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## Contents

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# Preliminary Petrology and Chemistry of Late Cenozoic Basalts in the Western Grand Canyon Region

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ABSTRACT: Late Cenozoic basaltic volcanism in the western Grand Canyon region of northwestern Arizona and adjoining Utah affords an opportunity to investigate the interrelations of volcanism and concurrent vertical tectonic movements, the origin and evolution of basaltic magmas, and the character of the upper mantle beneath an evolving plateau province. This paper presents preliminary data gained from a long-range petrographic and chemical study of the basalts, the puropse of which is to provide some answers to these fundamental geologic problems.

Although the lavas are all essentially alkali olivine basalts, considerable and significant variations occur in their mineral and chemical composition, allowing discrimination of at least six basalt-types. These types range from a mafic basalt rich in olivine and clinopyroxene and having 45 wt. % silica to basalts carrying xenocrysts of complexly zoned plagioclase and quartz with 52 wt. % silica. Gamma-ray spectrometry discloses certain types, including the most mafic basalts, contain as much as 1.5% K, 11 ppm Th, and 3 ppm U, whereas other types have much lower concentrations of these heat-producing elements, near values for average worldwide alkali olivine basalts. Ultramafic inclusions containing partially decomposed orthopyroxenes, as well as clinopyroxene and olivine, are unique to the youngest basalt flows in the southeastern part of the region. The lack of systematic chemical variations in the basalts as a function of time, together with basalt-types of similar age but greatly different compositions adjacent to one another, indicates several primitive or parental magmas were involved.

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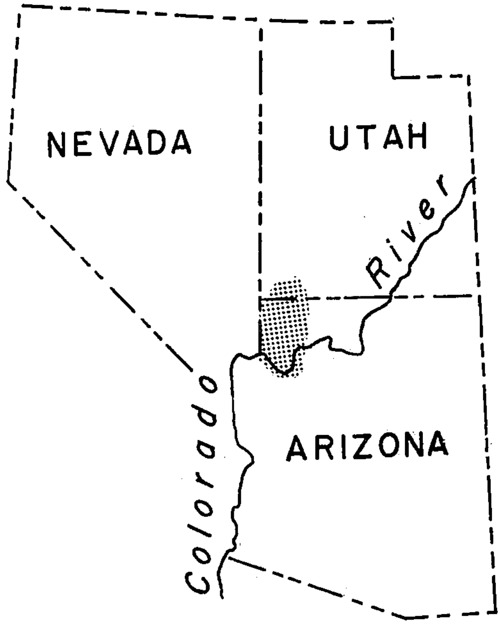
TEXT




TEXT-FIGURE 1.—Stippled pattern covers the area of this report.

## INTRODUCTION

Late Cenozoic basaltic volcanism in the western Colorado Plateaus was recognized by Powell (1875) and Dutton (1882) in their surveys of the region some 90 years ago. In subsequent investigations of the volcanic history of southern Utah by Gregory (1950) and of northwestern Arizona by Colton (1937) and Koons (1945) the basalts were considered in a geomorphic context, serving perhaps as means to a better understanding of regional geologic history. Current investigation by Hamblin (1963, and *ms*) indicates at least 16 periods of extrusion, during which recurrent movement developed along the major north-south normal faults marking the western margin of the Colorado Plateaus province. The basalts, therefore, serve as valuable keys in elucidating the history of tectonic movements and erosional processes in this region during the Late Cenozoic.

In all these earlier investigations only slight passing attention has been given to the mineralogy and chemistry of the basalts themselves, it being thought that they are all of uniform character, lacking any significant variations. In a preliminary petrographic examination of samples from the western margin of the Colorado Plateaus (hereafter referred to as the western Grand Canyon region, Text-fig. 1) it was indeed found that there is a uniformity in mineralogy; all are essentially alkali olivine basalts, being composed simply of plagioclase, Ca-rich clino-pyroxene, olivine, and Fe-Ti oxide. However, conspicuous and fundamental variations appear in the compositions of each of these minerals and as well in their modal proportions. Although less than 100 samples have been examined thus far from the entire region, petrographic types can be recognized having limits in both space and time.

Chemical analysis for major elements in 3 samples and for Th, U, and K in 40 others confirms that the chemical variations suggested by petrographic study are real and significant. For example, silica ranges from slightly under 45 wt. % to slightly over 52 wt. %. Th, U, and K concentrations range from values below those for average, worldwide alkali olivine basalt to values among the highest known.

This paper is a progress report on a long-range petrological and chemical investigation of the Late Cenozoic basalts in the western Grand Canyon region with the intended aim of casting light on the related problems of tectonic history and geophysical processes in the crust and upper mantle.

## ACKNOWLEDGMENTS

Appreciation is expressed to J. A. S. Adams and Rice University for their cooperation in the determination of Th, U, and K in the samples while W. H. Brimhall was on leave from Brigham Young University. J. Keith Rigby provided helpful assistance on the project and criticism of the manuscript.

Expenses for field work, thin sections, and the four major element chemical analysis were defrayed by a National Science Foundation grant GP-3923 to W. K. Hamblin.

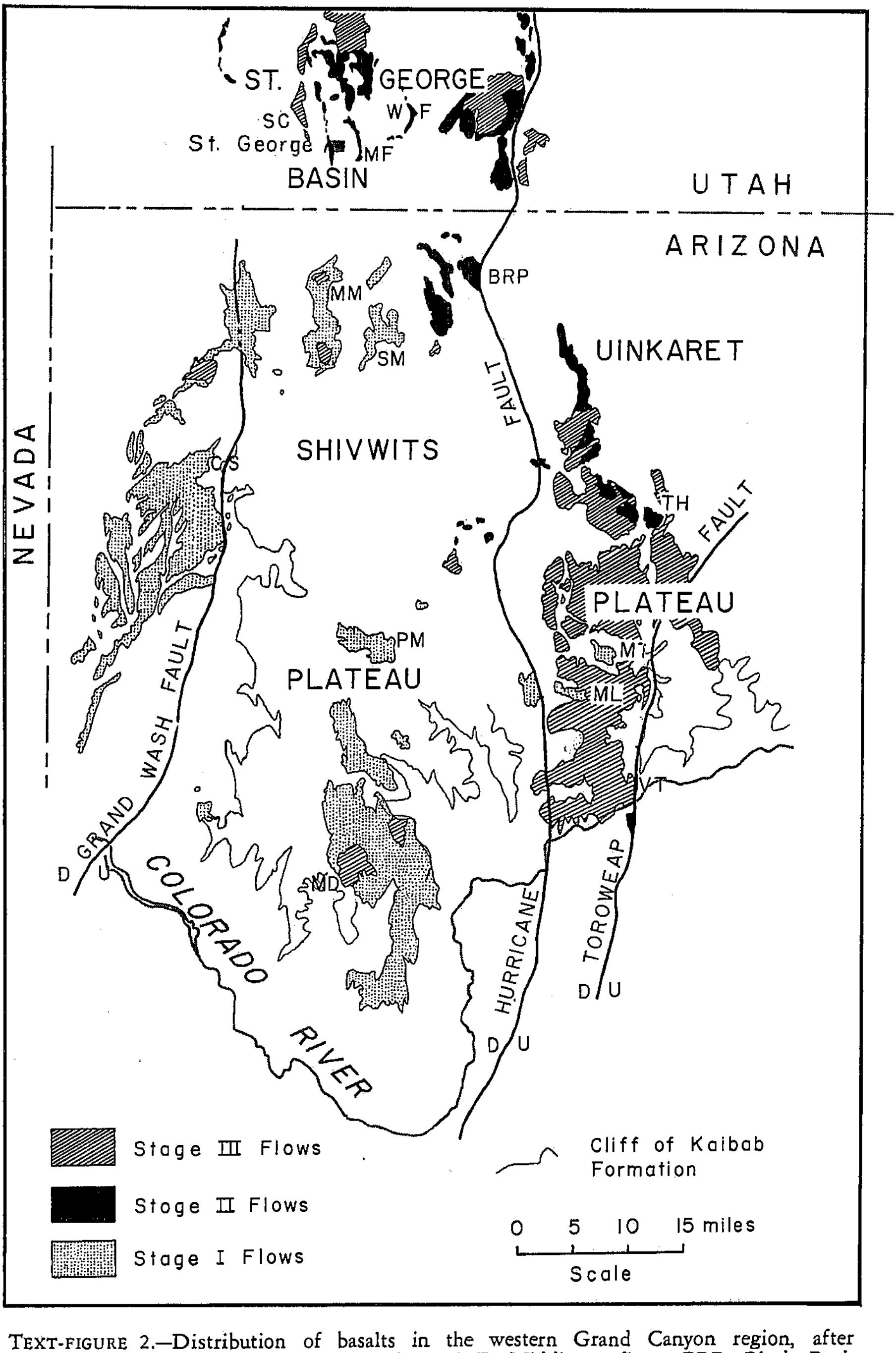
## CLASSIFICATION

Hamblin (1963, and *ms*) has established a chronologic grouping of basaltic flows in the region based primarily on the nature of the surface on which they were deposited. The oldest lavas*, Stage I, were extruded onto erosion surfaces bearing no relation to the present drainage system. They now cap high level mesas. Lavas of intermediate age, Stage II, were deposited on surfaces which can be demonstrated to be ancestral to the present drainage system. They occur on pediments, stream terraces, and on moderately high mesas in the region. Classic Stage II lavas near St. George, Utah, have caused development of inverted valleys; i.e., sinuous lava-capped mesas produced by erosion of soft rock from around lava-filled stream channels. Stage III lavas are defined as those which have been extruded on erosion surfaces of the present erosional system. Cinder cones are commonly associated with these young flows. The generalized distribution of the basalts, arranged by stages, is shown in Text-fig. 2, together with pertinent geographic names mentioned in this paper.

Petrographic basalt-types recognized in this preliminary investigation on the basis of mineralogical composition and certain textural features do not, in every case, correspond to the grouping by stages explained above. In this paper the basalts will be described in a petrographic context, rather than by stages. Each basalt-type will bring together basalts having common petrographic characteristics, the name for the type being drawn from a prominent occurrence exemplifying the type, as follows:

Segmiller Mountain Type
Middle flows above Cane Springs
Poverty Mountain Type
Middleton Type

*Although radiometric age dates on the basalts are pending, it is reasonable to expect an early Pliocene or perhaps late Miocene age for the oldest lavas.




TEXT-FIGURE 2.—Distribution of basalts in the western Grand Canyon region, after Hamblin (ms). SC, Santa Clara flow; MF, Middleton flow; BRP, Black Rock Pass; SM, Segmiller Mountain; CS, Cane Springs; TH, The Hat; PM, Poverty Mountain; MT, Mount Trumbull; ML, Mount Logan; VT, Vulcan's Throne; MD, Mount Dellenbaugh.

## Explanation of Plate 1

### PHOTOMICROGRAPHS OF BASALTS

FIG. 1.—Poverty Mountain type of basalt. Groundmass consists of minute granules of colorless clinopyroxene and slightly larger olivines jacketed by dark hematitic borders. The glomeroporphyritic clot (1.2 mm. in diameter) includes an olivine with a dark alteration border, a fresh, pale green clinopyroxene, and rather homogeneous bytownite subhedra.

FIG. 2.—Washington type of basalt. Slightly vesicular rock comprised of abundant olivine, zoned, pale brown clinopyroxene, and equant Fe-Ti oxides with minor amount of lathlike plagioclase. ol=olivine; cp=clinopyroxene. Photomicrograph is 1 mm. in length.

FIG. 3.—Segmiller Mountain type of basalt. Fine granules of olivine and colorless clinopyroxene crowd between laths of plagioclase. Fe-Ti oxide grains are somewhat larger. Phenocrysts of olivine (longer length of one in photo is 0.6 mm.) are scattered throughout the basalt.

FIG. 4.—Middleton type of basalt. Laths of plagioclase, barbed Fe-Ti oxide, and irregular colorless clinopyroxene make up the groundmass. Microphenocrysts of olivine occur elsewhere in the rock. Characteristic of this type of basalt are xenocrysts of quartz, with reaction rims of fibrous pyroxene and brown glass, and large, complexly zoned and inclusion-filled, probably xenocrystic, grains of plagioclase. Quartz xenocryst is 2 mm. long.

## Explanation of Plate 2

### PHOTOMICROGRAPHS AND COMPOSITIONAL VARIATIONS OF PLAGIOCLASE XENOCRYSTS IN THE MIDDLETON FLOW

FIG. 1.—Variation of An content in an east-west traverse across the larger phenocryst. Dotted portion of diagram indicates extent of inclusion-rich zone in plagioclase. Crossed nicols.

FIG. 2.—The outer margin of an anhedral xenocryst 5 mm. in diameter. Traverse indicating variation in An content runs east-west through twin lamellae (nearly extinguished) from left-hand margin of photo. Crossed nicols.

## Explanation of Plate 3

### PHOTOMICROGRAPHS OF BASALT AND ULTRAMAFIC INCLUSION

FIG. 1.—Peridotite inclusion from the Vulcan's Throne flow. Large olivine (ol), clinopyroxene (cp) and orthopyroxene (op) grains are surrounded by a finer aggregate of olivine, clinopyroxene, oxide, and plagioclase. The dark material around the orthopyroxenes was presumably formed by decomposition of the orthopyroxene, which is unstable at atmospheric pressure in magmas of the composition represented by the Vulcan's Throne flow. The photo is 5 mm. in length.

FIG. 2.—Santa Clara flow. Vesicular basalt containing fresh olivine phenocrysts set in a matrix of plagioclase laths with granules of olivine, clinopyroxene, and Fe-Ti oxide. Some dark turbid glass is present; Photo is 2 mm. long.

FIG. 3.—Enlarged view of decomposition rim on orthopyroxene (near extinction position under crossed nicols). Length of photo is 0.9 mm. The rim is a parallel intergrowth, parts of which are in optical continuity with one another and with either the planar lamellae or the "granule" lamellae in the adjacent orthopyroxene. Optical identification of the phases in the intergrowth is difficult, but clinopyroxene appears to be dominant.

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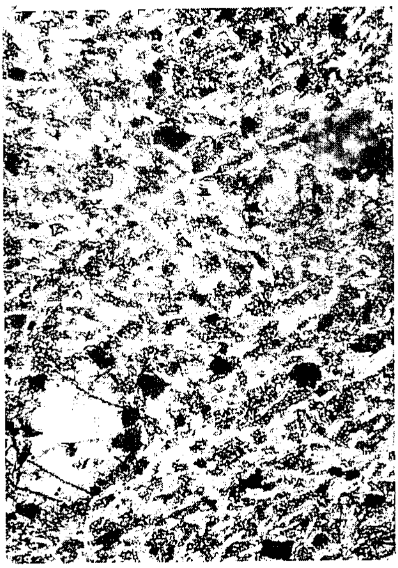

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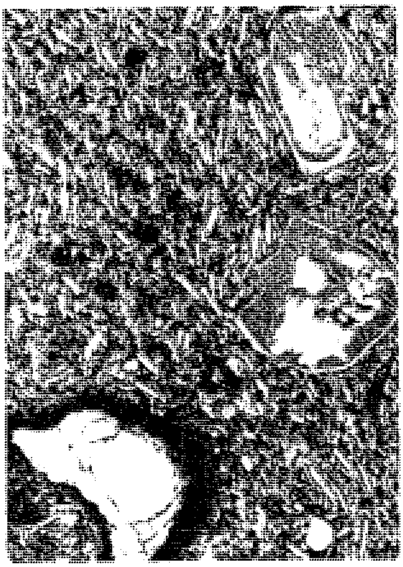

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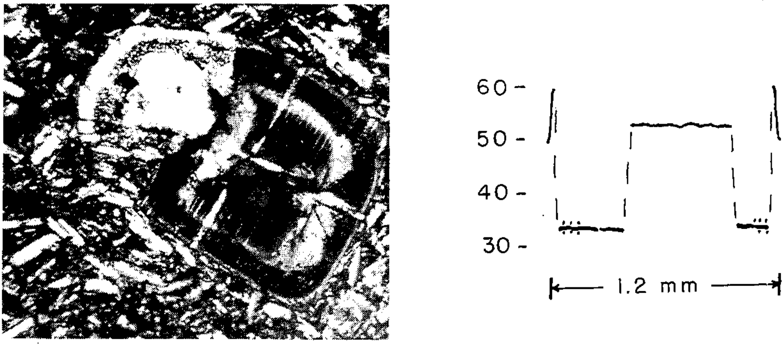
PHOTOMICROGRAPHS OF BASALT

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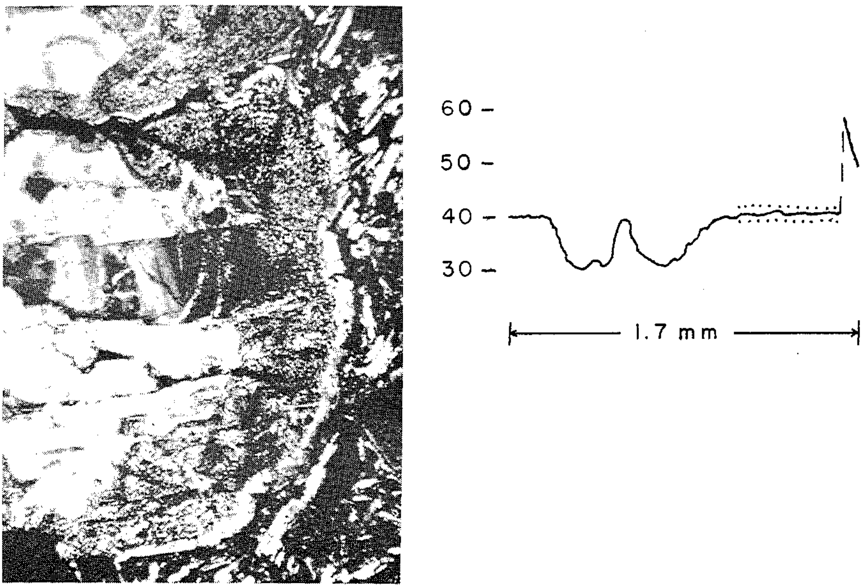


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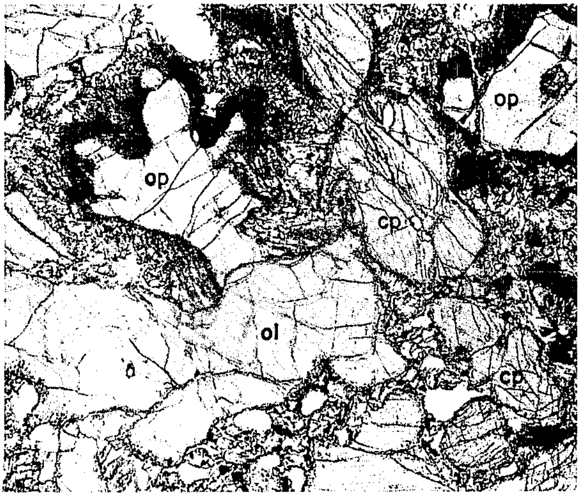
PLAGIOCLASE PHOTOMICROGRAPHS AND COMPOSITIONAL VARIATIONS IN THE MIDDLETON FLOW




1

2

3

PHOTOMICROGRAPHS OF BASALT AND ULTRAMAFIC INCLUSION

Washington Type
Craig's Knoll Type

In addition to these relatively widespread basalt-types, there are samples of rather unique Stage III lava flows not yet assigned to any type and which will be described separately. These flows are the Santa Clara and the Vulcan's Throne. Further work now in progress may necessitate revision of the basalt-types as conceived in this paper.

## PETROGRAPHY

*Segmiller Mountain type.*—The most widespread basalt-type in the region occurs as flows of Stage I west of the Grand Wash fault, in the northern part of the Shivwits Plateau at Moqui Mtn. and Segmiller Mtn., and in the Uinkaret Plateau at Mt. Trumbull and Mt. Logan. In hand specimen, this rock type, here called the Segmiller Mountain type, is medium gray with conspicuous small phenocrysts of olivine, generally showing marginal alteration to red-brown Fe-oxide. In thin section, the texture is intergranular, less commonly pilotaxitic. The principal constituent is slightly zoned andesine-labradorite. A smoky green clinopyroxene occurs as small aggregated granules between the plagioclase laths and only very rarely as phenocrysts. Olivine occurs both as phenocrysts and as a groundmass constituent. Every sample has individual and aggregated magnetite grains containing a small amount of (exsolved ?) ilmenite. Apatite is present in minute amounts. A typical sample, 58, having an average grain size is shown in Plate 1, fig. 3. Optical data on constituent minerals of the same sample are shown in Table 1.

*Middle flows above Cane Springs.*—These flows consist of a thick sequence of gray diabases of Stage I. Abundant fresh plagioclase, together with lesser amounts of dark pyroxene and olivine, the latter jacketed by orange-brown oxide, can be seen in hand specimen. Angular vesicles comprise a few percent by volume of samples from central portions of the flows, whereas samples from the exposed bases are scoriaceous and strongly oxidized. Aligned plagioclase laths characterize many parts of the flows. Laced through the flows are planar dikelets, 1-3 inches in width, superficially resembling the diabase but consisting of finer basaltic material with abundant rounded vesicles.

In thin section, the plagioclase in the diabase is found to be quite homogeneous with only slight peripheral normal zoning. Dotted throughout the mosaic of aligned plagioclase laths are large, pale brown anhedra of clinopyroxene and a lesser quantity of peripherally oxidized olivine. Some clinopyroxene anhedra are aggregated together into clots 2-3 mm. in diameter. Smaller clinopyroxenes, interstitial to the laths of plagioclase as well as the rims of large clinopyroxenes, are darker brown and have a lilac tint, indicating enrichment in $TiO_2$. Fe-Ti oxides in the diabases are typically barbed rods but some are irregular in outline, still fewer are cubic.

The basaltic dikelets contain no olivine, the mafic minerals being a dark, lilac-brown clinopyroxene, an oxide (approximately 15 modal %), and several percent of acicular, very pale green amphibole of undetermined character. The plagioclase is $An_{40}$. It would appear that these dikelets represent late differentiated liquids derived, perhaps by filter pressing, from the enclosing diabase and injected along planes of weakness in the just crystallized parts

TABLE I
Optical & Compositional Data on Minerals in the Grand Canyon Basalts

| Sample | Plagioclase[1] mole % An | Clinopyroxene[2] $2V_z$ | Olivine[3] mole % $F_0$ | Location of Sample |
|---|---|---|---|---|
| | *Segmiller Mtn. Type* | | | |
| 15A | 53 | 52 | 74 | middle flows (diabase) Cane Springs |
| | 40 m | 52 | | middle flows (basaltic dikelets) Cane Springs |
| 72 | 48 m | 52 | | Mt. Logan |
| 54 | 60 m | | | west base of Mt. Trumbull |
| 58 | 48 | 51 | 72 | west of Hurricane fault and Mt. Logan |
| | *Poverty Mtn. Type* | | | |
| 25 | 73, 76, 79 p | 53 | | west Poverty Mtn. |
| 24 | 45 m | | 79 | east central Shivwits Plateau |
| 26 | 37 m | 54 | | east central Shivwits Plateau |
| | 58-70 p | | | |
| 63 | 52 m | 54 | | Black Rock Pass |
| | 58-63 p | | | |
| | *Middleton Type* | | | |
| 3 | 46 m | | | 3 miles northwest of St. George |
| 42 | 49 m | | 83 | Middleton flow along highway east of St. George |
| | 32-58 p | | | |
| | *Washington Type* | | | |
| 8 | | 51-60[4] | 86[5] | east central Moqui Mtn. |
| | *Craig's Knoll Type* | | | north Moqui Mtn. |
| 68 | 45 m | | 87[5] | |
| | *Santa Clara Flow* | | | |
| 4 | | | 82[5] | head of Santa Clara flow along Highway |
| 5 | 48 m | absent | 78 | toe of Santa Clara flow south of Highway 91 |
| | *Young Stage III flows on Uinkaret Plateau* | | | |
| 30 | | | 85[5] | flow beneath Vulcan's Throne |
| 37 | 42 m | 50 | 85 | east of Hurricane fault, 8 miles north of state line. |
| 57 | 47 m | | 78[5] | cascade (?) on southeast side of Mt. Trumbull |

[1]The number indicated for microlites (m) was derived from the maximum extinction angle in sections ⊥ to (010) using the high temperature curve of Tröger (1959, p. 111); that for phenocrysts (p) was obtained by the bisectrix method using the high temperature curves of Tröger (1959, p. 101) or by the universal stage using curves of Slemmans (1962).
[2]$2V_z$ was measured by direct rotation between two axes on the universal stage; precision 1°.
[3]Measured by the X-ray method of Yoder and Sahama (1957); precision $< 1\%$.
[4]Rims have values in the low 50's, the cores in the high 50's. Analyzed sample was concentrate of core material.

of the flows. Kuno (1965) reached similar conclusions on other basaltic dikelets.

*Poverty Mountain type.*—Available samples from the southern part of the Shivwits Plateau plus samples from the flows at Black Rock Pass and at "The Hat" are of a type resembling the Segmiller Mountain type. They are called the Poverty Mountain type and occur as both Stage I and II flows. The groundmass is similar to the Segmiller type but in addition to ubiquitous phenocrysts of marginally decomposed olivine there are scattered phenocrysts of euhedral to subhedral labradorite-bytownite and Ca-rich clinopyroxene, (Plate 1, fig. 1). Weak oscillatory zoning is evident in some plagioclases; the pyroxenes are pale green, some very weakly zoned to darker rims, and commonly seived with groundmass material. Glomeroporphyritic clots up to 2.5 mm. in diameter of pyroxenes and plagioclases are characteristic of this rock type.

*Middleton type.*—Certain classic Stage II flows occurring as inverted valleys in the St. George Basin, plus the Stage II Pintura flows northeast of Hurricane, may be designated as the Middleton type. These flows are characterized by phenocrysts of complexly zoned plagioclase as much as 1 cm. long and constituting up to about 10% of the rock. The euhedral to subhedral crystals have a clear but narrow calcic rim enclosing an extensive area, quite sodic in composition, generally rounded in outline, and pervasively riddled with dusty opaque particles or matrix material in a crude mesh pattern. Inside this zone of inclusions there is, in some phenocrysts, a clear core of similar composition or one zoned towards more calcic compositions. The nature of this complex zoning is portrayed by the universal-stage data in Plate 2. These phenocrysts are remarkably similar to those from lavas of the San Juan Mountains illustrated by Larsen *et al.* (1938, especially figs. 15b, 16a, b) which were interpreted by them as xenocrystic. It is certain that at least some time during the magmatic history of the Middleton-type flows, these complex phenocrysts experienced resorption in the melt. Following partial resorption, magmatic conditions shifted, possibly upon extrusion of the lava, and the thin clear rims formed on the partially resorbed grains. In addition to xenocrystic plagioclase, some samples include 1 to 2% of glassy quartz xenocrysts—embayed and jacketed by brown glass and aggregated acicular clinopyroxene. Olivine is sparse. Pale green to brown clinopyroxene occurs mainly in the groundmass, although phenocrysts are common; a few have seived cores and one instance was found where such grains were clustered around an embayed xenocryst of hypersthene.

A chemical analysis of the sample from the Middleton flow, Table 2 (see also Plate 1, fig. 4) discloses the presence of considerable silica such that quartz is abundant in the norm. Fe is abundant compared to Mg. The feldspathic character of the rock is attested by the presence of 63% feldspar in the norm.

*Washington type.*—Unusually mafic basalts constitute the Washington flow (a classic Stage II inverted valley flow), a dike and associated small flow remnant 8 miles due south of Hurricane, and a flow on a small flanking terrace on the east side of Moqui Mountain. The latter two occurrences are possibly Stage II but accurate geomorphic classification is difficult. In hand

TABLE 2

Chemical & Normative Compositions of Some Basaltic Rocks from the western Grand Canyon region (A. G. Loomis, analyst)

| | 8<br>Stage II (?)<br>Washington type | 42<br>Stage II<br>Middleton type | 4<br>Stage III<br>Santa Clara flow |
|---|---|---|---|
| $SiO_2$ | 44.72 | 52.33 | 49.82 |
| $TiO_2$ | 1.94 | 1.81 | 1.57 |
| $Al_2O_3$ | 11.87 | 16.90 | 16.13 |
| $Fe_2O_3$ | 3.23 | 2.14 | 1.67 |
| FeO | 7.31 | 6.14 | 10.17 |
| MnO | 0.19 | 0.14 | 0.19 |
| MgO | 12.97 | 3.47 | 8.88 |
| CaO | 12.17 | 11.40 | 8.78 |
| BaO | 0.08 | 0.03 | 0.03 |
| SrO | tr | 0.00 | 0.00 |
| $Na_2O$ | 2.42 | 3.26 | 2.37 |
| $K_2O$ | 1.23 | 1.62 | 0.59 |
| $H_2O^+$ | 0.49 | 0.04 | 0.22 |
| $P_2O_5$ | 0.67 | 0.48 | 0.26 |
| TOTAL | 99.29 | 99.76 | 100.68 |
| Q | 0.00 | 0.00 | 1.26 |
| Or | 3.34 | 7.24 | 9.46 |
| Ab | 19.93 | 8.39 | 27.80 |
| Ne | 0.00 | 6.53 | 0.00 |
| An | 31.72 | 17.81 | 26.71 |
| Di | 8.18 | 30.37 | 22.14 |
| Hy | 25.68 | 0.00 | 4.69 |
| Ol | 5.55 | 18.55 | 0.00 |
| Mg | 2.31 | 4.63 | 3.01 |
| Il | 3.04 | 3.64 | 3.49 |
| Ap | 0.62 | 1.55 | 0.93 |
| S.I.* | 47.7 | 20.8 | 37.5 |
| D.I. | 22.2 | 38.5 | 23.3 |

$$*\text{S.I.} = \frac{\text{MgO} \times 100}{\text{MgO} + \text{FeO} + \text{Fe}_2\text{O}_3 + \text{Na}_2\text{O} + \text{K}_2\text{O}}$$ wt. %; D. I. = Σ normative kalsilite, nepheline, leucite, albite, orthoclase, quartz in wt. %.

specimen, the rock, designated as the Washington type, is a dense black aphanite dotted with small dark phenocrysts. Locally, the rock disintegrates into polyhedrons one or two centimeters in diameter.

Under the microscope it is found that clinopyroxene and olivine comprise more than half the rock, the olivine occurring as euhedral phenocrysts up to 2 mm. long and the pyroxene as somewhat smaller and less abundant phenocrysts and as an important groundmass constituent. The pyroxene is prismatic, having moderate dispersion and a stronger brown color on the margins than the cores. Chemical analysis of a concentrate of the lighter colored cores discloses (Table 3) the pyroxene is an augite with a high content of MgO and $Al_2O_3$. The remainder of the groundmass of this rock consists of a turbid material containing obvious cubic magnetite, some of rather large size, and minute laths of plagioclase, too small for optical determination of their composition (Plate 1, fig. 2).

TABLE 3

Composition of Clinopyroxene from sample 8 (A. G. Loomis, analyst).

| | wt. % | numbers of atoms per 6 O | | |
|---|---|---|---|---|
| $SiO_2$ | 48.85 | Si | 1.790 | 2.000 |
| $TiO_2$ | 1.40 | Al | 0.208 | |
| $Al_2O_3$ | 4.81 | Ti | 0.002 | |
| $Fe_2O_3$ | 2.42 | Ti | 0.038 | 2.063 |
| FeO | 4.52 | $Fe^{+3}$ | 0.066 | |
| MnO | 0.13 | $Fe^{+2}$ | 0.139 | |
| MgO | 19.04 | Mn | 0.004 | |
| CaO | 18.27 | Mg | 1.041 | |
| $Na_2O$ | 0.74 | Ca | 0.719 | |
| $K_2O$ | 0.13 | Na | 0.052 | |
| $P_2O_5$ | 0.07 | K | 0.004 | |
| TOTAL | 100.38 | Ca 36.5%; Mg 52.9%; $Fe^{+2}$ + $Fe^{+3}$ + Mn 10.6% | | |

A chemical analysis and a normative calculation of the sample from Moqui Mountain (Table 2) reveal the mafic character of this rock type; abundant alkalies and low silica being reflected in the appearance of over 7% orthoclase and 6% nepheline in the norm.

*Craig's Knoll type.*—These basalts, named from a hill 5 miles north of Mt. Trumbull, are essentially plagioclase-rich variants of the Washington type, the textures and optical properties of other constituents being similar. It is found as the earlier Stage III flows on the Uinkaret Plateau, the "A" and "B" flows of McKee and Schenk (1942) in ancestral Toroweap Valley, the basal flow at Prospect Point across the Colorado River from Toroweap Valley, most of the intra-canyon flow remnants in the canyon of the Colorado River from Prospect Point to Lake Mead, at Volcano Mountain west of Hurricane, and in the northern part of Moqui Mountain.

*Young Stage III flows.*—Available samples of the young Stage III basalts in the region are generally hypocrystalline, the glass being practically opaque because of abundant Fe-oxide particles. Glassy, light green olivine is common, both as phenocrysts and in the groundmass. Pyroxenes, restricted to the groundmass, are pale brown and prismatic.

One of the youngest Stage III flows—the Santa Clara northwest of St. George—has been chemically analyzed (see Table 2); it has a moderate amount of $SiO_2$, high FeO and $Al_2O_3$, but $K_2O$ is low compared to the other basalts in the region (see also data in the next section). A photomicrograph of this basalt is shown in Plate 3, fig. 2.

Young Stage III flows on the Uinkaret Plateau—the lava cascade associated with the cinder cone of Mt. Trumbull and the Vulcan's Throne flows—are unique basalts in the entire western Grand Canyon region because they contain rather abundant clots or inclusions of aggregated olivine and pyroxene. Blocks of similar aggregates lie scattered upon the slopes of Vulcan's Throne. Most inclusions are olivine-rich peridotite in which the olivines are coated with brick-red Fe-oxide. Dark green, olivine-bearing pyroxenites are less abundant, as are single, isolated anhedral crystals of jet black clinopyroxene up to 3 cm. in diameter (in the Vulcan's Throne flows). The texture in the peridotites and pyroxenites is typically xenomorphic; veinlets of basaltic material commonly permeate the pyroxenites along grain margins. Olivines are rich in the forsterite end-member (95% for inclusions in Vulcan's Throne flows and 97% for a block from the cone). Clinopyroxene ($2V_z$ 55°) and orthopyroxene seem about equally abundant in the pyroxenite inclusions but orthopyroxene is dominant or exclusive in peridotite.

Exsolution lamellae parallel to (100) are very weak in orthopyroxene of peridotite but strong in both pyroxenes of pyroxenites. Clinopyroxene grains tend to be smaller than the amoeba-like orthopyroxenes, some of which range up to 2 cm. and enclose the smaller olivines and clinopyroxenes. Orthopyroxenes show weak to strong pleochroism. Deep brown spinel was noted in peridotites. The network of basaltic material in the inclusions is not entirely related to physical entrance of host magma into a disintegrating inclusion. Much is related to chemical breakdown of the orthopyroxene, for these grains have conspicuous reaction rims of granular or aggregated acicular clinopyroxene (?) (Plate 3, figs. 1 & 3). Plagioclase and olivine may also be a by-product of this reaction but further work is necessary before its exact nature is known.

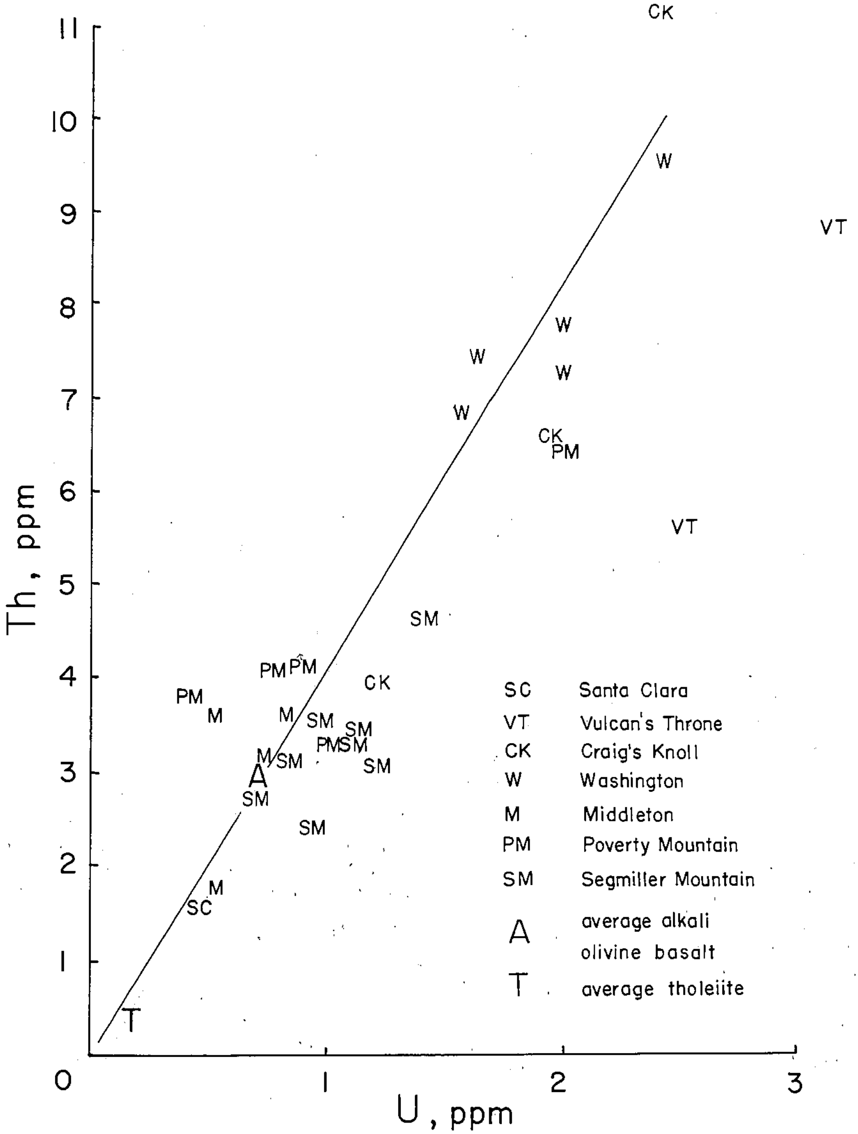
## Th, U, AND K IN THE BASALTS

Forty samples of basalt representing the major types of the region have been analyzed for Th, U, and K by Willis Brimhall using a gamma-ray spectrometer at Rice University. Variance of these elements, horizontally and laterally, within a single flow was not investigated in detail in this preliminary survey; however, analysis of 13 samples from 4 localities in the Santa Clara flow yielded standard deviations of 0.32 ppm, 0.11 ppm, and 0.05 ppm (20%, 25%, and 11%) for Th, U, and K, respectively.

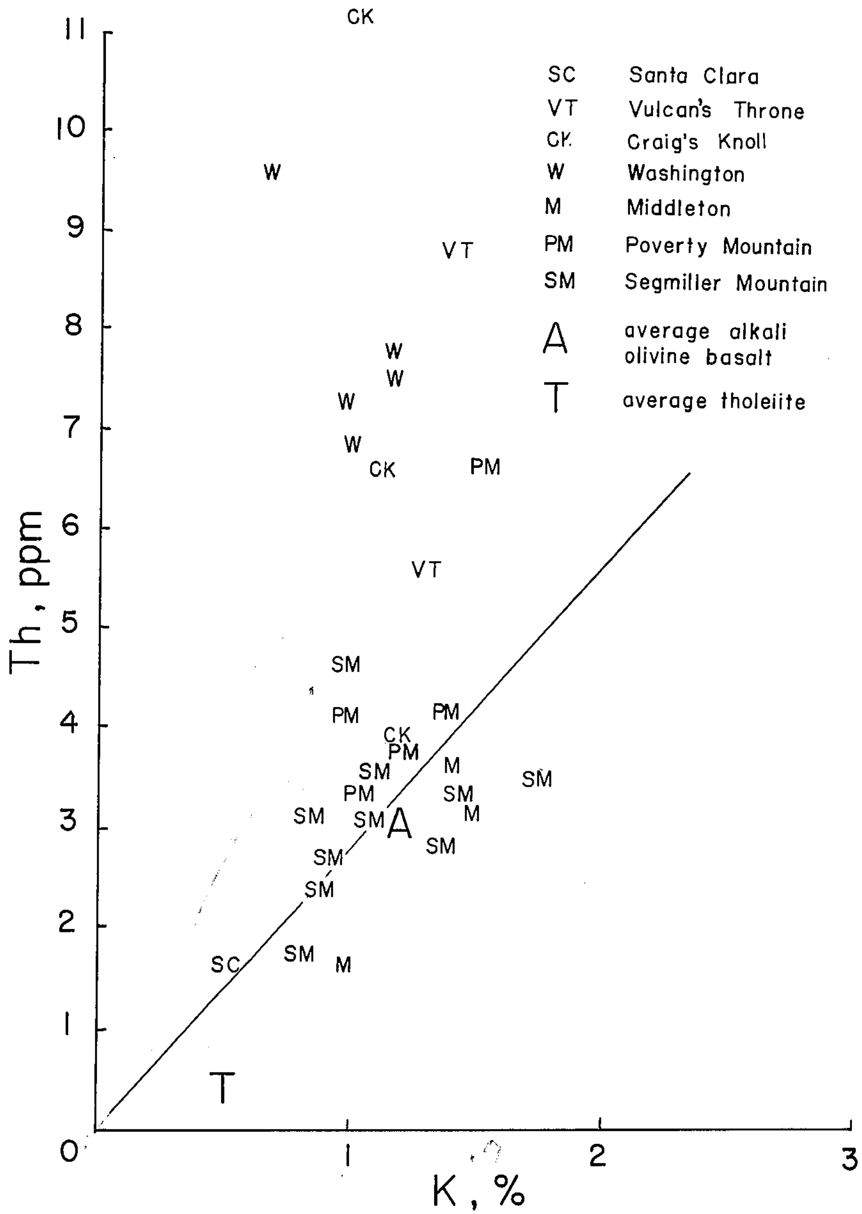
Four replicate analyses on a single sample of the Craig's Knoll type showed the analytical precision (as standard deviations) is 0.22 ppm, 0.23 ppm, 0.03 ppm (3%, 12%, and 3%) for Th, U, and K, respectively. If the "within-flow" variance and the analytical precision are compared to analyses on 28 other basalt flows, based on single analysis on a single sample, it is apparent (Text-figs. 3 & 4) that substantial variations in Th, U, and K occur on the scale of the region. Assuming that the individual analyses of flows plotted in Text-Figs. 3 & 4 are representative, one may make the following conclusions:

(1) There is a fairly consistent grouping of flows of a particular petrographic rock type, the major exception being the Craig's Knoll type, 3 analyses of which are widely scattered.

(2) All of the analyzed samples from the Grand Canyon region are richer in Th, U, and K than the worldwide average of tholeiitic basalts and most are richer than average alkali olivine basalts (averages from




TEXT-FIGURE 3.—Th and U concentrations in some basalts from the western Grand Canyon region. The line represents the mean U/Th ratio for Hawaiian basaltic rocks (after Heier *et al.*, 1964, Fig. 3). Data for average (worldwide) basalts are from Tatsumoto *et al.*, (1965).




TEXT-FIGURE 4.—Th and K concentrations in some basalts from the western Grand Canyon region. The line represents the mean K/Th ratio for Hawaiian basaltic rocks (after Heier *et al.*, 1964, Fig. 1). Data for average (worldwide) basalts are from Tatsumoto *et al.* (1965).

Tatsumoto *et al.,* 1965). The Santa Clara flow is particularly low in these heat-producing elements, whereas other late Stage III flows in the southern part of the region have very high concentrations of Th and U. The relatively mafic, silica-poor Washington type also has high concentrations of Th and U.

(3) The coherence of Th, U, and K, noted by Heier *et al.* (1964) in Hawaiian and other basalts holds true for Th-U but not for Th-K or U-K in the Grand Canyon basalts. Larger values of Th or U do not correspond with larger values of K in the Washington and Craig's Knoll types and Vulcan's Throne flow. (If it were not for the mafic basalts, mostly of Stage I but also the Washington flow (II), and some of Stage III near Mt. Trumbull, the coherence would be much better.) The coherence in the Th-U (i.e., the Th/U ratio) for the Grand Canyon basalts is displaced only slightly (0.5 ppm) toward higher U values, compared to the Japanese and Hawaiian values (Heier *et al.,* 1964), shown by the diagonal line in Text-figs. 3 & 4.

(4) Heier *et al.* (1964, p. 256) conclude that "the concentrations of thorium, uranium and potassium increase with petrogenic evolution, and the relative enrichment is thorium$>$uranium$>$potassium." Taking the three Grand Canyon basalts analyzed for major elements (Table 2) as an example, the sequence of evolving magmas would be according to samples 4, 42, and 8. Yet, the age relations are the reverse of this sequence. Consideration of other criteria, the differentiation index (D. I. $= \Sigma$ normative quartz, albite, orthoclase, leucite, kalsilite, and nepheline; Thornton and Tuttle, 1960) and the solidification index (S.I. $= MgO \times 100 / MgO + FeO + Fe_2O_3 + Na_2O + K_2O$ in wt. %; Kuno, 1965) indicates the sequence of evolution from primitive to differentiated magma should be 8, 4, and 42. Here, again, the age relations are scrambled. The only conclusion which can be drawn from the meager data at this point is that the Grand Canyon lavas did not all evolve from some single, primitive parent, nor is there necessarily a genetic relationship between many of the lavas. A more extended program of sampling and analyses is clearly needed.

## DISCUSSION & SOME TENTATIVE CONCLUSIONS

Basalt is the sole igneous rock-type exposed in the western Grand Canyon region; only to the north are other types—the silicic volcanics of the Great Basin and High Plateaus of Utah—found along with basalt. Mineralogically the basalts are fairly uniform, i.e., ubiquitous olivine, plagioclase, Fe-Ti oxide and Ca-rich clinopyroxene and lack of Ca-poor pyroxene, yet the proportions of the mineral constituents are variable and the chemical compositions of bulk basalt range from just ultrabasic (sample 8) to just intermediate (sample 42). Sample 8 has nepheline and sample 42 quartz in the norms. These mineralogical and chemical variations appear to occur relative to both space and time in the region.

It is apparent from the little data now available that differentiation of a single parent magma cannot explain all the observed compositional variations. It is more logical to consider the existence of several types of parent magmas from which the observed lavas were derived and likely differentiated to some extent. One might, for example, postulate that the Washington type of lava was such a primitive magma, yielding, perhaps the Craig's Knoll type. The Segmiller type might have yielded differentiates of the Poverty Mountain type. The Santa Clara flow with its remarkably low concentrations of Th, U, and K would appear to represent still another primitive magma.

The actual development of these parent and primitive magmas must lie within the upper mantle and it is an intriguing problem of fundamental concern to petrology as to how compositionally different magmas are produced.

Two especially interesting problems concern the origin of the inclusions of peridotite and pyroxenite in the Vulcan's Throne flow and xenocrysts of quartz and plagioclase in Middleton type flows.

It might be supposed that the inclusions represent accumulations of phenocrysts in the cooling lava. However, the flow lacks phenocrysts of any type of pyroxene, thus implying some other mode of origin. The presence of partially resorbed orthopyroxenes in the inclusions suggests that at least that phase was unstable in the magmatic environment just prior to solidification of the lava. Ultramafic inclusions have conventionally been interpreted as fragments from the upper mantle, caught up in the ascending magma. However, recent investigations (see for example, Kushiro, 1965; Kuno, 1964; Talbot, *et al.*, 1963) have suggested the alternate possibility that at high pressures, such as prevailing in the upper mantle and deep crust, phases precipitating from basaltic magma are of a different nature than those precipitating near surface. In simple basalt systems, Ne-Fo-$SiO_2$ and Di-Fo-En, increasing pressure causes the liquidus boundary between Fo and En to shift toward $SiO_2$-poor compositions. Thus, an alkali olivine basalt in which, at atmospheric pressure, Ca-poor pyroxene is unstable, could, at high pressure, crystallize it stably. Such Ca-poor orthopyroxenes brought from depth could exhibit resorption relations in surface lavas. If this argument is to be applied to the inclusions at Vulcan's Throne, one must also account for the presence of abundant Ca-rich clinopyroxene along with the resorbed orthopyroxene. Another unexplained point concerns the black clinopyroxenes occurring as single large crystals in the lava, which are different from the green ones in the inclusions.

It might seem reasonable to suppose that the xenocrysts in the Middleton flows were derived from crustal rock bordering the volcanic conduit and incorporated into the ascending magma. The fact that other nearby basalts (viz. the Santa Clara), or for that matter, the basalts throughout the region, lack xenocrysts could be explained, possibly, on the basis of a higher viscosity of the feldspathic magmas, retarding the rate at which foreign material was completely assimilated. Or, special conditions, such as very rapid ascent to the surface after picking up the xenocrysts might have prevailed for these lavas and none others. The nearby Pine Valley Mountain body, along the margins of which the Middleton type flows emanated, and proximate silicic ashflow tuffs may have supplied the plagioclase, quartz, and orthopyroxene occurring as xenocrysts. Alternately, the xenocrysts might have originated at high pressures where a shift in liquidus boundaries allowed orthopyroxene, a sodic plagioclase, and possibly even quartz to precipitate.

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