet in width, and one is forty feet wide for a short distance. Despite their thinness and shallow depth of intrusion, many are traceable at intervals for several miles, and must have been injected with almost explosive violence during the rapid wedging apart of fissures. The faces of the dikes are usually smooth or corrugated by broad, horizontal grooves, as if, locally at least, the magma had spread laterally rather than vertically. Most, if not all, of the volcanic vents must have been drilled before the phase of dike intrusion began. None of the straight dikes departs more than 10 degrees from the vertical, though the curved sheets dip at low angles.

Curved dikes or cone sheets.—Near the southern margin of the Hopi Buttes, there are three necks, partly surrounded by inward-dipping, arcuate intrusions. The best exposed of these lies about 5 miles north of Flying Butte (Fig. 9, no. 2). Here is a small neck, cut by dikes,

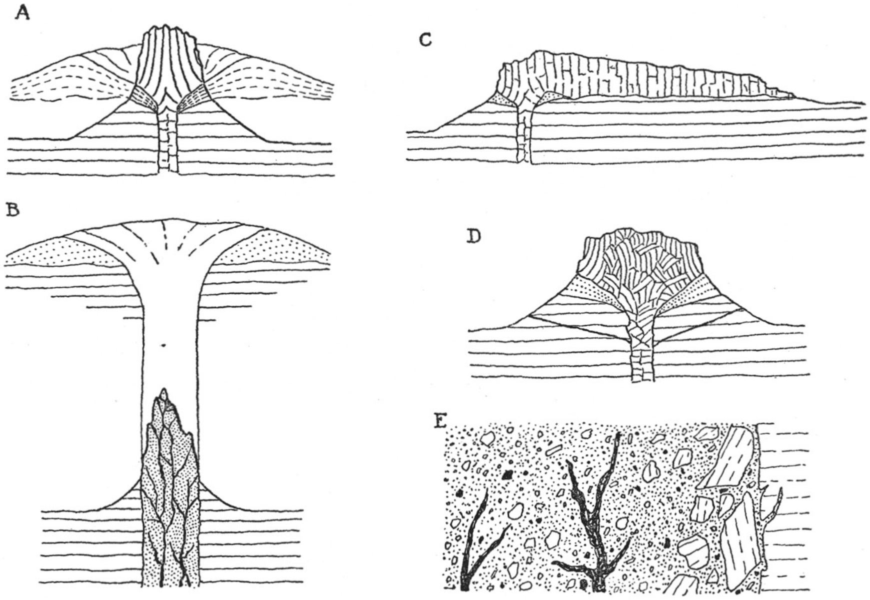

FIGURE 4.—*Diagrammatic sketches of Navajo-Hopi necks*

(*A*) Common type of Hopi neck. Diverging columns of lava resting on inward-dipping tuffs and surrounded by undeformed Mesozoic sediments. Possible form of original crater is suggested.

(*B*) Common type of Navajo neck, Agathla. Shaft of tuff-breccia riddled with dikes of minette. Conduit probably terminated at surface in an explosion pit or maar.

(*C*) Lava spilling from a Hopi vent.

(*D*) Neck forming Smith Butte, Hopi Buttes. Flat-lying Chinle shales; inward-dipping tuffs of crater, enclosing columnar lavas due to several upwellings into crater; cone sheets.

(*E*) Margin of typical Navajo neck. Fractured walls of sandstone (right), detached blocks, lying in a matrix of comminuted minette and sediments (left). Later dikes of minette.

which rises through flat-lying Chinle shales and is bordered by a sheet of monchiquite averaging only two feet in thickness and dipping inward at angles ranging from almost horizontal to almost vertical.

A curved sheet of limburgite, a foot thick, crops out along the north and east base of Smith Butte. In places, it lies horizontally, parallel to the bedding of the Chinle shales; elsewhere, it dips inward at angles up to 30 degrees. On the east side, it is cut by a vertical dike which continues inward to the central neck. Above the Chinle shales lie well-bedded lapilli-tuffs whose inward dip increases upward (Fig. 4D), indicating accumulation on the sides of a funnel-shaped crater. Intruding the tuffs, and resting upon them, is a cake of columnar lava, about 100 feet thick.

On Flying Butte, the central neck consists of downward-diverging columns of lava that rest on inward-dipping tuffs. Between 100 and 200 yards from the neck, there is a discontinuous belt of auto-brecciated and scoriaceous lava, which may represent a cone sheet.

Composition of the dikes.—Most of the dikes are made up of dense, black, porphyritic lava identical with that forming flows on the adjacent mesas. Marginally, these dikes contain fragments of shale and sandstone torn from the neighboring walls. Other dikes are principally composed of tuff-breccia. An excellent example is the striking wall-like intrusion that rises to a height of about 150 feet behind the Castle Butte Trading Post. For much of its course, it is only 10 feet wide, but toward the south end it widens to about 100 feet. A thin skin of horizontally bedded red sandstone still adheres to the face of the dike in places. Blocks of similar sandstone, up to 6 feet across, and fragments of Chinle shale abound within the dike, where they lie in a matrix of comminuted lava and sediment. A feature of this dike, not seen in any other, is a crude bedding of the tuff-breccia, suggestive of the accumulation of ejecta in an open fissure.

Contact metamorphism.—Alteration of the wall-rocks is surprisingly slight. Occasionally, red sandstone may be bleached for a few inches from an igneous contact, and shales may be slightly baked; for the most part, however, no trace of alteration can be detected. Most of the sedimentary inclusions also are unaffected, though some, probably those transported from considerable depth, may be partly vitrified or recrystallised.

Travertine vein.—About 3 miles south-southwest of Indian Wells, a sinuous dike of calcareous tufa forms a broken wall, up to 20 feet in height. It can be followed for almost three-quarters of a mile in a general east-west direction. Though averaging only 6 feet in width, it swells to 40 feet near its western end, where it splits into two parallel branches. The walls in most places dip southward at angles of more than 40 degrees; locally, they are vertical. Much of the travertine is massive and devoid of any regular structure and weathers in a cavernous fashion, but some of it is strongly banded parallel to the walls and exhibits botryoidal surfaces. Sandy and tuffaceous impurities, obviously picked up from the walls, are plentiful. Whether the travertine was formed by direct magmatic emanations of carbonate waters and is, in this sense, similar in mode of origin to the calcite and aragonite amygdules in the igneous dikes, or whether the carbonate was derived from solutions that were primarily meteoric in origin and acted upon calcareous sediments at depth has not been determined, though the presumption is in favor of the former view. Carbonate veins are not uncommon in association with the diatremes of South and Southwest Africa.

PETROGRAPHY OF THE HOPI ROCKS

GENERAL STATEMENT

No good purpose would be served by discussing the lava flows, neck fillings, and dike rocks separately. Neither in the field nor under the microscope is it possible to distinguish them. They are all dense, black or dark-gray rocks that would be classed in the field as basalts. Almost all are studded with glistening phenocrysts of augite, and many carry recognisable crystals of olivine. Few, however, contain biotite and still fewer, hornblende. Feldspar is nowhere visible to the unaided eye, and, indeed, in most of the rocks it is absent altogether. Where present, it is generally in the form of microlithic sanidine. Normal plagioclase basalts were found only along the southern margin of the Hopi province, in the small outlier south of Lithodendron Wash. This remarkable scarcity of feldspar among the Hopi rocks sets them apart from those of the Navajo volcanoes to the north, in which orthoclase and sanidine are almost ubiquitous. Of the colorless constituents in the Hopi lavas, analcite, a mineral rare in the Navajo rocks, is, by far, the chief, but leucite, occasionally present in the latter, is here unknown.

The typical Hopi lavas are the surficial equivalents of monchiquites; the Navajo lavas, of minettes. For convenience, the Hopi rocks may be classified into four types, though actually they grade into each other. These are:

Type 1—Limburgites
Type 2—Analcite basalts and monchiquites
Type 3—Trachybasalts
Type 4—Olivine-augite basalts

TYPE 1—LIMBURGITES

Many of the bombs, lapilli, and fragments of tuff blown out of the Hopi vents cooled rapidly to form glass-rich limburgites. Many of the lavas also were quickly chilled, so that the interstitial melt froze to dark glass.

Porphyritic augite is rarely lacking and in most specimens makes up between 5 and 10 per cent of the whole. Though black to the naked eye, the mineral is usually brownish-green and non-pleochroic under the microscope. Crystals half an inch long are not uncommon, and great numbers of smaller, perfect specimens may be picked up in the soil derived from the crumbling tuffs. The forms are 100, 010, 011, 111, and 110, and twinning on 100 is prevalent. The augite from a lapilli-tuff selected for analysis (No. 15) has these properties: $\alpha = 1.695$; $\beta = 1.706$; $\gamma = 1.720 \pm .002$: $2V = c.60°$; $Z \wedge c = 46°$; Sp. Gr. $= 3.20 \pm .02$. It is a lime-rich, diopsidic augite, chemically almost identical with an augite from the 1631 lava of Vesuvius.[8] Optically, it resembles the dominant pyroxene in the basic, alkaline lavas of Montana. In some of the Hopi rocks, the augite is distinctly zoned, the interior being colorless or very pale brown and showing only weak dispersion, while the exterior is purplish brown and has an optic angle of about 40 degrees. This indicates an outward passage from diopside to titanaugite. The microlithic augite appears to be rich in both iron and titanium, and in some limburgites may constitute almost two-thirds of the whole. Aegirin augite has not been detected.

In a typical limburgite, such as that analysed (No. 5), porphyritic olivine makes up about 10 per cent of the volume, though in some flows it is almost lacking. Crystals longer than 2 millimeters are rare, and, contrasted with the augite, most of them are extensively altered to pale antigorite, accompanied by calcite and hematite.

Hornblende has been recognised as only a minor accessory in a few sections. It is of the basaltic variety, and pleochroic from pale yellow, X, to a yellowish- or greenish-brown, Y and Z. $Z \wedge c = 5°$; dispersion intense.

Biotite is also unusual and is confined to rocks carrying hornblende. In a small neck, immediately southeast of Egloffstein Butte, it occurs as rich-brown flakes, half an inch across. $\gamma = 1.665 \pm .002$; Sp. Gr. $= 2.80$. In a dike near French Butte, the mineral has an optic angle of 5° and $\gamma = 1.658 \pm .002$.

The matrix of the limburgites is invariably rich in microlithic augite, granular titanomagnetite, and acicular apatite with interstitial brown glass ($n = 1.520$). Irregular patches of analcite, more or less altered to zeolites, increase at the expense of the glass as the limburgites grade into the analcite basalts and monchiquites. Figure 5, C, depicts the normal texture.

Amygdules are abundant. Most of them are composed of analcite and/or calcite, but many, especially in the southern part of the Hopi field, consist of aragonite. Elsewhere, vesicles are infilled with waxy chlorophaeite and ?nontronite, varying in color from lemon-yellow to bluish-green, or with zeolites.

Where chips of shale and sandstone are enclosed by limburgite they are generally quite free from alteration, though a few are partly vitrified, and others are surrounded by reaction rims of diopside. Solution of the fine felsitic matrix of some inclusions has caused their disruption

[8] M. Stark: *Die Augite in den Gesteinen der Euganeen*, Neues Jahrb. für Min., Abt. A, vol. 55 (1927) p. 1-35.

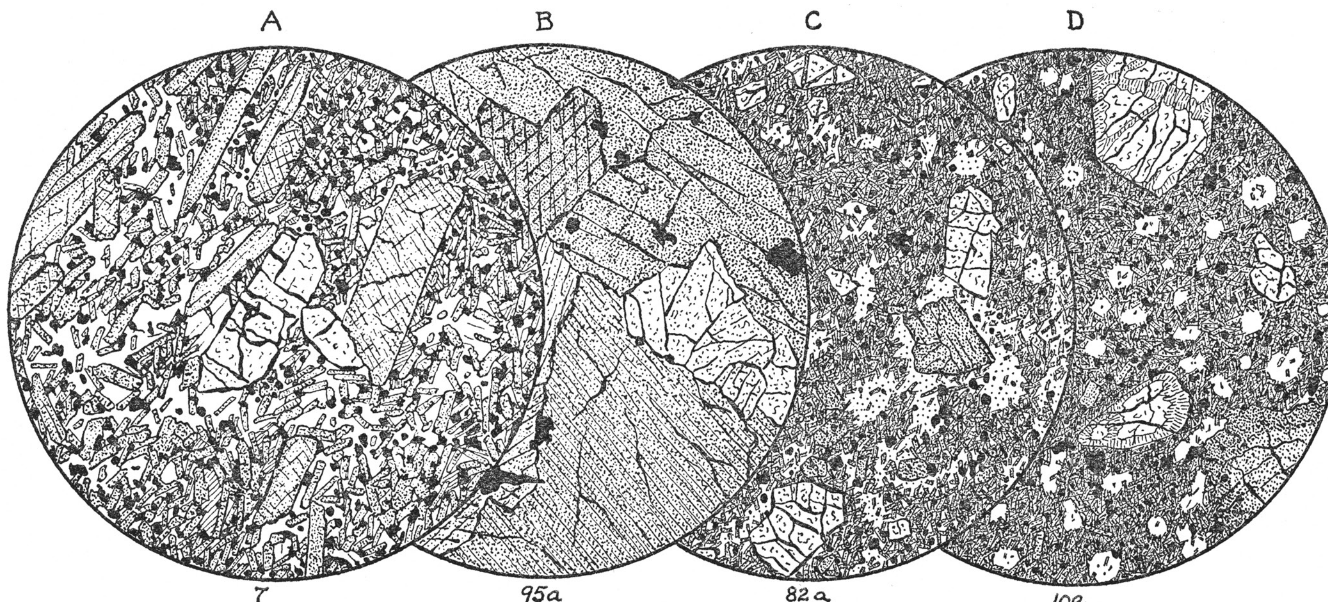

FIGURE 5.—*Navajo and Hopi igneous rocks*

(*A*) Nepheline monchiquite, Wildcat Peak. Analysis No. 1. Zoned crystals of augite, olivine, and ores in a colorless base of nepheline, with a little orthoclase or sanidine and analcite. ×27.

(*B*) Crystal lapillus from beneath lavas near Cottonwood Spring, Hopi Buttes. Green hornblende, augite, and iron ores. Other lapilli include biotite. ×27.

(*C*) Limburgite, 4 miles northeast of Roundtop, Hopi Buttes. Analysis No. 5. Phenocrysts of olivine and augite with microlithic augite and granular ores in a groundmass of pale-brown, alkaline glass. ×27.

(*D*) Monchiquite, Sunflower Butte, Hopi Buttes. Merely finer-grained than rock of Analysis No. 2. Phenocrysts of partly serpentinised olivine and zoned augite in a groundmass of weakly titaniferous augite, iron ores, and apatite. Clear leucite-like spots are of analcite with needles of augite and apatite. ×34.

so that the larger grains of quartz, bordered by needles of diopside, have been strewn out by flow.

TYPE 2—ANALCITE BASALTS AND MONCHIQUITES

Next in importance to the limburgites are those basic lavas and intrusions characterised by an abundance of analcite and the absence, or great scarcity, of feldspar. These bear such a marked resemblance to the monchiquitic rocks of the Highwood Mountains of Montana, so ably described by Lindgren and Pirsson,[9] that an extended discussion would be superfluous. A few examples, selected for analysis and illustration, are all that need description here.

The dense monchiquite (Analysis No. 5) forming the conspicuous neck behind the Dilkon Trading Post has the following percentage content:

15. Antigorite pseudomorphs after olivine, up to 0.2 mm.
4. Weakly titaniferous augite phenocrysts
1. Resorbed phenocrysts of basaltic hornblende, up to 2 mm.
60. Dense felt of titanaugite, titanomagnetite, and abundant stumpy prisms of apatite (4.70 per cent in the norm)
20. Analcite in irregular patches containing tiny laths of ?sanidine and a second generation of acicular apatite

A coarse-grained monchiquite (Analysis No. 2) from the crags behind Indian Wells Trading Post has approximately the following percentage content:

20. Porphyritic augite, pale-brown within and dark-brown rims
50. Microlithic augite with a slight purplish cast
5. Slightly serpentinised phenocrysts of olivine
10. Granular titanomagnetite
15. Clear analcite, both in irregular patches and in tiny spheres charged with apatite, a little calcite, and rare flakes of pale-brown biotite

In some of the Hopi analcite-rich rocks, the mineral is segregated in small spherical patches, whose resemblance to leucite is accentuated by regularly arranged inclusions (Figure 5, D). Apatite is unusually plentiful; in the norm of one monchiquite it makes up 6.05 per cent. Despite the fairly high content of soda in these rocks, reaction shells of aegirinaugite seem to be absent, and nepheline has not been certainly recognised.

TYPE 3—TRACHYBASALTS

The correct identification of the weakly bi-refringent minerals forming the groundmass of the trachybasalts presents great difficulty. Though plagioclase is developed in a few samples, microlithic sanidine is thought

[9] Waldemar Lindgren: *Eruptive rocks from Montana,* Calif. Acad. Sci., Pr., vol. 3 (1890) p. 51. L. V. Pirsson: *Igneous rocks of the Highwood Mountains, Montana,* U. S. Geol. Surv., Bull. 237 (1905) p. 149.

to be, by far, the principal feldspar, and nepheline is probably present in small amount. Except that in the trachybasalts these minerals take the place of the analcite and glass in the rocks already described, the two groups of lava are not essentially different. In none of the sections examined does plagioclase exceed more than one per cent by volume, and, though the small size of the crystals renders identification doubtful, none appears to be more basic than andesine. Curiously enough, however, the only intrusive rock described by Pirsson [10] from the Hopi Buttes is a teschenite from Montezuma's Chair, in which labradorite occurs as stout, irregular laths enclosing augite and accompanied by "orthoclase, analcite and probably nephelite."

TYPE 4—OLIVINE-AUGITE BASALTS

To find true basalts, rich in basic plagioclase, it is necessary to go beyond the limits of the Hopi Buttes proper, to the small outlier of lava on the south rim of Lithodendron Wash, at Desert View Inn. There are several flows at this place, and at the western end of the outlier there is much coarse breccia that suggests a nearby source. Whether or not these lavas were erupted at the same time as those discussed is still open to question, though the presumption is distinctly in favor of contemporaneity.

The dominant lava has this percentage content:

10. Porphyritic, partly serpentinised olivine
2. Porphyritic pale-brown augite
40. Pale-green to greenish-brown microlithic augite
10. Euhedral granules of magnetite
15. Microlithic labradorite
12. Interstitial deep-brown glass
5. Amygdules of serpentine
6. Patches and veins of calcite

At the western end of the outlier, some of the lavas have suffered from solfataric action, and in these the olivine (25 per cent) is replaced by magnetite and hematite, and the augite is rendered a bright yellow. In some flows, labradorite may be almost lacking, while analcite, accompanied by calcite, is plentiful both interstitially and in vesicles. Such lavas, to be classed as analcite basanites, suggest affinity with the rocks of the Hopi Buttes.

PLUTONIC EJECTA

It should be emphasised that the necks and dikes of the Navajo country are rich in fragments of plutonic rock, whereas the ejecta in the Hopi country are almost devoid of them. Indeed, they have only been found

[10] L. V. Pirsson *in* H. E. Gregory: *Geology of the Navajo country,* U. S. Geol. Surv., Prof. Pap. 93 (1917) p. 87.

at one locality in the Hopi Buttes—namely, among the tuffs involved in the cauldron subsidence near Indian Wells. Here, pieces up to 6 inches long are not uncommon.

Two types of plutonic rock are represented: one, a dark, salmon-pink granite, and the other, a pale-pink quartz diorite. The granite has the following percentage composition: quartz, 50; orthoclase, 30; altered plagioclase, 15; magnetite, 4; and accessories, 1. The quartz diorite is essentially made up of sericitised feldspar (andesine, 60, and orthoclase, 10), quartz, 15; chlorite, epidote, allanite, ore, and apatite.

These ejecta are believed to have been torn from the pre-Cambrian basement beneath the Hopi Buttes.

CRYSTAL LAPILLI AND BLOCKS

In the foregoing petrographic notes, reference has been made to the paucity of hornblende among the igneous rocks of the Hopi country. Locally, however, the mineral must have crystallised abundantly at depth, for among the explosive ejecta that carry pieces of granite and diorite and in those that underlie the lava cap near Cottonwood Spring, there are many ovoid fragments, chiefly composed of hornblende. Other crystal lapilli accompanying them are made up entirely of diopsidic augite, and yet others include both these minerals and biotite.

The principal type of crystal clot is illustrated in Figure 5, B. In this, hornblende crystals (c.70 per cent), up to 3 millimeters in length, enclose augite (20 per cent) poikilitically. The hornblende has these properties: X, pale-yellow or yellowish-green; Y, olive-green; Z, dark brownish-green; $Z \wedge c = 26°$; $2V = 70°$; dispersion strong, $r < v$; α' on $110 = 1.679$; $\gamma' = 1.706 \pm .002$. The augite resembles that described from the limburgite tuffs (p. 124). Iron ores and brown biotite ($2V = 10°$ to $15°$) make up the remainder.

Probably these crystal lapilli represent early segregations from the monchiquitic magma.

AGE OF HOPI VULCANISM

The Cretaceous beds had been widely stripped from the Navajo-Hopi region before volcanic activity commenced, and a surface of low relief had already been developed in the underlying rocks. This period of erosion must have extended throughout most of the Tertiary era. Moreover, it is apparent, merely from the similarity between the vent-fillings and the lava flows, that the Hopi volcanoes have not been deeply dissected.

At White Cone, close to the northern margin of the Hopi Buttes, and not far from the center of the old Hopi Lake, there are tuffs, which are, without question, products of the Hopi volcanoes, interbedded with fresh-water shales, marls, and sands. Some of the finer sediments, particularly those from 70 to 100 feet above the base of the cone, are crowded with excellently preserved shells. Reagan[11] identified these as *Unio, Planorbis trivolvis* Say, and *Limnaea stagnalis appressa* Say, and concluded that they could not be older than Pleistocene. New finds necessitate a revision of this view. Among the vertebrate remains found with the shells are great numbers of fish vertebrae, pieces of bird and amphibian bones, and the broken jaw of a new species of beaver. R. A. Stirton, who has kindly examined the last, considers it to be of Middle or Upper Pliocene age, probably Middle.

Further evidence for the age of the Hopi volcanoes has been obtained by Childs Frick, on the mesa about 5½ miles northeast of Jedito. There, in a small outlier of freshwater deposits, including gray sands with lenses of gravel and ash, his party obtained plentiful remains of "a huge species of camel, presumably of late Pliocene age."[12] Though detached from the main outcrop of Tertiary beds on the mesa to the south, there is little doubt that these fossiliferous sediments are of the same age. Some support is lent to this view by the finding of camel tracks in the upper sandstones of the main outcrop southwest of Jedito. Apparently both the camel tracks and the bones were preserved close to the northern shore of the Hopi Lake. It is of interest to note further that the cross-bedded and ripple-marked sands that form the topmost 70 feet of White Cone, above the shales carrying the beaver and fish remains, show a marked resemblance to the sandstones bearing the camel tracks.

The present valleys of the Hopi region must have been cut at the close of the Pliocene and during the Pleistocene, and they were largely infilled either during an interglacial stage or toward the close of the Pleistocene. Bones of mastodon have been obtained by Mr. Roberts in the valley-fill of Jedito Wash, a few miles below his trading post. From the paucity of volcanic detritus in this valley-fill, it may be concluded that the Hopi volcanoes had already been denuded almost to their present state before the valleys began to be choked.

NAVAJO VOLCANIC FIELDS

GENERAL STATEMENT

The igneous rocks of the Navajo region are segregated into fairly well-defined fields (Fig. 1). From the Hopi Buttes, they are at once distinguished by the paucity of lava flows. Hardly less distinctive is the fact that most of the Navajo volcanic necks are made up predominantly, not of columnar lava, but of coarse tuff-breccia and are crowded with frag-

[11] A. B. Reagan: *The Tertiary-Pleistocene of the Navajo country,* Kansas Acad. Sci., Tr., vol. 35 (1932) p. 258.

[12] Letter, dated September 24, 1934.

FIGURE 1. CHAISTLA AND UNNAMED VOLCANIC NECK
Surrounded by Chinle (Triassic) shales. Beyond, Comb Ridge monocline (upturned Jurassic sandstones). In background, outlier of Black Mesa (flat-lying Cretaceous rocks).

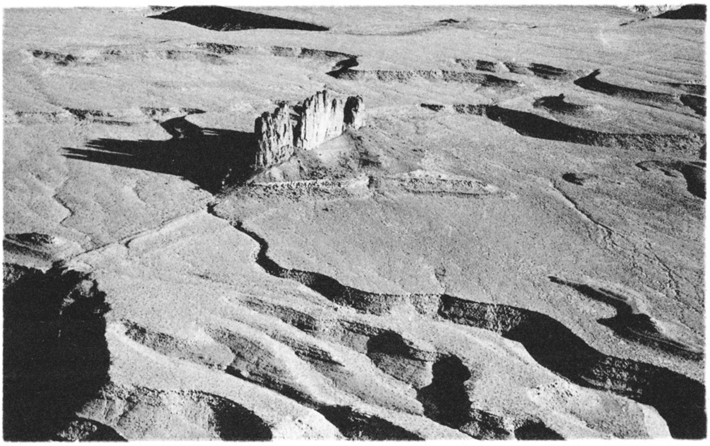

FIGURE 2. ALHAMBRA ROCK
Elongated neck from which two thin dikes extend southward, and one northward for ten miles, cutting Permo-Carboniferous sediments.
Photographs by "Rainbow Bridge-Monument Valley Expedition."

NECKS AND DIKES IN MONUMENT VALLEY

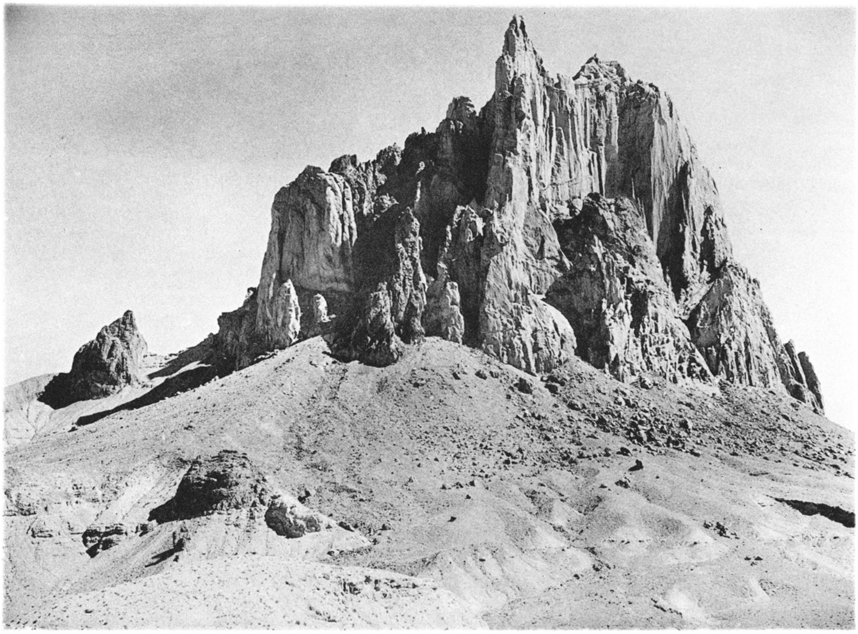

FIGURE 1. THE SHIPROCK NECK
Shows vertical jointing and, faintly, the synclinal structure near the summit of the tuff-breccia neck. Cretaceous (Mancos) shales, undisturbed (foreground).

FIGURE 2. SHIPROCK AND RADIAL DIKE
Shows large dike, about ten feet wide, extending south from the neck. Locally, the shales bordering the dike are baked and eroded to form a parapet.
Photographs by T. L. Mayes

THE SHIPROCK NECK

ments of plutonic rock, chiefly of granitic type. Petrographically, also, the two provinces differ markedly; in the Hopi Buttes, monchiquitic rocks are typical, while in the Navajo region these are far subordinate to minettes. Probably the Navajo vents were more explosive. Indeed, many of them can never have erupted lavas. How closely they resemble the well-known diatremes of the Schwabian Alb, the Rhöngebirge, and Central Scotland [18] will be apparent from what follows. Like those explosive vents, many of the Navajo volcanoes seem to be scattered at random, without regard to pre-existing structures. None is located on a fault.

MONUMENT VALLEY VOLCANIC FIELD

Structural Setting.—Monument Valley, with its fantastic, castellated crags, is carved from the De Chelly sandstones and the Moenkopi shales that occupy the broad and gently rippled top of a domical uplift, bordered on the south and east by the sharp monocline of Comb Ridge and on the west by less-prominent folds that traverse the Rainbow Plateau. On the summit of the upwarp, dips of more than 3 degrees are rare, but in the flanking folds they may reach 60 degrees. Many intrusions are to be found along the Comb Ridge monocline, extending from the village of Kayenta in an arc to the San Juan River. These tend to follow a strong system of joints, approximately normal to the trend of the monocline. In Monument Valley itself there is much less regularity in the trend and distribution of the intrusions.

Character of the necks and dikes.—For an account of the individual intrusions, the reader cannot do better than refer to the succinct descriptions already given by Gregory. Some general, and a few hitherto unrecorded, observations may be added here.

All the necks rise boldly from the surrounding sediments, despite the fact that they consist almost entirely of tuff-breccias. The few thin dikes which cut the breccias are not responsible for this resistance to erosion; it results, rather, from the compactness of the neck fillings, for the fine tuffaceous matrix has been indurated by hot solutions, and much of it is cemented by calcite. The absence of strong joints, such as cut the adjacent sandstones, is, doubtless, another contributing factor.

Agathla, the largest of the Monument Valley necks, may be selected for detailed description. This huge tapering monolith, visible from a distance of 50 miles, rises from a conical pedestal of flat-lying Chinle

[18] W. Branco: *Schwabens 125 Vulkan-Embryonen*, Stuttgart (1894).

H. Bücking: *Uber die vulkanischen Durchbrüche in der Rhön und am Rande des Vogelsberges*, Gerland's Beitrage für Geophysik, vol. 6 (1904) p. 267-308.

A. Geikie: *Geology of Eastern Fife*, Geol. Surv. Scotland, Mem. (1902) p. 200-283; *Ancient Volcanoes of Great Britain*, vol. 1 (1897) p. 271 *et seq.*

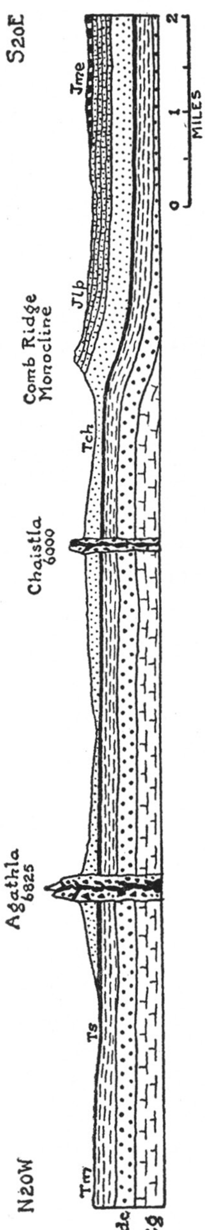

FIGURE 6.—*Section through Agathla, Chaistla, and the Comb Ridge Monocline*

Jme—Jurassic McElmo (Morrison) formation; Jlp—Jurassic La Plata sandstones; Tch—Triassic Chinle shales; Ts—Triassic Shinarump conglomerate; Tm—Triassic Moenkopi formation; Pdc—Permian De Chelly sandstone; Cg—Pennsylvanian Goodridge formation. Vertical scale, twice horizontal.

shales, to a height of more than 1,000 feet and is almost three times as wide at the base. Fully nine-tenths of this large column is made up of buff and gray tuff-breccia, the matrix of which is finely comminuted minette admixed with pulverised sediments. Of the larger fragments, perhaps two-thirds are pieces of minette, and the remainder are foreign inclusions, principally shales and sandstones, accompanied by a large variety of plutonic and metamorphic rocks torn from greater depth. Blocks more than a yard in diameter are scarce, though a few measure 20 feet across. By far the greater number measure less than an inch. Generally, the sedimentary fragments and those of schistose metamorphic rocks are angular. Most of the plutonic fragments, on the contrary, are well rounded, and some suffered so much attrition during the repeated explosions which carried them upward to the surface that they might well be mistaken for water-worn pebbles. Their source is discussed on page 167. In this neck, just as in the diatremes of the Schwabian Alb, the size, number, and angularity of the foreign inclusions generally diminish in proportion to the depth of origin.

Viewed from a distance, a crude, roughly synclinal structure may be discerned in the tuff-breccias near the summit of Agathla. A shallow, saucer-shaped structure may, likewise, be detected in the upper parts of the Shiprock neck (Pl. 2, fig. 1). Lower down the bedding disappears. Vague as it is, this stratification implies that the original craters cannot have been much higher than the tops of the present necks. How else, than by falling back into the conduit after explosion, could the ejecta have developed bedding?

Where dikes of minette cut the pyroclastic rocks of Agathla, they follow zig-zag courses, intersecting, branching, and swelling at random. Only for short distances do they exceed 50 feet in width; for most of their courses, they are only about 10 feet wide. At the margins, the dike-rocks are usually platy, owing to an alignment of the mica flakes parallel to the walls, but, within, they are massive and blocky. Noteworthy is the paucity of inclusions other than plutonic and schistose in the dikes, even though the adjacent breccias are heavily charged with fragments of sandstone and shale. Why the magma of the dikes failed to incorporate more than a slight amount of sediment and breccia is not clear, for it must still have been quite fluid after it had risen to the upper parts of the conduits.

Metamorphism of the xenoliths and wall-rocks is surprisingly rare. Veins of calcite and aragonite cut the breccias locally, but pneumatolytic minerals are completely lacking.

Though most of the necks of this region are approximately circular or oval in plan, some are extremely intricate, and tongues of tuff-breccia branch in a complex manner so as to enclose large masses of sediment. At Church Rock, for example, blocks of Jurassic sandstone, up to 100 yards across, were wedged free from the walls and incorporated in the neck so as to make, with the matrix of pulverised minette, a giant breccia. So plentiful and large are the masses of sandstone in a neck near Chilchinbito that they even exceed, in amount, the igneous debris. In the Black Rock neck, close to Kayenta, and in the Porras dikes, some of the sandstones merge gradually into the pyroclastic rocks or are altered to dense quartzites close to ribbons of minette.

Some of the necks of Monument Valley and vicinity are merely the wider parts of dikes. Such are the three necks near Rough Rock and that near Oljeto, each of which is infilled with columnar minette. Alhambra Rock, a high serrated wall of minette, bearing many inclusions of granite and sandstone, is an elongated neck about two miles south of the San Juan River. Two dikes, one a foot and the other only six inches across, extend southward from the neck, and one continues northward across the canyon of the San Juan (Pl. 1, fig. 2). According to T. L. Mayes, it is traceable at least as far north as Cedar Mesa, a distance of ten miles.

Necks and curved dikes at Boundary Butte.—This well-known landmark rises close to the Arizona-Utah line, near the road between Kayenta and Shiprock. Here are three volcanic necks associated with several curved dikes (Fig. 9, No. 4). Viewed from the northwest, the highest neck resembles a ruined castle, and the outermost dike, with its masonry-like jointing, a crumbled protecting wall. Rising, as they do, in an amphitheater backed by high cliffs of red sandstone, these features are imposing.

Together, the three necks extend for about a mile in a north-south direction. The largest measures a quarter of a mile across and forms a rude tower, 300 feet high (Pl. 3, fig. 2). Except for a few dikes of minette, it is composed of tuff-breccia like that of Agathla. A narrow ridge of breccia, strengthened by a sinuous dike of minette, joins this to a second neck, but the northern, and smallest, neck is detached and almost enclosed by a curved dike. At the edges of each neck, there are included boulders of Jurassic sandstone, as well as pieces of Chinle shale, limestone, quartzite, and many granitic fragments.

Bordering the necks are several arcuate dikes, ranging from a foot to 6 feet wide, composed of dense, locally columnar minette, lightly charged with round xenoliths of granite and pegmatite and xenocrysts of perthite up to 3 inches in length. Unlike the curved intrusions bordering some of the Hopi vents, these dikes are vertical.

Necks and dikes on the Garnet Ridges.—Near the western foot of the sharp peak known as Mule Ear, which rises from Comb Ridge, about 1½ miles south of the San Juan River, there is a craggy hill, oval in plan and measuring half a mile by three-quarters. On Woodruff's map,[14] it is indicated as "glacial ?debris"; on Miser's map,[15] as a volcanic neck. The Permian sandstone ridges, the valley cut in the Triassic shales, and the high cliffs of Jurassic sandstone near the hill run approximately north-south, the beds dipping eastward as part of the Comb Ridge monocline. The hill itself is composed of ?Permian sandstone, commonly coated with iron oxides, so as to resemble igneous rocks even from a short distance. These sandstones are much disturbed; in places, they strike at right angles to the surrounding rocks, and their dips vary from almost zero to verticality. Such a localised body of disrupted sandstones is best explained as the result of the upward-punching action of an igneous plug. The presence of many thin dikes of minette in the vicinity lends weight to this view. In its principal features, the disturbance resembles that caused by the cryptovolcanoes of Ohio, Kentucky, and Tennessee.

Another body of disrupted sandstones may be studied on the Garnet Ridge, about 5 miles north-northeast of Dinnehotso. Here, the Jurassic sandstones normally dip at angles of less than 3 degrees. But in an area measuring about 250 yards across they are broken into large masses that lie tilted at angles up to 90 degrees. Between these tilted masses are a

[14] E. G. Woodruff: *Geology of the San Juan oil field, Utah,* U. S. Geol. Surv., Bull. 471 (1910) pl. viii, p. 80.

[15] H. D. Miser: *Geologic structure of San Juan canyon,* U. S. Geol. Surv., Bull. 751 D (1924) pl. xv.

few thin dikes of decomposed minette charged with plutonic and schistose xenoliths. There can be no doubt that the fracturing is here due to a larger buried intrusion of minette.

Garnetiferous xenoliths are almost ubiquitous in the necks and dikes of the Navajo country, but nowhere are they more numerous than in the vicinity of the two bodies of disturbed sandstone just described. The garnet is of the pyrope variety and occurs in granitic and dioritic xenoliths of more or less gneissoid aspect, some of which are well rounded and measure up to 5 feet in diameter. Accompanying them are fragments of hornblende schist, tremolite, talc schist, quartzite, and limestone. Prior to Gregory's work, they were regarded as glacial in origin, but it is now clear that they were carried to the surface, partly by explosion and partly as inclusions in minette magma. Their significance is discussed hereafter.

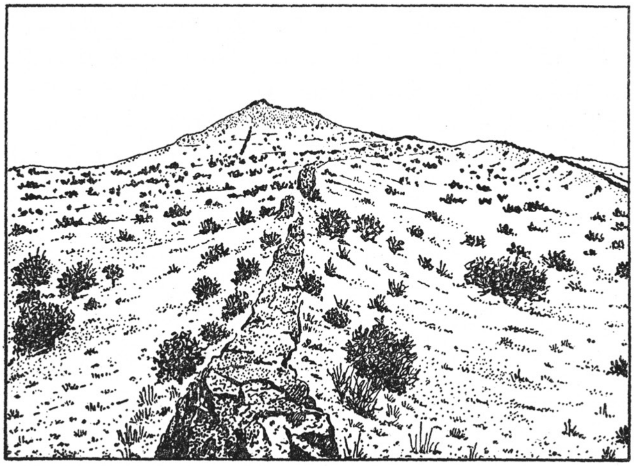

FIGURE 7.—*Wildcat Peak neck*

View from the south. Shows north-south monchiquite-alnoite dikes extending from neck.

TUBA VOLCANIC FIELD

General statement.—Along the western margin of the Navajo Reservation, there is a small igneous cluster, comprising two necks and several thin dikes. The general trend is north-south, parallel to the strike of the invaded sediments.

Tuba Butte.—Near the edge of the plateau, about 6 miles northwest of Tuba City, there is a neck of dense monchiquite enclosed by cross-bedded Jurassic sandstones, forming an oval hill about 600 yards long and 300 feet high. For part of its circumference, the central pipe is encased by an older sheath of pépérite, made up of compact, unbedded sandstone, stippled with monchiquite lapilli and cut by thin, curved sheets of lava. Apparently, when the vent was drilled by explosion, the cross-bedded

Jurassic sandstone was thoroughly pulverised, rather than coarsely brecciated, and was then admixed with tiny clots of magma at low temperature.

Wildcat Peak.—This neck rises on the Kaibito Plateau, northwest of Red Lake, and resembles the Tuba neck in having a central mass of monchiquite and a peripheral collar of pyroclastic debris. It differs, however, in the presence of associated dikes. Beyond the neck, these dikes range in width up to 8 feet, rarely depart more than 20 degrees from the vertical, and maintain an almost north-south direction (Figs. 7 and 9, No. 5). Their margins are usually platy and vesicular, and the sandstone walls appear to be unaltered. Petrographically, the dike-rocks are of interest because they include the only alnoites of the Navajo country.

The neck itself is very irregular in plan, and approximately a third of a mile in diameter. Primarily, it is formed by the coalescence and swelling of the dikes just mentioned. Within and surrounding this dike complex are huge masses of sandstone, some a hundred yards across, and tuff-breccias made up of fractured sandstone, shale, and monchiquite. Many of the smaller sandstone chips have been converted to quartzite, and the sandstone walls of the dikes have been altered locally to glass (buchites).

Moenkopi dike.—Southwest of the village of Moenkopi, on Ward Terrace, there is a prominent dike, about 2 miles long, bordered at its northern end by three short, parallel branches. For part of its course, the dike stands up as a vertical-sided comb, but, where the confining walls of sandstone have been slightly indurated and rendered more resistant to erosion, it forms the floor of a corridor between walls of sandstone. Thin screens of sandstone may be found incorporated in the dike, where it swells.

The dike itself varies from a foot to 9 feet in width. Marginally, it is composed of dense, black monchiquite, but, within, it is rotten and vesicular, and, owing to the much greater proportion of mica, merges into ouachitite. Veins of calcite run parallel to the walls. The dikes referred to by Gregory, near Moa Ave and in the Echo Cliffs, duplicate many of these features.

CHUSKA AND REDROCK VALLEY VOLCANIC FIELDS

General statement.—In the northeast corner of the Navajo Reservation, confined on one side by the Chuska Mountains and the laccolith of Carrizo Mountain, and, less distinctly, on the other by Dutton and Chaco plateaux, are the Redrock and the Chuska valleys. The former is cut principally in the eastward-dipping Triassic and Jurassic rocks, and the latter in a shallow syncline of Cretaceous beds (Fig. 8).

Chuska Valley field.—For a distance of about 30 miles, the highway from Gallup to Shiprock is bordered by at least six necks and about 20

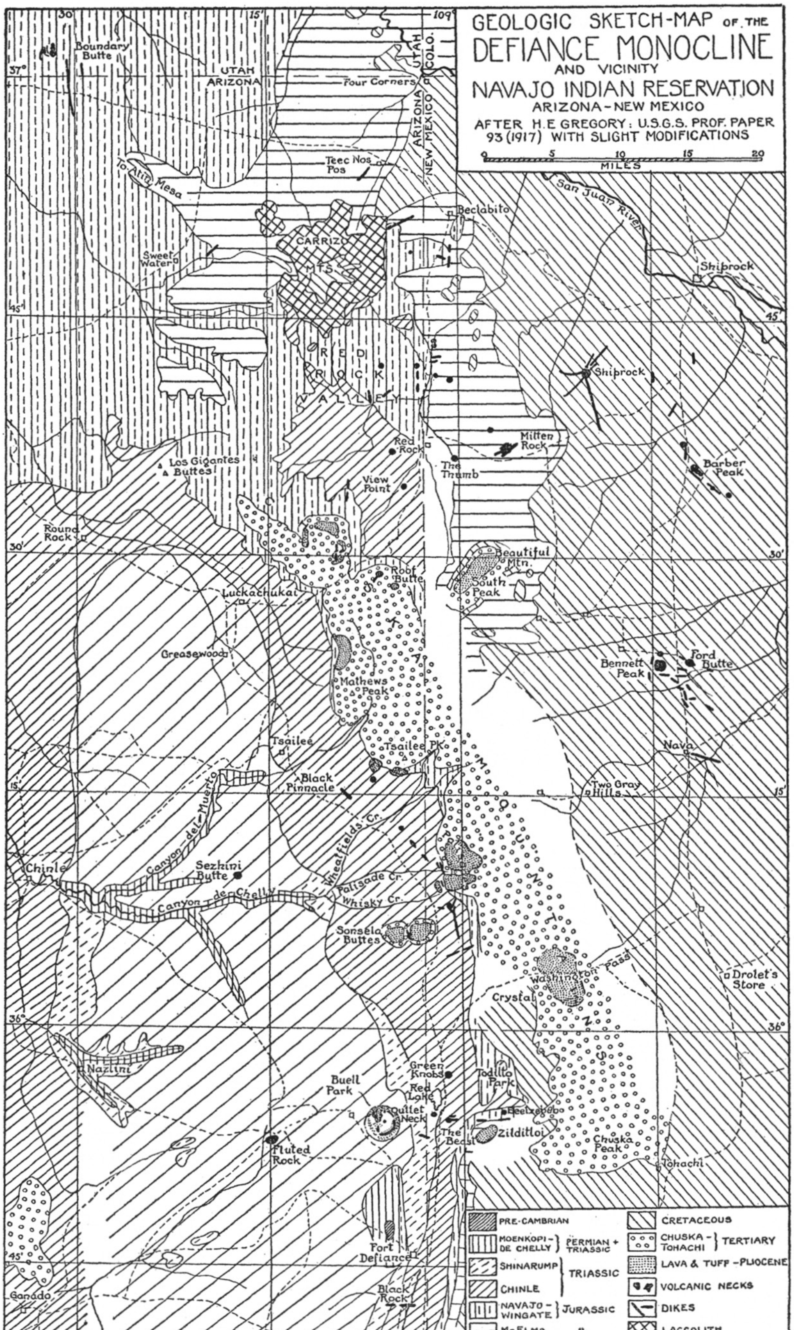

FIGURE 8.—*Geological sketch-map of the Defiance Monocline*

dikes, the remnants of an extensive volcanic field. Several of the necks are entirely composed of fragmental debris and can never have erupted lava.

Shiprock itself rises about 1400 feet above the surrounding flats and has a basal diameter of more than a quarter of a mile. This enormous mass is essentially made up of fine minette tuff-breccia, admixed with fragments of sediment and plutonic rocks. Toward the top of the neck, there is an inward-dipping stratification (Pl. 2, fig. 1). Irregular, anastamosing dikes traverse the breccia, but constitute only about a twentieth of the mass. In these, the inclusions are almost all of granite and diorite. Similar dikes radiate from the neck, one of them extending southward as a great black wall, up to 10 feet in width, for a distance of more than two miles. The courses of these radial dikes, though generally straight, are marked in detail by many small offsets arranged *en échelon.*

No better example of a linear series of vents can be found in the Navajo country than that which runs through Barber Peak. Indeed, the peak itself appears to represent a line of three or four necks, partly separated by thin screens of sandstone. Though closely associated with dikes of minette, the necks themselves are composed entirely of sand-like tuff charged with small lapilli of minette, sediment, and very rare chips of plutonic rocks. That these necks have not been deeply dissected is suggested by the fact that the northernmost is bordered by a small outlier of outwardly dipping tuffs, apparently a remnant of the original cone.

The southernmost of the Chuska Valley necks are Bennett Peak and Ford Butte, adjacent to which are many thin dikes. A few ribbons of minette cut Bennett Peak, but, otherwise, both necks are wholly made up of tuff-breccia. Sedimentary inclusions measuring more than an inch in length are rare, and it required a long search to find pieces of granite or diorite. Though the thorough mixture of finely comminuted sediments and minette is itself indicative, the proof that these vents were formed by repeated explosions is especially clear on Ford Butte, where blocks of red and brown tuff-breccia lie in a paler matrix of the same.

Redrock Valley field.—A cluster of dikes and necks occurs in the valley bordering the south and east base of the Carrizo laccolith. Several of these were not examined during the present study. Contrasted with the necks of the Chuska Valley, these conduits are mainly infilled with lava rather than with explosive ejecta. Mitten Rock, the largest vent, is approximately three-quarters of a mile in length, and extremely intricate in plan, with long fingers projecting into the enclosing shales. The minette of which this neck is composed is an unusually feldspathic variety, the most siliceous of the Navajo region. Lying in a pale-gray base are many nodules of diopside, up to 9 inches in length, and sporadic xenoliths, among which granites predominate over sandstone and shale. Much of the lava is columnar, and some of it may, indeed, represent a surface flow.

Some of the Redrock necks are particularly rich in foreign inclusions. Thumb Rock, for example, is a cylindrical column of vesicular, biotite-rich minette, in which xenoliths of garnetiferous granite, diorite, and gneiss, with fragments of varicolored shale, sandstone, quartzite, and marble make up approximately 10 per cent of the mass. Few of these inclusions exceed 3 inches in length, and none measures more than 3 feet across. As in other necks, the plutonic fragments are more rounded than the sedimentary. In the northern necks of this field, granitic inclusions are far subordinate to those of baked shale, and the lava-fillings are of olivine-rich monchiquite instead of minette.

ZILDITLOI VOLCANIC FIELD OF THE DEFIANCE MONOCLINE

General statement.—The Defiance monocline runs approximately north-south, close to the Arizona-New Mexico boundary. Within a zone from 5 to 8 miles wide, the beds dip eastward at angles up to 40 degrees, but beyond, they rapidly flatten. The Mesozoic and Paleozoic sediments of this monocline had already been folded and deeply eroded, and Tertiary sediments had been deposited upon them when vulcanism commenced. Of the broad sheets of lava and tuff that were erupted, there are now only a few remnants along the crest and flanks of the Chuska Mountains. These rest on a very irregular surface; thus, within 15 miles, between the outliers of Tubby and Sonsela buttes, the lava base shows a difference of elevation of about 1,000 feet.

In accordance with Gregory's division, three volcanic fields may be isolated for purposes of discussion—the Zilditloi, the Wheatfields, and the Chuska Mountains fields.

Most of the necks and dikes associated with the Defiance monocline are aligned in a direction at right angles thereto. One group of intrusions crosses the monocline about 10 miles north of Fort Defiance.

Fluted Rock, at the western end of this group, is a flat-topped laccolith, approximately oval in plan and with a major diameter of half a mile. It consists of a strongly columnar cake of minette, at least 150 feet thick, on top of which are a few relic patches of vitrified quartzite (p. 157).

Cauldron Subsidence of Buell Park.—The geologist who visits this volcanic country is not likely to forget the beautiful depression known as Buell Park, which lies north of Fort Defiance and close to the Arizona-New Mexico line. Even the aerial photograph (Pl. 4, fig. 2) will convey to the reader some idea of its unique setting. Let him imagine a basin, approximately 2½ miles in diameter, bordered by cliffs of bright red sand-

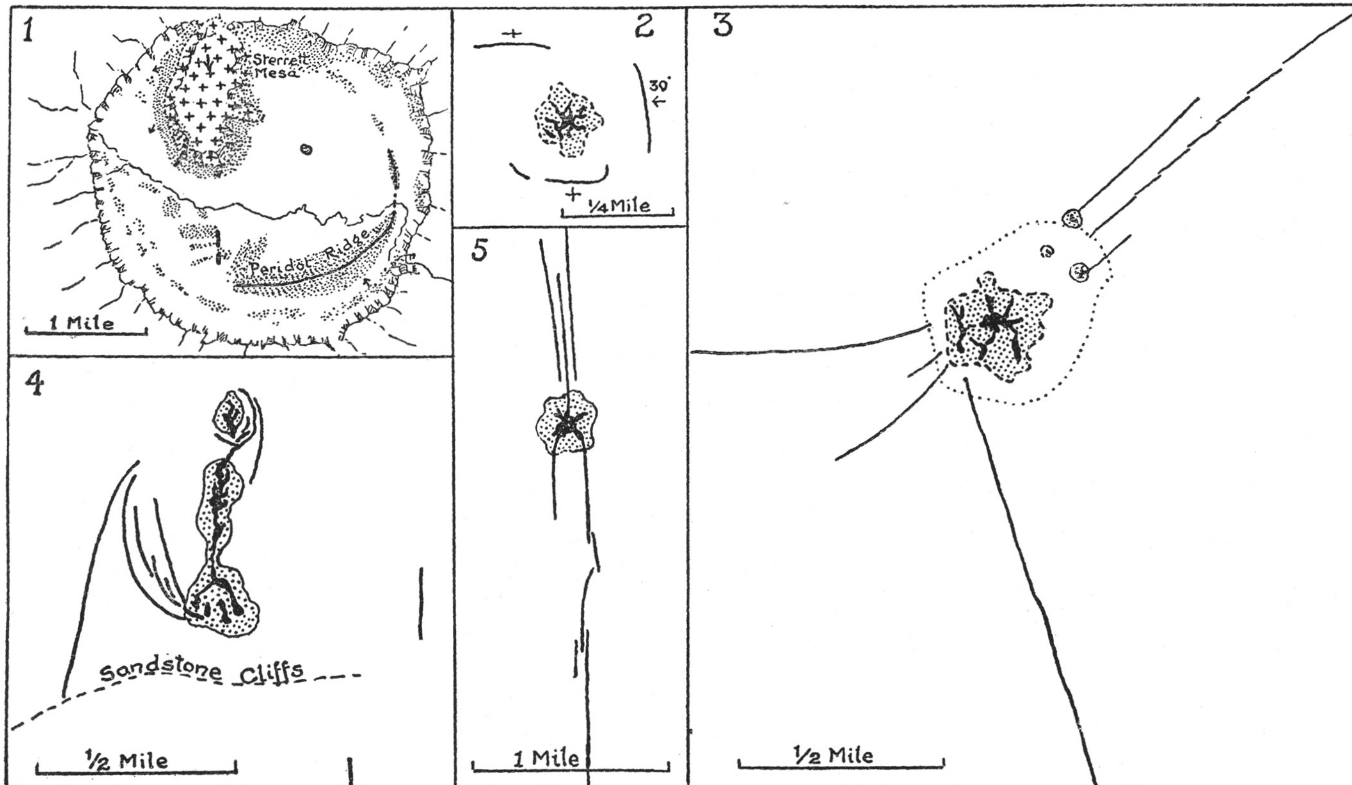

FIGURE 9.—*Navajo-Hopi intrusions*

(1) Buell Park. Arcuate dike of leucite minette; other dikes of minette; lava cap on Sterrett Mesa ends southward in a depression among pyroclastic rocks; tuff-breccias, stippled. (2) Tuff-breccia neck, 5 miles north of Flying Butte, Hopi country. Rises through horizontal Chinle shales. Bordered by thin dikes of monchiquite. Diagrammatic only. (3) Shiprock. Neck of minette tuff-breccia and dikes of minette. (4) Boundary Butte. Similar neck bordered by arcuate, vertical dikes. (5) Wildcat Peak. Tuff-breccia neck associated with dikes of alnoite, monchiquite, and allied rocks.

stone up to 1,000 feet in height, and a floor of pale-green pasture contrasting with the dark green forest on the surrounding plateau.

This depression lies at the margin of the Defiance plateau and on the edge of the Defiance monocline. To the west of Buell Park, De Chelly (Coconino, Permian) sandstones are either horizontal or nearly so; in the walls of the park, they dip eastward at low angles; farther east, they plunge beneath the Shinarump conglomerate and the Chinle (Triassic) shales, which form the floor of the Defiance Valley. The Triassic rocks, in turn, pass beneath Jurassic and Cretaceous sandstones which form the flanks of the Chuska Mountains, farther east. Resting unconformably on all these inclined beds are the white Chuska (Tertiary) sands and associated volcanic rocks that make up the even crest of the Chuska Mountains (Fig. 10).

Rocks of Buell Park.—The oldest volcanic deposits within the park are pale, sage-green lapilli-tuffs. These underlie the long banks of talus that descend from the sandstone cliffs, and, though partly covered by sandstone debris, they form most of the low, rounded hillocks on the floor of the park. They are also exposed on the lower slopes of Peridot Ridge and Buell Mountain. At the last-named locality, they are at least 800 feet thick. The matrix of the tuffs is a highly decomposed minette or trachybasalt, studded with bright green relics of diopside and yellowish-green, serpentinised granules of olivine (Fo_{93}). Bedding can rarely be detected. On Buell Mountain and elsewhere close to the walls of the park, the dips are inward at angles of 30 degrees, or less, but on the floor of the depression the beds roll irregularly at low angles. Enclosed in the green, poorly bedded matrix are abundant lapilli and small blocks, measuring up to 6 inches across. These include hornblende and biotite granite, hornblende diorite, garnetiferous diorite gneiss, marble, muscovite-, hornblende-, and chloritoid-schists, quartzite, chert, red and black slate, limestone, red sandstone, shale, and rare fragments of pyroxenite (websterite, made up of bronzite and bright green, pleochroic diopside). Decomposition of the garnetiferous gneisses has set free large numbers of rounded, pyrope crystals, which, together with the large grains of olivine from the enclosing tuffs, have long been collected by the Indians as gems.[16]

There can be no doubt that these green lapilli-tuffs underlie the entire floor of the park, but to what depth is unknown. Overlying them are dark-brown lapilli-tuffs, well-exposed in the isolated crag near the center of the park, and again on the flanks of Peridot Ridge. Their maximum

[16] H. E. Gregory: *Geology of the Navajo country,* U. S. Geol. Surv., Prof. Pap. 93 (1917) p. 94-95. D. B. Sterrett: *Mineral Resources of the United States,* Part ii (1909) p. 832-835.

thickness is approximately 300 feet. Sterrett, who referred to these rocks as peridotite agglomerates, was impressed by their resemblance to kimberlite. Except for their brown color, which results from finely disseminated iron oxides, they are not essentially different from the green lapilli-tuffs already described. Indeed, they may originally have been of the same color, but have suffered more from the oxidizing effect of hot gases.

The youngest pyroclastic deposits are scoriaceous tuff-breccias, charged with abundant blocks of lava. These are restricted to the southern end of Buell Mountain, where they are approximately 100 feet thick and dip toward the center of the park.

Resting on these fragmental rocks, and forming the higher parts of Buell Mountain, is a cap of pale-gray, columnar trachybasalt, which also dips inward. Lithologically, the lavas are almost identical with the pale minettes which form certain of the dikes on the floor of the park, being composed essentially of sanidine or orthoclase microliths, biotite, diopside, and a little olivine. Throughout most of their length, the flows dip from 10 to 20 degrees, but at their southern end they poured down a much steeper slope, following a narrow valley cut in the underlying breccias.

On Peridot Ridge, the lapilli-tuffs are intruded by a curved dike, up to 35 feet in width, composed of blocky and rudely columnar, black, leucite-bearing minette, markedly similar to the lavas forming the outlier on Zilditloi, 3½ miles east of the park. At several places, the course of the dike is interrupted by right angle offsets, the largest of which displaces the trend of the intrusion as much as 20 yards. For short distances, the dip of the dike is outward at high angles, but for the most part it is vertical. No metamorphism can be observed at the contact with the lapilli-tuffs, and there are no included fragments of foreign rock such as are common in the pyroclastic ejecta.

In addition to this ring dike, the map (Fig. 9, no. 1) shows two shorter, straight dikes. One of these is 40 feet wide, and the other 15 feet; both are composed of pale, leucite-free minette.

Origin of Buell Park.—Wherever the pyroclastic rocks are observed adjacent to the Permian sediments forming the walls of the park, the contact is either vertical or dips inward at high angles. In the gully north of Buell Mountain, this steeply inclined contact can be traced at intervals through a vertical distance of about 800 feet. At one point on the eastern wall of the park, the Permian sandstone is slickensided vertically along the contact. Unfortunately, the contact along the southern and western walls, which are much less steep, is obscured by talus.

From the foregoing it seems permissible to infer that Buell Park owes its origin to a cauldron subsidence.[17] A cylindrical block, approximately 2½ miles in diameter, must have collapsed at least 1,000 feet. Whether this occurred before or after the deposition of the volcanic rocks is not quite certain, for the inward dips of the latter may as well be due to the falling of the ejecta into a pre-existing depression as to downward sagging during collapse. In many other cauldron subsidences, an inward dip has been attributed to this second cause. If the lapilli-tuffs were not so obscurely bedded, it might be possible to decide between the two possibilities.

Source of the volcanic rocks.—In the whole Navajo country, there are no other tuffs that remotely resemble those of Buell Park, except those in the Green Knobs neck, about 4 miles to the northeast, and even those bear only a general similarity to the green lapilli-tuffs. They differ chiefly in the size and proportions of the various foreign lapilli. Thus, at the Green Knobs the foreign fragments are generally larger, and some of them measure as much as a yard across, and the granitic fragments are relatively much more abundant than in the tuffs of Buell Park. Changes in the proportions of lapilli and blocks are to be expected at different levels in a volcanic neck, and, of course, if the Green Knobs neck were really the source of the tuffs of Buell Park it should be expected that the fragments would become smaller with increasing distance therefrom. It cannot be denied, however, that the source may be within the park itself. Although the dips of the tuffs are too indefinite to suggest that an open fissure may once have existed beneath Peridot Ridge, it is possible that a vent lies beneath the alluvium in the center of the depression.

The source of the lava flows is also open to question. It was thought that perhaps they rose through curved fissures near the north wall of the park, but no such channels could be found. Apparently, the source lies beyond the rim of the park. Thirteen miles to the north, on East Sonsela Butte, there are lavas which are almost identical in appearance, and it may be that they are products of the same vent. Had the lavas of Buell Park risen from a conduit near the center of the depression, some trace of it might reasonably be expected.

Though not conclusive, the evidence seems to favor the view that a thick mantle of tuffs and lavas formerly covered Buell Park and an extensive area beyond. All that remains of this mantle is the part preserved in Buell Park by cauldron subsidence, and even this is rapidly being removed by erosion. The stream that now crosses the park, cutting

[17] As defined by C. T. Clough, H. B. Maufe, and E. B. Bailey: *The cauldron-subsidence of Glen Coe and the associated igneous phenomena,* Geol. Soc. London, Quart. Jour., vol. 65 (1909) p. 611-678.

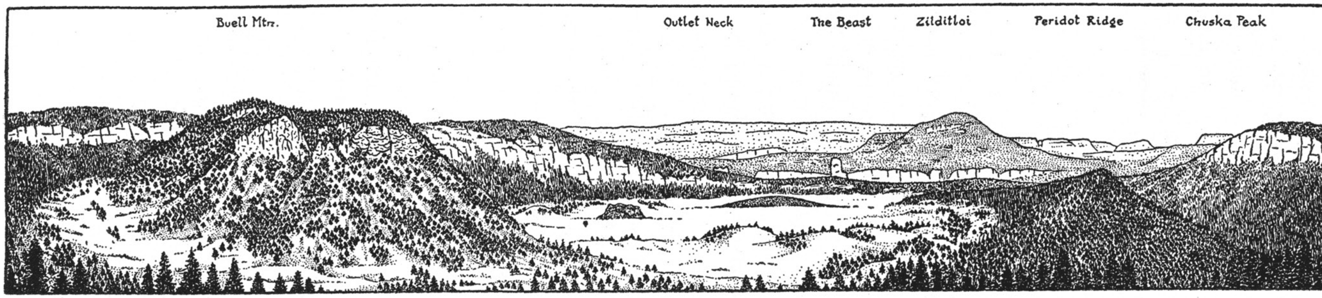

FIGURE 10.—*Buell Park*

Panoramic sketch from west rim. Tertiary (Chuska) sandstones on distant Chuska Mountains; cap of trachybasalt on Zilditloi, underlain by Cretaceous and Jurassic sandstones; the valley cut in Triassic (Chinle) shales is obscured from view, though the two necks, Outlet and the Beast, that rise from it, are seen beyond the rim of the park. The walls of the park are chiefly of De Chelly sandstone. Hillocks on the floor of the park are of tuff-breccias, overlain on Buell Mountain by inwardly dipping lava flows.

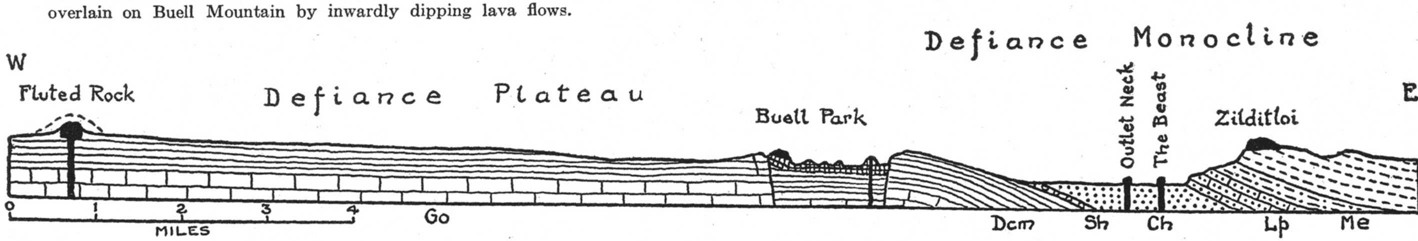

FIGURE 11.—*Section illustrating relation of Defiance Monocline to Fluted Rock laccolith, the cauldron subsidence of Buell Park, the Zilditloi lava cap, and two volcanic necks in Defiance Valley*

Go-Goodridge (Pennsylvanian); Dcm-De Chelly (Permian) and Moenkopi (Triassic); Sh-Shinarump (Triassic); Ch-Chinle (Triassic); Lp-La Plata (Jurassic); Me-McElmo (Morrison, Jurassic); C-Cretaceous.

through its walls at their lowest points, was possibly consequent on the initial slope of the volcanic rocks before the subsidence.

Outlet Neck and the Beast.—Outlet Neck, at the south end of Red Lake, has a core of blocky minette, partly encased in a sheath of breccia, composed essentially of comminuted lava, pieces of Chinle shale, pebbles from the Shinarump conglomerate, and enormous blocks of Jurassic sandstone. Many of the sandstone blocks, as they slumped down into the volcanic pipe from the fractured walls, were tilted at high angles, and, in places where they were later cut by dikes of minette, they were converted to columnar quartzites and buchites. For a few inches from the dikes, the vitrified sediments are usually peppered with tiny inclusions of minette that must have been incorporated while the sandstones were still incoherent and unaltered. It should be emphasised, however, that the metamorphism of sediments bordering this and the adjacent necks is extremely local.

The Beast, a neck so called from its resemblance to a crouching lion, duplicates many of the features of Outlet Neck, though tuff-breccias here predominate far over dikes. Some of the latter reveal an interesting transition of minette into monchiquite. In both necks, xenoliths of plutonic rocks are very rare.

The Green Knobs.—A group of low, rounded, sage-green hills borders the Fort Defiance road, a mile and a half north of Red Lake. These are the remnants of a circular neck, a third of a mile in diameter. The singular color of these hills and their gently molded slopes, in contrast with the dark crags of The Beast and Outlet Neck, result from the peculiar character of the neck-filling. Here, instead of a massive tuff-breccia stiffened with dikes of minette, is a paste of minette so soft and rotten as almost to resemble a micaceous mudstone. No less distinctive is the abundance and variety of xenoliths, and especially the great number of plutonic fragments. Throughout much of the neck, the xenoliths actually make up a third of the bulk, and, among them, granitic types constitute about two-thirds. A few of these inclusions measure a yard across, but most of them are less than an inch in diameter, and all are fairly well rounded. Accompanying the granites are garnetiferous diorites and diorite-gneisses, dark-green nodules of harzburgite and lherzolite, pegmatites, large crystals of perthite, and chips of blue-black slate, as well as the usual pieces of Chinle shale and Jurassic sandstone derived from the adjacent walls.

Zilditloi lava cap.—Outlet Neck, The Beast, and the Green Knobs lie in a valley eroded from the Chinle shales. Bordering this valley on the east is a line of imposing cliffs of Jurassic and Cretaceous sandstones that dip eastward at angles of 10 to 20 degrees. On Zilditloi Mountain, about 1,500 feet above the valley floor, these inclined beds are capped unconformably by an outlier of volcanic rocks, up to 250 feet in thickness (Figs. 11, 12), composed of columnar trachybasalt, in which lie sporadic xenoliths of norite, biotite granite, and quartzite, resting on lapilli-tuffs. Either The Beast or Outlet Neck may have been the source

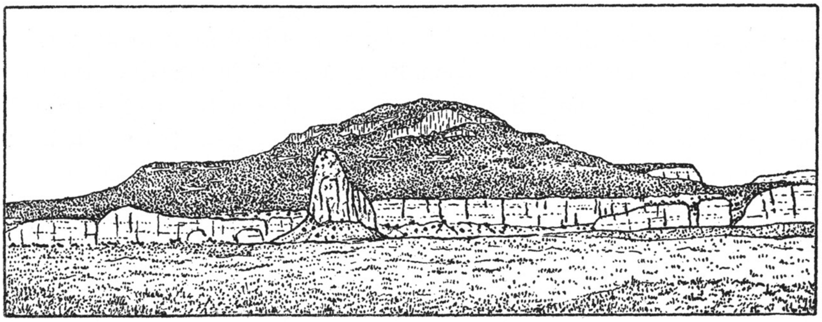

FIGURE 12.—*The Beast*

The volcanic neck, with Zilditloi Mountain in the background. Cliffs at base, of pink La Plata Sandstone; wooded slopes above, of McElmo (Morrison) and Cretaceous beds, overlain by a cap of columnar trachybasalt.

of these ejecta; if so, the necks have been eroded to a depth of at least 1,200 feet.

Intrusions in Todilto Park.—At the eastern end of the Zilditloi volcanic field, among the gently folded sandstones of Todilto Park, rises Beelzebub, a prominent neck of lava, coated with coarse tuff-breccia. In addition to the several short dikes that spread from this neck, there are others in the vicinity, the largest of which attains a width of about 100 yards. This intrusion is noted particularly, for it is made up of irregular sheets of olivine leucitite and minette that cut a sandstone-lava breccia. It is the most leucitic intrusion of the Navajo country.

WHEATFIELDS VOLCANIC FIELD OF THE DEFIANCE MONOCLINE

General statement.—Another cluster of dikes, necks, and lava caps lies to the north of the Zilditloi field, in the drainage area of the streams that flow westward into the Canyon de Chelly (Fig. 8).

Necks and dikes.—The largest vent in this field was perhaps at Black Pinnacle, a neck of platy and columnar minette, elongated in a northwest-southeast direction. At the western end of this body the sandstone walls have been converted to quartzite and buchite for a few inches from the contact. Breccia forms only a small part of the intrusion, and fragments of granite are both rare and small.

A second neck lies in the wooded flats about a mile south-southwest of Tubby Butte. Contrasted with Black Pinnacle, this vent is almost wholly made up of coarse tuff-breccia in which are scattered many large, angular blocks of unaltered red sandstone and gray shale, though the dike of platy minette which traverses the neck carries few other than granitic inclusions.

A third breccia pipe, cut by dikes of minette, crops out at the western end of East Sonsela Butte and may well represent the vent from which the lavas capping the two Sonsela Buttes were erupted.

A fourth breccia neck rises between the Sonsela Buttes and the Palisades and is associated with three radial dikes.

Lava caps.—The flows and tuffs erupted from the necks just enumerated form the outliers of the Palisades, Sonsela and Tubby buttes, but there is nothing of material importance to add to the notes of Gregory concerning them.

CHUSKA MOUNTAINS VOLCANIC FIELD OF THE DEFIANCE MONOCLINE

The rocks just described under the headings, Zilditloi and Wheatfields volcanic fields, occur near the western base of the Chuska Mountains; other groups of dikes and flows of lava lie scattered near the crest of the range (Fig. 8). In some places, the lavas rest on bedded tuffs, up to 300 feet in thickness, but usually they were deposited directly on white Chuska sands of Tertiary age. That broad valleys had been cut in these sands before the lavas escaped is clear from a study of the outliers in Washington Pass and east of Greasewood, where series of superposed flows, up to 400 feet in total thickness, occupy old channels. The lavas vary widely in field appearance, though all are trachybasalts. Some flows, including those near Greasewood and in the Lukachukai Mountains, are dense, black, columnar rocks, lightly sprinkled with pieces of granite, diorite, sandstone, and shale; in Washington Pass, on the contrary, extremely coarse-grained flows, with large crystals of olivine, augite, biotite, and sanidine, are overlain by pale-gray, highly feldspathic types, in which it is difficult for the unaided eye to recognise more than an occasional phenocryst. This succession of flows is identical with that on East Sonsela Butte and in the Palisades. Concerning the dikes of this volcanic field, it is enough to say that among those in the Lukachukai Mountains are several which are characterised by their low content of mica; these approach vogesites in composition.

TWIN CONES VOLCANIC FIELD

No more instructive nor conveniently studied volcanic necks can be found than those which rise from the Cretaceous sandstones a short distance south of the main highway, about 6 miles southwest of Gallup.

The largest of these is selected for description. In outline it is extremely complicated, and the fragmental filling is riddled with branching dikes of minette. Cliffs, up to 150 feet high, reveal the character of the neck to perfection. Fully 90 per cent of the fine tuff-breccia consists of pulverised Cretaceous sandstone; the remainder is made up of lapilli and blocks of minette. Noteworthy are the many small high-angle faults, of a foot, or even smaller, displacement, and the contorted ribbons of white sand that run through the dominant buff sand of the filling. The impression is forced upon one that the neck was drilled by repeated explosions, in such a fashion that the massive Cretaceous sandstones were so finely comminuted that individual grains were intimately admixed with tiny chips of minette. A feature difficult to account for is the absence of any large blocks of sandstone; the unbedded sandstone-tuff mixture abuts sharply against the undisturbed, evenly bedded wall of the neck. It may be that the sandstone in the neck was already partly disintegrated, by vapors and hot solutions which dissolved the cement, before the vent was opened by explosion. The minor faults and the contorted ribbons of white sand are to be ascribed to a settling and a resorting of the ejecta, following explosion. When it is observed that beds of coal show no trace of coking within a few feet of the sides of the neck, it cannot be doubted that the eruptions were of low temperature.[18] One other feature of the neck deserves mention; namely, the presence in the tuff-breccias of many rounded fragments of alaskite, up to 18 inches across, and fewer pieces of quartz porphyry, Jurassic and Cretaceous sandstone, and baked ? Chinle shale.

AGE OF THE NAVAJO VOLCANOES

No fossils have been found in the Tertiary sediments associated with the Navajo lavas and tuffs. There is, however, no reason for doubting that the Navajo volcanoes were active at the same time as those of the Hopi Buttes—namely, during the Middle and the Upper Pliocene. After volcanism had ceased, at least 1,200 feet of igneous and sedimentary material were removed from the tops of the necks in the Defiance Valley, whereas in Monument Valley, according to Gregory, the thickness of strata removed amounts to 2,000 or 2,500 feet. In these two regions, erosion must have been much more rapid than in the Hopi Buttes.

PETROGRAPHY OF THE NAVAJO ROCKS

SUMMARY

The dike rocks and lavas of the Navajo country are basic, alkaline rocks, characterised by a high content of potash. Associated with them, though only briefly mentioned in these notes, is a large laccolith of diorite

[18] J. D. Sears: *Geology and coal resources of the Gallup-Zuni basin, New Mexico*, U. S. Geol. Surv., Bull. 767 (1925) p. 19; *see* pl. vi for a view of this neck.

porphyry. By far, the dominant type of dike-rock is minette. In Monument Valley this is, indeed, the only type, but along the Defiance monocline and among the intrusions of the Redrock and Chuska valleys, it is accompanied by monchiquites. Still farther south, as already noted, minettes are entirely lacking in the Hopi Buttes. Some of the Navajo minettes carry leucite, and these merge into olivine leucitites. Vogesites are only poorly represented, and alnoite is restricted to a single intrusion.

The lavas of this region are perhaps best termed trachybasalts, and are identical mineralogically with the minettes. Acid and intermediate flows and dikes are completely absent.

Xenoliths, especially acid plutonic rocks and sedimentary fragments torn from the adjacent walls, are strikingly abundant in the Navajo intrusions. Metamorphism is remarkably slight, though locally thin zones of quartzite and buchite are developed.

INTRUSIVE ROCKS

Minettes.—There is, of course, much variation in the texture of the minettes over this wide area, but the proportion of the main constituents remains roughly the same. All are essentially intergrowths of alkali feldspar, diopside, and biotite in the approximate ratio 2 : 2 : 1, accompanied by accessory ores, olivine, apatite, and calcite. They range in color from pale gray in the feldspar-rich varieties to almost black through shades of brown and green. Though generally massive and blocky, they become platy at the margins of intrusions, owing to a parallel alignment of the mica flakes.

Contrasted with the brownish-green pyroxene of the Hopi rocks, the pyroxene of the Navajo minettes, though pale green in hand specimens, is usually colorless in thin section. Analysis (No. 16) and optical data indicate diopside. $\alpha = 1.676$; $\beta = 1.683$; $\gamma = 1.706 \pm .002$; $2V = 55°$-$60°$; $Z \wedge c = 38°$-$40°$; Sp. Gr. $= 3.46$. The larger phenocrysts are rarely longer than one millimeter and may be spongily infilled with brown glass. In a few minettes, the diopside is fringed with aegirinaugite, and occasionally it is terminated by small needles of sodic amphibole, pleochroic from deep bluish-green, X, to yellowish-green, Z, and extinguishing, $X \wedge c =$ up to $5°$. Clots of diopside crystals occur as lapilli in some of the minette tuffs.

Biotite is generally present as two generations. The phenocrysts are commonly arranged in flow-bands and show an intense zoning from deep brown or russet on the outside ($\gamma = 1.658$) to pale yellow within ($\gamma = 1.640$). The analysed biotite (Nos. 17 and 18) is distinctly phlogopitic ($\gamma = 1.602$-1.625; Sp. Gr. $= 2.67 \pm .02$). The microlithic biotite has the same color as the dark rims of the phenocrysts.

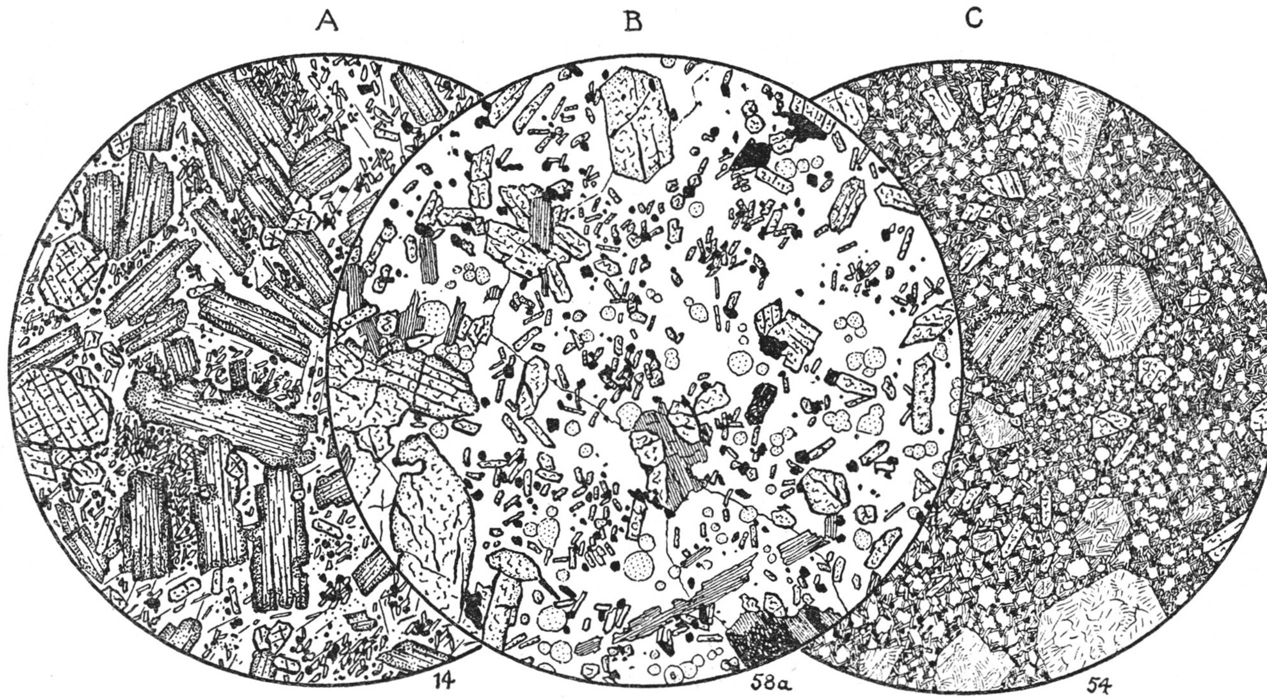

FIGURE 13.—*Navajo lava and dike rocks*

(*A*) Minette, Chaistla, Monument Valley. Phenocrysts of diopside, iron ore, and apatite in a matrix of orthoclase. Analysis No. 8.

(*B*) Trachybasalt, Palisades. Except for leucite (stippled) and large crystals of sanidine instead of orthoclase, the minerals are as in *A*. Parts of only five large sanidine crystals appear in the section; their boundaries are indicated. Analysis No. 12 is of a similar flow except for altered relics of olivine.

(*C*) Olivine leucitite, Dike "B", near Beelzebub, Todilto Park. Phenocrysts of serpentinised olivine, diopsidic augite and one of biotite (in center). Groundmass of augite, ores, apatite and leucite. Analysis No. 6. All ×29.

Olivine is rare and is largely replaced by serpentine and/or iron oxides. In most of the minettes, it constitutes less than 2 per cent of the volume, though in a few it makes up about 10 per cent, and may there be attended by small grains of green spinel.

Hornblende is all but absent; in its only occurrence, in a minette from Conical Butte, Monument Valley, it is restricted to a few resorbed olive-green crystals.

The iron ore (4 to 10 per cent) is a titanium-poor magnetite.

Plagioclase has not been detected, all the determinable feldspar being orthoclase and sanidine, the latter predominating. In many of the minettes, uniaxial sanidine forms subhedral crystals, up to 2 millimeters long, enclosing all the other constituents poikilitically, as it does in the trachybasalts. Normally, however, the feldspar occurs as a felt of microliths. Analcite, more or less zeolitised, may appear in small amount, but nepheline, if present, escapes detection. The leucite-bearing minettes are referred to on page 152. Interstitial glass is confined to a few fine-grained types.

Calcite is widespread both interstitially and in amygdules; barite occurs in a minette from Boundary Butte. Apatite forms between one and two per cent of an average specimen. Finally, primary quartz mosaics are developed in the interstices of the acid minette of Mitten Rock (Analysis No. 13; Fig. 14, A).

Compared with the minettes of most other regions, those of the Navajo country are poor in xenocrysts. Corroded crystals of quartz, with reaction rims of diopside, are seldom seen, and xenocrysts of microcline and perthite have only been noted in a single slide, from a dike on Whiskey Creek.

Modes of three analysed specimens

	33a (Dike south of Shiprock)	33b (Dike in Shiprock)	34a (Mitten Rock)
Diopside	33	30	20
Biotite	23	10	18
Olivine	..	2	2
Feldspar	37	46	50
Ores	5	5	5
Apatite	2	2	2
Glass	..	5	..
Quartz	..	..	3

The acid minette of Mitten Rock is heavily charged with hornblendic inclusions (Fig. 14, B) almost identical with those in the diorite porphyry of the Carrizo laccolith. Clots of hornblende may also be found in some of the minette tuff-breccias.

Mica-poor dikes.—At View Point, in the Lukachukai Mountains, there are several intrusions characterised by their low content of biotite. It seems inadvisable to coin a new name for these rocks; consequently, they are here referred to as analcite- and olivine-bearing diopside vogesites. Texturally, they do not differ from the minettes.

Modes of two extreme types of mica-poor dikes

	Per cent of volume	
Colorless and pale-green diopside	29	24
Orthoclase or sanidine	38	34
Analcite, largely zeolitised	13	23
Serpentinised olivine	11	13
Brown biotite	3	2
Iron ores	5	3
Apatite	1	1

Leucite-bearing dikes.—Among the Navajo dikes, only two have been observed to carry leucite. One is an olivine leucitite, forming part of the intrusion in Todilto Park referred to by Gregory as "Dike B," and the other is a leucite minette, forming part of Peridot Ridge in Buell Park. Each type merges in the same intrusion into normal minette as the content of olivine and leucite falls, with a relative increase of mica and orthoclase. The reciprocal relation of these two pairs of minerals has often been recorded.

Figure 13, C, illustrates the texture of the leucitite. Mineralogically and chemically (Analysis No. 6), it bears a notable resemblance to the missourites of the Highwood Mountains of Montana. Leucite (28 per cent), slightly altered and carrying granules of pyroxene, ranges in diameter up to 0.5 millimeter. Phenocrysts of diopsidic augite and serpentinised olivine, in the ratio 2 : 1, together constitute 38 per cent. Pale phlogopitic biotite (4 per cent), microlithic brown augite (16), titanomagnetite (4), tiny laths of either orthoclase or sanidine (8), with perhaps a little analcite and acicular apatite (2 per cent), make up the dense groundmass. Specks of purple fluorite appear in some of the rocks transitional between leucitite and minette in this intrusion.

The leucite minette dike in Buell Park is so nearly identical with the columnar lava flows described on page 154 that further reference may here be omitted. It may be noted, however, that the olivine, which is so plentiful in the tuff-breccias bordering this dike, carries only about 7 per cent of the fayalite molecule ($\alpha = 1.650$; $\beta = 1.668$; $\gamma = 1.684$; Sp. Gr. $= 3.333$).

Monchiquites and alnoites.—Feldspar-free intrusions are not common in the Navajo country. In some of the dikes of Chuska Valley and on

The Beast, however, normal minettes merge into monchiquites as orthoclase gives place to analcite.

Dikes of coarse-grained, olivine-rich monchiquite crop out in the Redrock Valley field. In one of these, olivine, largely altered to antigorite, actually comprises a quarter of the bulk; diopsidic augite, 38 per cent; biotite, 15; iron ore, 10; the remainder consists of interstitial fresh analcite, bearing needles of apatite. Somewhat similar monchiquites, heavily charged with calcite, form the intrusions on Echo Cliffs and Tuba Butte.

An interesting variation may be examined in the large dike of amygdaloidal monchiquite near the village of Moenkopi. Marginally, the dike contains 60 per cent of pale-brown augite; 10, of altered olivine; 5, of biotite; 7, of ore; the remainder consisting of interstitial serpentine, calcite, and zeolites with accessory apatite. Toward the interior of the dike, the content of olivine falls to 5 per cent, that of biotite rises to almost 20 per cent, and fresh analcite makes up 4 per cent. The proportion of augite and ore is nearly constant. There is, thus, an inward passage from monchiquite to a type not far removed from ouachitite.

It remains to discuss the nepheline- and melilite-bearing dikes of Wildcat Peak. In the coarse-grained type (Fig. 5, A; Analysis No. 1), augite forms long blades, elongated along both the 'b' and the 'c' axes, the interiors being very pale-brown ($Z \wedge c = 48°$) and the exteriors a greenish color due to a higher content of soda ($Z \wedge c = 56°$). In addition, olivine, partly altered to bowlingite and hematite, biotite ($\alpha = 1.645$-1.662), and granules of ore lie in a colorless matrix, which staining methods indicate to be chiefly nepheline, accompanied by orthoclase or sanidine and a little analcite. This rock may be termed a nepheline monchiquite. In the long dike that extends southward from the peak the same minerals recur, though in different proportions (*see* modes), and accompanied by small prisms of melilite, first detected by the keen eye of Pirsson.[19]

Modes of Wildcat Peak intrusions

	Nepheline monchiquite	Alnoite
Augite	56	64
Olivine	6	16
Biotite	2	2
Titanomagnetite	12	8
Nepheline and orthoclase	20	5
Apatite	4	3
Melilite	..	2

[19] L. V. Pirsson, *in* H. E. Gregory: *Geology of the Navajo country*, U. S. Geol. Surv., Prof. Pap. 93 (1917) p. 103-104.

THE NAVAJO LAVAS

Just as the predominating lavas of the Hopi Buttes are the surface equivalents of the associated dikes of monchiquite, so the Navajo lavas correspond to the associated minettes, and may be classed as sanidine basalts (trachybasalts).

The earliest flows in the outliers of East Sonsela Butte, Washington Pass, and the Palisades, are dark-green, columnar, and coarse-grained lavas, rich in red pseudomorphs after olivine, large prisms of augite, and glistening flakes of biotite. An average micrometric analysis shows the following percentages: olivine, 5; augite ($\alpha = 1.685$; $Z \wedge c = 40°\text{-}42°$), 35; biotite ($\gamma = 1.640\text{-}1.650$), 8; iron ores, 5; sanidine, 35; 'leucite,' 10; apatite, 2. Thin sections are no less striking in appearance than are hand specimens, for the sanidine is developed in anhedral and subhedral plates, up to a centimeter in diameter, and encloses all the other minerals poikilitically (Fig. 13, B). It is fresh, glassy, and pseudo-uniaxial. Scattered at random within it, are irregular and spherical blebs, between 0.05 and 0.15 millimeter across, of a colorless to pale-cream mineral, partly isotropic, but mostly altered to ?kaolin and zeolites. Though devoid of sector twinning and regularly arranged inclusions, the mineral seems to be leucite. Olivine, almost wholly replaced by iron oxides and bowlingite, forms phenocrysts, up to 2 millimeters long. The porphyritic augite is distinctly zoned, the interior being a colorless or pale-green diopsidic variety, whereas the rim is dark green and rich in the aegirite molecule, and may be fringed with sodic amphibole. To judge from its brownish-green tint and extinction angles, the microlithic augite is notably sodic. Biotite occurs both as rims around the altered olivine and as detached flakes enclosing microlithic augite. It is pleochroic from pale yellow to rich russet, and some flakes have an optic angle of about 15 degrees. Occasionally, olive-green hornblende forms rims about the porphyritic augite. Titanomagnetite crystallised throughout, but apatite developed after the ferromagnesian constituents, as slender needles in the sanidine. Small, irregular patches of zeolitised analcite may occur interstitially.

In the later flows of the aforementioned outliers, the grain is usually finer, and the sanidine, attended by a little albite, forms either a crisscross felt or parallel bundles of tiny microliths. Where olivine is lacking, the supposed leucite is also absent.

Nepheline has not been identified in the present study, but Pirsson thought that it might be mixed with feldspar in the fine groundmass of the lava on Zilditloi Mountain.

Finally, reference must be made to the lavas of Buell Park. These are chiefly composed of a trachytoid groundmass of sanidine microliths with

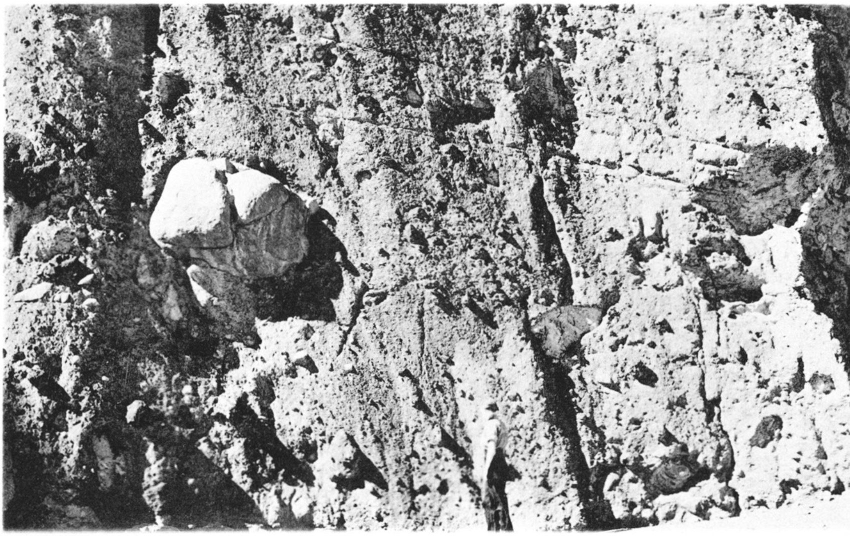

FIGURE 1. TYPICAL TUFF-BRECCIA INFILLING OF A HOPI NECK
Small butte east of Twin Cones. Note person for scale.

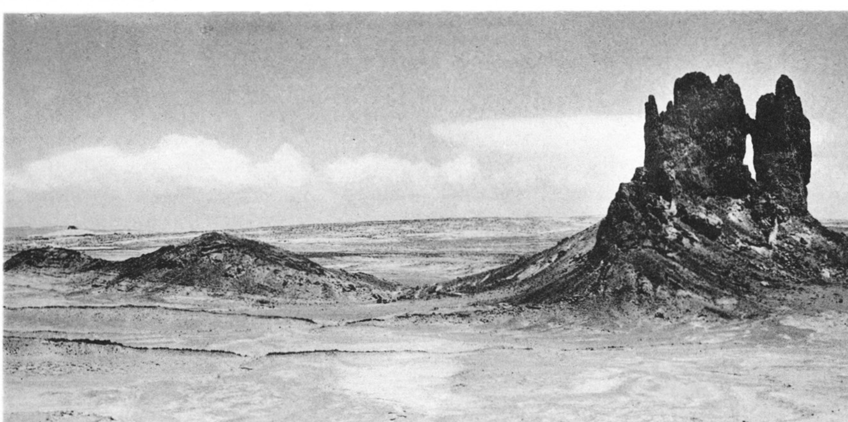

FIGURE 2. BOUNDARY BUTTE
Shows three tuff-breccia necks and two curved dikes (foreground). Note horizontal Jurassic sandstones bordering the necks (left).

HOPI AND NAVAJO NECKS

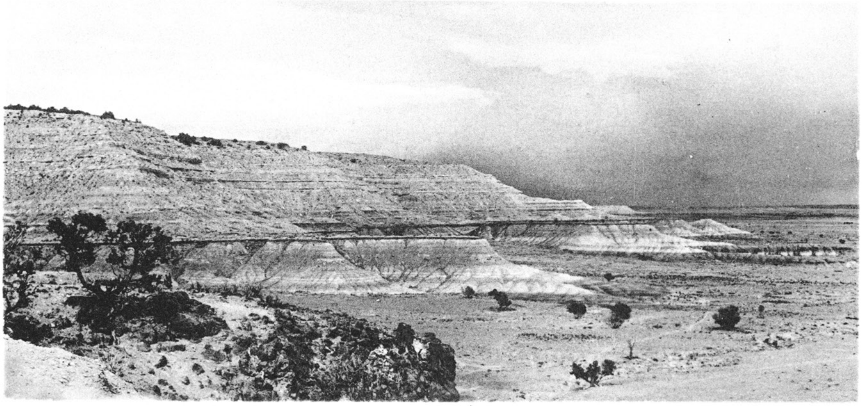

FIGURE 1. SOUTH WALL OF JEDITO MESA, HOPI BUTTES
Lava flow (foreground) is on same horizon as the dark band of coarse tuff beyond. Slightly tuffaceous, varicolored muds and silts underlie this band and recur above, interbedded with freshwater limestones and sands. These cliffs afford the fullest exposures of the Hopi lake beds.

Photo by Fairchild Aerial Surveys, Inc.

FIGURE 2. CAULDRON SUBSIDENCE OF BUELL PARK, THE NECKS OF DEFIANCE VALLEY, AND THE ZILDITLOI LAVA CAP

HOPI LAKE BEDS AND BUELL PARK

prisms of diopsidic augite and rare flakes of resorbed biotite. Titanite, apatite, and granular ore are constant accessories. An identical rock forms the north-south dike on the floor of the park.

How closely the trachybasalts, just described, resemble the minettes of the Navajo region may be judged from the table of analyses (Nos. 7-10).

DIORITE PORPHYRY OF THE CARRIZO LACCOLITH

The laccolithic rocks of the Southwest vary little. Monzonite and syenite porphyry have been recognised among the laccoliths of the La Sal Mountains,[20] but diorite porphyry is the dominant type, and in the Carrizo laccolith, covering an area of about 100 square miles, it makes up the entire mass. Similar rocks, originally referred to as "trachytes" and "hornblende porphyrites," form the laccoliths of the Henry Mountains. In view of the description of the Carrizo porphyries, already published by Emery,[21] it is here necessary to include only a few lines, for the sake of completeness.

The matrix of the porphyry is a fine microgranular intergrowth of quartz and orthoclase crossed by tiny laths of both orthoclase and acid plagioclase. Lying in it, and making up between a third and a half of the rock, are large phenocrysts of green hornblende, corroded and zoned phenocrysts of andesine, a few rounded grains of quartz and rare flakes of biotite (Fig. 14, C). Occasionally, cores of diopside are preserved inside the hornblende. Apatite, titanite, and iron ores are present in small amount. Alteration is almost restricted to the development of a little epidote and kaolin, though in the large dike of porphyry which extends from the laccolith toward Beclobito the hornblende is largely replaced by chlorite and calcite. Hornblende-rich autoliths are lightly scattered throughout.

That the porphyry was viscous and poor in volatiles is indicated, not alone by the deformation of the enclosing sediments but also by the remarkable paucity of metamorphic effects along the contact. Except for the conversion of sandstone to quartzite for a few inches from the margin of the laccolith, no alterations have been observed.

METAMORPHISM OF SEDIMENTS AROUND NECKS AND DIKES

General statement.—Attention has already been drawn to the rarity of metamorphosed sediments, both adjacent to the necks and dikes of the Navajo country and as inclusions within them. Around most of the intrusions, the wall-rocks remain unaffected, and, even where present,

[20] L. M. Gould: *The geology of La Sal Mountains, Utah,* Mich. Acad. Sci. Arts and Letters, vol. 7 (1926) p. 78-79.

[21] W. B. Emery: *The igneous geology of Carrizo Mountain,* Am. Jour. Sci., 4th ser., vol. 42 (1916) p. 356-357.

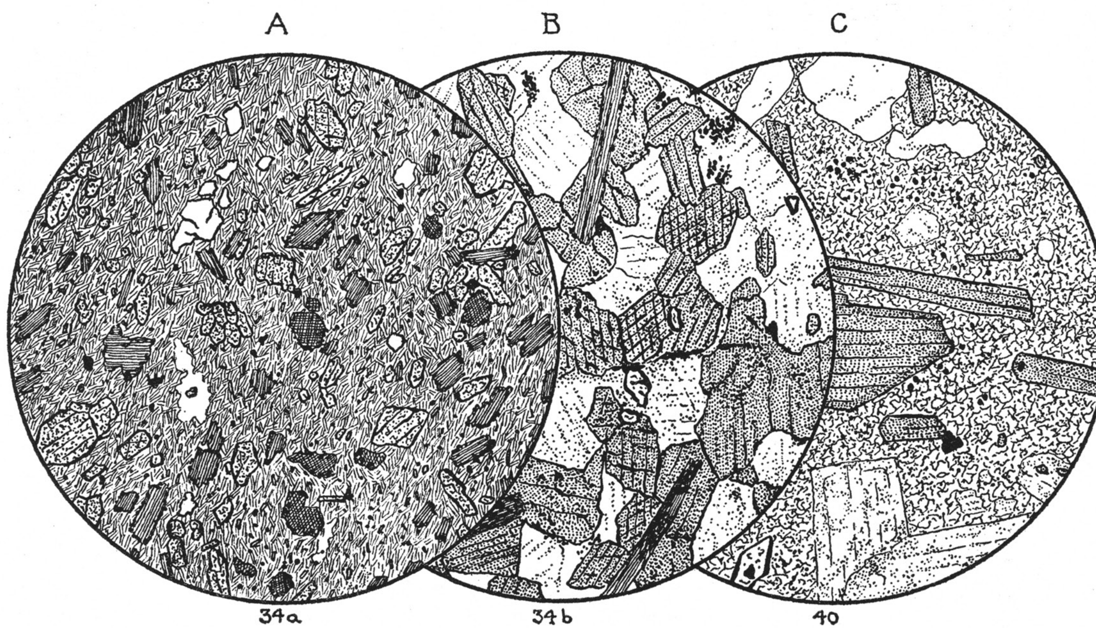

FIGURE 14.—*Navajo igneous rocks*

(*A*) Pale, acid minette, Mitten Rock. Analysis No. 13. Diopside and biotite phenocrysts with accessory apatite, ore, and quartz in a matrix of alkali feldspar laths, showing fluxion structure.

(*B*) Hornblendic clot in *A*. Green hornblende, 60 per cent; orthoclase, 9; andesine, 3; ore, 3; biotite, 2; quartz, 2; apatite, 1.

(*C*) Hornblende diorite porphyry, Carrizo laccolith. Analysis No. 14. Microgranular quartz - orthoclase - oligoclase matrix, enclosing phenocrysts of green hornblende, andesine, and quartz. All ×26.

metamorphism is strongly localised. Sandstones and shales may be either bleached or reddened, for a few inches from the contact. Calc-silicate rocks are conspicuously absent, and, indeed, most limestones have even escaped conversion to marble. Locally, sandstones may be altered to quartzites by the recrystallisation of the felsitic matrix, and in some there is a development of diopside, granules of ore, and a few flakes of biotite. A conversion of detrital orthoclase to sanidine has been observed close to certain dikes of minette.

Buchites.—Along the margins of a few intrusions—notably, at Fluted Rock, Outlet Neck, Black Pinnacle, and Wildcat Peak—the sandstones are extensively converted to glass (buchite) and may exhibit a strong columnar jointing, perpendicular to the contacts. These merit fuller description. Examples are illustrated in Figure 15. The altered sandstone from the walls of Outlet Neck (Fig. 15, C) is still partly composed of residual quartz, but the amount of spongy, half-dissolved feldspar, both orthoclase and plagioclase, is three times as great. The remaining third is a pale-cream glass ($n = 1.494 \pm .002$), lightly stippled with magnetite dust and minute needles of an unknown mineral that varies from colorless to pale tints of green and brown. Though the mineral is straight extinguishing, slow along the length, and has a bi-refringence of about .015, doubt remains as to its identification as sillimanite. Near the contact, the buchites become increasingly admixed with small lapilli of minette and discrete crystals of re-heated biotite and diopside. It is clear that the sandstone must have been comminuted and explosively mixed with the minette, prior to vitrifaction.

Thin zones of buchite are to be found bordering some of the dikes on Wildcat Peak. These differ from the preceding only in the following features: the glass is colorless and charged with needles of apatite as well as ?sillimanite, and also with curved, black, hair-like trichites of an unidentifiable substance; accompanying these are many spheroidal and reniform bodies of chalcedony, up to 0.5 millimeter across, suggesting blebs of what may have been hydrous silica gel (Fig. 15, B).

Finally, the sandstones forming the cap of the Fluted Rock laccolith have been largely altered to chalcedony, opal, and a little interstitial, partly devitrified glass. No trace of detrital feldspar remains, and even the relic quartz is deeply embayed by corrosion (Fig. 15, A). Similarly altered sandstones are present as lapilli in the tuff-breccias on Tubby Butte, and at the western end of the lava cap on East Sonsela Butte.

In all these metamorphosed rocks, the feldspar and the fine felsitic base are the first to be converted into glass, while the larger quartz grains survive. Water and phosphorus seem to be the only constituents added

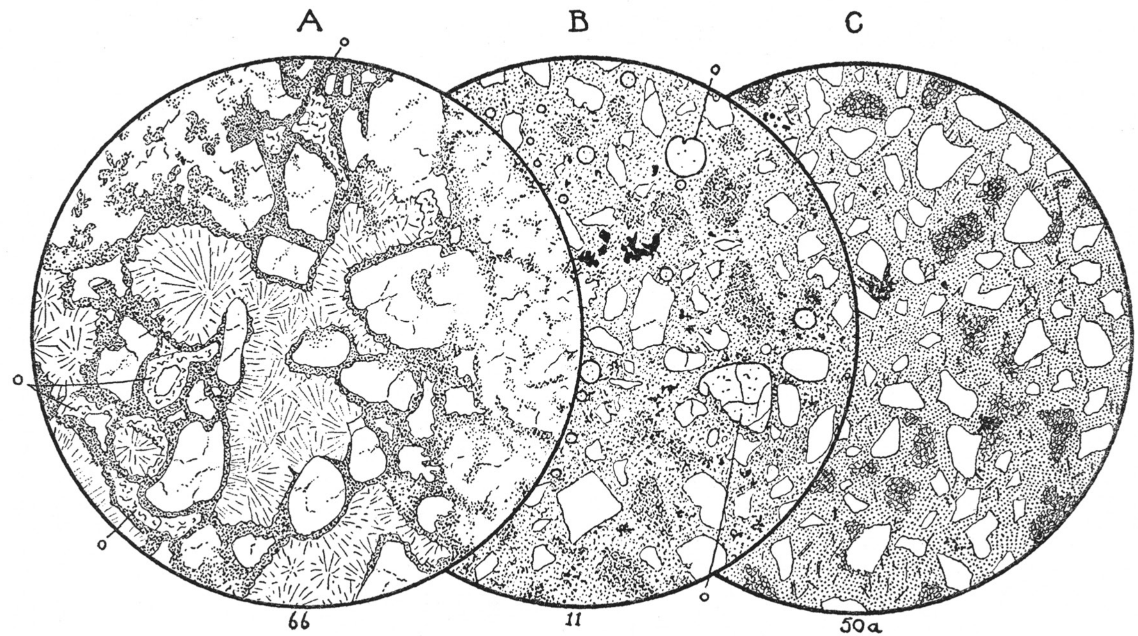

FIGURE 15.—*Vitrified sandstones*

(*A*) From cap of Fluted Rock laccolith. Shows quartz grains partly corroded and embayed, lying in a matrix chiefly of "microfelsite" with a little glass. Large irregular patches of radiating chalcedony and smaller patches of opal (*o*).

(*B*) From Wildcat Peak. Relic quartz grains and rounded blebs of opal (*o*) lie in a groundmass of glass, varying from colorless to gray. Darker patches, due to ?clayey decomposition products, probably indicate original clastic feldspar.

(*C*) From Outlet Neck, north of Fort Defiance. Sharply bordered grains of quartz, spongy relics of feldspar, and acicular microliths of an unknown mineral (?sillimanite) lie in a base of cream-colored glass. All ×26.

from the minettes. In their presence, the changes noted may well have been effected at quite low temperature, a supposition that finds support in the absence of metamorphism at all but these few contacts. Even seams of coal have not been coked close to the dikes of minette in the Twin Cones.

ACID PLUTONIC AND GNEISSOID XENOLITHS IN THE NECKS AND DIKES

General statement.—Emphasis has already been laid on the abundance of foreign inclusions in the volcanic rocks of the Navajo country. In the tuff-breccias, most of these xenoliths are fragments of sediment torn from the adjacent walls, chief among which are pieces of Jurassic sandstone and Chinle shale. Next in number, and especially common in the Garnet Fields, are the plutonic and gneissoid xenoliths transported from greater depth and incorporated both in the tuff-breccias and in the later dikes. Most of these are of granitic, dioritic, or gneissoid character; the remainder vary widely.

Most of the rounded lumps of white and gray, coarsely crystalline, plutonic rocks that stand out so conspicuously among the dark minettes, are of alaskite and alkali granite, almost devoid of ferromagnesian minerals. Many of these have a pronounced gneissoid banding. With them are fragments of acid pegmatite, a few biotite granites, granodiorites, and diorites.

Certain features of the more acid xenoliths call for immediate attention. Hardly a section fails to show that part, at least, of the orthoclase has been converted to sanidine or shows a marked diminution in the size of its optic angle. Commonly, the xenoliths are cut by 'veins' of comminuted quartz and feldspar that have suffered partial fusion or solution; others are riddled with channels of calcite and glass and may reveal a recrystallisation of clear feldspar. These alterations are almost restricted, however, to the granites and alaskites.

Noteworthy, also, is the alkaline and siliceous nature of most of the xenoliths. The few colored minerals present are types rich in magnesia—namely, pyrope, biotite, and hypersthene. Hornblende and augite are extremely rare.

Alaskites and granites.—These are especially plentiful in the Monument Valley region. The proportion of quartz and feldspar varies within wide limits. A common type contains from 60 to 70 per cent of orthoclase and perthite, partly changed to water-clear sanidine ($2V = 0°-30°$), intergrown sub-graphically with strained crystals of quartz and a little albite, and attended by granules of ore. Branching veins of brown, partly devitrified glass follow the sutured contacts between many of the quartz and the feldspar grains, being more sharply defined against the quartz.

Cracks infilled with calcite cross the rock, in haphazard fashion. Where hypersthene is present it displays reaction rims of aegirinaugite against adjacent feldspars. Where pyrope is present (forming up to 10 per cent of some xenoliths) it is usually bordered by iron ore and "limonitic pigment."

Cataclastic effects are widespread. Not only is the quartz strained and the orthoclase partly converted to microcline, but these minerals and secondary sanidine are crushed in irregular zones that later became favorable channels for the development of glass. In certain of these glass channels, calcite, titanite, and apatite are found, suggesting that the emanations from the minette were charged with carbonic, phosphoric, and titanic acid. Elsewhere, the channels of glass carry acicular and forked microliths of clear sanidine, flakes of green biotite, and tiny grains of diopside fringed with aegirinaugite, suggesting the development of minette.

In some of the alaskite nodules, grains of unmodified orthoclase lie next to others rendered uniaxial by heat. Again, crystals of cloudy orthoclase are rimmed by thin shells of clear sanidine laths, arranged in cuneiform patterns in a base of devitrified glass. A similar phenomenon has been described by Tidmarsh [22] as "frit-channeling" and ascribed by him to the rapid reheating of feldspar.

The coarse pegmatitic inclusions consist essentially of perthite crystals, up to 5 millimeters long, and quartz. In some specimens, the perthite within a millimeter of the contact with minette may be recrystallised to clear microliths of sanidine intergrown with needles of ?aegirinaugite or sodic amphibole and calcite.

The formation of glass in these xenoliths must have taken place at fairly low temperatures, for it may be seen even where the orthoclase has escaped conversion to sanidine, and in rocks bearing brown biotite whose optic angle remains near zero. It seems likely that the vitrifaction is not a simple process of fusion but probably is one of solution brought about partly by a rise in temperature and partly by emanations from the minette magma.[23]

Biotite granites and granodiorites.—In the Green Knobs neck, there are sporadic nodules of a graphic granite, principally composed of quartz and perthite, with a few crystals of albite and chloritised biotite, attended by specks of fluorite and a colorless ?lithium mica. In the Shiprock neck

[22] W. G. Tidmarsh: *The Permian lavas of Devon,* Geol. Soc. London, Quart. Jour., vol. 88 (1932) p. 733.

[23] Leonard Hawkes: *On a partially fused quartz-felspar rock and on glomerogranular texture,* Miner. Mag., vol. 22 (1929) p. 163-173. *Also* Arthur Holmes: Geol. Soc. London, Quart. Jour., vol. 88 (1932) p. 411-412.

Deffner (quoted by Branco in *Schwaben's 125 Vulkan-Embryonen*) noted the development of sanidine in the granite xenoliths of the Schwabian diatremes, and of glass at the contacts of feldspar with mica.

and in the Porras dikes, biotite-rich granodiorites are not uncommon, and in them the feldspars may exhibit vitrifaction and recrystallisation, as described in the preceding section. Many of these xenoliths carry clusters of pyrope grains.

Diorites.—Between these and the foregoing there are all gradations as orthoclase gives place to andesine and the content of quartz diminishes. A third of one diorite fragment from the Agathla neck is made up of pyrope crystals, up to 4 millimeters across, including rare grains of a green spinel. Half the fragment consists of oligoclase-andesine and small patches of sanidine after orthoclase. The remainder is composed of biotite, ore, apatite, and cracks filled with 'limonite' and calcite. In other xenoliths, quartz and andesine are almost the only constituents. Pyroxene diorites are exceptional. One piece from the Chaistla neck, in Monument Valley, has this percentage content: diopsidic augite, 25; pyrope, 25; basic andesine, 40; the remainder, magnetite and apatite. Only one hornblende diorite was seen in thin section. This came from Conical Butte, in Monument Valley, and is of interest because both its hornblende and its biotite show no sign of re-heating.

Gneissoid types.—While most of the plutonic rocks just listed are free from banding, others of similar composition exhibit a crude gneissoid appearance, due in part to the alteration of more feldspathic and more quartzose fractions, in part to an alignment of the dark minerals, and in part to the development of cataclastic zones. Except that microcline here tends to be more abundant, the rocks do not differ materially from those already described. They were presumably derived from fluxion- and crush-zones in an underlying batholith.

MISCELLANEOUS XENOLITHS

General statement.—Accompanying the acid plutonic rocks, though in much smaller numbers, are basic and ultrabasic types and a wide variety of metamorphic rocks typical of the epi-zone. As these furnish a further key to the nature of the pre-Cambrian basement beneath the Navajo country, the principal types merit a short description.

Harzburgites and lherzolites.—Rounded xenoliths of coarsely crystalline ultrabasic rocks are to be found in the Green Knobs neck and among the pyroclastic ejecta in Buell Park. These are particularly interesting because of their highly magnesian character. Among them, harzburgites predominate. An average specimen has this percentage content: olivine, 25; serpentine, 10; pale, schillerised enstatite, 40; the remainder, a mixture of actinolite, chlorite, and magnetite. In some varieties, diallage accompanies the enstatite; in others, olivine makes up 70 per cent of the whole, enstatite, 20 per cent, and the remainder consists of their alteration products.

Norites.—Occasional grains of hypersthene have been noted in the acid plutonic rocks, but in the gabbroid types the mineral is much more plentiful. Fragments of norite occur in the necks of Monument Valley and in the lava cap on Zilditloi Mountain. About two-thirds of an average norite is made up of labradorite, while the rest is formed of intensely pleochroic hypersthene ($2V - 70°$), and deep-green augite, in proportions ranging from 3 : 1 to 1 : 1.

Garnetiferous talc-anthophyllite schists.—These are associated with the garnetiferous diorites on the Garnet Ridge near Mule Ear. Whether derived from the schists or from the diorites, the garnet is invariably of the pyrope variety and ranges in color from pale rose to a deep Burgundy-red. Those with a slight purplish tint probably contain a considerable proportion of the almandine molecule and, perhaps, also, of the spessartine. According to the depth of color, they vary in specific gravity between 3.65 and 3.75. In addition to talc, anthophyllite, and pyrope, the schists carry much penninite (with sagenite webs), zoisite, epidote, and granoblastic quartz.

Quartz-sericite and quartz-chlorite schists.—A few small flat slabs of these rocks have been collected from the necks of Monument Valley and vicinity. Some of them carry flakes of graphite and tiny needles of pale bluish-green tourmaline.

Other types.—Hornblende-rich schists are present in the tuff-breccias of Buell Park and in the lava cap on Zilditloi. Here, yellowish-green hornblende is associated with fine quartz-orthoclase mosaics, accessory biotite, titanite, epidotes, and ore.

Quartz-albite gneiss, carrying a little microcline and biotite, is an unusual type of xenolith in the Green Knobs neck. Green biotite-chlorite-quartz schists may also be collected at this neck.

Soapstone and tremolite are fairly common in the Garnet Ridge, both near Mule Ear and north of Dinnehotso. Uralitised andesite porphyries, black slates, hornstones, quartzite, and basalt complete the list thus far obtained.

None of the foregoing xenoliths appears to have suffered even the slightest alteration in its upward passage through the volcanic pipes. Their source and significance is discussed on page 168.

GENERAL PETROLOGY OF THE NAVAJO-HOPI REGION

GENERAL STATEMENT

If exceptions be made of the diorite porphyries of the Carrizo laccolith and the plutonic fragments in the necks and dikes, practically all the igneous rocks of the Navajo-Hopi region are basic, alkaline types. Normal plagioclase basalts are extremely rare, and are confined to the southern margin of the area. Acid and intermediate flows and dikes are absent. In the Hopi Buttes, it has been shown that monchiquites and their surface equivalents—soda-trachybasalts, analcite basalts, and limburgites—predominate. Farther north, in the Navajo country, monchiquites, though present, are rare, while minettes and their heteromorphs —olivine leucitites and sanidine-rich trachybasalts—are widespread.

Thus, a regional progression of magma-types is discernible, from slightly sodic in the south to strongly potassic in the north. If a wider region be considered, the lateral variation is even more striking. To the north of the Navajo potassic province, in Utah and Colorado, lie the somewhat sodic laccolithic rocks of the Henry, La Sal, Abajo, and La Plata mountains; to the southwest, lie the soda-rich rocks of the San Francisco volcanic field. Long ago, Pirsson [24] noted a similar lateral variation among the igneous rocks of central Montana, where, likewise, a strongly potassic group is bordered by provinces rich in soda.

MINERALOGICAL CHARACTER OF THE NAVAJO-HOPI ROCKS

The alkaline rocks of the Navajo-Hopi necks, dikes, and flows bear many mineralogical resemblances to those of other alkaline provinces, and notably to those of Montana and Wyoming.

In the monchiquitic rocks of the Hopi Buttes, the typical pyroxene is a greenish-brown, weakly- or non-pleochroic, lime-rich augite, closely comparable with some of the augites found in the lavas of Vesuvius [25] and Haleakala, Maui.[26] It is not far removed from the diopside-hedenbergite series. Even in lavas fairly rich in titanium, the augite is only faintly purple at the margins. In the minettes and trachybasalts of the Navajo country, the pyroxene is very close to pure diopside. Fringes of aegirinaugite develop locally by reaction with analcite or alkali feldspar. Orthorhombic pyroxenes are entirely lacking.

In the Hopi rocks, mica is extremely rare and, where present, is a warm-brown biotite, fairly rich in iron. In the Navajo rocks, on the

[24] L. V. Pirsson: *The petrographic province of central Montana,* Am. Jour. Sci., 4th ser., vol. 20 (1905) p. 35-49.

[25] Rosenbusch-Osann: *Elemente der Gesteinslehrs* (1923) p. 422, 465.

M. Stark: *Die Augite in den Gesteinen der Euganeen,* Neues Jahrb. für Min., Abt. A, vol. 55 (1927) p. 1-35.

[26] T. F. W. Barth: *Mineralogical petrography of Pacific lavas,* Am. Jour. Sci., 5th ser., vol. 21 (1931) p. 387.

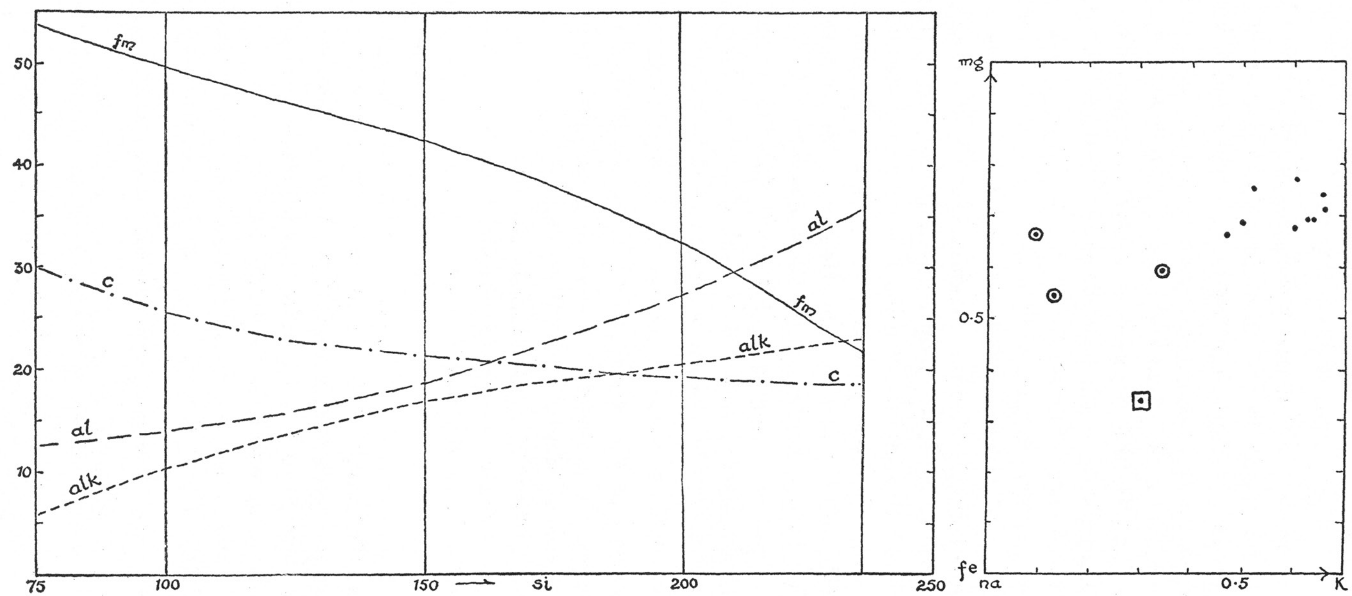

FIGURE 16.—*Variation diagrams of the Navajo-Hopi rocks*

Niggli diagram (left); k-mg diagram (right). Dots indicate Navajo rocks; circles with dots, Hopi rocks; square with dot, the Carrizo diorite porphyry.

contrary, mica is abundant and is usually zoned from a pale core of phlogopitic biotite to a deep-brown rim approaching lepidomelane.

The scarcity of hornblende is one of the most distinctive features of the entire province. It is virtually restricted to the Carrizo diorite porphyry laccolith and to a few crystal bombs and lapilli of the Navajo-Hopi volcanoes.

Olivine is ubiquitous as a minor constituent, and is invariably very poor in the fayalite molecule.

Basic plagioclase has only been recognised in certain flows along the southern edge of the Hopi field, and even acid plagioclase is meager. The characteristic feldspars throughout are sanidine and orthoclase.

Nepheline is present in such small amount and in such minute crystals as to make its recognition difficult. The only exceptions to this are in the monchiquites and alnoites of Wildcat Peak.

Leucite is much less plentiful than in the alkaline provinces of Montana and Wyoming, and is known only from the Navajo region, not from the Hopi. It is restricted to rocks rich in olivine.

Analcite is widespread among the Hopi rocks and is not rare as a minor, interstitial accessory of the Navajo intrusions and flows.

Apatite, as in most alkaline suites, is extremely abundant. Melilite has been detected in only a single rock, a Navajo dike. Perovskite appears to be absent, and titanite, except as a secondary constituent derived from the breakdown of biotite, is rare. Titaniferous magnetite is the prevalent ore. Quartz is virtually absent.

CHEMICAL CHARACTER OF THE NAVAJO-HOPI ROCKS

The minette-sanidine basalt assemblage of the Navajo country is characterised especially by its high content of potash. In Niggli's classification,[27] the Navajo rocks belong to the Mediterranean type (Kalireihe), and, as the k-mg diagram (Fig. 16) shows, they bear a marked resemblance to his lamprosommaite, shonkinite, and missourite magma-types. According to the classification suggested by Burri,[28] the rocks fall into the Maros-Highwood type of the Mediterranean province, while showing some affinities with the Yellowstone type of the Pacific province. The laccolithic rocks of the Henry, El Late, and Carrizo mountains are, also, of the Yellowstone type. Among the Navajo rocks, the k-value—that is, the ratio of potash to the total alkali content—ranges between 0.47 and 0.77; among the Hopi rocks, on the contrary, the range is from 0.09 to 0.34.

Omitting the Carrizo diorite porphyry, all the Navajo and Hopi rocks

[27] P. Niggli: *Gesteins- und Mineralprovinzen* (1923) p. 172-197.

[28] R. C. Burri: *Chemismus und provinziale Verhältnisse der jung-eruptiven Gesteine des pazifischen Ozeans und seiner Umrandung,* Schweiz Min. u. Petr. Mitt., vol. 6 (1926).

TABLE 1.—*Analyses of Navajo-Hopi rocks*

Constituents	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18
SiO_2	37.80	39.00	39.50	40.70	41.10	47.50	49.05	49.80	51.50	51.60	51.80	55.10	58.75	63.18	49.60	52.90	37.00	37.00
Al_2O_3	9.47	11.72	11.84	......	12.50	9.62	10.65	11.58	11.55	10.54	11.10	13.85	12.70	16.47	4.45	2.25	16.42	12.75
Fe_2O_3	5.64	4.11	4.80	......	4.01	3.37	4.80	3.27	2.38	3.30	3.55	1.53	1.80	2.36	2.53	1.43	4.72	3.80
FeO	5.21	8.19	8.64	......	9.30	4.74	3.00	4.50	4.72	3.66	3.42	2.02	2.44	2.28	4.73	3.34	2.16	2.20
MgO	11.30	12.24	8.43	......	10.02	13.00	9.45	9.25	7.90	9.30	8.15	6.65	6.40	1.33	14.75	16.58	21.30	18.90
CaO	15.20	11.80	11.25	......	10.60	9.00	10.30	9.60	9.10	8.70	7.95	7.45	5.50	4.77	20.50	21.05	Nil	7.05
Na_2O	1.70	3.04	3.90	4.08	2.94	1.96	1.92	2.80	2.55	1.87	2.25	2.54	2.22	4.40	.58	.42	.96	.79
K_2O	2.23	.43	.89	.58	2.26	3.28	5.00	4.23	5.65	5.76	5.97	5.93	6.44	2.93	.06	.50	8.29	6.32
H_2O-	2.45	1.30	.80	......	.70	.90	1.15	.60	.45	.90	1.00	1.10	1.10	......	.20	.30	......	1.20
H_2O+	2.20	3.30	2.80	......	1.50	3.90	2.15	1.35	1.10	1.30	1.90	1.25	1.15	......	.40	.50	6.23	4.80
TiO_2	3.05	3.60	4.75	......	3.70	1.85	1.70	1.70	1.85	2.30	1.80	1.55	.80	.60	2.10	.35	2.71	2.10
CO_2	1.70	Nil	Nil	......	Tr.	Nil	0.20	Nil	Nil	Nil	Nil	Nil	Nil	......	Nil	Nil	Nil	2.70
P_2O_5	1.68	1.03	1.96	2.53	1.24	1.05	.94	.95	.96	.73	.95	.82	.58	......	Tr.	.21	.17	.16
MnO	.20	.16	.22	......	.18	Tr.	.08	.16	.10	.08	Tr.	.08	.08	.15	.05	.09	.04	.05
Total	99.83	99.92	99.78	......	100.05	100.17	100.39	99.79	99.81	100.04	99.84	99.87	99.96	......	99.95	99.92	100.00	99.82
si	75	77	84	......	84	105	115	117	128	127	133	156	180	236	......	......	......	......
al	11	14	15	......	15	12.5	14	16	17	15	16.5	23	23	36	......	......	......	......
fm	51	55	50	......	53	57.5	48	47	44	48	46	36	40	22	......	......	......	......
c	32	25	26	......	23	21	26	24	24	23	22	23	18	19	......	......	......	......
alk	6	6	9	......	9	9	12	13	15	14	15.5	18	19	23	......	......	......	......
k	0.47	0.09	0.12	......	0.34	0.52	0.63	0.50	0.60	0.67	0.64	0.61	0.66	0.30	......	......	......	......
mg	0.66	0.66	0.54	......	0.59	0.75	0.69	0.69	0.67	0.71	0.69	0.77	0.74	0.34	......	......	......	......
qz	−49	−47	−52	......	−52	−31	−33	−35	−32	−29	−29	−16	+4	+44	......	......	......	......

1. Nepheline monchiquite (7). Wildcat Peak, northwest of Red Lake (Tuba Cluster).
2. Monchiquite (114). Crags north of Indian Wells Trading Post, Hopi Buttes.
3. Analcite Basalt (77). Dilkon Butte, Hopi Buttes.
4. Apatite-rich monchiquite (88b). Central of three crags, northwest of Egloffstein Butte, Hopi Buttes.
5. Limburgite (82a). 4 miles northeast of Roundtop, Hopi Buttes.
6. Olivine leucitite (54). Dike B, near Beelzebub, Todilto Park.
7. Minette (17e). Black Rock, east of Kayenta.
8. Minette (14). Chaistla, Monument Valley.
9. Minette (33b). Shiprock.
10. Trachybasalt (59a). Washington Pass.
11. Minette (33a). Dike running south from Shiprock.
12. Trachybasalt (58b). Palisades; below columnar flows.
13. Pale minette (34a). Mitten Rock.
14. Diorite porphyry. Carriso Mountain.
15. Augite (81a). From tuffs, 7 miles south of Egloffstein Butte, Hopi Buttes.
16. Diopside from minette of Black Rock, Kayenta (Analysis 7).
17. Biotite from same as 16 (calculated). CaO of 18 allotted to calcite + diopside.
18. Biotite (impure) from same as 16.

Analysis 14, by W. F. Hillebrand; all other analyses by Frank Herdsman.

are typified by their strongly magnesian character; the *mg*-value—ratio of magnesia to magnesia plus iron oxides—ranges from 0.54 to 0.77, being highest in the most acid trachybasalt and minette. Equally striking are the low *al*-values throughout, owing to the paucity of basic plagioclase and the alumina-poor character of the pyroxenes.

Calculation of the norms shows that all but one of the analysed specimens—namely, the most acid minette—are free from normative quartz. The degree of undersaturation as expressed by the *qz*-values of Niggli ranges from —47 to —52 in the Hopi rocks, and from —35 to —16 in the Navajo rocks, if exception be made of the one acid minette just mentioned. Even in this the *qz*-value is only +4 (corresponding to 4.20 per cent normative quartz).

In common with the alkaline rocks of Montana and Wyoming, those of the Navajo-Hopi region are fairly rich in phosphorus, so that the amount of normative apatite reaches a maximum of 6.05 per cent. Though barium has not been estimated by analysis, the presence of barite in some of the Navajo rocks suggests that the element may be comparatively abundant, as it is in many minettes. Titanium is much more plentiful in the Hopi rocks than in those of the Navajo intrusions, the percentage of normative ilmenite in the former ranging from 6.84 to 8.97 and in the latter from 1.52 to 4.41.

PLUTONIC EJECTA

Before proceeding to a discussion of differentiation, it seems best to refer once more to the plutonic ejecta. Branco found that in the Schwabian Alb, fragments of plutonic rocks are only present in the diatremes of a restricted zone. In the region here discussed, they are extremely rare locally and abundant elsewhere. Thus, among the ejecta of the Hopi volcanoes, plutonic fragments are all but absent, and none have been observed in the monchiquitic intrusions of the Tuba field. Among the necks and dikes of the Chuska Valley, they are comparatively few, and they are also uncommon in the southernmost intrusions of the Fort Defiance Valley. Among the Navajo intrusions farther north, the pieces of plutonic rock may comprise up to two-thirds of the total number of foreign fragments, reaching their largest number and size in the Green Knobs neck, in the intrusions at the south end of Redrock Valley, along the Garnet Ridge, and in Monument Valley.

In an earlier section, it has been found that alaskites and leucogranites are the dominant type. These are marked by their high content of silica and potash and by the presence of such magnesian minerals as pyrope, hypersthene, and biotite. Next in importance are granodiorites and diorites. More basic types are rare, but among them are rocks characterised by their high magnesian-content—namely harzburgites, lherzolites, and norites.

It seems probable that all these plutonic rocks were derived from a pre-Cambrian basement. So, also, were the fragments of epi-zone metamorphic rocks associated with them. Both schists and acid plutonic rocks of Archean age crop out beneath Carboniferous sediments in the core of the Zuni uplift, a short distance southeast of Gallup, but further study is necessary before it may be determined how closely they compare with the xenoliths of the Navajo-Hopi volcanoes.

The question now arises: do these acid plutonic ejecta, with their high content of potash and the basic ejecta, with their high content of magnesia, bear a genetic relation to the enclosing minettes with their high content of both potash and magnesia, or is the association quite accidental? The facts are clear: where granitic fragments are rare or absent, the volcanic rocks are monchiquites, limburgites, and analcite basalts; where such fragments are abundant, only minettes and sanidine-rich basalts accompany them.

DIFFERENTIATION

Many suggestions have been offered to explain the origin of such basic, potash-rich rocks as those of the Navajo country. Among those to be considered are:

(1) De-silication of magma by the assimilation of limestone and/or dolomite, and a passive enrichment in potash by the escape of soda at fumaroles, from the craters and into the walls of the magma reservoirs. This process has been invoked by Rittmann [29] to account for the leucitic rocks of Vesuvius.

(2) Depth-pressure control, as suggested by Holmes,[30] in the case of the leucitic province near Ruwenzori, Africa. Here, a primary peridotite is supposed to yield mica peridotite and its heteromorph, olivine leucitite, by the abstraction of soda-rich eclogite and olivine. The formation of enstatite and other pyroxenes under high pressure impoverishes the parent magma in silica.

(3) Sinking and re-solution of biotite crystals, a process advocated by Bowen and Beger.

Among the sedimentary rocks through which the Navajo-Hopi vents were blasted, those of a calcareous nature are very subordinate, and almost restricted to the lower part of the Goodridge (Pennsylvanian) formation.

[29] A. Rittmann: *Die geologisch Bedingte Evolution und Differentiation des Somma-Vesuvmagmas,* Zeitschr. für Vulkanologie, vol. 15 (1933) p. 8-94.

[30] A. Holmes and H. F. Harwood: *Petrology of the volcanic fields east and southeast of Ruwenzori, Uganda,* Geol. Soc. London, Quart. Jour., vol. 88 (1932) p. 370-443.

Fragments of limestone are extremely rare as ejecta, and those observed are, at most, weakly marmorised. Though obviously far from conclusive, the available evidence lends no support to the view that the potassic magmas of this region have been de-silicated by reaction with calcareous deposits. Nor is there any evidence of a passive enrichment in potash by loss of soda into the wall-rocks. None of the fragmental ejecta appears to have suffered from sodic emanations.

Whether or not a depth-pressure control operated here, is still more difficult to answer with certainty. Backlund[31] and others have emphasised the generality that deep-seated granitic intrusions may be characteristic of orogenic phases, basaltic intrusions of epeirogenic phases, and alkaline intrusions of a perforation of stable continental areas (*epeirodiatresis*). It may be that the well-known concentration of Tertiary alkaline provinces in a broad, north-south zone, extending from central Montana, through Wyoming, western Colorado, and the Navajo country, to the Mexican border in western Texas, is related in some obscure way to tectonic influences. Many have advocated the theory that alkaline magmas migrate away from regions of active folding to regions of comparative stability, but the process is difficult to conceive in detail and fails to explain the separation of sodic from potassic magmas. If high-pressure eclogites were ever developed at depth beneath this north-south alkaline zone, none has been discovered among the exploded ejecta.

The sinking of biotite crystals, though a possible cause of the potassic character of the Navajo rocks, may be objected to on the grounds that the mineral usually forms at such a late stage that it may no longer be able to sink in large amount. Moreover, resorbed biotite is very rare among the ejecta of the Navajo volcanoes.

A fourth, and preferred, hypothesis involves the selective solution of granitic rocks by an ultrabasic magma. That this is not an idle speculation is borne out, first, by the granite-minette association already noted, and, second, by the fact that many of the granitic fragments blown out of the Navajo vents have suffered a partial solution of their alkali feldspars. It may be noted, in passing, that granitic xenoliths are occasionally to be found among the volcanic rocks of the Leucite Hills of Wyoming. Moreover, the minettes of other regions are rich in corroded xenocrysts of quartz, and, less commonly, of alkali feldspar, possibly because of partial assimilation of granite by basic magma.

If the potassic stamp of the Navajo magma is primarily due to the preferential solution of alkali feldspars in a body of Archean granites,

[31] H. G. Backlund: *On the mode of intrusion of deep-seated alkaline bodies*, Geol. Instit. Upsala, Bull., vol. 24 (1933) p. 1-24.

it is clear that the original magma was one rich in lime, iron, and magnesia and low in both silica and alumina. Such a magma is approximated by the most basic of the monchiquites analysed (No. 1, page 166), the one from Wildcat Peak. The settling and re-solution of olivine crystals from the Hopi monchiquitic magma might provide the requisite parent. That the minettes and monchiquites of the Navajo-Hopi region are intimately related, is beyond question. It is enough to recall that in certain intrusions the two types actually grade into each other. Nor does it seem unlikely that in some way the minettes were derived from the monchiquites. The monchiquites were extruded in regions free from, or poor in, granitic xenoliths and may be assumed to approximate most closely the original magma of the Navajo-Hopi province. Dissolving the feldspars of the potash-rich granites, and, perhaps, to a lesser extent, the magnesian minerals of the granites and associated ultrabasic rocks, this monchiquitic magma might have given rise to the minette-sanidine basalt assemblage of the Navajo volcanoes.

How the monchiquitic magma, in turn, was derived is not clear, though it is of interest to recall, in view of Bowen's suggestion,[32] that some sodic magmas may be developed by the sinking and selective solution of hornblende, that crystal lapilli largely composed of hornblende are far from rare among the ejecta of the Hopi volcanoes. Possibly, on the other hand, the monchiquitic magma was derived from an ultrabasic parent by an agpaitic type of differentiation, involving the early separation and upward floating of alkali feldspar and feldspathoidal minerals. If such a hypothetical ultrabasic parent ever existed, how did it originate? Could it have been from a deep-seated peridotite layer, or by the palingenesis of the basic complements of the Archean granites? Is it mere coincidence that in this region of magnesia-rich volcanic rocks, the fragments torn up from the Archean basement include many pyrope-bearing plutonic types, a few harzburgites, lherzolites, norites, and talc-rich schists?

Some might argue that the potassic stamp of the Navajo igneous rocks is not the result of partial assimilation and that the minette-granite association is fortuitous. They might affirm that the potassic stamp goes further back, to a biotite pyroxenite magma derived from a primary peridotite. In support of their view, they could point to the similarities between the Navajo minette-trachybasalt suite and biotite pyroxenite, and they could say that the highly explosive character of the Navajo volcanoes accords well with the idea of a volatile-rich biotite pyroxenite parent magma.[33] It must be admitted that there is nothing in the pre-

[32] N. L. Bowen: *Evolution of the igneous rocks* (1928) p. 270-273.

[33] For a stimulating discussion of "The Genetic Significance of Biotite-Pyroxenite and Hornblendite," *see* D. L. Reynolds: Min. u. petr. Mitt., vol. 46 (1935) p. 447-490.

ceding notes to disprove such a contention. But to speculate further on these interesting problems is beyond the scope of this report.

DEPTH OF THE MAGMA RESERVOIRS

The maximum thickness of the pre-Cretaceous sediments resting on the pre-Cambrian floor of the Navajo region is approximately a mile, but the average thickness is only about 4,500 feet. Most of the volcanic necks rose to the surface where the Jurassic cover had already been removed; at such places, the pre-Cambrian rocks are no more than half a mile below the surface. Unfortunately, the thickness of the Algonkian rocks is unknown. They are exposed to a thickness of 100 feet near Fort Defiance,[34] but in the core of the Zuni uplift they are absent. It is clear, therefore, that the presence of Archean metamorphic and plutonic fragments among the products of the Navajo-Hopi volcanoes does not necessarily imply a deep source for the magma. At some vents, the fragments may have been carried upward for only 3,000 feet.

The wide extent and more or less random scattering of the volcanoes suggests broad reservoirs of sill-form, such as might readily form at the contact of the Archean and overlying rocks. Small cupolas on the upper surfaces of such reservoirs might determine the location of the vents. The highly explosive character of the volcanoes and their close spacing accord well with the idea of shallow magmatic supplies.

From the paucity of metamorphism, both in the included xenoliths and in the walls of the necks, it is concluded that the explosions were of low temperature and that they were essentially phreatic in type, resulting principally from the tension of water vapor.

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[34] According to N. E. A. Hinds [*Ep-Archaean and Ep-Algonkian intervals in western North America*, Carnegie Instit. Wash., Pub. 463 (1935) p. 22-23] these rocks resemble the pre-Beltian Mazatzal quartzites of central and southern Arizona.