

OLIVINE-SANIDINE TRACHYBASALT FROM THE SIERRA NEVADA, CALIFORNIA*

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ABSTRACT

Near Huntington Lake in the central Sierra Nevada are three peaks formed of Cenozoic olivine-sanidine trachybasalt. Intrusive masses form Black Point and Red Mountain; Chinese Peak is capped by flows. The Black Point mass, largest of the exposures, is half a mile in diameter. Surrounding rocks are Mesozoic granites.

Most of the trachybasalts consist of granular mosaics of sanidine crystals, which are densely crowded with microlites and minute granules of plagioclase ($An_{\sim 50}$), augite, and magnetite, and contain abundant phenocrysts and microphenocrysts of olivine and augite. Sanidine content of holocrystalline specimens ranges from 15 to 30 per cent, olivine ranges from 5 to 25 per cent, and augite from 20 to 30 per cent. The rocks contain many vuggy ellipsoidal masses of augite and sanidine and ellipsoidal aggregates of augite. Many of the larger augite crystals are poikilitic and enclose numerous anhedral sanidine.

The average chemical composition of 3 analyzed specimens of intrusive trachybasalt and one of the extrusive type is $SiO_2=54$ per cent, $Al_2O_3=14$, $Fe_2O_3+FeO=9$, $MgO=7$, $CaO=7$, $Na_2O=3$, $K_2O=3$, and $TiO_2=1$.

Magmatic differentiation is inadequate to explain the composition of the rocks. Assimilation of granitic rock is shown by relationships of xenoliths and xenocrysts, and the origin of the trachybasalts seems best explained as the result of assimilation of large quantities of wall rock in a basaltic magma.

INTRODUCTION

Olivine-sanidine trachybasalt, a rock type not recognized previously in California, forms three peaks in the Huntington Lake area of the Sierra Nevada (Fig. 1). The peaks are on the central part of the west slope of the Sierra, and have summit elevations between 8,100 and 10,000 feet. The trachybasalt is younger than the surrounding granitic rocks of late Mesozoic age, and formation of the volcanic rocks was followed by major erosion so that the intrusive masses of trachybasalt of Red Mountain and Black Point now stand as peaks. Of whatever extrusive lavas were formed, only the tiny remnant capping Chinese Peak remains.

The trachybasalts are composed of subequal amounts of sanidine, olivine, augite, and calcic plagioclase. Except for the sanidine, the mineral content (though not the mineral proportions) is basaltic, and the rocks are best classed as potassic basalts or trachybasalts. The combination of large amounts of both potassium feldspar and the ferromagnesian minerals olivine and augite is uncommon in igneous rocks. The association is commonest in the lamprophyres, and particularly in the volcanic lamprophyres as designated by Williams (1936).

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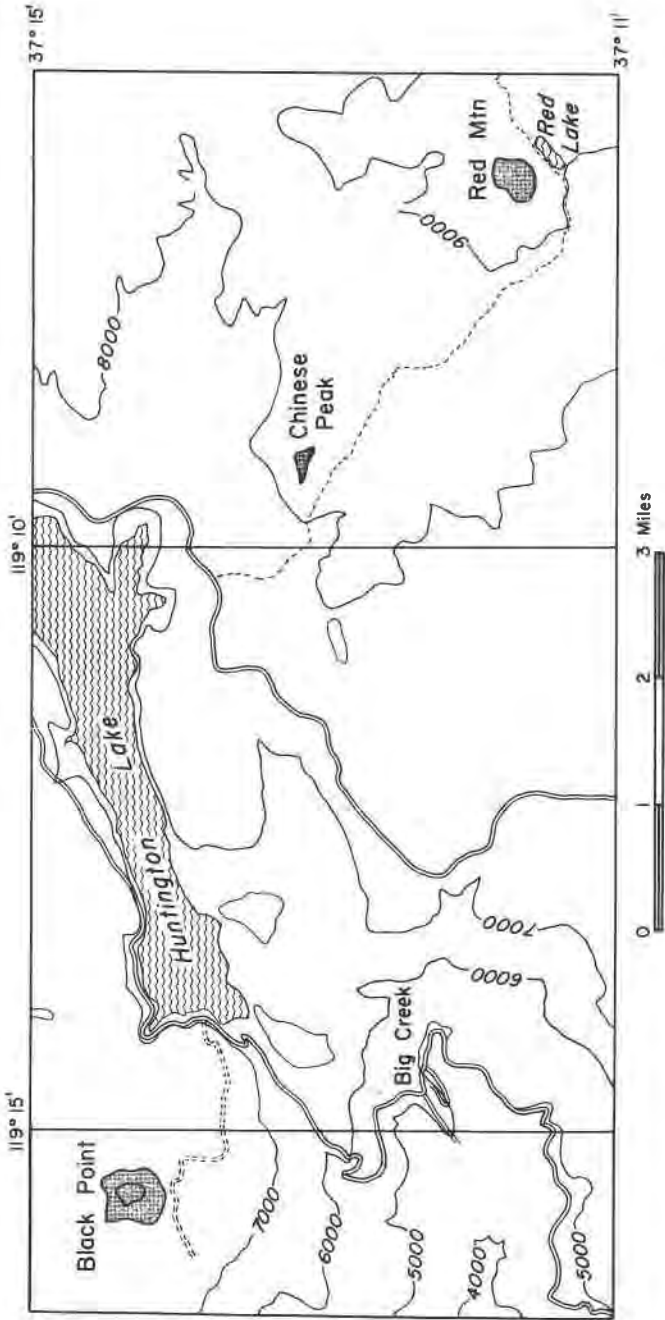


FIG. 1. Map of Huntington Lake area, California, showing areas of trachybasalt (stippled), Contour interval 1000 feet.

TABLE 1. ESTIMATED AND MEASURED MODES OF TRACHYBASALTS FROM THE HUNTINGTON LAKE AREA IN VOLUME PER CENT

	Black Point					Chinese Peak				Red Mountain				
	HL 199-11 ²	HL 199-4	HL 200-4 ¹	HL 201-2	HL 202-2	HL 75A ³	HL 75-1	HL 75-2 ⁴	HL 84A-1	HL 84A-2	HL 84A-3	HL 84A-4 ⁵	HL 85 ²	
Sanidine	26	25	28	28	25	20	24	20	29	15	25	25	30	
Plagioclase	20	20	23	20	25	24	18 ²	29	?	29	25	20	20	
Quartz		0.1								?				
Olivine	20	25	20	20	20	20	20	15	10	15	15	15	5	
Augite	28	25	24	25	25	25	24	27	30	25	25	25	32	
Biotite	0.8	0.5	0.3	1	tr	tr	tr	0.5	tr	tr	tr	tr	tr	
Amphibole						tr	1	8	0.1	8	5	5	0.5	
Magnetite	5	5	5	5	5	10	10	8	5	5	5	5	10	
Apatite	nc	0.1	nc	a	0.5	tr	?	tr?	?	?	?	?	?	
Analcime	0.4			a		tr	tr	tr	tr	0.1	tr	tr	tr	
Carbonate	0.1	0.5		1										
Glass														
Xenocrysts														
Quartz														
Plagioclase		tr	0.1	tr	tr			1 ⁶	5	3	3	3	tr	
Biotite(?) ³	nc	(0.1)		(0.1)	(tr)		2	1	1	5	2	2	3	
Clinopyroxene							(10)	(5)	(tr)	(5)	(tr)	(tr)	(5)	

¹ Point-counter modal analysis based on 2000 counts per section.
² Chemical analysis available (see Table 2).
³ Listed as magnetite in the mode.
⁴ Contents of rock inclusion and its reaction rim not included.
⁵ In a hybrid trachybasalt adjacent to a xenolith.
⁶ nc—Present but not intersected in point-counter traverses.

The composition of these trachybasalts is unique as far as now known among the rocks of the Sierra region, although latites (trachyandesites) are known in the northern Sierra Nevada (Ransome, 1900, p. 6). Basaltic lavas and breccias which share some of the textural, but not compositional (?), peculiarities of the trachybasalts are present as the remnant on the high ridge of Volcanic Knob, some miles northeast of the present areas; the Volcanic Knob rocks are being studied by P. Lydon. In view of the fragmentary knowledge of the widely separated Cenozoic volcanic rocks of the central Sierra Nevada, no suggestions of regional correlations seem warranted.

Modal analyses of 13 specimens are given in Table 1, and chemical analyses of 4 samples in Table 4.

FIELD RELATIONSHIPS AND MEGASCOPIC CHARACTER

Black Point. Largest of the exposures of trachybasalt is that of Black Point, an intrusive mass with a roughly circular plan and an area of about $\frac{1}{4}$ of a square mile (Fig. 2). Outcrops are virtually limited to the central summit area, as the rest of the mass is covered by block rubble. The rocks are very fine-grained to aphanitic holocrystalline trachybasalt, commonly gray but locally reddish, with scattered phenocrysts of green augite and red-stained olivine. Variations in texture are mostly irregularly gradational, with changing grain sizes and varying propor-

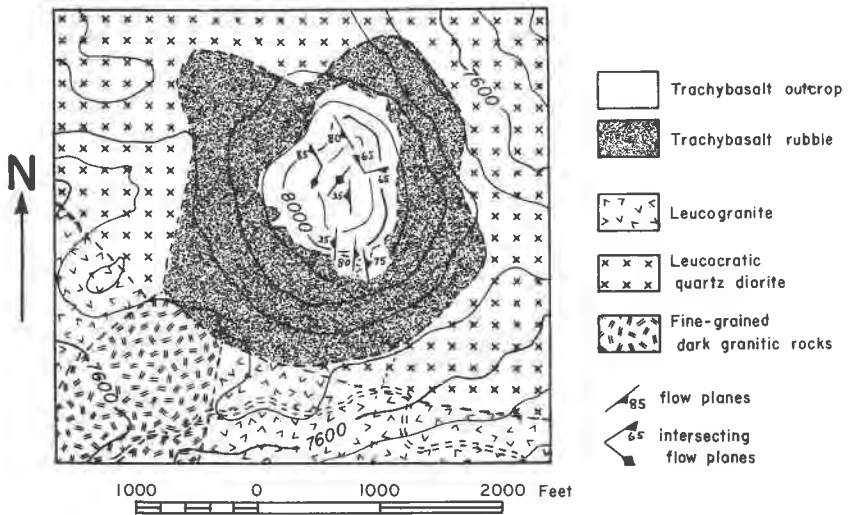


FIG. 2. Geologic map of Black Point. Contour interval 80 feet; base from USGS Shaver Lake quadrangle.

tions of phenocrysts, vesicles, ellipsoidal structures of augite, and inclusions.

Some contacts between diverse types are sharp, as is a steep and irregular contact zone less than an inch thick between vesicular and less vesicular gray trachybasalt. The more vesicular rock is coarser grained than the other, and has two generations of vesicles—one with biotite and calcite, the other empty or with an analcime (?) crust.

Inclusions are small and mostly feldspathic, with some inclusions of volcanic rocks. No breccias, tuffs, or other fragmental rocks are present.

Planar flow structures are discernible in most of the outcrop area, and are in general steep (Fig. 2). The structures are marked by streaks of vesicular rock, by elongation of vesicles and vugs, and locally by orientation of tabular crystals of sanidine. Flow structures with drusy coatings of tabular sanidine in elongate vesicles are present over considerable areas. Steep flow structures intersect and cross in many exposures (Fig.



PLATE 1. Intersecting flow structures, Black Point. The structure parallel to the knife is marked by elongation of vesicles. The structure parallel to the pencil is marked by elongate vesicles with drusy coatings of tabular crystals of sanidine. A small xenolith of granite is present to the right of the knife.

2, and Plate 1), indicating diverse directions of movement at a stage when the mass was still mobile enough to deform viscously.

Red Mountain. The trachybasalt of Red Mountain forms an elliptical intrusive mass with dimensions of 1,500 by 2,000 feet, and is exposed for a vertical distance of 500 feet (Fig. 3, and Plate 2). The granitic country rock is leucocratic medium-grained biotite quartz monzonite. The contact between trachybasalt and quartz monzonite is covered by rock waste, but the topographic expression of the contact shows it to be steep.

The western and northern part of the Red Mountain mass is composed

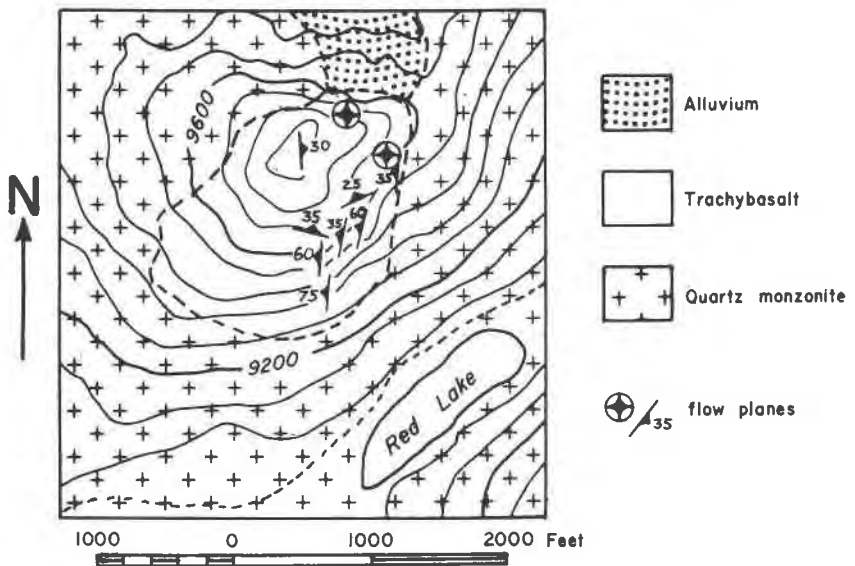


FIG. 3. Geologic map of Red Mountain. Contour interval 80 feet; base from USGS Huntington Lake quadrangle.

of reddish trachybasalt which has few outcrops, most of the surface being covered with a rubble of big blocks. The rocks are red brown where weathered, and where fresh are reddish, purplish, or chocolate brown. The trachybasalt is aphanitic and vesicular, and much of it contains glass. Inclusions are common in it, and are mostly of red volcanic rocks, either dense or coarsely vesicular; other types of inclusions include coarse and highly vesicular feldspar porphyry, pyroxenite, and graphic granite.

The trachybasalt of the southeastern part of Red Mountain is gray, with flow structures indicating that it underlies the red rocks with a west-dipping contact; the contact between gray and red rocks was not



PLATE 2. Red Mountain, seen from the south across Red Lake. The upper part of the mountain is formed of dark trachybasalt, and the lower slopes are of white quartz monzonite.

observed. Within the gray trachybasalt, the lower and southeastern part has much glass, whereas the upper part has little or no glass; the contact between glassy and holocrystalline rock is smoothly gradational over tens of feet. The gray trachybasalt forms many cliffs, but the rock disintegrates to a fine rubble. A northwest-dipping dike, 20 feet thick, in the west part of the gray trachybasalt, is of reddish-brown crystalline trachybasalt with abundant empty shells of augite.

Most exposures of the gray trachybasalt show conspicuous flow structures, with parallel joints and elongate vesicles. Most of the measured flow structures dip westerly, with the dip decreasing eastward (Fig. 3); although this suggests an intrusive body shaped like an asymmetric funnel, the eastern contact is steeper than the flow structures near it. No fragmental rocks were seen.

Chinese Peak. The small thin remnant of flows of trachybasalt on Chinese Peak is of bluish and reddish gray aphanitic rocks, sparsely porphyritic. The rocks are microvesicular and contain scattered ellipsoids of augite and sanidine and of augite alone.

PETROGRAPHY

Table 1 shows modes of trachybasalt specimens from the three peaks. Two of the modal analyses were made with the point counter method,

and these two served as a guide for visual estimates of mineral proportions of the other specimens.

The specimens studied are composed of subequal amounts of sanidine (15–30 per cent), plagioclase (20–29 per cent), olivine (5–25 per cent), and augite (24–32 per cent). In three specimens from Red Mountain, the place of the sanidine is taken by glass; the chemical composition of the one such specimen analyzed shows that the glass must be largely of sanidine composition. Olivine is in general less abundant at Red Mountain than at Black Point and Chinese Peak. Magnetite makes up 5 to 10 per cent of the rocks.

Most of the specimens studied are similar, with seriate phenocrysts of olivine and augite in a xenomorphic matrix of sanidine which is packed with microlites and minute granules of plagioclase, augite, and magnetite. Sanidine encloses all of the other pyrogenic minerals. Most minerals other than sanidine neither enclose nor interfere with each other, although augite uncommonly encloses minute amounts of plagioclase and apatite (?), and olivine commonly encloses a few magnetite crystals. Phenocrysts of olivine and augite have an average grain size of 0.5 to 1 mm.

Three of the specimens of Red Mountain rocks, both gray and reddish, are similar to the holocrystalline specimens except that they contain glass in place of sanidine. Abundant phenocrysts of olivine and augite and xenocrysts are set in a very fine-grained felted microvesicular hypocrySTALLINE groundmass. Xenocrysts include quartz, plagioclase, and biotite (?) pseudomorphed by magnetite. The groundmass is composed of nearly colorless pinkish-brown glass, plagioclase ($An_{\sim 50}$), and minor quantities of augite and olivine granules.

Ellipsoidal aggregates of granular augite are abundant, and many ellipsoids are rimmed with sanidine.

Sanidine. Sanidine differs widely in grain size among the thin sections studied. In two of the Black Point specimens it averages 0.1 mm., in two others it ranges from 0.4 to 1 mm., and in the fifth it ranges from 0.1 to 1 mm. In the samples from Chinese Peak, sanidine ranges from 0.01 to 0.1 mm., and averages 0.02 mm. In the holocrystalline specimens from Red Mountain, sanidine has an average grain size of 0.01–0.02 mm. in one section and 0.1 mm. in the other section. A coarse sanidine fabric is illustrated on Plate 3, and a fine sanidine fabric on Plate 4.

Sanidine is densely crowded with inclusions. Exceedingly fine-grained sanidine replaced cores of zoned plagioclase xenocrysts and rims of quartz xenocrysts. No alterations of sanidine were seen. Around microvesicles, common in the coarser rocks, sanidine is coarser than average and contains fewer inclusions of other minerals. In the finer grained

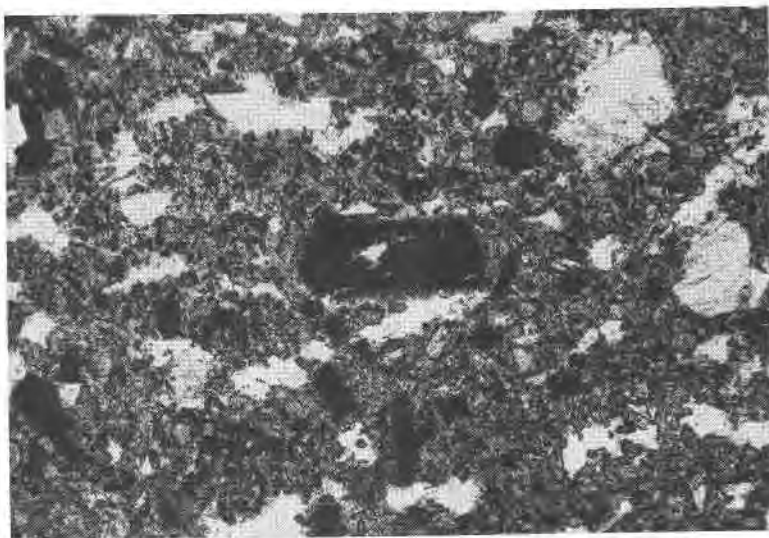


PLATE 3. Tabular magnetite pseudomorphs (?) after biotite in vesicular trachybasalt containing masses of clear sanidine and microphenocrysts of augite and olivine. Picture area is about 4 mm. long. Ordinary light.

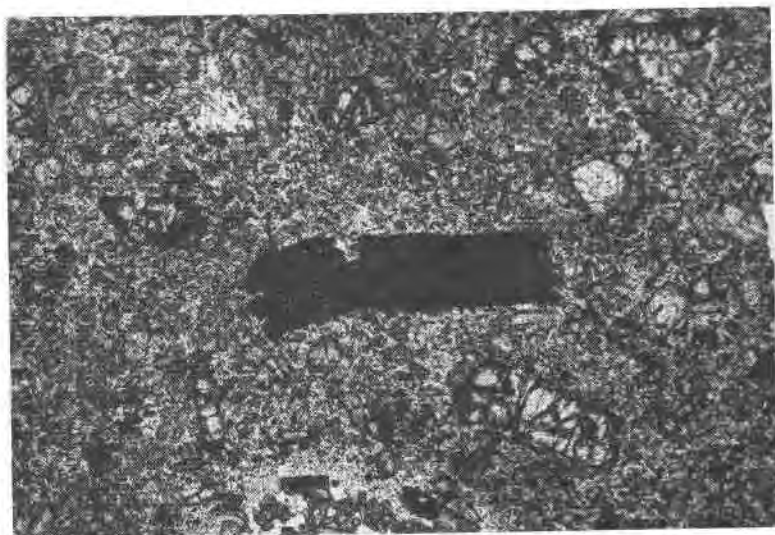


PLATE 4. Tabular mosaic of magnetite granules, possibly pseudomorphous after biotite, in trachybasalt with phenocrysts and microphenocrysts of olivine and augite and very fine-grained sanidine and plagioclase. Picture area is about 3 mm. long. Ordinary light.

fabrics, sanidine is anhedral and equant; in the coarser fabrics, it is tabular euhedral to subhedral. The range of $2V_x$ is from 38° to 57° , with most measurements near 42° to 45° . Different optic angles are found within single crystals as well as in separate grains. The extinction angle X to a ranges from 2° to 6° . Indices of the sanidine analyzed chemically (see below) were determined by B. H. Bieler as $\alpha=1.528-1.530$, $\beta=1.531-1.534$, and $\gamma=1.535-1.539$.

A chemical analysis of a sanidine separate from tabular vugs is given in Table 2. The specimen contains nearly 2 per cent of non-feldspathic

TABLE 2. CHEMICAL COMPOSITION OF SANIDINE FROM SPECIMEN HL 561 A, TRACHYBASALT FROM WEST PART OF SUMMIT SURFACE OF BLACK POINT

Sanidine analyzed came mostly from ellipsoids rather than rock groundmass. Major-element analysis by Faye H. Neuerburg, Denver rock analysis laboratory, Lee C. Peck, supervisor, spectrographic analysis by Ray Havens.

SiO ₂	64.40	
Al ₂ O ₃	19.50	Cr 0.00X ¹
Fe ₂ O ₃	0.35	Cu 0.00X+
FeO	0.05	Ga 0.00X-
MgO	0.07	Mn 0.00X-
CaO	1.19	Ni 0.00X+
Na ₂ O	4.19	Pb 0.00X-
K ₂ O	9.40	Sr 0.X-
H ₂ O(-)	0.10	V 0.00X-
H ₂ O(+)	0.03	Zr 0.00X-
TiO ₂	0.27	
P ₂ O ₅	0.03	
BaO	0.27	
	99.85	

¹ X—denotes an amount between 1 and 2.16, X, between 2.16 and 4.64 and X+, between 4.64 and 10.

impurities. The normative composition of the analyzed feldspar, recalculated to a sum of 100 (from 98.2), is as follows:

KAlSi ₃ O ₈	56.6 per cent
NaAlSi ₃ O ₈	36.2
CaAl ₂ Si ₂ O ₈	6.0
BaAl ₂ Si ₂ O ₈	0.7
SrAl ₂ Si ₂ O ₈	0.5 ^a
	100.0

^a A content of 0.15 per cent Sr is assumed from the semiquantitative "0.X-."

The sanidine appears clear and uniform under microscopic examination, but an x -ray diffraction study by A. J. Gude III showed the presence of distinct lattices of sanidine and plagioclase; the feldspar must be submicroscopically perthitic.

Plagioclase. Except for xenocrysts, plagioclase is confined to the groundmass and is present only as tabular polysynthetically twinned microlites averaging about 0.01 or 0.02 mm. in length in all specimens except one from Chinese Peak, in which the average length is about 0.002 mm. Plagioclase gives the groundmass of the Red Mountain and Chinese Peak rocks a felted appearance, lacking in the Black Point rocks although the plagioclase contents of the rocks of the three areas are similar. Plagioclase microlites are crowded between the mafic minerals, and the visual estimates of their abundance are uncertain. The composition is estimated from relief and from difficult measurements of maximum extinction angles in the (010) zone to be about An_{50} .

Olivine. Olivine crystals are short subhedral prisms, many of them apparently broken fragments of larger grains. Olivine is confined to phenocrysts and microphenocrysts; the crystals range to small sizes, but not as small as the groundmass grains. The range of $2V_x$ is from 85° to 95° , indicating a magnesian composition. The variation in optic angle is not a zonal feature of single crystals, but is between different grains in any slide; similar variations in olivine of the volcanic rocks of the Hakone caldera have been described by Kuno (1950, p. 970). Alteration of olivine is ubiquitous, and consists of dark red-brown staining, probably iddingsite, largely along cracks and margins of grains; anhedral magnetite is enclosed in the more densely stained olivines. The stain renders most grains opaque or nearly so, and particularly near augite-sanidine ellipsoids.

Augite. Augite shows the greatest range in grain size in the rocks, varying from the largest of the phenocrysts to barely visible microlites in the groundmass. The larger grains are subhedral, and some appear to be broken from still larger crystals; smaller grains are short subhedral prisms. Some grains are twinned polysynthetically. The augite of the phenocrysts and of the groundmass is a very light grass green, whereas that in the ellipsoids is light yellowish green. In thin section, the augite is faintly greenish, non-pleochroic, with a 36° extinction angle between Z and c . The $2V_z$ is about 60° , without apparent dispersion. Indices, given in Table 3, are within the range 1.682–1.715. A semi-quantitative spectroscopic analysis, by A. A. Chodos of the California Institute of Technology, of an inadequate amount of pyroxene from an ellipsoid suggested Mg and Si as major elements, Fe and Al as less than major elements, Mn and Ca as minor elements, and Ba as a trace. These data do not fit

TABLE 3. REFRACTIVE INDICES OF PYROXENE

- A: Groundmass pyroxene, specimen HL 558 C, trachybasalt below east end of Black Point summit surface.
 B: Groundmass pyroxene, specimen 561 A, trachybasalt from west part of summit surface of Black Point
 C: Pyroxene in ellipsoid, trachybasalt from Red Mountain.
 Determinations by B. H. Bieler.

	A	B	C
$\alpha =$	1.690-1.694	1.685-1.690	1.682-1.688
$\beta =$	1.692-1.698	1.690-1.695	1.685-1.692
$\gamma =$	1.700-1.715	1.703-1.708	1.692-1.704

any of the pyroxenes in Tröger's tables (Tröger, 1952, pp. 53-64), but, as the pyroxene is aluminous, it is tentatively named augite; if this designation be correct, then Ca must be more abundant than the minor amount suggested by the spectrographic analysis.

Cores of many of the larger augite crystals are poikilitic or vesicular,



PLATE 5. Augite phenocryst with vesicular core. The vesicles are filled with sanidine. Picture area is 2 mm. long. Ordinary light.

variously empty or filled with fine-grained xenomorphic sanidine with minute apatite inclusions (Plate 5), or, rarely, nearly empty but partially lined with analcime. A few large solid phenocrysts have cores with a faintly purplish color like that of titaniferous augite.

Accessory and secondary minerals. Dust and small euhedra of titaniferous magnetite crowd the groundmass. In the coarser specimens, there is a slight clustering of magnetite on peripheries of olivine crystals. Magnetite is generally absent from ellipsoid interiors. Apatite forms swarms of minute slender prisms in sanidine, and a few larger prisms are present in the plagioclase xenocrysts. Most of the identifiable apatite is in and around the augite-sanidine ellipsoids.

Biotite is almost confined to the Black Point rocks, where its occur-

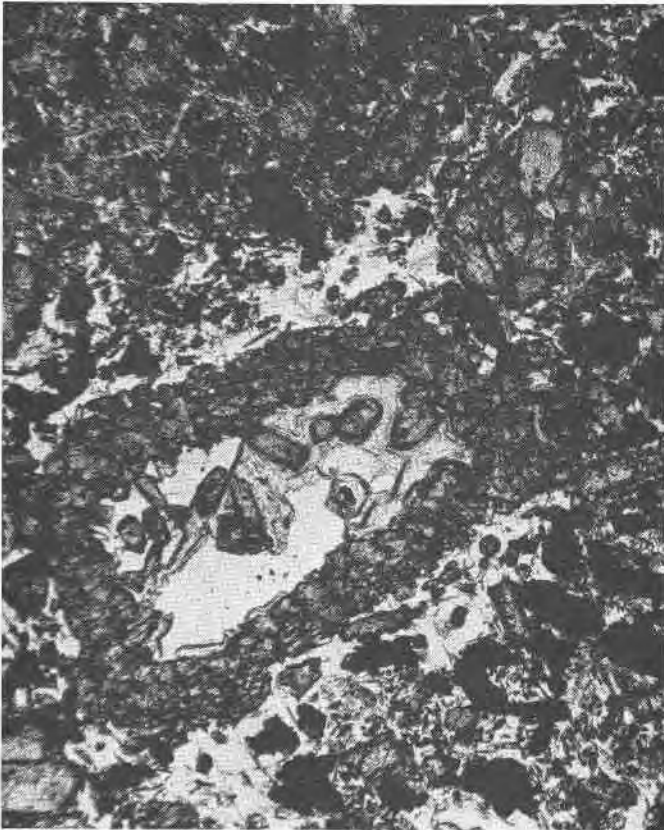


PLATE 6. Granular augite vug, with internal crusts of sanidine, prismatic augite, and reniform analcime crystals. Black bodies in groundmass are dense masses of granular magnetite, possibly pseudomorphous after biotite xenocrysts. Picture area is 2 mm. long. Ordinary light.

rence varies from specimen to specimen. Thin tabular euhedral crystals project into many vuggy ellipsoids, and small anhedral are strewn sparingly in the groundmass. Biotite is pleochroic from very light yellow (X) to reddish brown (Y, Z).

Amphibole occurs as short, minute prisms projecting into vesicles in rocks of Chinese Peak and Red Mountain. These crystals are colorless except for their terminated ends, which are pale olive brown. The extinction angle is small, and $2V_x = 70^\circ$.

Reniform crusts of analcime and of carbonate partly line some of the vuggy ellipsoids and microvesicles. Carbonate is the more abundant, and fills some cavities in ellipsoids. It is variable in grain size from sub-microscopic to 0.1 mm. Analcime occurs mostly in microvesicles where it commonly forms one or several small reniform masses attached to a small fraction of the cavity wall (Plate 6). Where analcime and carbonate are present in the same cavity, the carbonate is perched on the analcime crusts. In two specimens, sanidine crystals contain 0.1–0.5-mm. ellipsoidal cavities, like bubbles in quartz, successively and incompletely lined with augite and analcime.

Xenocrysts. Xenocrysts of quartz and plagioclase are abundant in specimens from Red Mountain and are present in some specimens from Black Point and Chinese Peak. Tabular aggregates of minute magnetite granules which may be pseudomorphous after biotite xenocrysts are present in most thin sections, and make up 10 per cent of one of them (Plates 3, 4, 6); small amounts of intergrown biotite (?) are present in some of the magnetite masses.

Quartz and plagioclase xenocrysts are fragmental and partly embayed. Some of the quartz xenocrysts are rimmed by augite (Plate 7) or contain rings of augite, one granule thick, two-thirds of the distance from their centers. Otherwise, quartz is in corroded subrounded fragments partly rimmed by replacement aggregates of extremely fine-grained sanidine.

The plagioclase xenocrysts have had a complex thermal and chemical history, and optical determinations of their composition are unreliable. Universal-stage determinations of 26 grains, using high-temperature curves, are mostly within the range An_{30-50} , and all but one are within the range An_{20-60} ; the most calcic part of one crystal was determined as An_{78} . If low-temperature curves were used, all but the most calcic determination would be increased by An_{5-8} . Relief of the crystals suggests that none are more sodic than An_{30} , and few more than An_{40} .

One of the specimens from Chinese Peak contains an inclusion of a fine- and even-grained (0.3 mm.) xenoblastic and gneissic rock, composed largely of layers of altered labradorite alternating with layers of augite, amphibole, and magnetite. The magnetite is in dense tabular aggre-

gates, intergrown with biotite (?), and appears to be pseudomorphous after biotite.

Ellipsoidal and vesicular structures. Ellipsoidal augite-rich masses from 5 to 20 mm. in diameter are common in trachybasalts from all three areas. Most ellipsoids also contain sanidine, though in smaller quantity than in the enclosing rock, in 0.3-mm. grains. The ellipsoids are composed principally of subhedral to euhedral granules of augite, 0.1 \times 0.2 mm. in size, variously aggregated into dense masses or into shells and rings. The centers of some are occupied by xenocrysts (Plate 7) or

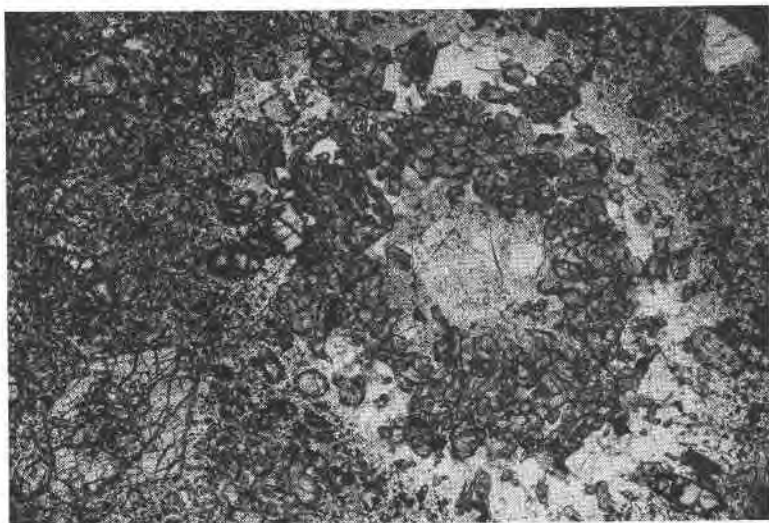


PLATE 7. Ellipsoid of sanidine with internal shell of augite granules enclosing a quartz xenocryst. Adjacent augite phenocryst has vesicular core. Picture area is 5 mm. long. Ordinary light.

by vugs containing biotite, analcime and carbonate. The ellipsoids are bounded sharply against the finer or glassy fabrics, gradationally against the coarser.

At Black Point, ellipsoids of sanidine with medial shells of augite make up several per cent of some outcrops; less common ellipsoids or hollow shells are of augite alone. At Red Mountain, ellipsoidal aggregates of augite with interstitial plagioclase, quartz, and sanidine, all crowded with acicular apatite, are common. Vuggy ellipsoids are locally common in the gray rocks, but rare in the reddish rocks, which are generally more microvesicular than the trachybasalts from the other areas. The red rocks contrast further in having a larger proportion of xenoliths of various sorts than was noted in the trachybasalts containing abundant

ellipsoidal masses. The ellipsoids of Chinese Peak are composed mostly of augite alone, but some have a minor development of coarse sanidine crystals around their margins.

The microvesicles of the trachybasalts contrast with the ellipsoidal structures. Microvesicles are sharply bounded by the fabric of the trachybasalt, and commonly contain partial crusts of analcime. Rarely, they contain carbonate or projecting crystals of groundmass minerals. Very rarely, they are surrounded by groundmass of coarsened texture. In many of the Black Point rocks, carbonate is virtually confined to ellipsoids and analcime to microvesicles; these contrasting structures within single specimens must have formed at different times.

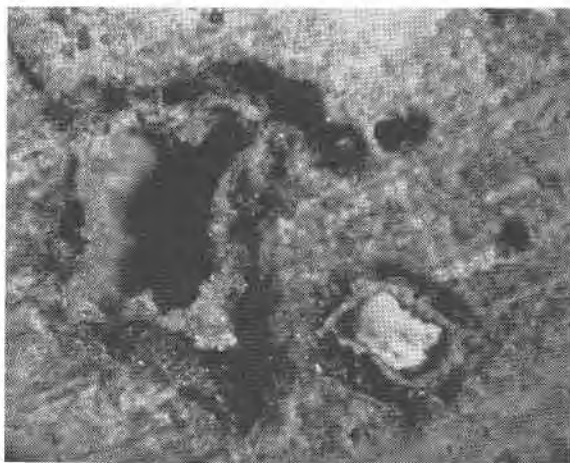


PLATE 8. Hand specimen of vugs containing partly attached shells of granular augite
One vug has a core of calcite. Picture area is 1 cm. long.

A peculiar variety of vug was noted only at Chinese Peak. These vugs contain loosely attached shells of augite, the walls of which are one crystal thick (Plate 8). The surrounding trachybasalt, from which project terminated crystals of amphibole, is notably coarsened. Partial fillings of analcime and/or carbonate are commonly present (Plate 8), and a single biotite crystal was noted.

Vesicular and vuggy flow structures, examined only in outcrop, consist of vesicular and vuggy shear planes along which the trachybasalt texture is coarsened and into which euhedral crystals of sanidine project from the groundmass. The planes commonly contain a small number of biotite tablets and perhaps also secondary minerals. Such vesicular structures are abundantly developed at Black Point (Plate 1), but only poorly at Red Mountain.

Sequence of crystallization. The salient feature of the texture of these

rocks is the almost complete lack of interference of crystals with one another and the general lack of inclusions of one mineral species in another, except that sanidine includes all other minerals. Except around microvesicles and ellipsoids, all other minerals are evenly strewn throughout the sanidine (or glass) matrix and densely crowd this matrix. This suggests that the bulk of the minerals other than sanidine (or glass) crystallized concurrently, and the fine grain suggests they crystallized rapidly. The sanidine in textural situations indicating early crystallization, such as in poikilitic cores of augites, might not have the same origin as does that comprising the bulk of the groundmass, as it might be a product of reaction.

Sanidine was the last pyrogenic mineral to finish crystallizing at Black Point, for euhedral crystals of it project into vesicles. At Chinese Peak, augite occurs in vugs and was the last pyrogenic mineral to complete crystallization if these vugs are a late feature of the rocks; in any case, anhydrous augite formed later than did hydrous amphibole in these vugs. Plagioclase and magnetite have positions barely within the outer confines of microvesicles, so that they must have finished crystallizing earlier than did sanidine. Olivine finished crystallizing early, for it is confined to the phenocrysts. A small proportion of the magnetite present is included in olivine; the euhedral cubes may indicate that magnetite had begun crystallization concurrently with or before olivine, but the anhedral crystals are closely related to the deep red staining and may be an alteration effect.

CHEMISTRY

Chemical analyses of major oxides in four specimens and of minor elements in one of them are presented in Table 4. All analyses are similar. The glass in the hypocrySTALLINE specimen must be composed largely of sanidine, as that specimen is obviously a trachybasalt chemically. The unusual mineralogic composition of the trachybasalts is reflected most obviously in the high content of magnesia and the low content of alumina. The major-element analyses differ markedly from published analyses of trachybasaltic and kindred rocks from other areas: e.g., latites of the northern Sierra Nevada, normal trachybasalts and mugearites of basaltic provinces, and volcanic lamprophyres of provinces such as Arizona, Montana-Wyoming, and East Africa. Published analyses of rocks reminiscent in their mineralogy of the trachybasalts near Huntington Lake are generally strikingly different in at least several oxides. Thus the average of two analyses of Tertiary latites of the northern Sierra Nevada (Table 4, no. 6), rocks which may be related genetically to the trachybasalts, is a little higher in SiO_2 , much higher in Al_2O_3 , and much lower in MgO .

TABLE 4. CHEMICAL ANALYSES OF TRACHYBASALTS OF THE HUNTINGTON LAKE AREA, AND OF LATITES FROM THE NORTHERN SIERRA NEVADA

	(1)	(2)	(3)	(4)	(5)	(6)
SiO ₂	53.8	55.4	54.4	52.1	53.9	56.7
Al ₂ O ₃	13.2	14.4	13.3	13.7	13.6	18.8
Fe ₂ O ₃ (Total	6.2	6.4	3.6	9.0	6.3	3.9
as FeO)	3.1	2.0	5.0	1.31	2.9	3.0
MgO	6.9	5.6	8.6	8.5	7.4	1.7
CaO	7.2	6.6	7.2	6.8	6.9	5.9
Na ₂ O	3.0	3.0	2.8	2.60	2.9	4.0
K ₂ O	2.5	2.6	2.2	3.06	2.6	3.7
TiO ₂	1.5	0.94	1.1	1.38	1.2	1.5
P ₂ O ₅	0.48	0.48	0.44	0.71	.5	0.5
MnO	0.12	0.10	0.14	0.24	.15	
H ₂ O	1.4	2.2	0.63	n.d.	1.4	?
CO ₂	0.05—	0.05—	0.05—	n.d.	.05	
Total	99.45	99.77	99.46	99.40		
B				0.004		n.d.
Ba				0.1		0.2
Be				0.0002		n.d.
Co				0.004		0.003
Cr				0.01		0.003
Cu				0.003		n.d.
Ga				0.002		0.003
Mn				0.06		0.1
Ni				0.02		0.003
Pb				0.001		0.002
Sc				0.003		—
Sr				0.1		0.2
V				0.01		0.02
Y				0.004		0.004
Yb				0.0004		n.d.
Zr				0.01		0.03

- (1) Holocrystalline trachybasalt specimen HL 75 A, Chinese Peak. Rapid-method analysis by H. F. Phillips, P. L. D. Elmore, and K. E. White.
- (2) Hypocrystalline trachybasalt specimen HL 84A-4, Red Mountain. Rapid-method analysis by Phillips, Elmore, and White.
- (3) Holocrystalline trachybasalt specimen HL 85, Red Mountain. Rapid-method analysis by Phillips, Elmore, and White.
- (4) Holocrystalline trachybasalt specimen HL 199-1, Black Point. Major-element analysis by W. Blake; spectrographic analysis by A. A. Chodos.
- (5) Average of 1-4.
- (6) Average of two water-free analyses of Tertiary latites from the northern Sierra Nevada (Nockolds and Allen, 1954, p. 280, numbers 4 and 5, major elements recalculated to oxides). Major-element analysis by Halsey, spectrographic analysis by Nockolds and Allen.

The minor-element content of the one specimen analyzed spectrographically is similar to that in analyzed rocks of similar silica content in a number of basaltic provinces.

Determinations of uranium and thorium have been made of several trachybasalt specimens (Table 5), showing an average content of 3 ppm uranium and 17 ppm thorium. The uranium content is higher than that common in volcanic rocks of similar silica content, and the thorium content is higher by a factor of several times. Both are comparable with the

TABLE 5. CONTENT OF URANIUM AND THORIUM IN TRACHYBASALTS OF THE HUNTINGTON LAKE AREA

	U ppm	Th ppm
<i>Black Point</i>		
HL 199-1	4.8	32.2 ¹
HL 559	4.0	n.d.
HL 560A2	2.3	15.5
HL 560C	1.5	n.d.
HL 561A	2.6	24.3
HL 561B2	2.5	4.6
<i>Red Mountain</i>		
HL 553	2.6	16.1
HL 557	2.1	9.5
Average	3	17

¹ A mistaken analysis of 130 ppm was reported previously (Neuerburg and Hamilton, 1955).

Analyst: J. C. Antweiler, 1955.

volcanic lamprophyres of the Colorado Plateau (Shoemaker, 1955), and the uranium content is comparable with potassic basalts in Table Mountain near Golden, Colorado (Neuerburg, Antweiler, and Bieler, unpub. data, 1956). Like the Sierran trachybasalts, the basalts from Table Mountain contain groundmass sanidine, but are otherwise chemically dissimilar (Waldschmidt, 1939, p. 31).

PETROGENESIS

Among the mechanisms advocated for the formation of basaltic rocks with alkali feldspars are (1) differentiation of a normal basaltic magma, (2) assimilation of felsic rocks into basaltic magma, (3) a combination of (1) and (2), and (4) the selective fusion of a complex of rocks.

The composition of the trachybasalts of the Huntington Lake area indicates that magmatic differentiation of the common type documented for many basaltic provinces could not have been a dominant process in

forming the rocks, although it might have been a complicating factor. These rocks are distant in both chemical and mineralogical content from the basaltic andesites, oligoclase andesites, and normal trachybasalts of the types present in many basaltic suites.

Direct evidence shows that assimilation operated. The area is underlain almost entirely by granitic rocks, mostly leucocratic, which range in composition from alaskite to quartz diorite, with an average composition of quartz monzonite; the granitics are in steep-walled intrusive plutons, and metamorphic rocks at the surface are restricted to small areas of contact-metamorphosed rocks (Hamilton, in press). The granitic rocks are composed mostly of quartz, andesine and oligoclase, and potash feldspar, with lesser amounts of biotite and hornblende. Xenocrystic quartz and plagioclase with corroded outlines are present in the trachybasalt, and these can in part be attributed to contamination by the granitic wallrock, although much of the xenocrystic plagioclase appears to be too calcic to have been derived directly from granitic rocks. Xenocrystic biotite is believed to have been pseudomorphed by magnetite as most of its components went into the magma. (Similar pseudomorphing of xenocrystic biotite by magnetite in intrusive basalt in the Owens Valley was described by Knopf [1938, p. 374].) Potash feldspar and hornblende must also have been incorporated, and as they are not preserved must have dissolved completely.

Both the ellipsoidal augite structures and the vesicular cores of some augite phenocrysts may have an origin in reaction of basic magma with silicic rocks. Quartz xenocrysts (?) form the cores of some augite ellipsoids. The poikilitic cores of some phenocrysts may be due to the replacement by augite of the mafic components of fine-grained metamorphic (?) rocks, leaving the felsic components as chadacrysts, some of which were later removed. Augite reaction coronas on quartz and feldspar xenocrysts were also noted by Knopf (1938) in the Owens Valley.

Table 6 shows the composition of two hypothetical parent magmas calculated by assuming that the trachybasalts contain large quantities of material assimilated from granitic rocks. The calculated composition of the "average granitic rock" of the area is based on a detailed petrographic study (Hamilton, in press). The hypothetical magmas of columns 3 and 4 are basaltic, suggesting olivine-rich slightly sodic basalts. The composition of the trachybasalts might thus be explained as the result of assimilation of large amounts of granitic rock in an unusual olivine-rich basaltic magma, perhaps modified by differentiation to produce the final rock. Compared to most basalts, however, the hypothetical parents thus calculated are notably low in alumina and notably high in magnesia. Many analyses of individual specimens of olivine basalt similar to these hypothetical compositions are present in the literature, but none of the

TABLE 6. HYPOTHETICAL PARENT MAGMAS, ASSUMING FORMATION OF TRACHYBASALT BY ASSIMILATION OF GRANITIC ROCK IN BASIC MAGMA

	(1)	(2)	(3)	(4)
SiO ₂	55.2	69.3	50.0	45.0
Al ₂ O ₃	14.0	15.8	13.3	12.5
Fe ₂ O ₃	6.4	.9	8.3	10.3
FeO	2.9	1.2	3.6	4.3
MgO	7.6	1.2	9.8	12.2
CaO	7.2	3.1	8.5	10.0
Na ₂ O	2.9	2.8	3.1	3.1
K ₂ O	2.6	5.5	1.8	.7
TiO ₂	1.2	.2	1.6	1.9

- (1) Average of four analyses of trachybasalt from the Huntington Lake area, recalculated to 100% for the oxides listed.
- (2) Average granitic rock of Huntington Lake area, calculated from ideal formulas assuming 25 per cent by weight quartz, 30 per cent potash feldspar, 23 albite, 12 anorthite, 5 hornblende, 4 biotite, 0.5 magnetite, and 0.5 sphene.
- (3) Hypothetical parent magma of 50 per cent SiO₂, assuming contamination by granitic rock of column 2. Amounts to 25 per cent granite assimilated.
- (4) Hypothetical parent magma of 45 per cent SiO₂. Amounts to 41 per cent granite assimilated.

averages of basalts presented by Green and Poldervaart (1955) for several scores of continental basaltic provinces are closely similar to the hypothetical compositions.

Nearly all of the rocks of the Huntington Lake area are granitic, and there is no sign of change in the preponderance of granitic rocks in the lowest parts of the deep gorges of the central Sierra Nevada. Nevertheless, non-granitic rocks might have been assimilated by basaltic magma to produce the trachybasalts. It might be argued on theoretical grounds that the leucocratic granitic rocks of the Sierra give way at depth to a complex of metamorphosed rocks including many mafic and intermediate types such as amphibolite, eclogite, biotite-rich schist, and meta-peridotite. Basic contamination of the trachybasalt is suggested by the calcic composition of some of the xenocrystic plagioclase, and by the rare inclusions of mafic and ultramafic rocks, coarse-grained crystalloblastic aggregates rich in hedenbergitic pyroxene.

Table 7 presents hypothetical contaminants, calculated by assuming the trachybasalts to have formed by contamination of ordinary basaltic magmas. The calculations were thus made in the opposite direction to those of Table 6. The hypothetical contaminants must have SiO₂ contents greater than that of the trachybasalt, as the assumed parental basalts have lower contents of SiO₂ and likely contaminating rocks or combinations of rocks have SiO₂ contents of less than 70 per cent. The

TABLE 7. HYPOTHETICAL CONTAMINANTS, ASSUMING FORMATION OF TRACHYBASALT BY CONTAMINATION OF NORMAL BASALTIC MAGMAS

	(1)	(2)	(3)	(4)	(5)	(6)	(7)	(8)
SiO ₂	54.8	47.8	51.0	65.0	70.0	60.0	65.0	65.0
Al ₂ O ₃	13.9	15.4	15.6	11.7	10.8	11.6	9.7	11.0
Fe ₂ O ₃	6.4	4.8	1.1					
FeO	2.9	8.2	9.8	3.2	.5	5.8	3.1	3.1
MgO	7.5	6.6	7.0	8.8	9.5	8.2	8.8	8.8
CaO	7.1	9.5	10.5	3.7	1.9	2.4	0*	2.0
Na ₂ O	2.9	3.2	2.2	2.4	2.2	3.9	4.8	4.4
K ₂ O	2.6	1.4	1.0	4.3	5.2	4.8	6.9	5.3
TiO ₂	1.2	2.4	1.4	0*	0*	.9	.7	.4
P ₂ O ₅	.5	.5	.2	.5	.5	.9	1.3	.2
MnO	.2	.2	.2	.2	.2	.2	.2	

* Calculation gives small negative value; totals in these columns may be >100.

- (1) Average of 4 analyses of trachybasalt, water free, from the Huntington Lake area.
- (2) Assumed olivine basalt parent magma: average of averages from Otago, Victoria, and the Midland Valley.
- (3) Assumed olivine-poor basalt parent magma: Green and Poldervaart (1955, p. 185, column 67).
- (4) Hypothetical contaminant with 65% SiO₂ to have produced (1) from (2); requires 41% of contaminant.
- (5) Hypothetical contaminant with 70% SiO₂ to have produced (1) from (2); requires 32% of contaminant.
- (6) Hypothetical contaminant with 60% SiO₂ to have produced (1) from (3); requires 42% of contaminant.
- (7) Hypothetical contaminant with 65% SiO₂ to have produced (1) from (3); requires 27% of contaminant.
- (8) Average of (4)-(7).

calculations are based on assumed SiO₂ contents of the contaminants, and the upper limit of SiO₂ in hypothetical contaminants of the olivine-poor basalt magma was chosen as slightly above that at which the calculation for CaO gave a negative value. (The calculated small negative quantities of TiO₂ in hypothetical contaminants of the olivine basalt magma are regarded as of little consequence to the discussion because of the wide variability of abundance of this oxide in basaltic provinces.) The calculated contaminants do not resemble any single reasonable rock type; the high MgO and low Al₂O₃ are incompatible with the SiO₂ and alkalis. The petrographic evidence shows the probable incorporation of both granitic and mafic or ultramafic material. If the actual contaminants had a composition near the hypothetical ones of Table 7, then a combination of several times as much felsic rock as ultramafic rock would probably satisfy the chemical requirements.

The hypothetical parent magmas of Table 6 and the hypothetical contaminants of Table 7 would require that the trachybasalt be composed of about 25 to more than 40 per cent assimilated rock. The mechanism of assimilation of such proportions deserves an adequate explanation which is not now possible. Unusual volatile action at an early stage of crystallization is shown by the augitic ellipsoidal structures and by the poikilitic cores of many augite phenocrysts; the volatile activity repre-

sented might have aided assimilation. If the parental magma rose into the Sierran granitic rocks when they were still hot, assimilation might have been made easy.

Conclusions. Differentiation is inadequate to explain the composition of the trachybasalts from the Huntington Lake area, and a source in varied materials seems likely. The petrographic evidence shows the assimilation of both felsic and mafic materials, and chemical calculations suggest that the most likely origin of the rocks is in the assimilation of large amounts of granitic rock and lesser amounts of mafic and ultramafic rock in a basaltic magma. Similar conclusions have been reached by other petrologists for the genesis of somewhat similar rocks in other provinces, e.g. by Williams (1936), and by Turner and Verhoogen (1951, p. 174).

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