

GEOLOGY STUDIES

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Shoshonitic Lavas in West-Central Utah*

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Texaco Inc., Denver, Colorado

ABSTRACT

Several isolated mafic volcanic flows of Tertiary age occur along the eastern margin of the Great Basin in Utah. The Oligocene to Miocene flows in the Honeycomb Hills and Fish Springs Flat in Juab County, and at Grayback and Stansbury Mountains in Tooele County, are chemically and mineralogically members of the calc-alkaline shoshonite association. Shoshonitic lavas contain up to 4.46% K_2O and are characterized by K_2O/Na_2O ratios near 1.0 and as high as 1.5. The lavas contain varying proportions of magnesian mafic minerals plus calcic-plagioclase phenocrysts in a fine-grained groundmass containing plagioclase and alkali feldspar or K-rich glass. In contrast, the Late Cenozoic basaltic andesite and tholeiitic basalt flows at Fumarole Butte, Juab County, contain a smaller proportion of total alkali elements and Na_2O predominates over K_2O . The younger lavas also contain mafic minerals with a higher iron content. The shoshonitic lavas probably resulted from deep-seated processes related to an early Cenozoic subduction system under the western United States. The basaltic lavas were generated by shallower magmatic processes related to crustal extension and basin-range faulting.

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INTRODUCTION

Around the eastern margin of the Great Basin are many isolated lava flows, ranging in composition from latite to basalt with characteristic high-potassium contents. Volcanic activity has occurred sporadically throughout Cenozoic time, with some of the earliest flows predating basin-range faulting and the latest flows being contemporaneous with Lake Bonneville. Most of the later flows are middle to late Tertiary and have been subjected to extensive erosion.

Recent interest in the widespread Cenozoic volcanic rocks in the Great Basin has been stimulated by recognition of the interaction of the East Pacific and North American plates during the Cenozoic. If Great Basin volcanism is a product of processes in the crust and upper mantle related to plate motion, then the petrologic nature and age relations of the volcanic rocks should reflect these deep-seated processes.

The discovery that the potassium content of Cenozoic igneous rocks increases in proportion to the sodium-silica content, from the western to the eastern Great Basin (Gilluly, 1932; Merriam and Anderson, 1942; and Moore, 1962), has led some researchers to correlate the increase in potassium with a corresponding increase in the depth of the region of magma generation associated with a Benioff subduction zone (Christiansen and Lipman, 1972; and Lipman, Prostka, and Christiansen, 1972). In addition, the general nature of volcanism in the Great Basin changed from predominately rhyolitic-andesitic in the middle Tertiary to predominately basaltic in the Quaternary (Leeman and Rogers, 1970). This change in type of volcanism is related by McKee (1971) to a basic change in the nature of plate interaction with western North America. The lava flows in west-central Utah provide an opportunity to study the change in the nature of volcanism produced from middle Tertiary to early Quaternary.

The principal purposes of this study are (1) to document the petrographic and chemical nature of two diverse magmatic associations, one middle Tertiary shoshonitic and the other late Cenozoic tholeiitic; and (2) to infer their petrologic evolution and relate this information to current plate tectonic theories regarding the origin and Cenozoic history of the eastern Great Basin.

Mafic flows in the Honeycomb Hills, at Fumarole Butte, and in Fish Springs Flat, in Juab County, were selected for detailed study. Similar volcanic rocks at Grayback Mountain and in the Stansbury Mountains, in western Tooele County, were also sampled for regional comparisons. The locations of these areas are shown in Text-figure 1.

Method of Study

Areal extent of the flows was determined by mapping on 1:62,500-scale topographic maps and aerial-mosaic photographs. Representative samples were collected from each significant flow unit. Most of the field work was concentrated in the Honeycomb Hills and at Fumarole Butte, where critical multiple-flow age relationships exist.

Whole-rock chemical compositions were obtained for 29 samples using an electron microprobe technique developed by Rucklidge et al. (1970). Thin sections were prepared from all significant volcanic units to determine their modal and textural relationships. Electron microprobe analyses were also made on selected olivines, pyroxenes, and feldspars.

Previous Work

Other than general reconnaissance and brief petrographic descriptions, studies of the latitic and andesitic volcanic rocks in west-central Utah have not been made. The mafic flows in the Honeycomb Hills and at Fumarole Butte were briefly described by Erickson (1963) in a regional study of the volcanic rocks in western Juab County. Erickson's main interest was in the rhyolitic flows and pyroclastic rocks in the nearby Thomas and Keg mountains, but he noted the general age relations between the mafic units and the more extensive silicic rocks. Uranium and beryllium were discovered in tuffs underlying the mafic flows in the Honeycomb Hills (Staatz and Bauer, 1950; Montoya, Baur, and Wilson, 1963). Because of the economic potential, a small area near the center of the Honeycomb Hills was mapped in detail by McNulty and Levinson (1964). Staatz and Osterwald (1959) and Staatz and Carr (1964) have described in detail the petrology and age relations of the complex of rhyolite flows in the Thomas and Dugway ranges, which are located northeast of Fish Springs Flat. The small occurrences of mafic volcanic rocks in Fish Springs Flat have not been previously described. The andesites and latites in the northern Stansbury Mountains were first briefly described by Rigby (1958) and later by Davis (1959), who made a petrographic study of them. Doelling (1964) mapped and described what he called basalts in the Grayback Mountain area.

Cenozoic volcanism in other areas of western Utah has been described in several studies. Lindgren and Loughlin (1919) and Morris (1957) have described the extensive latite flows in the Tintic Mountains, eastern Juab County. Nolan (1935) noted the petrographic and chemical character of small, isolated latite flows at Gold Hill, 30 miles northwest of the Honeycomb Hills, near the Utah-Nevada border. In addition, brief descriptions of mafic volcanic rocks in the Oquirrh Mountains and in the Sheeprock-Simpson Mountains, eastern Tooele County, were made by Gilluly (1932) and by Cohenour (1959), respectively.

Relatively detailed petrologic investigations have been made in the late Cenozoic basaltic provinces surrounding west-central Utah. To the southeast the chemical nature of basalts in the Black Rock Desert has been described by Condie and Barsky (1972). Other recent studies of basalts include those in the western Grand Canyon (Best and Brimhall, 1970) and in the Great Basin generally (Leeman and Rogers, 1970).

Acknowledgments

The writer would like to express appreciation to many individuals who aided in this study, particularly to Myron G. Best for his advice and continual interest in this study, to Willis H. Brimhall for his advice on geochemical techniques, and to Lehi F. Hintze for the aerial photographs used in this study. In addition, special appreciation is due William P. Nash and the Department of Geological and Geophysical Sciences, University of Utah, for the assistance with and the use of the electron microprobe. The writer would also like to thank Paul Lewis for his assistance and advice in electron microprobe techniques, and Steve Leedom and Verne Fallstrom for assistance in the field. Special thanks are due my wife, Cheryl, for her constant encouragement and support during this study.

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FIELD RELATIONS AND GEOLOGIC AGE

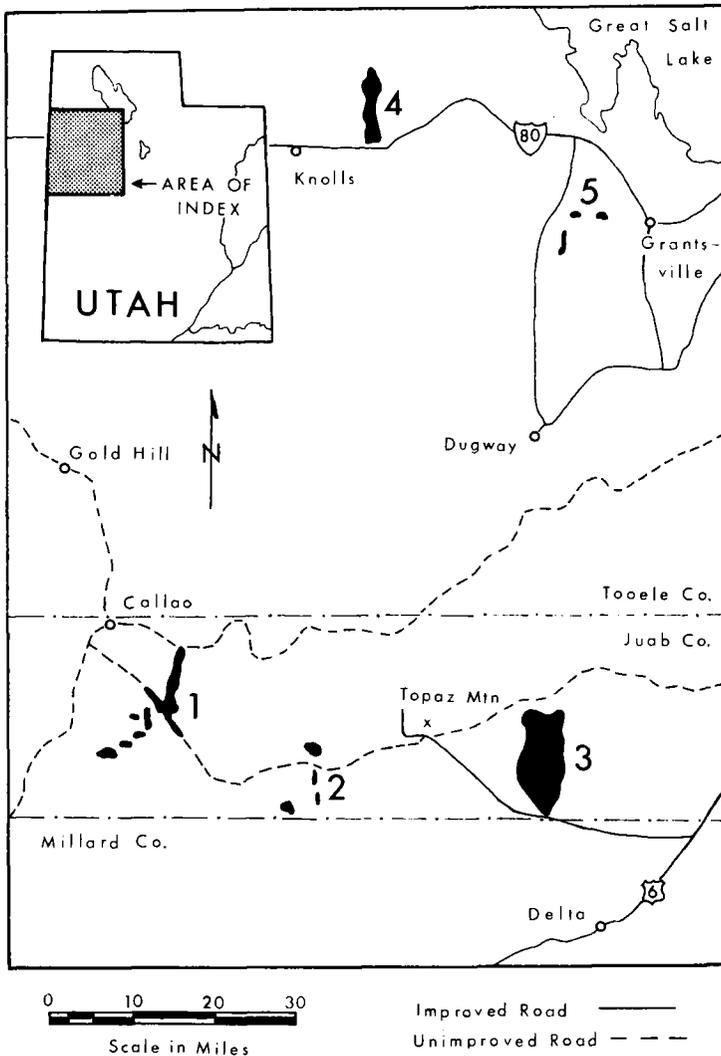
General

Text-figure 1 shows the distribution and areal extent of the mafic lava flows in west-central Utah that are the subject of this report. The ages of the lavas range from the early Tertiary, prebasin-range structure, typified by flows in the Stansbury Mountains, to Quaternary flows, typified by the Fumarole Butte flows. The flows in the Honeycomb Hills, Fish Springs Flat, and Grayback Mountain represent events of intermediate age, contemporaneous with later stages of basin-range faulting. Except for the Fumarole Butte flows, most of the individual mafic flows are of limited extent, covering only one or two square miles, and are extensively eroded and show evidences of faulting and tilting. All of the flows, except those at high elevations in the Stansbury Mountains, have been partially covered with gravels associated with Lake Bonneville. The mafic lavas vary from black, massive aphanitic flows at Fumarole Butte and in the southern Honeycomb Hills to porphyritic vitrophyres found in the northern Honeycomb Hills and in Fish Springs Flat. Except for the andesitic and basaltic lavas at Fumarole Butte, rock types in the other mafic flows are similar to the potassic, calc-alkaline shoshonite association (absarokite-shoshonite-banakite-latite) described by Joplin (1968).

Honeycomb Hills

The Honeycomb Hills consist of a number of isolated mafic and silicic flows that lie along a narrow, 15-mile-long arcuate belt trending northeast-southwest (Text-fig. 2). A smaller northwest-southwest belt of flows intersects the main belt of flows near the center of the Hills. Near the juncture of the two trends are two prominent rhyolitic buttes which give the name "Honeycomb Hills" to the area because of their conspicuous cavernous weathering patterns (McAnulty and Levinson, 1964).

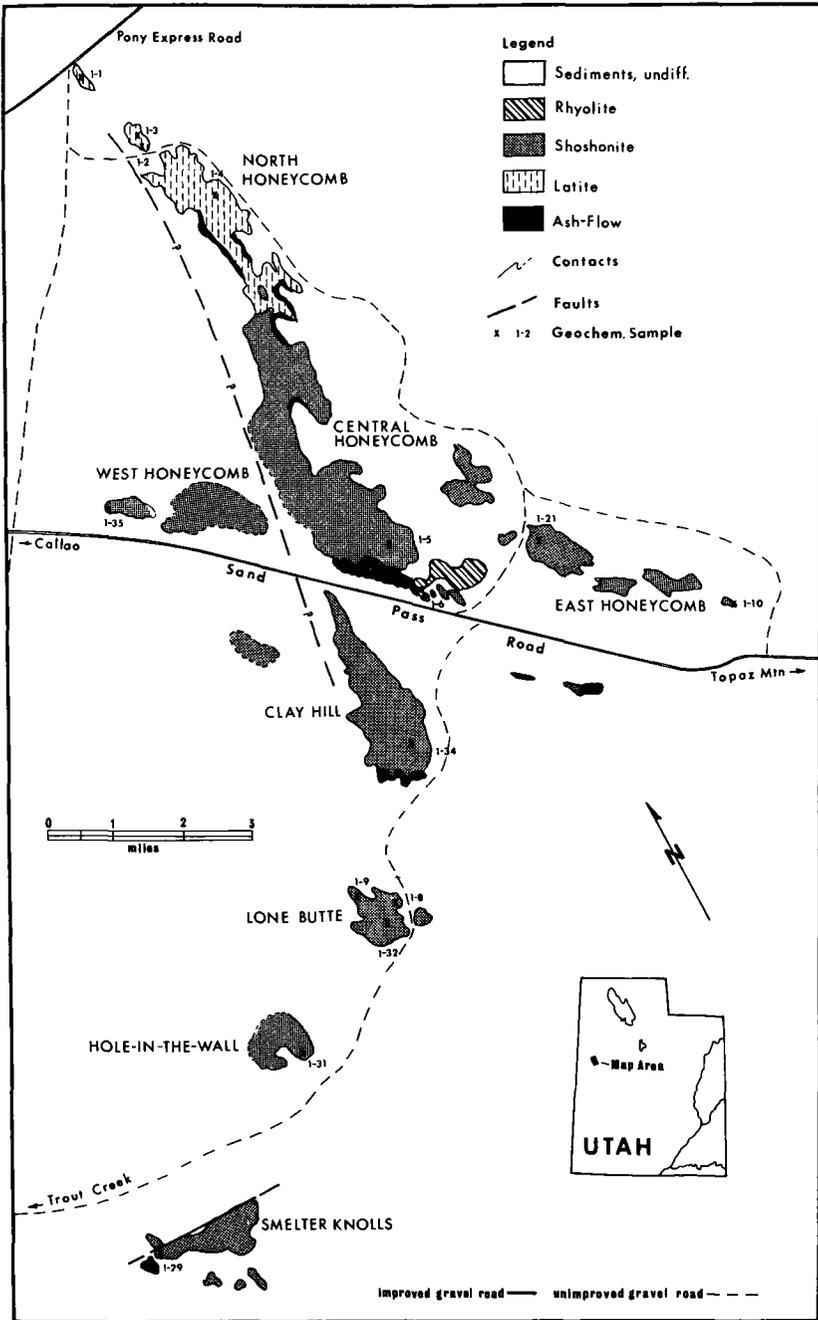
Within the Honeycomb Hills are eight distinct flow areas which cover a combined total of 16 square miles. North of the Sand Pass Road are four units: a large central complex of flows, which includes the rhyolitic Honeycomb Buttes; a small group of flows extending westward from the buttes; another series of small flows paralleling the Sand Pass Road to the southeast; and a complex of latitic flows and pyroclastic flows at the north



TEXT-FIGURE 1.—Locations of potassic calc-alkaline volcanic flows studied in this report: 1. Honeycomb Hills; 2. Fish Springs Flat; 3. Fumarole Butte; 4. Grayback Mountain; 5. Stansbury Mountains.

end of the hills. The southern Honeycomb Hills consist of four separate, isolated flows. From north to south, these are the Clay Hill flows, the Lone Butte flows, the Hole-in-the-Wall flow, and the Smelter Knolls flows.

The first igneous event in the Honeycomb Hills area was extrusion of an ash-flow tuff sequence upon folded and deeply eroded Paleozoic sediments. The pyroclastic sequence probably covered the entire Honeycomb area. The next event was extrusion of a series of latite flows at the north end of the



TEXT-FIGURE 2.—Generalized geologic map of the Honeycomb Hills, Juab County, Utah.

hills. The latite flows only partially covered the pyroclastic sequence. Aphanitic shoshonite flows, representing the greatest volume of extrusive rock, then covered most of the pyroclastic rocks and part of the latite flows. The last igneous event was limited to the vicinity of the Honeycomb Buttes, where rhyolite and associated rhyolite-breccia intruded the older volcanic sequence. Representative members of all four extrusive episodes are found in the central and northern parts of the Honeycomb Hills.

Exposures of the ash-flow tuff are limited in extent, occurring mainly where overlying mafic flows have been eroded away. The ash-flow sequence consists of at least two and possibly three members. In the northern Honeycomb Hills, beneath the shoshonitic and latitic flows, is a crystal-poor, lithic tuff that is quite variable in external appearance, ranging from light gray to light pink, and from a fine ash to a tuff-breccia that contains pumice fragments up to six inches in diameter. The 30- to 40-foot-thick exposures of tuff exhibit very little evidence of welding, and in some outcrops the tuff contains features indicating that the finer-grained ash was reworked by water. The lithic tuff contains only 10 to 15 percent small phenocrysts of plagioclase (An_{15-30}) and biotite, with lesser amounts of sanidine and traces of pyroxene. The coarser basal parts of the flow also contain, in addition to pumice, 10 to 20 percent small mafic volcanic fragments.

On the south sides of the Honeycomb Buttes, Clay Hill, and Smelter Knolls are outcrops of a welded tuff, characterized by flattened pumice fragments. The dark gray lower portions of the tuff are more intensely welded and glassy than the devitrified brownish orange upper portions. The welded tuff contains percentages and compositions of phenocrysts similar to those of the unwelded lithic tuff. On the south side of Clay Hill this unit is about 50 feet thick.

Beneath the welded tuff at Clay Hill is an unwelded, very fine grained gray ash approximately 30 feet thick. Small crystals of biotite (1 to 2 mm) increase in abundance upward in the ash, reaching a maximum of 15 to 20 percent near the top. On the west side of the Honeycomb Buttes, in an exposure of the lithic tuff of the northern hills, a somewhat similar biotite ash lies beneath a tuff-breccia zone.

Correlation between the welded tuff and the lithic tuff is difficult because no outcrops were found where a definite member of each of these units is in close proximity. However, a drill hole, which penetrated 160 feet of rhyolitic breccia, aphanitic flow, tuff, welded tuff, and tuffaceous conglomerate before entering the Paleozoic limestones on the north side of the Honeycomb Buttes (McAnulty and Levinson, 1964), indicates that the welded tuff represents an intense intermediate ash-flow event during a period of variable extrusive activity.

Erickson (1963) indicated that the most probable source for the tuffaceous sequence of the Honeycomb Hills was in the immediate area. The Honeycomb tuffs, except for the welded member, are somewhat similar to young vitric tuffs exposed in the Thomas and Keg ranges (Erickson, 1963). Although the ash-flows in the Honeycomb Hills and in the Thomas Range contain similar ratios of pumaceous material to crystals, the Thomas Range tuff contains mainly phenocrysts of quartz and sanidine (Staatz and Carr, 1964).

In the northern Honeycomb Hills, between the pyroclastic flows and the overlying latite flows is a dark gray to reddish brown tuffaceous conglomerate

about 15 feet thick. This unit consists of pebble- to boulder-sized, subangular to rounded fragments of pumice, fine-grained ash-flow, and a dark gray latite, all cemented together by a fine-grained latitic groundmass. The tuffaceous latitic conglomerate fills some small channels cut into the upper surface of the pyroclastic sequence (Pl. 1, fig. 1).

The latites, which range in texture from porphyritic-aphanitic to vitrophyric, are confined to the northernmost section of the Honeycomb Hills, where they cover about two square miles. They contain from 20 to 40 percent phenocrysts of plagioclase feldspar with smaller quantities of pyroxene, amphibole, and biotite also present. The colors of the flows range from very dark gray to light reddish gray. The vitrophyres represent only a small portion of the latites, being confined mainly to one low hill one mile south of the Pony Express Road. This low hill is made up of a large, basal, light gray vitrophyre capped with a smaller black vitrophyric flow. The porphyritic latite flows seem to consist of a number of individual flows, but because of extensive erosion it is difficult to determine their original extent and spatial relations. The total thickness of the latite sequence is also variable, ranging from 10 to 15 feet near its southern limit to at least 100 feet two miles south of the Sand Pass Road. Some outcrops exhibit well-developed columnar jointing, while others show either massive or platy structures. The latite flows have been faulted on the west side of the hills and have been tilted 10 to 20 degrees to the east. The underlying pyroclastic flows show a similar orientation.

Shoshonite lavas make up the greatest volume of extrusive rock in the Honeycomb Hills, covering about 12 square miles. Erickson (1963) named these mafic flows the "Honeycomb Basalt" on the basis of hand-specimen appearance. But when whole-rock geochemical data is taken into account, the flows, although basaltic in appearance, are too silicic and potassic to be basalts. The shoshonites are commonly finely aphanitic, with some flows carrying up to 15 percent phenocrysts of pyroxene and occasionally olivine. Quartz xenocrysts from one to five millimeters in diameter are characteristic of some flows. The textures and colors of the lavas vary from a black to dark gray, massive rock near the centers of the flows to a dark reddish brown rock on the vesicular margins.

The shoshonite flows in the central area cover about four square miles and reach thicknesses of 100 to 200 feet immediately north of the Honeycomb Buttes. The flows thin to the north, where 15 to 20 feet of shoshonite flow-breccia covers a small portion of the latite flows. The flows within the central Honeycomb Hills seem to have been limited in their areal extent and were probably confined to a chain of low, domelike extrusions.

The small, discrete flows that form the east and west Honeycomb flows were probably governed in their formation by either a common fracture zone or a topographic low. The east-Honeycomb flows are characterized by the presence of quartz xenocrysts, 10 to 15 percent pyroxene phenocrysts, and several discontinuous shoshonite-breccia dikes. The west-Honeycomb flows consist of several thin aphanitic flows which carry traces of olivine phenocrysts. Between the central area and the west-Honeycomb flows is a major north-south trending normal fault that has dropped the western side at least 200 feet. Alluvial material derived from the upthrown block then covered most of the western flows. This old alluvial surface is now being dissected (Pl. 1, fig. 2). Undoubtedly more lava exists under the alluvium on the west side



1



2

EXPLANATION OF PLATE I

VIEWS OF ASH-FLOW TUFF AND WEST HONEYCOMB HILLS

- FIG. 1. Ash-flow tuff overlain by tuffaceous conglomerate and a thin latite flow the northern Honeycomb Hills. Note channel fillings of conglomerate in tuff.
- FIG. 2. West Honeycomb shoshonite flows.

of the fault than is shown on Plate 1, but it is difficult to estimate the actual extent of lavas under the alluvium.

The Clay Hill flow covers about $2\frac{1}{2}$ square miles and consists of a large, rounded hill rising 350 feet above exposed Paleozoic rocks on its east and south sides, and a long flow extending north from the hill for $2\frac{1}{2}$ miles. The shoshonite at Clay Hill is similar in appearance and composition to the shoshonite in the east-Honeycomb flows. A small outcrop of lava about one-half mile west of Clay Hill is also similar to the east-Honeycomb and Clay Hill shoshonite, and may represent the top of a large lava flow related to Clay Hill.

Lone Butte (Pl. 2, fig. 1) is unusual in the Honeycomb Hills because it contains what appear to be two distinctly different shoshonite flows. The base of the 250-foot-high hill consists of a gray shoshonite flow with a prominent platy fracture that dips into the center of the butte (Pl. 2, fig. 2). The gray basal unit is capped by a 15- to 20-foot-thick flow of black aphanitic shoshonite similar to the west-Honeycomb flows. Two small flows of the black aphanitic unit extend a short distance to the west from the base of the butte.

The Hole-in-the-Wall and the Smelter Knolls shoshonite flows are finely aphanitic lavas containing only rare phenocrysts of olivine or pyroxene. The Hole-in-the-Wall flow is flat-lying, only 10 to 15 thick, and covers about two-thirds of a square mile. The flow is covered with alluvium on all but the south side, where stream erosion has cut through the flow, exposing the Paleozoic sediments below it.

The Smelter Knolls flows represent the southwesternmost occurrence of mafic lava in the Honeycomb Hills. The flows, which cover about one square mile, lie unconformably upon Paleozoic sediments of the Confusion Range on the south side of the flow and are bounded by an east-west-trending fault on the north side. The displacement on the fault, measured from the top of the upthrown block to the top of a small-flow outcrop on the downthrown block, is 275 feet. The flow itself is only 50 feet thick but appears much thicker because of the large talus slopes covering the fault scarp.

The occurrences of rhyolite in the Honeycomb Buttes represent the last volcanic event in the Honeycomb Hills. Two steep-sided buttes covering a little more than one-half square mile are all that remain of a viscous rhyolite dome that must have been at least 500 feet high. Both buttes consist of gray porphyritic rhyolite containing abundant phenocrysts of glassy sanidine and quartz. A small percentage of sodic-rich plagioclase and biotite also occurs as phenocrysts. Erickson (1963) noted the presence of topaz in the groundmass and as small phenocrysts in the rhyolite. Erickson also indicated that the rhyolite is similar in appearance and chemistry to the Topaz Mountain rhyolite described in detail by Staatz and Caar (1964). A thin unit of rhyolite-breccia containing fragments of shoshonite and Paleozoic sediments underlies the westernmost exposures of the rhyolite.

The volcanic rocks in the Honeycomb Hills have not been dated radiometrically, but an age estimation can be made by comparing the sequence of dated volcanism in the nearby Thomas Range and the age of general basin-range faulting to similar events in the Honeycomb Hills. In the Thomas Range, volcanic events began with the extrusion of crystal-rich ash-flow tuffs (now welded) and minor latite flows which were followed by biotite-



1



2

EXPLANATION OF PLATE 2
VIEWS OF LONE BUTTE

FIG. 1. Lone Butte from the northeast, showing the eroded and rounded nature of mafic flows in the Honeycomb Hills.

FIG. 2. Basal shoshonite flow at Lone Butte, showing platy fracture.

bearing rhyolite. Younger igneous events began with the extrusion of crystal-poor vitric tuffs, immediately followed by the topaz-bearing Topaz Mountain rhyolite. The older volcanic rocks have been cut and tilted by basin-fault structures (Staatz and Carr, 1964; and Erickson, 1963). One of the basal ash-flows of the older sequence was dated at 20 million years old (Jaffe et al., 1959) and the older rhyolite, at 16.2 million years (Whelan, 1969). Armstrong (1970) dated the younger Topaz Mountain rhyolite at 6 million years. In the eastern Great Basin the major movements along the main basin-range faults took place during the late Miocene or early Pliocene (Staatz and Carr, 1964; Gilluly, 1965; and Hamilton and Myers, 1966).

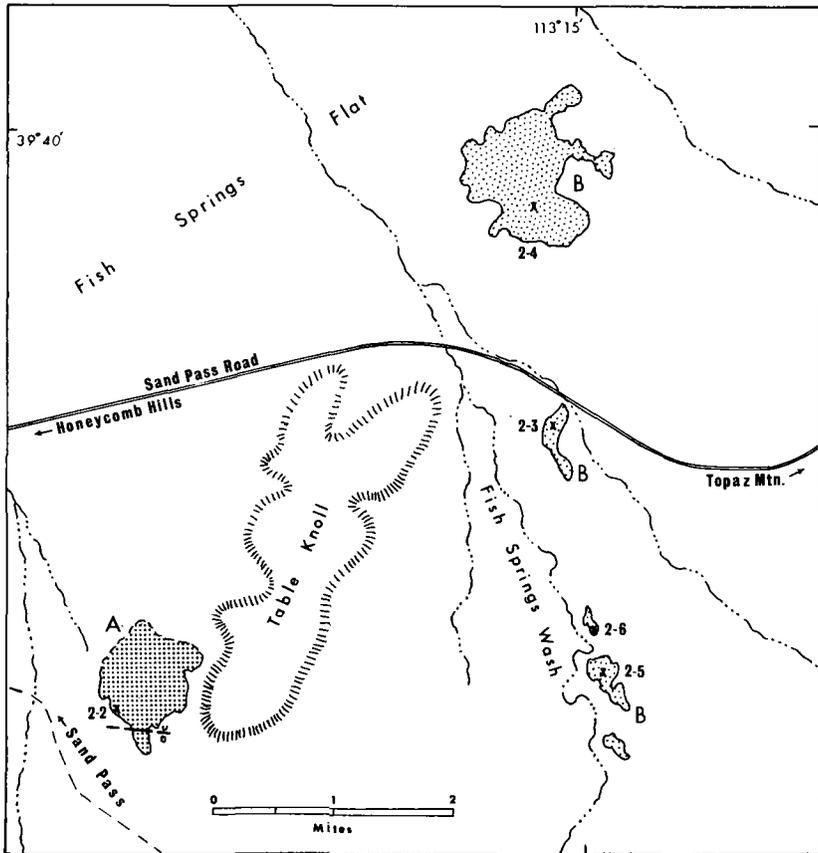
The early sequence of pyroclastic and latite flows in the Honeycomb Hills is similar in composition to members of the older volcanic sequence in the Thomas Range. In both areas early volcanic flows are involved in basin-range faulting and tilting to a similar extent. The Honeycomb Buttes rhyolite dome probably postdates most of the faulting and correlates with the Topaz Mountain rhyolite as Erickson (1963) has suggested. The early sequence of volcanism in the Honeycomb Hills probably began in the middle Miocene and continued into the very early Pliocene. The rhyolite intrusion ended the period of volcanism in the early to middle Pliocene.

Fish Springs Flat

Fish Springs Flat, a graben valley about eight miles wide between the Fish Springs and Thomas ranges, contains two distinctly different types of mafic lava (Text-fig. 3). The Table Knoll flow, which is exposed on the southwest corner of the valley, consists of a very dark-colored aphanitic basalt, locally containing pyroxene and feldspar phenocrysts. Located near the south-central part of the valley, the Fish Springs Wash flows consist of a porphyritic-latite vitrophyre containing 20 to 40 percent plagioclase phenocrysts.

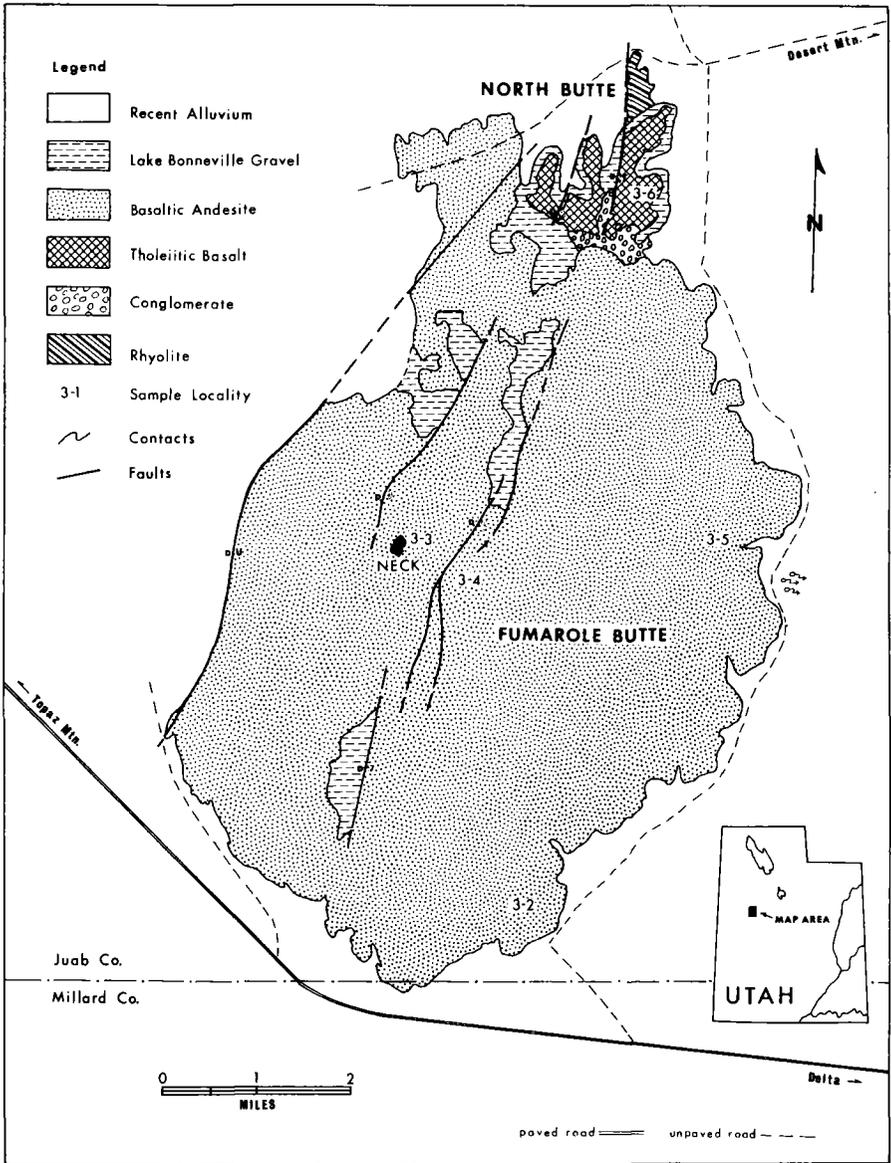
The Table Knoll flow is roughly circular in shape, is 10 to 15 feet thick, and covers about three-quarters of a square mile. This flow appears to have been extruded upon an old alluvial surface that now stands as much as 100 feet above the current erosion surface. This old surface dips gently to the north, where it merges with the main valley surface. Near the southern limit of the flow is an east-west trending fault, which has dropped a small portion of the flow 80 feet. The flow is generally quite massive and dense near the center but is quite vesicular along the margins.

The Fish Springs Wash flows consist of a semicircular flow covering about $1\frac{1}{2}$ square miles and a small series of disconnected flows extending directly south for about four miles. The flows are all similar texturally and compositionally. The latite flows are characterized by abundant gray to pink plagioclase feldspars ($\frac{1}{4}$ to $\frac{3}{4}$ cm) in a vitrophyric groundmass which varies from brownish red to gray or black. The Fish Springs Wash flows also appear to have been extruded upon an old erosion surface. The main flow stands 40 to 50 feet above the current erosion surface. The small series of flows to the south is extensively eroded and represents either remnants of a much larger elongate flow connected to the main flow or contemporaneous extrusion along a common fracture zone. The main flow is capped by a 20-foot-high volcanic neck composed of rounded blocks of latite-vitrophyre in a predominately glassy matrix. Similar autoclastic textures were observed in some of the southern flows.



TEXT-FIGURE 3.—Distribution of mafic flows in Fish Springs Flat and geochemical sample localities. A. Table Knoll banakite; B. Fish Springs Wash latite.

The exact age of the flows in Fish Springs Flat is difficult to determine. The Table Knoll flow lies unconformably upon Paleozoic sediments and is faulted, but all of the lavas are extensively eroded and seem to be related to an old erosion surface. All of the flows are either partially buried by gravels or have terraces related to Lake Bonneville cut into them. Latite flows having a similar composition and general appearance occur on the southwestern side of the Thomas Range near Spor Mountain and have been described by Staatz and Osterwald (1959). Staatz and Carr (1964) included the Spor Mountain latite flows in the older volcanic sequence in Thomas Range. The Fish Springs Flat flows seem to be late Tertiary and if they are genetically related to the Spor Mountain flows, they might represent the same late Miocene events as are represented by the very similar latite flows at the northern end of the Honeycomb Hills.



TEXT-FIGURE 4.—Generalized geologic map of the Fumarole Butte area.

Fumarole Butte

Fumarole Butte is a large volcanic complex covering about 30 square miles (Text-fig. 4). The complex consists of two distinctly different units: the large shieldlike Fumarole Butte flow and the older and much smaller North Butte flow. The name "Fumarole Butte" is derived from a 100-foot-

high volcanic neck near the center of the main flow. The neck is clearly visible for many miles. The main Fumarole Butte flow is elongate, with the center standing 150 feet above the margins three to five miles away. The margins of the flow are prominent cliffs, 20 to 30 feet high, whose tops stand as high as 100 feet above the current erosion surface on the eastern side of the flow. The top surface of the flow almost merges with the alluvial plain on the western margin. Many steep-sided gullies have also been eroded into the margins of the flow. The Fumarole Butte flow is a very fine aphyric basaltic andesite and is generally scoriaceous on the margins of the flow and in a zone surrounding the neck. Several hot springs are located on the eastern side of the flow at Crater Springs, also known as Baker Hot Springs.

The North Butte flow is only 15 to 20 feet thick and covers about two square miles. The flow caps a butte that rises as much as 400 feet above the surrounding alluvium. The North Butte lava is a basalt and is somewhat coarser grained than the Fumarole Butte flow. Underneath the North Butte flow is a reddish brown conglomerate 200 feet thick, containing sand, pebble- and cobble-sized fragments of Paleozoic sediments (mainly white to pink quartzite with minor dark gray limestone), and lesser quantities of pumice, rhyolite, and mafic lava, all cemented by calcareous material (Text-fig. 5). The conglomerate and the overlying basalt strike almost due north and dip from 10 to 15 degrees to the east.

Staatz and Carr (1964, p. 116) have described a similar red conglomerate from Dugway Range, where the conglomerate underlies the youngest rhyolite flows associated with the Thomas Range. They related the conglomerate in the Dugway Range to a widespread, thick, middle Miocene to middle Plio-



TEXT-FIGURE 5.—Basal conglomerate (50-foot-high cliff) and eroded basalt flow capping North Butte.

cene, reddish brown and tan conglomerate described by Van Houten (1956), exposed in east-central Nevada and northwestern Utah.

A small, elongate outcrop of gray, flow-banded rhyolite and black porphyritic-vitrophyre also underlies the North Butte flow. The rhyolite contains mainly phenocrysts of sanidine and smoky quartz and two to three percent small phenocrysts of biotite. This rhyolite possibly correlates with rhyolite flows of the older volcanic sequence in the Thomas Range (Staatz and Carr, 1964). The relationship of the rhyolite to the conglomerate is difficult to determine because Lake Bonneville gravels hide the contact between them. The rhyolite appears to be the older unit, because the conglomerate contains fragments very similar to the rhyolite and occurs at a much higher elevation.

The Fumarole Butte flow is younger than the North Butte basalt because it flows around North Butte and is less extensively eroded.

A series of subparallel faults trending north 20° east cuts both the North Butte and the Fumarole Butte flows (Text-fig. 4). One of the faults forms the western margin of the Fumarole Butte flow. Additional lava occurring west of the fault is probably covered with alluvium. The western side of each fault-block is consistently dropped. Displacements of the normal faults vary from 50 to 100 feet. Presumably because of its greater age, North Butte seems to have been more affected by the faulting than Fumarole Butte. The faulting and volcanism in the area were undoubtedly contemporaneous with the extrusion of lava through the areas of weakness along the faults.

Erickson (1963) estimated the age of the mafic lavas in the Fumarole Butte area to be late Tertiary both because of the underlying rhyolite, which he correlated with Topaz Mountain, and because the lavas were not as extensively eroded as the Honeycomb Hills flows. If the rhyolite and conglomerate are middle Miocene to middle Pliocene events, then a realistic age for the North Butte flows would be late Pliocene, with the Fumarole Butte flow following in the late Pliocene or early Quaternary.

Grayback Mountain

Grayback Mountain lies on the eastern side of the Bonneville Salt Flats, near Knolls, Utah (Text-fig. 1), and consists almost entirely of mafic extrusive rocks. The mountain stands only 350 feet above surrounding alluvium and the lavas are concentrated in an elongate flow about six miles long and from one-half to one mile wide. Doelling (1964), who briefly described the geology of Grayback Mountain, divided the flow into a vent facies and a flow facies, the latter made up of "basalt porphyry" containing as phenocrysts 80 percent labradorite, 15 percent augite, and 5 percent magnetite. Chemically (See Appendix B), the flow is better termed a *banakite*. The volcanic rocks are typically light gray and exhibit prominent parallelism of fracture and flow structure. Doelling also noted the presence of a small, eroded plug near the north end of the flow.

The flow has been faulted along north-south-trending faults on both margins, and some parts of the flow seem to dip at a small angle to the west. The flow lies unconformably upon Paleozoic sediments at the north end of the mountain, and the margins of the flow are partially covered with Lake Bonneville gravels. Doelling (1964) estimated the age of the flow

to be Miocene or Pliocene. He based this date on the reported ages of other volcanic events in west-central Utah. Composition and degree of faulting and erosion of the flows at Grayback Mountain are similar to those of the lavas at Fish Springs Flat and in the Honeycomb Hills. Volcanism probably occurred at all three areas at approximately the same time during the late Miocene to early Pliocene. One sample was collected for analysis from the south end of the flow, about one-half mile north of Interstate Highway 80, in what Doelling described as the "vent facies."

Stansbury Mountains

On the eastern and western flanks of the Stansbury Mountains (Text-fig. 1) are several exposures of Tertiary extrusive and shallow intrusive igneous rocks. The igneous rocks, first mapped by Rigby (1958) and later described in more detail by Davis (1959), are predominately andesites, breccias, and tuffs. Davis also reported the scattered occurrence of what he termed "nepheline basalt" at three localities within the range. The flows at Mack Canyon, Muskrat Canyon, and Salt Mountain are small in area, are extensively weathered and eroded, and have been involved in the uplift of the range. The volcanism has not been dated radiometrically, but Davis (1959) estimated that the igneous activity occurred at about Eocene or Oligocene time. Samples were obtained from all three of the reported "nepheline basalt" flows. Volcanic rocks from all three localities in the Stansbury Mountains are similar in appearance, consisting of a dark gray to black aphanitic groundmass with abundant phenocrysts of pyroxene and iddingsite-altered olivine. Nepheline was not observed in any of the flows, but the groundmass contains an alkali feldspar whose appearance is similar to that of nepheline. Chemically (See Appendix B), the lavas are absarokites.

The Mack Canyon flows lie on the ridge that separates Mack Canyon from Miner's Canyon on the east side of the range. The outcrops occur at an elevation of 7,200 feet, strike north-south, and have been tilted about 20 degrees to the east. The volcanic rocks cover about two square miles and are made up of several flows having a total thickness of about 300 feet.

The small Muskrat Canyon flow is on the western side of the range, almost due west of the Mack Canyon flows but at a much lower elevation (5,700 feet). The flow covers less than one square mile, strikes almost east-west, and dips about 15 degrees to the north. The flow is quite weathered, and limited exposures make it difficult to determine its original extent and features.

On the east side of Salt Mountain, which is four miles south of Muskrat Canyon, is a series of andesites, breccias, and tuffs similar to the larger volume of andesite flows and intrusive rocks occurring on the eastern side of the range south of Mack Canyon. On the top of the andesite flows is a 100-foot-thick capping of volcanic rock very similar to the Mack and Muskrat Canyon flows. The volcanic outcrop, which probably consists of more than one flow, covers about two square miles, strikes north-south, and dips about 10 to 15 degrees to the east. Exposures are limited because the flow has been deeply eroded and is covered with soil and thick vegetation.

All three flows are also similar in that they possibly represent the final igneous event in the Stansbury Mountains before basin-range uplift. The

extent to which these flows have been tilted, uplifted, and eroded is greater than in any of the other areas studied and is consistent with the Eocene-Oligocene age estimate of Davis (1959).

SUMMARY OF AGE RELATIONS

Several recent studies have outlined the general chronology of Cenozoic igneous events in the Great Basin (Armstrong, 1970; McKee, 1971; Lipman et al., 1972; and Christiansen and Lipman, 1972). These studies indicate that volcanism in the Great Basin occurred sporadically throughout the Cenozoic but was concentrated in two pulses, the first during the early to middle Cenozoic (40 to 20 million years ago), the second starting about 16 million years ago and continuing to the present. From the late Eocene to early Miocene, Great Basin volcanism was occurring mainly in northern and central Nevada and in central Utah (Armstrong, 1970). The volcanic rocks consist mainly of calc-alkaline intermediate lavas associated with silicic ash-flows (Lipman et al., 1972). During the late Cenozoic, the main centers of volcanism shifted to the margins of the Great Basin, with a corresponding change in volcanism to fundamentally basaltic (Leeman and Rogers, 1970; and Christiansen and Lipman, 1972). McKee (1971) also noted the decrease in volcanic intensity during the late Miocene and relates this hiatus to a basic change in interaction of lithospheric plates in the area of the Great Basin.

Volcanic rocks formed during both the early and late Cenozoic igneous phases and the Miocene transition period are found in western and central Utah. In addition to the Eocene-Oligocene (?) Stansbury Mountain flows, representative early Cenozoic flows are located in the Oquirrh Mountains (Moore, W. J., et al., 1968), the Tintic Mountains (Laughlin et al., 1969), and in the Park City—Kamas area in the Wasatch Mountains (Bromfield, 1968; and Best et al., 1968). Armstrong (1971) indicated that the volcanism in the Gold Hill area may also be of Oligocene age. The late Cenozoic igneous period is represented by basaltic flows in the Fumarole Butte area and in the Black Rock Desert, south of Delta, Utah (Condie and Barsky, 1972).

Igneous activity in the Honeycomb Hills, Fish Springs Flat, and Grayback Mountain areas occurred during the middle to late Miocene, but the general nature of the lavas is more typical of early Cenozoic lavas. Igneous flows in the Thomas Range, Keg Mountains, and Drum Mountains (southeast of Fish Springs Flat) are also areas in which volcanism began in the Miocene and continued into the second igneous phase.

PETROLOGY OF THE POTASSIC LAVAS OF WEST-CENTRAL UTAH

Introduction

Petrography and chemistry of the lavas sampled in west-central Utah indicate that at least two distinctly different types of magmas were involved. The Oligocene-Miocene lavas typified by flows in the Honeycomb Hills, Fish Springs Flat, Grayback Mountain, and the Stansbury Mountains are very similar to members of the potassic shoshonite association described by Joplin (1965, 1968). The much younger Fumarole Butte lavas are more representative of tholeiitic rock types and relate to the fundamentally basaltic

lavas typical of late Cenozoic volcanism in the western United States (Leeman and Rogers, 1970; Christiansen and Lipman, 1972).

Shoshonite lavas were first recognized by Iddings (1895) in the Yellowstone Park area of Wyoming. The absarokite-shoshonite-banakite series, which Iddings named after local Indian tribes, is characterized by a high potassium content with respect to sodium, a general mafic appearance, and gradational chemical and petrographic transitions between the members of the series. The Wyoming absarokites contain abundant phenocrysts of olivine and augite in a fine-grained groundmass consisting of both plagioclase and potassium feldspar along with other mafic minerals. The shoshonites are similar to the absarokites but contain phenocrysts of labradorite in addition to olivine and augite. The banakites are the most feldspathic member of the Iddings series, containing abundant plagioclase feldspars and minor quantities of the other mafic minerals found in the series. Joplin (1968) added to Iddings's Wyoming series the latite and banakite lavas—similar to those described by Ransome (1898) from the western Sierra Nevadas—to form the shoshonite association.

Joplin (1968) and Jakeš and White (1972) have noted the distinctive chemical properties of the shoshonite association and have compared the shoshonite to the tholeiitic, alkali basalt and the calc-alkaline magma series. The shoshonite association characteristically contains a high percentage of total alkali elements (greater than 5 percent oxide by weight), as do many alkali basalts. But in contrast to the alkali basalts, in which sodium is more abundant than potassium, K_2O/Na_2O weight ratios are about 1.0 or greater. In the tholeiitic association the ratio is less than 0.35 and in the calc-alkaline association it is between 0.35 and 0.75. (Jakeš and White, 1972). Tholeiitic and calc-alkaline lavas show a positive increase of K_2O with increasing silica content, in contrast to the shoshonite association in which there is little change in K_2O with increasing silica. Members of the shoshonite association also exhibit a high but variable Al_2O_3 content and, like the calc-alkaline series, do not exhibit the marked iron enrichment characteristic of the tholeiitic series (Jakeš and White, 1972). Usually, they are saturated or oversaturated in silica. Joplin (1965) indicated that the shoshonite association is possibly the extrusive equivalent of monzonite and quartz monzonite.

In addition to the occurrences in the Yellowstone and Sierra Nevada areas, members of the shoshonite association have also been described in western Italy (Washington, 1906), Puerto Rico (Jolly, 1971), New Guinea—Papua (Ruxton, 1966; Jakeš and Smith, 1970), Fiji (Dickinson et al., 1968), Indonesia (Iddings and Morley, 1915), and New South Wales, Australia (Joplin, 1965, 1968).

Geochemistry

Analytical Methods.—Whole-rock geochemical analyses of the various lava flows sampled in western Utah were made using a method described by Rucklidge et al. (1970), in which glasses formed by the fusion and quenching of rock powder are analyzed with an electron microprobe. Rocks selected for analyses were first crushed to a fine powder (minus 100 mesh) and then fused in a furnace. Graphite crucibles were used as sample containers. Between 0.3 and 0.5 grams of rock powder were heated for 10 to 15 minutes in a partial vacuum. Furnace temperatures varied from 1210° to 1290° C. The fused samples were then quenched by partially submerging the crucibles in water at the end of each run. All of the glasses were checked for the

presence of any unmelted crystalline material with the petrographic microscope. The use of the vacuum helped to reduce the number of vesicles in the glass and slowed oxidation of the graphite crucibles. Some difficulty was encountered in achieving complete fusion of the latites and the banakites containing feldspar phenocrysts. This problem was solved by slightly increasing both the furnace temperature and the length of the run.

Chips of 14 to 15 different glasses were cemented with epoxy to a one-inch-diameter glass disk and polished in the normal manner for microprobe samples. The glasses were analyzed with an ARL-EMX electron microprobe using a sample current of 0.05 microamps, 15 kv. of power, and 40,000 integrated counts. Beam diameter was set at 20 microns and the samples were moved continuously under the beam. Ten sets of counts were made on each sample. Individual mineral phases were analyzed using a beam diameter of 5 microns and a sample current of 0.03 microamps. Computer reduction of microprobe data was made using a modified EMPADR Program (Rucklidge, 1967).

A sample of BCR-1 (Flanagan, 1969) was fused and analyzed with the other unknown rock samples to provide a comparison of the microprobe method with standard geochemical techniques. The results of the BCR-1 fusion analysis and the accepted average for BCR-1 are shown in Table 1. In general, the fusion technique is comparable to standard analytical methods, the majority of the determined oxides being very close to the accepted average or within the maximum/minimum values for BCR-1. However, the analyses of SiO_2 were one percent below the accepted mean, and Al_2O_3 was nearly one percent above the accepted value. Rucklidge et al. (1970) also noted that the analyses of Al_2O_3 using the fusion technique were generally higher than accepted values. The majority of the samples fused do not appear to have lost significant quantities of alkali elements as a result of volatilization in the molten state. However, one latite sample from the northern Honeycomb Hills (sample 1-1) exhibited an abnormally low potassium content, perhaps because of loss during fusion.

Oxide Variations.—Analyses were made on 24 samples from the older group of lavas and 5 samples from the younger Fumarole Butte area. The major chemical difference between the two lava suites is in the nature of their alkali contents. Older lavas are characterized by a high but variable K_2O content, and in most of the flows the K_2O percentage is higher than that of the Na_2O . The younger mafic lavas, on the other hand, are less potassic, and Na_2O is always greater than K_2O . Compositions of the older lavas generally lie within or very close to the range proposed by Joplin (1968) for members of the shoshonite association. Composition of the large flow at Fumarole Butte is that of a basaltic andesite and the smaller flow is a quartz tholeiite. Complete chemical analyses and CIPW norms for each sample analyzed are listed in Appendix B.

Average chemical compositions of members of the western Utah shoshonite association are listed in Table 2. Variations of the major oxides as compared with those of the silica in samples of both the shoshonite and the basaltic lavas are shown in Text-figure 6. Except for a small gap between the absarokites and the shoshonites, transitions between the members of the shoshonite association are gradational. The characteristic feature of the shoshonitic lavas is absence of any significant increase in K_2O with increasing

TABLE 1

Comparison of published data on basalt standard BCR-1 with those obtained in this study.

	BCR-1		BCR-1	
	Published ^a		This Study ^b	
SiO ₂	55.24	+1.27* -1.72*	54.22	+1.80 -1.81
TiO ₂	2.26	+0.24 -0.38	2.19	+0.56 -0.37
Al ₂ O ₃	13.84	+0.50 -0.75	14.45	+0.56 -0.65
FeO**	12.20	+0.70 -0.48	12.24	+0.21 -0.34
MnO	0.17	+0.07 -0.06	0.22	+0.03 -0.02
MgO	3.33	+0.52 -1.36	3.39	+0.16 -0.15
CaO	7.05	+1.40 -0.80	7.08	+0.24 -0.52
Na ₂ O	3.36	+0.53 -0.26	3.40	+0.08 -0.08
K ₂ O	1.70	+0.15 -0.18	1.62	+0.16 -0.16
P ₂ O ₅	0.36	+0.12 -0.07	0.38	+0.06 -0.04
Total	99.52		99.19	

* Maximum/minimum difference from mean

** Total Fe reported as FeO

a. Flanagan (1969). BCR-1 recalculated H₂O and CO₂ free.

b. Microprobe analysis. Maximum/minimum limits determined from ten sets of counts on the sample.

silica as in the younger Fumarole Butte lavas and in calc-alkaline associations. The K₂O content is almost constant in the absarokites and shoshonites but drops slightly in the latites and the Fish Springs Flat banakites. Mafic lavas exhibiting a similar decrease in K₂O have also been noted in the shoshonitic lavas from Papua (Ruxton, 1966) and in the alkali basalts of the Mount Taylor area of New Mexico (Lipman and Moench, 1972). The relationship between potassium and sodium is shown in Text-figure 7. Except for one anomalously low latite analysis (sample 1-1, 1.88 percent K₂O), the K₂O/Na₂O ratios of the association are near 1.0 or are greater. The K₂O/Na₂O ratios also exhibit a decrease proportionate to the increase in silica, but the decrease is due in part to a small corresponding increase in the sodium content of the more siliceous members of the association. In most of the shoshonitic lavas which Joplin (1968) used to determine the nomenclature of the sho-

TABLE 2
Average chemical compositions of the Shoshonite association of west-central Utah.

	ABSAROKITE (Ave. 3)	SHOSHONITE (Ave. 11)	BANAKITE (Ave. 3)	LATITE (Ave. 7)
SiO ₂	50.39	57.38	59.46	64.35
TiO ₂	2.08	0.94	1.02	0.74
Al ₂ O ₃	14.52	15.71	16.58	15.17
FeO*	9.48	7.93	6.71	5.13
MnO	0.15	0.15	0.09	0.08
MgO	6.19	3.88	3.16	3.03
CaO	8.90	6.77	5.76	5.24
Na ₂ O	2.61	2.66	3.07	3.02
K ₂ O	3.60	3.49	3.37	2.70
P ₂ O ₅	1.08	0.37	0.37	0.16
Total	99.00	99.28	99.59	99.62
K ₂ O/Na ₂ O	1.4	1.3	1.1	0.9
TTI**	44.1	53.5	57.9	62.1

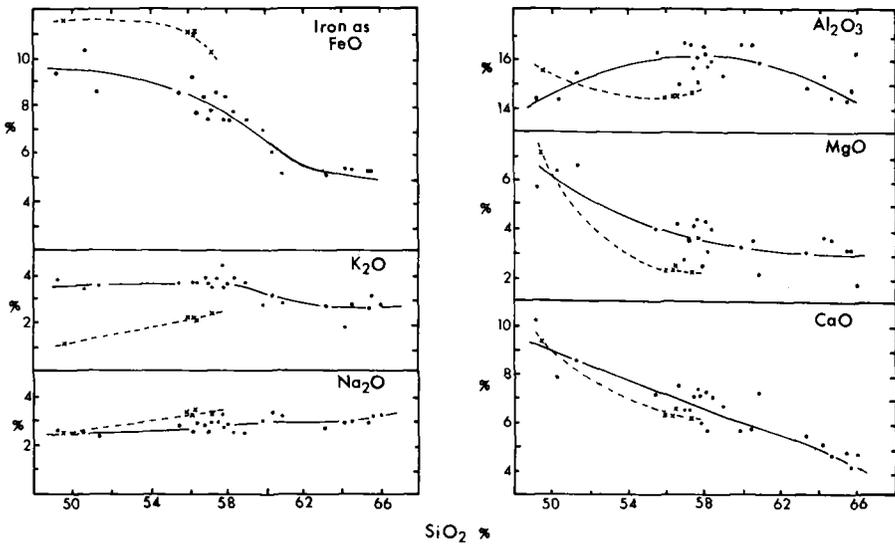
*Total Fe reported as FeO.

**Thornton Tuttle Index (Thornton and Tuttle, 1960).

shonite association there is a small positive increase of K₂O with silica, resulting in latites with almost twice the potassium content observed in the latites of west-central Utah.

Silica content and Thornton-Tuttle indices (sum of normative *q*, *or*, *ab*, *ne*; Thornton and Tuttle, 1960) both increase from the absarokites to the latites. The percentages of FeO, TiO₂, MgO, CaO, and P₂O₅ are highest in the absarokites and decrease markedly with increasing silica. Alumina contents of the members of the association exhibit some variation, but the Al₂O₃ percentage is highest in the intermediate members and is lower in the absarokites and latites. Except for two absarokites, which contain small percentages of normative olivine, shoshonitic lavas are silica saturated and contain up to 23 percent normative quartz. High potassium content of these lavas is reflected in the normative orthoclase content, which averages about 20 percent throughout the series.

Association of basaltic andesite and tholeiitic basalt, as at Fumarole Butte, has also been noted at several other locations on the margins of the Great Basin (Leeman and Rogers, 1970). The large basaltic andesite flow exhibits very little chemical variation, except for a sample collected at the bottom of a deep gully cut into the east side of the flow. Sample 3-5, which may represent the top of an earlier flow, is slightly more silicic and contains about one percent less iron than the main flow. The small quartz tholeiite flow at North Butte is chemically very dissimilar from the main flow, as is shown



TEXT-FIGURE 6.— SiO_2 (Harker) variation diagrams for shoshonitic lavas of west-central Utah (\bullet) and for Fumarole Butte basaltic lavas (\times). Trend lines for the shoshonitic lavas (—) and the basaltic lavas (-----) drawn by inspection.

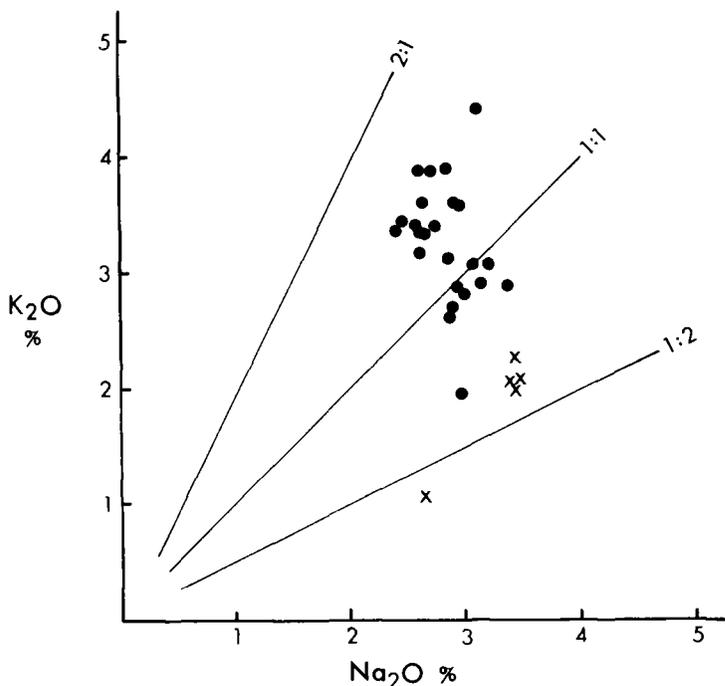
in Text-figure 6. This flow contains the highest percentage of iron and the lowest percentage of total alkalis of any flow sampled.

The Fumarole Butte basaltic lavas are in some respects chemically similar to and in other respects very dissimilar from the older potassic lavas. Percentages of Na_2O , CaO , and Al_2O_3 are generally similar in both lava groups, and the silica content and the Thornton-Tuttle indices of the basaltic andesite and Honeycomb Hills shoshonite are comparable. Both types of lavas are quartz and hypersthene normative. The Fumarole Butte lavas, in contrast to the older lavas, exhibit positive increases of K_2O and Na_2O with increasing silica. In addition, the younger lavas contain a higher percentage of iron and a lower magnesium content. Because the younger lavas are less potassic and more sodic than the shoshonitic lavas, the percentages of normative albite are significantly higher while the percentages of normative orthoclase are much lower.

The AFM diagram (Text-fig. 8) also indicates a major difference between the two lava groups. Shoshonitic lavas exhibit a general trend away from iron enrichment, toward increasing alkalis. A similar trend was observed in the scatter of data points from the shoshonitic lavas of New Guinea (Jakeš and White, 1969). The trend of the Fumarole Butte lavas is more toward iron enrichment and is similar to the tholeiitic trends observed in the Oregon-Idaho basalts and Craters of the Moon basalts by Leeman and Rogers (1970).

Petrography and Mineralogy

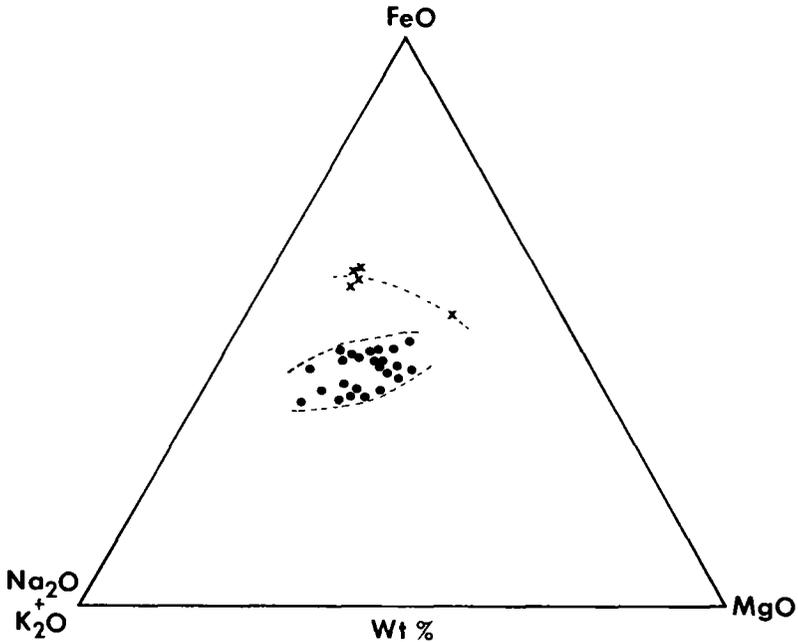
The characteristic mineral constituents of each member of the Utah shoshonite association and the Fumarole Butte basaltic lavas were analyzed with



TEXT-FIGURE 7.—Relationship between K_2O and Na_2O for the shoshonitic lavas (●) and the basaltic lavas (x) of west-central Utah.

the electron microprobe, using both analyzed minerals and synthetic glasses as standards. The mineral compositions are shown graphically in Text-figures 9 through 12, and the averages of these minerals are listed in Appendix A.

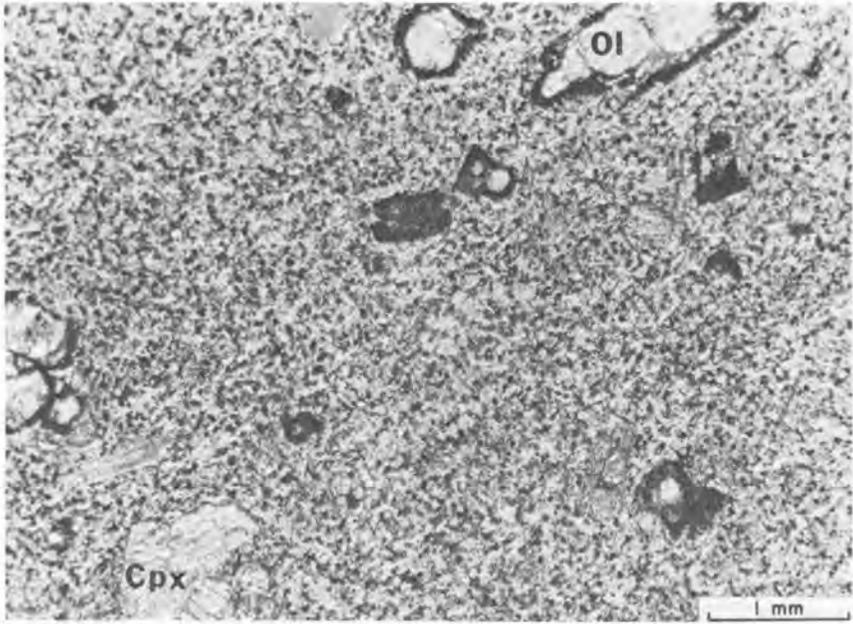
Absarokites.—The Stansbury Mountain absarokite flows, like the absarokite described from the Yellowstone Park area (Iddings, 1895), contain phenocrysts of olivine and clinopyroxene in a fine-grained groundmass which contains both plagioclase and alkali feldspars in addition to clinopyroxene and iron-titanium oxides (Pl. 3, fig. 1). The microphenocrysts, which range in size from 0.5 to 2 millimeters, make up 5 to 20 percent of the rock. In the Mack Canyon and Muskrat Canyon flows, phenocrysts of olivine predominate slightly over clinopyroxene, and in the Salt Mountain flow almost all of the phenocrysts are olivine. The olivine crystals are generally subhedral and exhibit partial to complete replacement by iddingsite. The olivine phenocrysts are the most magnesian olivines found in the various members of the shoshonite association, ranging from Fe_{83} to Fe_{77} . The augite phenocrysts are subhedral to euhedral and are found locally in small glomeroporphyritic clusters. The phenocrysts and groundmass grains of augite are almost chemically identical (Text-fig. 10) and, like the other ferro-magnesian minerals in the association, exhibit limited compositional variation. Nicholls and Carmichael (1969) noted that the shoshonite series of the Yellowstone Park area is also characterized by limited compositional variations of pyroxenes and olivines.



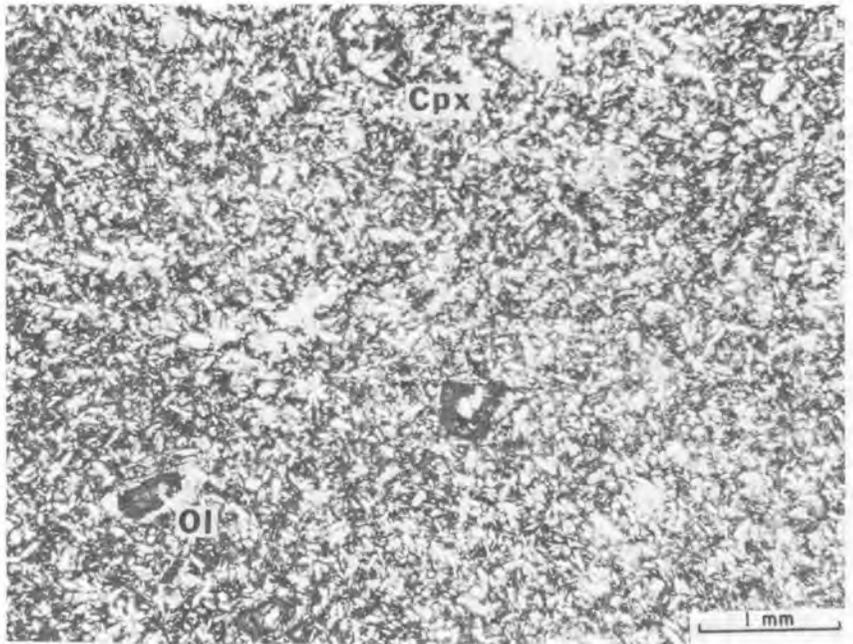
TEXT-FIGURE 8.—AFM diagram for the shoshonitic lavas (●) and the basaltic lavas (x) of west-central Utah.

The intergranular to subtrachytic groundmasses of the Mack Canyon and Salt Mountain flows contain about equal proportions of labradoritic plagioclase laths and anhedral alkali feldspars. In the Muskrat Canyon flow the alkali feldspars make up a larger portion of the groundmass, forming oikacrysts up to five millimeters long in the upper portions of the flow. The alkali feldspars commonly contain abundant apatite needles as inclusions. About 15 to 20 percent of the groundmasses of the absarokite flows are made up of small elongate to equidimensional crystals of augite. In the Muskrat Canyon flow small granules of iddingsitic-altered olivine are also found with groundmass clinopyroxene. Iron-titanium oxides are found as a fine dusting of extremely small granules distributed evenly throughout the groundmasses of all the flows.

Shoshonites.—The shoshonites of the Honeycomb Hills can be divided into two petrographically different groups, olivine shoshonites and orthopyroxene shoshonites, which cannot be chemically distinguished from each other because they both exhibit similar oxide variations. The olivine shoshonites are generally similar to the Stansbury absarokites in containing phenocrysts of olivine and clinopyroxene, but the shoshonites contain fewer and smaller phenocrysts (0 to 15 percent), and in many flows clinopyroxene predominates over olivine (Pl. 3, fig. 2). The orthopyroxene shoshonites characteristically contain as much as 35 percent xenocrysts and phenocrysts of orthopyroxene, clinopyroxene, quartz, plagioclase, and amphibole in a fine-grained groundmass containing a significant amount of glass (Pl. 4, fig. 1). The orthopyroxene shoshonites are found in the



1



2

EXPLANATION OF PLATE 3
ABSAROKITE AND SHOSHONITE

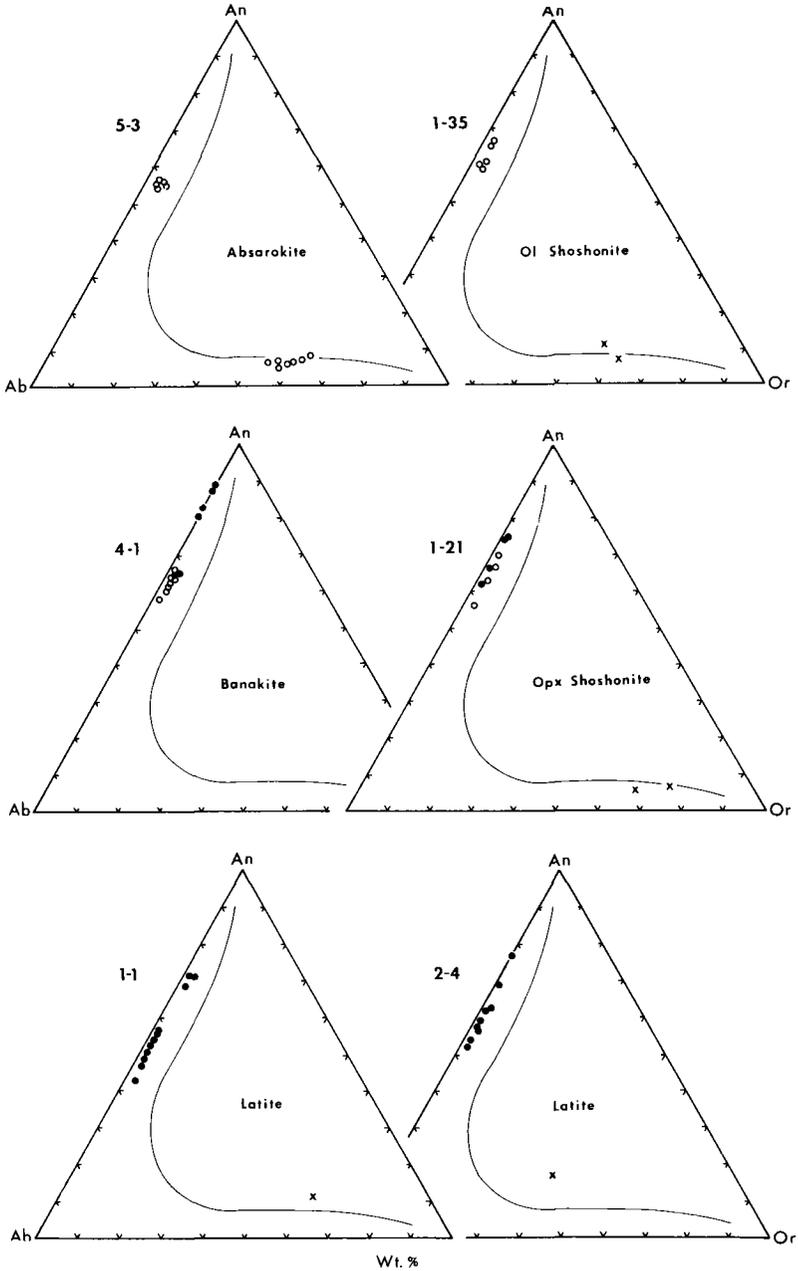
FIG. 1. Absarokite, Stansbury Mountains (Mack Canyon flow).
FIG. 2. Olivine shoshonite, West Honeycomb Hills.

central Honeycomb Hills, eastern Honeycomb Hills, and at Clay Hill. The flows that contain predominately olivine shoshonites are located in the western Honeycomb Hills, Hole-in-the-Wall flow, Smelter Knolls flow, and the easternmost flow in the eastern Honeycomb Hills. At Lone Butte both lava types are found with the orthopyroxene-bearing flows forming the basal portions and the olivine shoshonites capping the Butte and forming two of the flows extending from the base.

The olivine shoshonites are very fine-grained and vary from completely aphyric (Smelter Knolls flow) to moderately phenocrystic (up to 10 to 15 percent phenocrysts in the western Honeycomb Hills). The euhedral to subhedral microphenocrysts, which range in size from 0.5 to 1.5 millimeters, vary compositionally from equal proportions of olivine and pyroxene to entirely clinopyroxene. Compositions of the augite phenocrysts in the olivine shoshonites are similar to those found in the absarokites. The magnesian olivine phenocrysts, however, contain a slightly higher proportion of iron (Fo_{71} to Fo_{86}) than is found in the absarokite olivines. Small clusters of augite crystals are also locally present. Traces of quartz xenocrysts were also found in the upper Lone Butte and in the easternmost Honeycomb Hills olivine-bearing flows. The groundmass, which comprises 80 to 100 percent of the flows, contains about 40 to 50 percent labradoritic plagioclase laths, about 20 percent equidimensional clinopyroxene crystals, and from 10 to 15 percent olivine crystals, many of which exhibit iddingsitic alteration. The groundmass also contains 5 to 10 percent grayish brown to black glass whose composition is similar to that of the alkali feldspar in the absarokites. About 5 percent very small granules of iron-titanium oxides are also present in the groundmass.

The orthopyroxene shoshonites are petrographically the most complex and variable rock unit sampled. Almost all of the phenocrystic constituents are in disequilibrium with the groundmass and should therefore be considered xenocrysts. They exhibit reaction rims, embayed margins, and sieved internal structures, and many appear to be broken fragments. The plagioclases and amphiboles are the most extensively altered. Glomeroporphyritic clusters, found locally in all members of the west-central Utah shoshonite association, are more abundant in the orthopyroxene shoshonites. The clusters vary in content from entirely clinopyroxene (Pl. 4, fig. 1) to mixtures of clinopyroxene-orthopyroxene, clinopyroxene-orthopyroxene-plagioclase, and plagioclase-amphibole. The clusters also vary in size from 1 to 10 millimeters and in number of component crystals from five to over 500.

Clinopyroxene and orthopyroxene generally comprise the bulk of the 20- to 35-percent xenocrysts found in these lavas. In most flows clinopyroxene predominates slightly over orthopyroxene. Both pyroxenes exhibit a wide variety of crystal forms, ranging from euhedral and subhedral in some lavas to rounded and broken anhedral remnants in flow-layered lavas, where phenocryst-groundmass reactions (see below) are conspicuous. Pyroxene crystal sizes range from 0.5 to 2 millimeters. Many orthopyroxene phenocrysts are characterized by a pinkish brown pleochroism, and a small number of clinopyroxene crystals contain complex oscillatory zonation. Quartz xenocrysts are variable in abundance, either representing less than 3 percent of the rock or being entirely absent. Quartz crystals range in size from 0.5 to 2 millimeters and are always deeply embayed with surrounding thin to extensive reaction rims of clinopyroxene. Traces of anhedral amphibole xenocrysts with characteristic opaque reaction rims and deep brown pleochroism are found in several flows. Generally,



TEXT-FIGURE 9.—Feldspar and residual-glass analyses for members of the Utah shoshonite association: (5-3) absarokite, (1-35) olivine shoshonite, (1-21) orthopyroxene shoshonite, (4-1) banakite, (1-1, 2-4) latites. Solid circles represent analyses on phenocrysts; open circles, analyses on groundmass grains; x, analyses on residual glass. The solid line indicates the limit of ternary solid solution in natural feldspars (Smith and MacKenzie, 1958).

amphibole crystals represent less than one percent of the flows and are found mainly in the central and eastern Honeycomb Hills. Many large, irregular, opaque grains in these flows may represent complete replacement of amphibole grains. Compositionally, the amphiboles are hornblende with a moderately high TiO_2 content (3.1 to 2.8 percent).

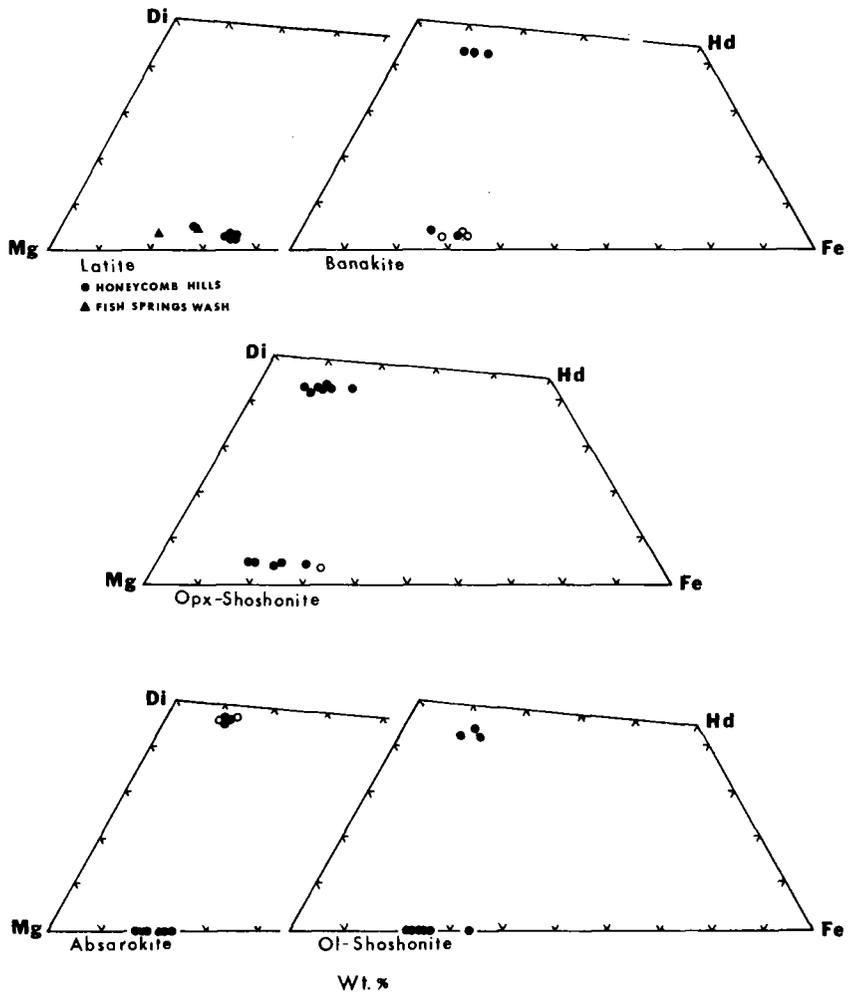
In contrast to shoshonites described from Indonesia (Joplin, 1968) and from the Yellowstone area (Nicholls and Carmichael, 1969), which contain significant quantities of calcic-plagioclase phenocrysts, the shoshonites of the Honeycomb Hills contain very limited quantities of plagioclase as a phenocryst. Plagioclase phenocrysts were not observed in the olivine shoshonites, and in the orthopyroxene shoshonites they are either absent or make up less than 10 percent. The calcic-plagioclase phenocrysts range in composition from bytownite to labradorite ($\text{An}_{7.5}$ to $\text{An}_{1.2}$) and, where they do occur, are generally extensively sieved by abundant opaque inclusions. Many of the sieved crystals are rimmed with almost unaltered calcic-plagioclase. The feldspar crystals range in size from 0.5 to 10 millimeters and in shape from rounded and partially resorbed anhedral crystals to broken angular fragments. A few unaltered phenocrysts contain complex oscillatory zonation.

Groundmass constituents of the orthopyroxene-bearing flows include 30 to 40 percent calcic-plagioclase laths, 5 to 15 percent irregularly shaped grains of both orthopyroxene and clinopyroxene, about 5 percent very small granules of iron-titanium oxides, and from 5 to 20 percent grayish brown glass. The groundmass plagioclase crystals are generally slightly less calcic than most of the phenocrysts. The groundmass pyroxene are slightly more iron rich than their phenocryst counterparts. The residual glass is similar to the glass found in the olivine shoshonites but contains a somewhat higher percentage of K_2O .

The nature and the degree of crystallization of the groundmass govern the overall textural properties of the shoshonite flows more than any other factor. In flows where higher proportions of glass are found, the xenocryst assemblage exhibits less reactive textures, in contrast to flows where glass is almost absent and xenocrysts are extensively reacted. In the basal Lone Butte flow the groundmass is completely crystalline and contains an intergranular mixture of small plagioclase laths and anhedral alkali feldspar similar to the absarokite groundmasses. Reaction rims of the many corroded pyroxene xenocrysts and clusters also contain alkali feldspar. Lone Butte orthopyroxene shoshonitic lavas are the only shoshonitic lavas encountered with two distinctly different groundmass feldspars large enough to be observed.

Groundmasses of the orthopyroxene shoshonites are also characterized by a subtrachytic to strongly trachytic orientation of both groundmass and phenocryst constituents. Many flows exhibit a pronounced flow layering. In the central Honeycomb Hills some of the flow-layered lavas contain elongate irregular patches generally less than 1 millimeter long, commonly in the "pressure-shadows" of some pyroxene phenocrysts. The patches consist of a magnesium-rich biotite (Appendix A, Table 5) and tridymite and seem to represent the selective breakdown of both orthopyroxene and clinopyroxene phenocrysts with solutions rich in alkali feldspar. Small remnants of pyroxenes were noted in several of these patches.

Banakites.—Banakites, which are found in Fish Springs Flat and at Grayback Mountain, are chemically and petrographically transitional between the sho-



TEXT-FIGURE 10.—Pyroxene and olivine analyses for members of the Utah shoshonite association. Solid circles represent analyses on phenocrysts; open circles, analyses on groundmass grains. Olivine analyses plotted on base of quadrilateral.

shonites and the latites. The banakites contain a higher proportion of calcic-plagioclase phenocrysts than is found in the shoshonites, but although similar texturally to many latites, the banakites are less siliceous.

In Fish Springs Flat, banakite lavas make up the entire Table Knoll flow, and banakite xenoliths (sample 2-5) were found in one of the latitic flows in Fish Springs Wash. The Table Knoll banakite contains 30 to 35 percent phenocrysts, the bulk of which are labradoritic plagioclase laths up to 2 millimeters long. Banakites, like shoshonites, exhibit some reaction between phenocrysts and the groundmass, but the degree of reaction is much less. The feldspar phenocrysts are generally not extensively altered, but many

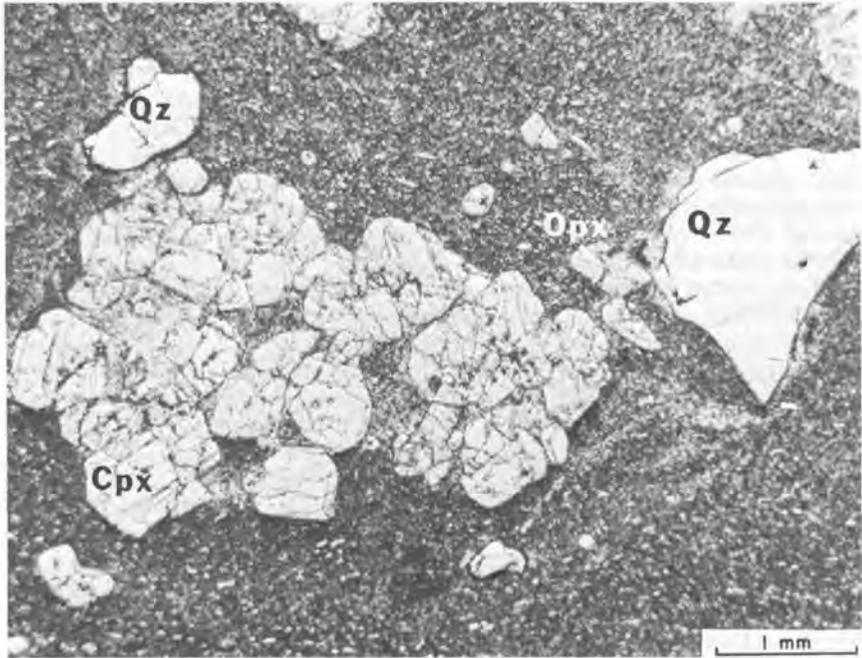
grains are rounded and contain a small proportion of internal sieved textures. Pyroxene phenocrysts, which make up slightly less than 10 percent of the flow, are primarily small, lath-shaped orthopyroxene crystals. Traces of very ragged and altered clinopyroxene phenocrysts and small clusters of plagioclase phenocrysts with smaller quantities of orthopyroxene and traces of clinopyroxene are also present. The groundmass contains mainly small plagioclase laths oriented in subtrachytic to trachytic patterns; about 10 percent elongate orthopyroxene crystals; traces of clinopyroxene; about 5 percent iron-titanium oxides, which vary from very fine granules to larger irregular shapes; and 5 to 10 percent brownish gray glass.

Fish Springs Wash banakite xenoliths contain somewhat similar proportions of phenocryst and groundmass constituents. Labradoritic phenocrysts are slightly more abundant and are generally larger (up to 5 mm). Plagioclase phenocrysts also have more extensive sieved textures and are more fractured. The xenoliths also contain about 25 percent groundmass glass. A one-millimeter-diameter cluster of very small clinopyroxene crystals found in this rock may represent the complete replacement of a quartz xenocryst, although quartz was not observed in any of the banakites.

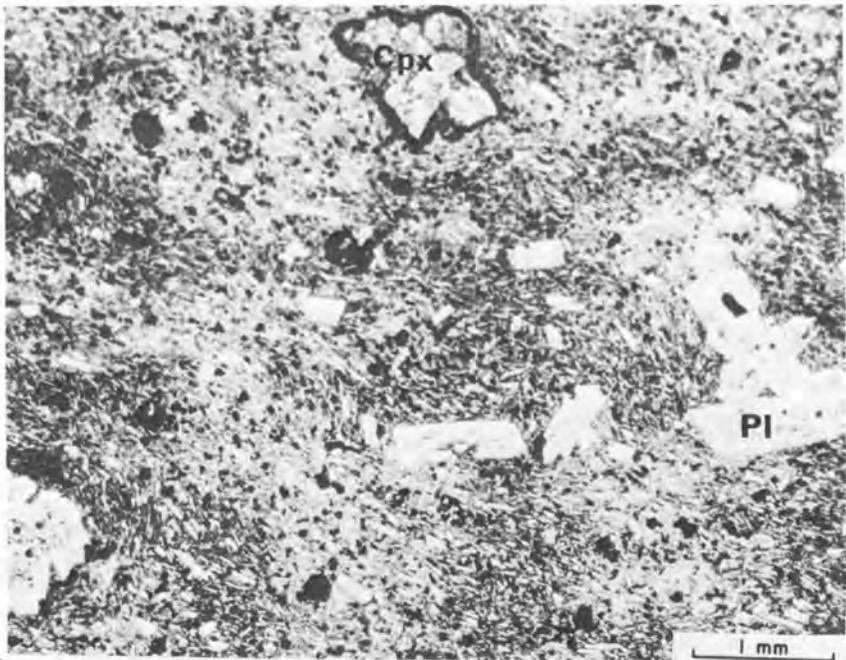
Grayback Mountain banakites contain a smaller proportion of phenocrysts (20 to 30 percent) to groundmass than the Fish Springs banakites. The very calcic-plagioclase phenocrysts range in composition from An_{87} to An_{68} and form both elongate lath-shaped and equidimensional crystals up to 3 millimeters in diameter. Feldspar phenocrysts contain reaction textures similar to those found in plagioclase crystals in Fish Springs Flat. Both orthopyroxene and clinopyroxene crystals are found in about equal proportions as phenocrysts. The subhedral laths of bronzite-hypersthene range in length from 0.5 to 1.5 millimeters and are very slightly altered in comparison to the anhedral augite phenocrysts, which are rimmed with orthopyroxene grains (Pl. 4, fig. 2). The augite phenocrysts are compositionally similar to the clinopyroxenes found in the other members of the association.

The groundmass in the Grayback Mountain flow is slightly more coarse grained than the Table Knoll banakite. The strongly trachytic groundmass plagioclase laths, which make up the greatest volume, are less calcic than the feldspar phenocrysts. The groundmass also contains about 10 percent small orthopyroxene grains, which are compositionally identical to their corresponding phenocrysts, plus 5 to 10 percent interstitial alkali feldspar, 2 to 5 percent glass, 5 percent iron-titanium oxides, and a trace of apatite needles associated with the alkali feldspar. Traces of small, highly iddingsitic-altered olivine grains also occur in the groundmass in some parts of the flow.

Latites.—Feldspar-rich latites are found in the northern Honeycomb Hills and in Fish Springs Wash. Glass generally makes up a significant proportion of the groundmasses of these lavas. For the most part, the latite flows in both areas are petrographically very similar. The latites contain about 40 to 55 percent phenocrysts, the bulk of which are phenocrysts of calcic-plagioclase (Pl. 5, fig. 1). Plagioclase phenocrysts in both areas exhibit wide compositional ranges (northern Honeycomb Hills, An_{71} to An_{64} ; Fish Springs Wash, An_{88} to An_{82}). The feldspar phenocrysts, which range in size from 1 to 7 millimeters and in form from euhedral to anhedral, contain sieved features similar to those found in feldspars in the other members of the association. The remaining 10 to 15 percent phenocrysts are orthopyroxenes



1



2

EXPLANATION OF PLATE 4
SHOSHONITE AND BANAKITE

- FIG. 1. Orthopyroxene shoshonite, Central Honeycomb Hills.
FIG. 2. Banakite, Grayback Mountain.

and clinopyroxenes similar to those found in the Table Knoll banakite. In the latites, orthopyroxene is generally more abundant than augite.

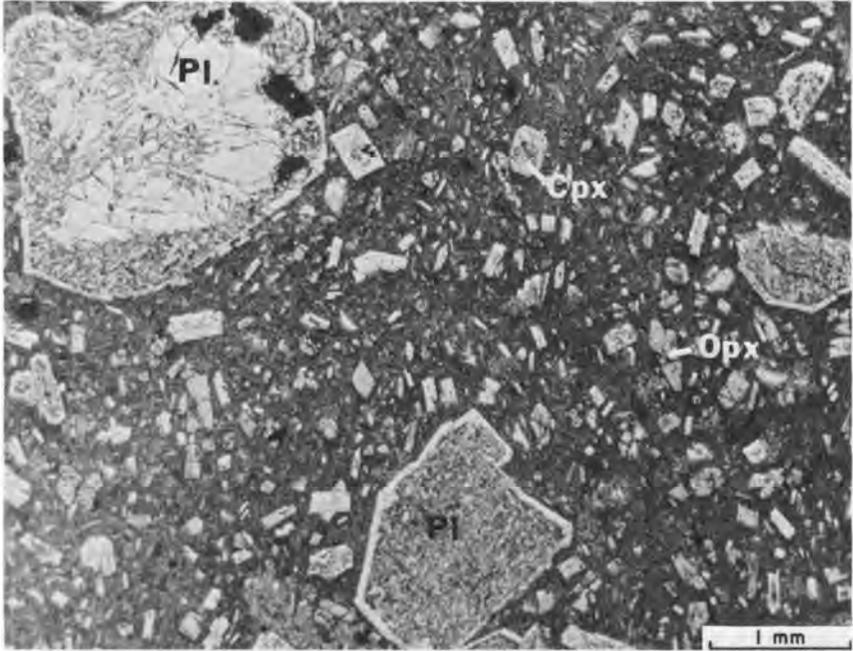
Traces of altered pleochroic hornblende crystals similar to those found in the central Honeycomb Hills were noted in sample 1-1 from the northern Honeycombs and in sample 2-6 from Fish Springs Wash. Glomeroporphyritic clusters up to 15 millimeters in diameter are locally abundant in the latite flows. The clusters are composed mainly of calcic-plagioclase feldspar phenocrysts. Clinopyroxene and orthopyroxene crystals are also present in varying amounts in these clusters.

Groundmasses of the Fish Springs Wash latites are almost entirely composed of glass, and in the northern Honeycomb Hills the groundmasses vary in composition from entirely glass to glass and crystalline material in equal proportions. In those latites containing groundmass crystals as well as glass the proportions of plagioclase, orthopyroxene, and clinopyroxene are similar to those found in the phenocryst assemblage. Glass in the latites contains varying proportions of feldspathic microlites and crystallites. Spherulitic devitrification of portions of the glassy groundmass was noted in several flows. The potassic residual glasses in the Honeycomb and Fish Springs latites are more calcic and sodic than residual glasses found in the shoshonites.

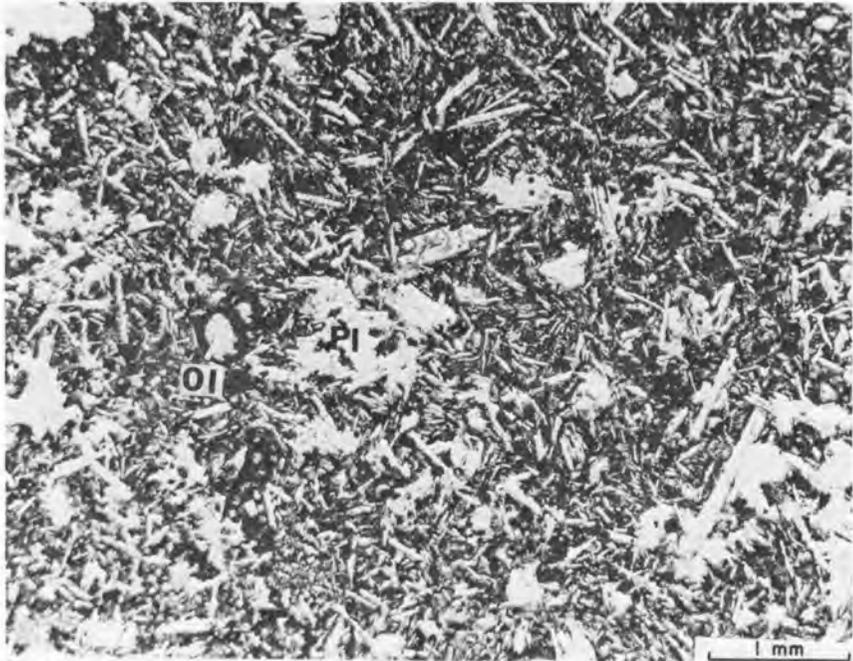
A unique vitrophyric latite flow that forms the base of a small hill in the northern Honeycomb Hills (sample 1-2) contains, in addition to phenocrysts of calcic-plagioclase, 10 to 15 percent broken and embayed hornblende crystals up to 1.5 millimeters long. About 5 to 10 percent fragmental biotite crystals and traces of small, irregular clinopyroxene crystals also occur in this flow. The hornblende phenocrysts, unlike those altered crystals found in the central Honeycomb Hills and in the other latitic flows, are not rimmed with opaque reaction rims. The hornblende crystals are also less titaniferous than the central Honeycomb hornblendes, and the biotite contains less magnesium than is present in the alteration-zone biotites found in the shoshonites. The flow capping the hornblende latite vitrophyre also has a glass-rich groundmass but contains a phenocryst assemblage similar to the more abundant latites.

Fumarole Butte Lavas.—The basaltic andesite which makes up the large main flow at Fumarole Butte and the tholeiitic basalt at North Butte are both typically very fine grained with only traces of phenocrysts. The basaltic andesite contains about 60 to 65 percent small andesite laths in an intergranular groundmass that contains about 15 to 20 percent intermediate pigeonite crystals, 10 to 15 percent iron-titanium oxide granules, and about 5 to 10 percent glass. The iron-titanium oxides are distinct, irregular granules about the same size as the feldspar laths and the pyroxene granules. Glass varies in extent but increases toward the volcanic neck, which contains only 10 to 20 percent crystalline material. Traces of phenocrysts found in the main flow comprise about equal proportions of intensely sieved-textured plagioclase crystals 0.5 to 1 millimeter in diameter and anhedral quartz xenocrysts of similar size with prominent reaction rims of small clinopyroxene crystals.

The North Butte tholeiitic basalt (Pl. 5, fig. 2), is slightly coarser grained than the main flow and contains 10 to 15 percent subhedral olivine microphenocrysts, which vary in size from 0.5 to 1 millimeter and which range from $F_{0.3}$ to $F_{0.5}$. The holocrystalline groundmass contains about 50 to 60 percent labradoritic plagioclase laths that vary from 0.1 to 1 millimeter. The



1

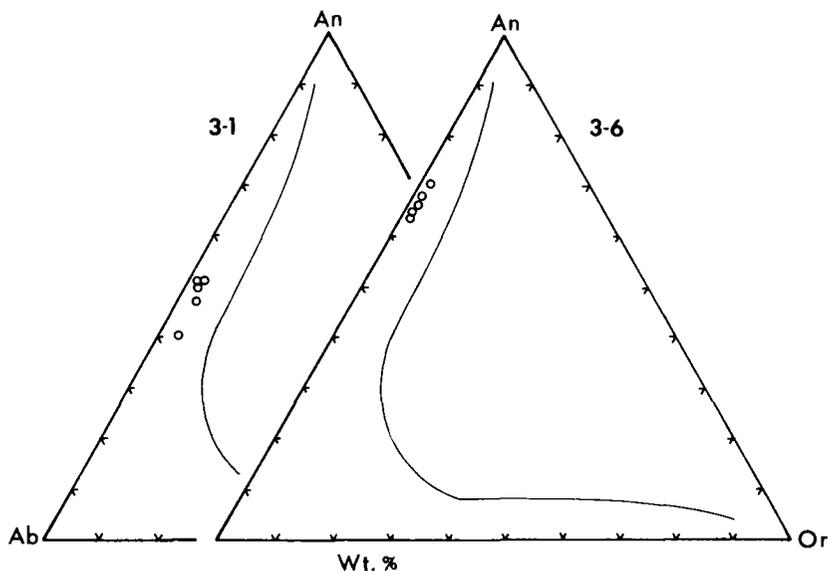


2

EXPLANATION OF PLATE 5
LATITE AND THOLEIITIC BASALT

FIG. 1. Latite, Northern Honeycomb Hills.

FIG. 2. Tholeiitic basalt, North Butte.



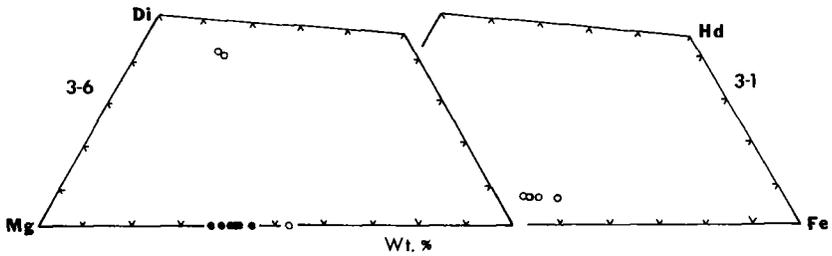
TEXT-FIGURE 11.—Feldspar analyses for the Fumarole Butte lavas: (3-1) basaltic andesite, (3-6) tholeiitic basalt. Open circles represent analyses on groundmass grains. Solid line indicates limit of ternary solid solution in natural feldspars (Smith and MacKenzie, 1958).

groundmass also contains 10 to 15 percent olivine granules (Fo_{48}) and about 5 percent small, irregular crystals of augite. Small, irregular grains of iron-titanium oxide are also found in the intergranular groundmass. The olivine phenocrysts and groundmass crystals contain irregular zones of iddingsitic alteration. Traces of small, sieved-textured calcic-plagioclase xenocrysts are also present in the tholeiitic flow.

Summary

The older shoshonitic and the younger basaltic lavas in west-central Utah are distinguished by significant differences in both their bulk geochemical and mineralogical compositions. The shoshonitic lavas are characterized by high magnesium and total alkali contents, which produce a differentiation trend similar to those found in most calc-alkaline associations (Text-fig. 8). In contrast, the lower alkali and higher iron contents of the basaltic lavas produce a tholeiitic iron-enrichment trend on the AFM diagram.

Members of the shoshonite association of Utah are chemically similar in most respects to shoshonitic lavas in the Yellowstone Park area and in Pacific island-arc systems. The major differences between Utah and oceanic shoshonites (Jakeš and White, 1972) are in the slightly higher (1 to 2 percent) CaO and MgO contents and in the lower (1 to 2 percent) K₂O and SiO₂ contents of the oceanic lavas. The only major difference between the shoshonitic series of Yellowstone Park (Iddings, 1895) and the Utah lavas is the higher (2 percent) MgO content of the less siliceous members of the Yellowstone association. Three shoshonites and a banakite



TEXT-FIGURE 12.—Pyroxene and olivine analyses for the Fumarole Butte lavas: (3-1) basaltic andesite, (3-6) tholeiitic basalt. Solid circles represent analyses on phenocrysts; open circles, analyses on groundmass grains. Olivine analyses plotted on base of quadrilateral.

from Yellowstone, analyzed by Nicholls and Carmichael (1969), are dubious members of the series, their K_2O content and K_2O/Na_2O ratios resembling those of the more common calc-alkaline lavas in the region.

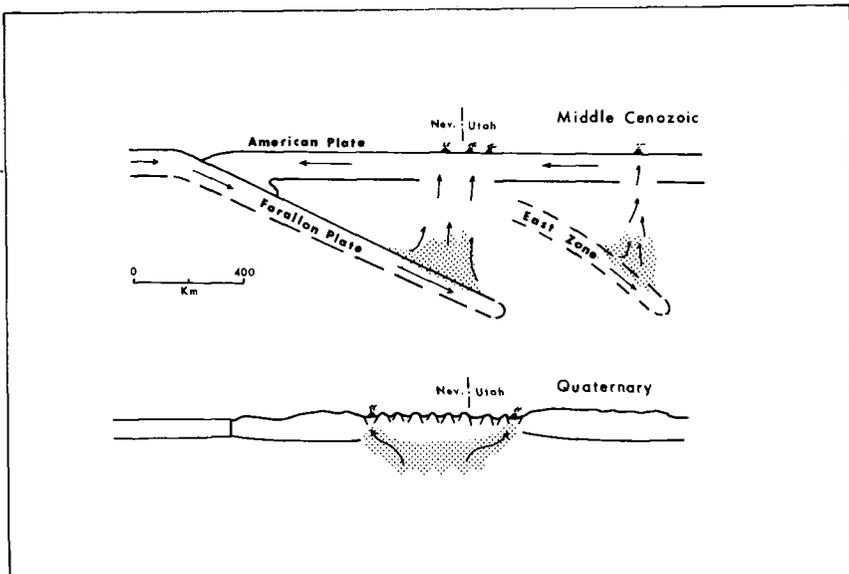
Comparison of mineralogic properties of the shoshonitic association of the Utah and of the Pacific series is difficult because of scarcity of mineralogical data from oceanic shoshonites. The only other microprobe study of shoshonitic minerals is the analyses performed by Nicholls and Carmichael (1969). The high potassium contents which typify the shoshonite association are produced from either the alkali feldspar or the potassic residual glasses in these lavas. In the Utah shoshonitic lavas there is a strong partition of potassium between (1) the alkali feldspars and residual glasses (with 58 to 70 percent *or*) and (2) the plagioclases as phenocrysts and groundmass grains (0 to 3 percent *or*). The potassium partition was also noted in the shoshonite series of the Yellowstone Park area by Nicholls and Carmichael (1969), but the plagioclase fraction in these lavas contains a somewhat higher *or* content (3 to 10 percent), and unlike the Utah shoshonites, many plagioclase phenocrysts have alkalic rims compositionally similar to the groundmass alkali feldspars. Plagioclase phenocrysts and groundmass crystals in both the Yellowstone and Utah lavas exhibit wide ranges in calcium content, but the phenocrysts in the Utah lavas are generally more calcic. Compositional ranges of olivine and orthopyroxene are very similar in both shoshonitic suites, but clinopyroxenes in the Yellowstone lavas exhibit a greater variation in calcium content than the Utah pyroxenes.

Nicholls and Carmichael (1969) questioned the validity of the shoshonite association as a truly unique magma series, because in the Yellowstone area the shoshonitic lavas are richly porphyritic and because fine-grained aphyric lavas, necessary to define a liquid line of descent for the series, are not present. In the Honeycomb Hills, however, the essentially aphyric olivine shoshonites, which are compositionally identical to the porphyritic orthopyroxene shoshonites, are clearly noncumulative and attest to the existence of shoshonitic magmas. In addition, some of the absarokites and banakites are not strongly porphyritic, at least in comparison to the latites and orthopyroxene shoshonites, and magmas of absarokite and banakite compositions could well exist.

REGIONAL CONSIDERATIONS AND CONCLUSIONS

Chemical and mineralogical properties of the older shoshonitic and younger basaltic lavas, as outlined in the preceding section, indicate that distinctly different magmas and/or magmatic processes were responsible for their origins. In addition to their petrologic differences, the two associations are related to different phases in structural evolution of the eastern Great Basin. Shoshonitic lavas were extruded immediately prior to and during early phases of basin-range faulting; by contrast, the younger Fumarole Butte basaltic lavas were erupted after most of the main basin-range structures had already been formed. The volcano-tectonic models for the western United States, developed by Atwater (1970), McKee (1971), and Lipman et al. (1972), postulate that during the early to middle Cenozoic, intermediate calc-alkaline igneous rocks were erupted through fairly stable crust in response to the overriding and the subduction of the Farallon plate (Text-fig. 13). In the late Cenozoic, after consumption of the lithospheric plate, the Great Basin underwent crustal extension, developing basin-range normal faulting (Scholz et al., 1971) and changing the nature of volcanism to fundamentally basaltic (Christiansen and Lipman, 1972).

Recent studies of circum-Pacific island arcs indicate that there is a close correlation between nature of recent volcanic activity and depth to the Benioff seismic zone (Kuno, 1966; Dickinson and Hatherton, 1967; Sugimura, 1968; and Dickinson, 1968). These studies have found that the least potassic tholeiitic lavas are erupted closest to an island arc, and that surficial volcanism becomes increasingly potassic with increasing distance (i.e., depth to the seismic or subduction zone) from the arc. Jakeš and White (1969) noted that the sho-



TEXT-FIGURE 13.—Schematic sections across the western United States showing the differences in plate interaction and the regions of associated magma generation.

shonitic lavas of Papua were located in a zone of volcanic activity at the greatest distance from the New Guinea-New Britain arc.

Using Dickinson and Hatherton's (1967) method of relating K_2O content of volcanic rocks to the depth of the subduction zone, Lipman et al. (1972) calculated the depths to the early Cenozoic subduction zone for the major volcanic fields of the western United States and found that two subparallel imbricate subduction zones were influencing volcanic activity. Lipman et al. (1972, p. 235) indicate that during the middle Cenozoic, the depth of the more westerly of these two subduction zones under Utah was from 300 to 350 kilometers. Depth calculations using a similar method for the shoshonitic lavas of my study indicate a depth range of from 200 to 350 kilometers for this western zone. The wide variance in depth estimation is due to the flat to slightly negative slope of the K_2O-SiO_2 variation diagram (Text-fig. 6). Depths indicated by the absarokites and shoshonites, which contain 3.5 percent K_2O at 50 to 58 percent SiO_2 , are in agreement with Lipman's estimates, but the more silicic members (greater than 59 percent SiO_2) indicate much shallower depths. Jakeš and Smith (1970), who noted similar flat to negative slopes in K_2O-SiO_2 diagrams of the potassium-rich volcanic rocks of Eastern Papua, explained this anomalous decrease in potassium as follows: early partial melting of a mica phase produced low-silica melts enriched in potassium while subsequent extensive partial melting produced more silicic lavas depleted in potassium.

Exact mechanisms for generation of potassic lavas at depth are not fully understood but probably involve changes in both the underthrust lithospheric plate and the upper mantle above it. Jakeš and White (1972) indicate that the potassic lavas of island arcs could be produced by one of two models or by a complementary combination of the two. In their first model, the upper mantle contributes very little to magma generation: the partial melting of some sort of mica and of tholeiitic material in the underthrust plate produces the observed lavas. In their second model, the underthrust plate simply introduces volatiles and siliceous fluids into the upper mantle, where partial melting and magma generation occur at much shallower depths. A recent study by Green (1972) on the effect of high-pressure hydrous conditions upon calc-alkaline magmas indicates that at depths greater than 150 kilometers, melting is governed by eclogite fractionation, but the interaction of ascending melts with wall rocks and the breakdown of phlogopite could produce highly potassic calc-alkaline lavas.

Magmas responsible for shoshonitic and latitic flows in the Honeycomb Hills produced lavas of similar compositions but with distinctly different mineralogies. Shoshonitic magmas produced either pyroxene-bearing or hornblende-biotite latite flows. Two different but possibly complementary mechanisms operating before eruption could be responsible for producing these different mineral assemblages. For the shoshonitic magma, changes in the total pressure of the magma could shift the phase equilibria back and forth across a phase boundary or boundaries, producing different mineral assemblages with constant bulk composition (Kushiro, 1969). A rapidly ascending liquid acting in the manner described by Jamieson (1970) might not allow sufficient time for crystals and melt to equilibrate, producing a disequilibrium assemblage similar to that found in the orthopyroxene-shoshonites. Alternatively, the magma could rise more slowly, allowing a closer approach to equilibrium yielding an olivine shoshonite. The shoshonitic association lavas of west-central

Utah are the end product of a complex history of partial melting and differing crystallization paths, which involve processes in both the upper mantle and crust.

The late Cenozoic Fumarole Butte lavas were probably produced at depths much shallower than those involved in producing the members of the shoshonite association. In the late Cenozoic, crustal extension with an accompanying high heat flow and with formation of a low-velocity layer in the upper mantle at depths as shallow as 40 kilometers, moved the sites of magma generation much closer to the surface (Scholz et al., 1971). Mechanisms for formation of basaltic andesite and quartz tholeiite in west-central Utah are no doubt consistent with those proposed by Leeman and Rogers (1970). They postulate that alkaline olivine basaltic magmas were produced by a small amount of partial melting in the upper mantle at depths of about 40 to 60 kilometers and that these magmas underwent low-pressure fractionation, governed by the wetness of either the lower crust or the upper mantle, to produce basaltic andesite or tholeiitic lavas.

Because the volumes of shoshonitic lavas discovered in this study are limited, further petrologic investigations of the other early to middle Cenozoic volcanic centers in western Utah would aid in determining the actual extent of potassic volcanism and would provide a better estimate of the age of the volcanic-tectonic transition in Utah. In addition, further experimental research into (1) mechanisms of potassic magma generation at high pressures and (2) the nature of phase equilibria of these lavas at varying pressures would aid in better explaining the unusual chemical and mineralogical features characteristic of the shoshonite association. Studies of the trace elements and isotopes of the older group of mafic lavas in west-central Utah would also aid in determining the nature of the source materials from which these lavas were derived and the possible effects of crustal interaction with these magmas.

APPENDIX A

Average Microprobe Mineral Analyses

TABLE A-1
Average Microprobe Analyses of Feldspar and Residual Glass

	1A	1B	2A	2B	3A	3B	3C
Spec. No.	5-3	5-3	1-35	1-35	1-21	1-21	1-21
SiO ₂	---	62.65	---	---	51.73	51.76	61.92
TiO ₂	---	0.23	---	---	0	0	0.12
Al ₂ O ₃	---	19.49	---	---	30.15	30.36	19.12
FeO*	---	0.46	---	---	0.24	0.41	0.31
MnO	---	0.05	---	---	0.01	0.02	0.01
MgO	---	0.11	---	---	0	0	0.01
CaO	11.40	1.55	12.53	1.33	13.61	12.75	0.36
Na ₂ O	4.48	3.58	3.79	2.59	3.39	3.69	2.51
K ₂ O	0.60	9.55	0.52	7.37	0.20	0.33	11.82
Total	---	97.67	---	---	99.25	99.32	96.08
ab	40.11	33.48	34.30	31.70	30.59	33.44	22.95
an	56.37	8.09	62.62	9.06	68.49	64.74	6.78
or	3.52	58.43	3.08	59.24	0.92	1.82	70.27

* Total Fe reported as FeO

- 1A. Absarokite, Salt Mountain, groundmass plagioclase
 1B. Absarokite, Salt Mountain, groundmass sanidine
 2A. Olivine shoshonite, West Honeycomb Hills, groundmass plagioclase
 2B. Olivine shoshonite, West Honeycomb Hills, residual glass
 3A. Orthopyroxene shoshonite, East Honeycomb Hills, phenocryst
 3B. Orthopyroxene shoshonite, East Honeycomb Hills, groundmass plagioclase
 3C. Orthopyroxene shoshonite, East Honeycomb Hills, residual glass

TABLE A-2
Average Microprobe Analyses of Feldspar and Residual Glass

	1A	1B	2A	2B	3A	3B	4	5
Spec. No.	4-1	4-1	1-1	1-1	2-4	2-4	3-1	3-6
SiO ₂	51.05	---	52.57	71.55	53.11	---	---	50.59
TiO ₂	0	---	0	0.08	0	---	---	0
Al ₂ O ₃	29.29	---	29.97	13.24	28.92	---	---	30.14
FeO*	0.49	---	0.29	0.39	0.37	---	---	0.69
MnO	0.04	---	0.01	0.03	0.01	---	---	0.01
MgO	0.05	---	0.04	0.02	0.04	---	---	0
CaO	15.98	12.96	11.44	1.35	12.65	2.21	9.52	13.80
Na ₂ O	2.23	3.88	4.74	1.96	4.41	3.08	6.06	3.60
K ₂ O	0.12	0.28	0.26	5.98	0.21	4.08	0.56	0.14
Total	99.16	---	99.32	94.60	99.72	---	---	98.97
ab	20.77	34.77	42.05	28.10	38.11	44.07	52.25	32.18
an	78.42	63.42	56.42	11.20	60.71	17.46	45.00	67.21
or	0.81	1.81	1.53	60.10	1.18	38.46	2.75	0.61

* Total Fe reported as FeO

- 1A. Banakite, Grayback Mountain, phenocryst
- 1B. Banakite, Grayback Mountain, groundmass
- 2A. Latite, Northern Honeycomb Hills, phenocryst
- 2B. Latite, Northern Honeycomb Hills, residual glass
- 3A. Latite, Fish Springs Wash, phenocryst
- 3B. Latite, Fish Springs Wash, residual glass
4. Basaltic andesite, Fumarole Butte, groundmass
5. Tholeiitic basalt, North Butte, groundmass

TABLE A-3
Average Microprobe Analyses of Clinopyroxene

	1	2	3	4	5
Spec. No.	5-2	1-35	1-21	4-1	3-6
SiO ₂	49.42	51.53	51.47	51.63	49.75
TiO ₂	1.39	0.54	0.32	0.45	1.23
Al ₂ O ₃	3.58	3.09	2.79	3.48	2.34
FeO*	7.25	8.00	7.73	8.70	10.90
MnO	0.18	0.30	0.24	0.24	0.27
MgO	14.39	14.68	15.43	14.36	13.73
CaO	22.50	20.76	20.92	20.34	19.41
Na ₂ O	0	---	0.16	---	---
Total	98.71	98.90	99.06	99.20	97.63
wo	46.70	43.82	43.19	43.15	41.28
en	41.54	43.00	44.28	42.41	40.63
fs	11.75	13.17	12.51	14.41	18.09

* Total Fe reported as FeO

1. Absarokite, Muskrat Canyon, phenocrysts and groundmass
2. Olivine shoshonite, West Honeycomb Hills, phenocrysts
3. Orthopyroxene shoshonite, East Honeycomb Hills, phenocrysts
4. Banakite, Grayback Mountain, phenocrysts
5. Tholeiitic basalt, North Butte, groundmass

TABLE A-4
Average Microprobe Analyses of Orthopyroxene

	1A	1B	2	3	4	5
Spec. No.	1-21	1-21	4-1	1-1	2-4	3-2
SiO ₂	54.25	51.82	52.83	51.99	53.46	50.29
TiO ₂	0.14	0.20	0.14	0.08	0.09	0.48
Al ₂ O ₃	2.15	2.57	1.98	0.76	1.48	0.66
FeO*	14.49	19.19	18.38	21.59	15.82	25.60
MnO	0.35	0.49	0.40	0.60	0.33	0.65
MgO	26.11	23.19	23.95	23.36	25.93	17.18
CaO	2.16	1.62	1.61	1.15	1.89	3.18
Total	99.65	99.08	99.29	99.53	99.06	98.04
wo	4.33	3.31	3.27	2.29	3.67	6.67
en	72.90	66.03	67.63	64.34	72.18	49.76
fs	22.77	30.66	29.11	33.38	24.15	43.57

* Total Fe reported as FeO

- 1A. Orthopyroxene shoshonite, East Honeycomb Hills, phenocryst
- 1B. Orthopyroxene shoshonite, East Honeycomb Hills, groundmass
2. Banakite, Grayback Mountain, groundmass
3. Latite, Northern Honeycomb Hills, phenocryst
4. Latite, Fish Springs Wash, phenocryst
5. Basaltic andesite, Fumarole Butte, groundmass

TABLE A-5
Average Microprobe Analyses of Olivine, Amphibole, and Biotite

	1	2	3A	3B	4	5	6	7
Spec. No.	5-2	1-35	3-6	3-6	1-21	1-2	1-2	1-5
SiO ₂	36.68	37.93	36.09	34.54	40.79	44.43	37.38	42.18
TiO ₂	0	0	0	0.02	2.98	1.88	3.88	3.31
Al ₂ O ₃	0	0	0	0	12.17	9.96	14.79	11.42
FeO*	17.95	23.21	34.66	41.65	12.81	13.91	14.24	10.93
MnO	0.27	0.31	0.49	0.66	0.26	0.36	0.10	0.11
MgO	41.51	37.47	28.43	21.39	11.99	13.40	14.60	18.08
CaO	0.85	0.30	0.38	0.36	11.35	11.21	0.69	1.02
Na ₂ O	0	0	0	0	1.68	1.38	0.62	0.27
K ₂ O	0	0	0	0	1.41	0.49	8.48	10.04
Total	99.26	99.22	100.05	98.65	95.38	97.02	94.74	97.36
fo	80.45	74.14	57.73	47.79				
fa	19.55	25.86	42.27	52.21				

* Total Fe reported as FeO

1. Olivine, phenocrysts, absarokite, Muskrat Canyon
2. Olivine, phenocrysts, olivine shoshonite, West Honeycomb Hills
- 3A. Olivine, phenocrysts, tholeiitic basalt, North Butte
- 3B. Olivine, groundmass, tholeiitic basalt, North Butte
4. Hornblende, orthopyroxene shoshonite, East Honeycomb Hills
5. Hornblende, latite vitrophyre, Northern Honeycomb Hills
6. Biotite, latite vitrophyre, Northern Honeycomb Hills
7. Biotite, orthopyroxene shoshonite, Central Honeycomb Hills

APPENDIX B

Geochemical and Normative Compositions

Fe₂O₃/FeO ratios for the normative calculations are based upon ratios of chemically similar rocks reported in the literature.

TABLE B-1
Lavas of the Honeycomb Hills

	1	2	3	4	5	6
Spec. No.	1-1	1-2	1-3	1-4	1-5	1-6
SiO ₂	64.28	65.98	63.23	60.81	58.27	56.73
TiO ₂	0.77	0.62	0.69	0.65	0.81	0.90
Al ₂ O ₃	15.63	16.13	14.89	15.89	15.99	16.69
FeO*	5.36	4.50	5.08	5.03	7.53	7.67
MnO	0.11	0.07	0.08	0.07	0.12	0.14
MgO	3.63	1.92	3.16	2.11	3.95	2.73
CaO	5.66	4.81	5.33	7.18	6.84	6.32
Na ₂ O	2.96	3.32	2.82	3.14	2.55	2.97
K ₂ O	1.88	2.78	2.73	2.81	3.34	3.56
P ₂ O ₅	0.14	0.14	0.15	0.15	0.31	0.41
Total	100.41	100.26	98.16	97.83	99.70	98.61
Q	21.75	21.81	20.43	14.84	11.72	9.19
or	11.13	16.70	16.14	16.70	19.48	21.15
ab	25.13	28.27	23.55	26.70	21.46	25.13
an	23.04	20.07	19.53	20.34	21.97	21.15
di	2.91	2.72	4.49	11.21	7.36	5.59
hy	11.19	6.53	9.10	3.13	9.74	7.34
mt	3.01	2.55	2.78	2.78	5.56	5.56
il	1.52	1.21	1.37	1.21	1.52	1.67
ap	0.37	0.37	0.37	0.37	0.74	1.11
K ₂ O/Na ₂ O	0.64	0.84	0.97	0.90	1.31	1.23
TTI**	58.0	66.8	60.1	58.2	52.7	55.5

* Total Fe reported as FeO **Thornton Tuttle Index

1. 1-1. Latite, Northern Honeycomb Hills
2. 1-2. Latite vitrophyre, basal flow, Northern Honeycomb Hills
3. 1-3. Latite vitrophyre, upper flow, Northern Honeycomb Hills
4. 1-4. Latite, Northern Honeycomb Hills
5. 1-5. Orthopyroxene shoshonite, Central Honeycomb Hills
6. 1-6. Orthopyroxene shoshonite, Honeycomb Buttes

TABLE B-2
Lavas of the Honeycomb Hills

	1	2	3	4	5	6
Spec. No.	1-8	1-9	1-10	1-21	1-29	1-31
SiO ₂	57.28	55.57	57.52	58.04	57.17	56.47
TiO ₂	0.82	1.07	0.85	0.88	1.12	0.99
Al ₂ O ₃	15.36	16.07	14.85	15.79	16.47	14.73
FeO*	7.23	8.47	7.75	7.28	8.35	9.32
MnO	0.12	0.16	0.15	0.18	0.17	0.14
MgO	4.31	3.94	4.27	3.01	3.38	4.24
CaO	7.04	7.11	7.23	5.45	6.31	7.24
Na ₂ O	2.45	2.72	2.55	2.92	2.77	2.52
K ₂ O	3.43	3.41	3.23	3.60	3.92	3.46
P ₂ O ₅	0.30	0.41	0.32	0.34	0.43	0.43
Total	98.36	98.93	98.72	97.50	100.10	99.54
Q	10.39	7.39	10.94	11.84	8.65	9.31
or	20.04	20.04	18.93	21.15	23.38	20.60
ab	20.94	23.03	21.46	24.60	23.55	21.46
an	20.34	21.15	19.26	18.98	20.34	17.90
di	9.56	8.73	11.36	4.48	6.25	11.67
hy	9.34	9.47	8.63	8.53	8.56	7.07
mt	5.33	6.48	5.56	5.33	6.02	8.10
il	1.52	1.97	2.55	2.55	2.12	1.82
ap	0.74	1.11	0.74	0.74	1.11	1.11
K ₂ O/Na ₂ O	1.40	1.26	1.29	1.25	1.44	1.37
TTI**	51.4	50.5	51.3	57.6	55.6	51.4

* Total Fe reported as FeO **Thornton Tuttle Index

1. 1-8. Orthopyroxene shoshonite, basal flow, Lone Butte
2. 1-9. Olivine shoshonite, upper flow, Lone Butte
3. 1-10. Orthopyroxene shoshonite, East Honeycomb Hills
4. 1-21. Orthopyroxene shoshonite, East Honeycomb Hills
5. 1-29. Olivine shoshonite, Smelter Knolls
6. 1-31. Olivine shoshonite, Hole-in-the-Wall Flow

TABLE B-3
Lavas of the Honeycomb Hills and Stansbury Mountains

	1	2	3	4	5	6.
Spec. No.	1-32	1-34	1-35	5-1	5-2	5-3
SiO ₂	57.40	58.83	57.90	51.25	49.24	50.67
TiO ₂	1.01	0.92	0.93	1.60	2.21	2.42
Al ₂ O ₃	15.89	14.93	16.09	15.32	14.15	14.19
FeO*	8.16	7.22	8.22	8.63	9.44	10.38
MnO	0.14	0.13	0.16	0.15	0.14	0.16
MgO	3.45	5.27	4.17	6.61	5.62	6.32
CaO	7.03	6.72	7.18	8.56	10.26	7.86
Na ₂ O	2.68	2.42	2.69	2.64	2.57	2.63
K ₂ O	3.89	3.39	3.13	3.58	3.88	3.34
P ₂ O ₅	0.44	0.35	0.36	0.77	1.28	1.18
Total	100.08	100.17	100.82	99.11	98.78	99.17
Q	8.65	12.44	11.72	0	0	2.94
or	22.82	20.04	18.37	21.15	22.82	19.48
ab	25.13	20.41	22.51	22.51	21.46	21.98
an	18.17	19.26	22.24	18.71	14.84	16.82
di	10.58	9.16	7.91	14.55	20.79	11.04
hy	4.90	9.59	7.87	9.09	0.10	10.64
ol	0	0	0	0.71	2.95	0
mt	7.18	7.18	7.18	7.63	5.56	6.95
hm	0	0	0	0	0.48	2.08
il	1.97	1.82	1.82	3.04	4.25	4.55
ap	1.19	0.79	0.81	1.85	3.32	2.95
K ₂ O/Na ₂ O	1.45	1.40	1.16	1.36	1.51	1.27
TTI**	56.6	52.9	52.6	43.7	44.3	44.4

* Total Fe reported as FeO **Thornton Tuttle Index

- 1-32. Olivine shoshonite, upper flow, Lone Butte
- 1-34. Orthopyroxene shoshonite, Clay Hill
- 1-35. Olivine shoshonite, West Honeycomb Hills
- 5-1. Absarokite, Mack Canyon, Stansbury Mountains
- 5-2. Absarokite, Muskrat Canyon, Stansbury Mountains
- 5-3. Absarokite, Salt Mountain, Stansbury Mountains

TABLE B-4
Lavas of Fish Springs Flat and Grayback Mountain

	1	2	3	4	5	6
Spec. No.	2-2	2-3	2-4	2-5	2-6	4-1
SiO ₂	59.73	64.67	65.82	60.74	65.73	57.93
TiO ₂	1.21	0.91	0.78	0.99	0.79	0.87
Al ₂ O ₃	16.53	14.68	14.91	16.55	14.17	16.65
FeO*	6.87	5.30	5.36	6.05	5.31	7.22
MnO	0.11	0.07	0.08	0.08	0.10	0.09
MgO	3.51	3.78	3.30	3.52	3.32	2.44
CaO	5.43	4.75	4.12	5.93	4.84	5.93
Na ₂ O	2.88	2.90	3.10	3.21	2.91	3.13
K ₂ O	2.61	2.76	3.16	3.04	2.72	4.46
P ₂ O ₅	0.43	0.18	0.18	0.34	0.18	0.35
Total	99.31	100.00	100.72	100.45	100.08	99.07
Q	17.00	21.09	21.39	12.62	23.01	7.15
or	15.59	16.14	18.93	17.81	16.14	26.16
ab	24.08	24.60	25.65	27.22	24.60	26.17
an	23.87	18.44	17.09	21.15	17.09	17.90
di	0	3.13	1.57	4.73	4.49	7.54
hy	9.06	11.25	11.04	10.80	9.63	7.30
mt	6.02	3.01	3.01	3.01	2.78	4.18
il	2.28	1.67	1.52	1.82	1.52	1.67
ap	1.19	0.40	0.40	0.79	0.40	0.74
K ₂ O/Na ₂ O	0.84	0.95	1.05	0.95	0.93	1.42
TTI**	56.7	61.8	66.0	57.7	63.8	59.5

* Total Fe reported as FeO **Thornton Tuttle Index

1. 2-2. Banakite, Table Knoll, Fish Springs Flat
2. 2-3. Latite vitrophyre, Central Fish Springs Wash
3. 2-4. Latite vitrophyre, Northern Fish Springs Wash
4. 2-5. Banakite xenolith, Southern Fish Springs Wash
5. 2-6. Latite vitrophyre, Southern Fish Springs Wash
6. 4-1. Banakite, Southern Grayback Mountain

TABLE 5-B
Lavas of Fumarole Butte

	1	2	3	4	5
Spec. No.	3-2	3-3	3-4	3-5	3-6
SiO ₂	56.14	55.97	56.17	57.34	49.68
TiO ₂	2.24	2.23	2.10	2.04	2.03
Al ₂ O ₃	14.57	14.54	14.52	14.71	15.63
FeO*	10.92	10.97	11.00	10.05	11.40
MnO	0.21	0.20	0.18	0.20	0.21
MgO	2.55	2.50	2.60	2.47	7.08
CaO	6.33	6.38	6.53	6.17	9.41
Na ₂ O	3.33	3.40	3.37	3.34	2.64
K ₂ O	2.10	2.12	2.00	2.29	1.04
P ₂ O ₅	1.37	1.22	1.19	1.20	0.67
Total	99.78	99.53	99.67	99.80	99.81
Q	12.62	11.66	12.26	13.34	2.88
or	12.25	12.80	11.69	13.36	6.12
ab	28.27	28.79	28.27	28.27	22.51
an	18.17	17.63	18.17	17.90	26.85
di	3.01	4.41	5.10	3.93	11.49
hy	12.59	11.81	11.93	11.29	16.04
mt	5.33	5.33	5.33	4.86	8.33
il	4.25	4.25	3.95	3.95	3.79
ap	3.69	3.32	2.95	2.95	1.85
K ₂ O/Na ₂ O	0.63	0.62	0.61	0.69	0.39
TTI**	53.1	53.3	52.2	55.0	31.5

* Total Fe reported as FeO **Thornton Tuttle Index

1. 3-2. Basaltic andesite, Southern Fumarole Butte
2. 3-3. Basaltic andesite, Fumarole Butte volcanic neck
3. 3-4. Basaltic andesite, Central Fumarole Butte
4. 3-5. Basaltic andesite, Eastern Fumarole Butte
5. 3-6. Tholeiitic basalt, North Butte

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