

QUATERNARY TRACHYBASALTS FROM SOUTHEASTERN CALIFORNIA

A. L. SMITH¹ AND I. S. E. CARMICHAEL, *Department of Geology and
Geophysics, University of California, Berkeley,
California 94720.*

ABSTRACT

Quaternary volcanism in southeastern California has produced scattered cinder cones and lavas of trachybasalt. Typically the lavas contain magnesian olivine and titanaugite which becomes progressively enriched in Ca, Al and Ti towards the crystal margins. Oscillatory and hourglass zoning with abrupt changes in Ti, Al and Si (inversely) have been observed in some titanaugites. Plagioclase may zone from labradorite to anorthoclase, and discrete sanidine is present in the coarsest grained lavas; the iron-rich residual glass is enriched in normative nepheline which is absent modally. Titanomagnetite (microphenocryst and groundmass phases) is notably rich in MgO and Al₂O₃ in contrast to equivalent tholeiitic assemblages. Analyses show that the lavas are not simply related to one another by fractionation of their phenocryst phases; the controlling factor remains obscure as typically the most silica-poor lavas are the most alkali rich.

INTRODUCTION

Quaternary volcanism in California has produced at least three distinct volcanic suites: (1) the orogenic basalt-andesite-rhyolite suite of the Cascades (N. California); (2) the basalt-rhyolite suite of the eastern flank of the Sierra Nevada; and (3) the alkali-rich basaltic suite of south eastern California. Rocks belonging to this third (trachy-basalt) suite occupy a belt extending from Barstow, San Bernardino County, to the California-Nevada border; however, lavas of similar age and composition have been described from Nevada (Vitaliano and Harvey, 1965) and Arizona (Brady and Webb, 1943). In southeastern California these lavas were erupted mainly through a basement of Mesozoic and older granitic and metamorphic rocks, examples of which are now found as inclusions in some lavas. Ultramafic nodules (dominantly lherzolites) are particularly common in the ejecta of Dish Hill (White, 1966).

Earlier descriptions of these lavas are included in the publications of Gardner (1940), Hewitt (1956) and Parker (1959, 1963). The inclusions have been described by Brady and Webb (1943), Hess (1955) and White (1966). Recently Wise (1966) has published chemical and mineralogical data on the lavas of Dish Hill, and some preliminary information on several other cones (Wise, 1967). This paper is concerned with six lava flows from three (Mt. Pisgah, Amboy Crater and Cima Dome) of the many cinder cones in this province.

¹ Present address: Department of Geology, University of Puerto Rico, Mayaguez, Puerto Rico 00708.

MINERALOGY

The trachybasalts¹ are relatively fine-grained (Table 1), composed of titanaugite, forsteritic olivine, plagioclase (sometimes highly zoned) and titanomagnetite; ilmenite is found in two of the samples. All these minerals may occur both as scattered phenocrysts and as groundmass constituents. Sanidine occurs in three lavas, but nepheline has not been found. Perhaps the most distinctive feature is the presence of relatively abundant residual glass. All the minerals together with the residual glass were analyzed with an electron-probe. For techniques of analysis and

TABLE 1. MODAL ANALYSIS IN VOLUME PERCENT

	Olivine	Titanaugite	Plagioclase	Groundmass
1	4.2	0.6	4.2	91.0
2	6.8	0.5	3.6	89.1
3	10.9	0.5	0.0	88.6
4	7.6	4.6	1.3	86.5
5	7.2	5.5	1.9	85.4
6	1.8	0.6	2.7	94.9

Key to Specimen Localities

1. Trachybasalt, western most flow	Mt. Pisgah	256
2. Trachybasalt, later flow unit	Mt. Pisgah	255
3. Trachybasalt, bomb	Mt. Pisgah	258
4. Trachybasalt, older flow unit	Mt. Pisgah	254
5. Trachybasalt, east side of cone by Salt Workings	Amboy Crater	253
6. Trachybasalt, snout of most recent flow	Cima Dome field	252

calculation the reader is referred to Carmichael (1967a, 1967b) and Evans and Moore (1968).

Olivines. Olivine, which is the dominant phenocryst (Table 1), is zoned, and in both phenocryst and groundmass phases, iron, calcium and manganese increase towards the grain margins. Although the average groundmass olivine is usually more iron-rich than the average coexisting phenocryst, there are a few cases when individual phenocrysts show greater apparent enrichment in iron than the associated groundmass olivine

¹ The term trachybasalt is used in the same sense as Le Maitre (1962) and Baker *et al.* (1964) to describe lavas transitional between alkali basalts and intermediate alkaline lavas. The trachybasalts from southeastern California are characterized by relatively low silica (47%) and high magnesium (7½%), compared to their total alkali content (6%). The high alkali content is reflected in the amount of normative orthoclase (approximately 10%) and in the composition of the normative feldspar (andesine); the modal feldspar is labradorite-andesine. All of the lavas are undersaturated and contain up to 11% normative nepheline.

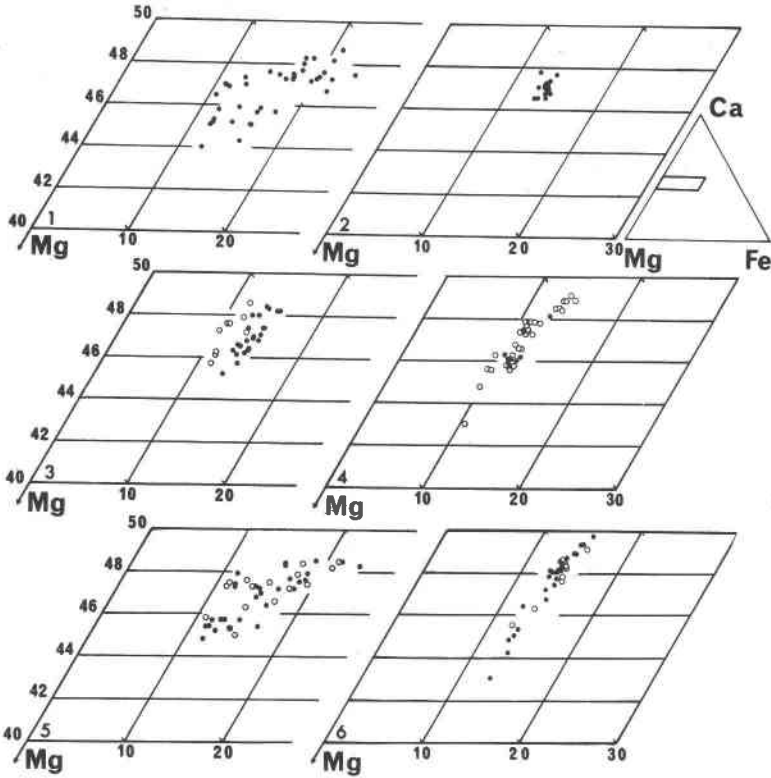


FIG. 1. Variation in Ca, Mg and Fe of the pyroxenes plotted on a molecular basis. Note the expanded scale of the diagrams, and the key in the top right. Filled circles represent groundmass pyroxenes; open circles represent phenocrysts.

(Table 2)¹. This is probably due to the difficulty in analyzing the margins of small grains with the electron-probe. The amount of zoning of Mg and Fe in the olivines is variable (6% to 36% Fa) and in a few cases is less than that of the coexisting pyroxenes.

Pyroxenes. Analyses of the pyroxenes (slightly sodic titanaugites) are given in Table 3. Individual determinations of Ca, Mg and Fe for these pyroxenes are plotted in Figure 1, while the average analyses of the pyroxenes and their associated olivines are shown in Figure 2. In both

¹ To obtain a copy of Tables 2, 3, 4 and 5, order NAPS Document #00323 from ASIS National Auxiliary Publications Service, c/o CCM Information Sciences, Inc., 22 West 34th Street, New York, New York 10001; remitting \$1.00 for microfiche or \$3.00 for photocopies made payable to ASIS-NAPS.

Figures 1 and 2, it can be seen that there is little difference in composition between the phenocryst and groundmass pyroxene phases in terms of Ca, Mg and Fe. It is to be noted that the average compositions of the pyroxenes (Fig. 2) give little indication of the progressive change in composition (zoning) towards the diopside-hedenbergite join shown by individual pyroxene crystals (Fig. 1). This trend is perhaps analogous to that found in the system diopside-forsterite-silica (Kushiro and Schairer, 1963) where liquids piercing the diopside-forsterite join crystallize a diopsidic pyroxene which becomes progressively enriched in the diopside ($\text{CaMgSi}_2\text{O}_6$) component with falling temperature.

The pyroxenes are rich in TiO_2 (avg. 3.2%) and Al_2O_3 (avg. 6.5%) both

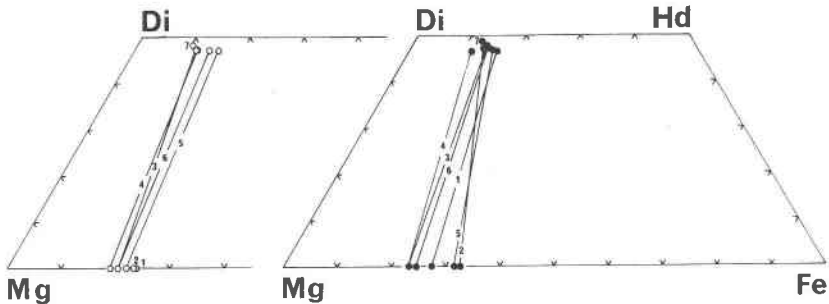


FIG. 2. Average analyses of the pyroxenes (Table 3) plotted in terms of (molecular) Ca, Mg and Fe (Mn not included). Average analyses of olivines (Table 2) plotted on the base. Filled circles represent groundmass pyroxenes; open circles represent phenocrysts. Analyses of pyroxenes labelled 7 are taken from White (1966).

of which show greater relative increase from core to margin than either Ca or Fe (Table 3). In addition to this progressive zoning, many titanaugites show oscillatory zoning (pronounced variation of Ti and Al, and inversely, Si); a few crystals also show "hourglass" zoning so typical of titanaugites in general. A map of Ti, Al and Si distribution has been made of one-half of such a crystal (Fig. 3). The zones of Ti, which have corresponding concentrations of Al and Si (Figure 3) have junctions with neighboring zones which are abrupt rather than transitional, similar to the oscillatory zones noted above.

The abundance of a Tschermak's component ($\text{CaAl}_2\text{SiO}_6$, MgAlSiO_6) in the pyroxenes of basic alkaline lavas has led some workers (Kuno, 1964; Wise, 1966) to suggest that they crystallized under conditions of high pressure. However, Yagi and Onuma (1967) have shown experimentally that TiO_2 (or $\text{CaTiAl}_2\text{O}_6$) decreases with pressure in calcium-rich pyroxenes, and the relative enrichment of many of the groundmass

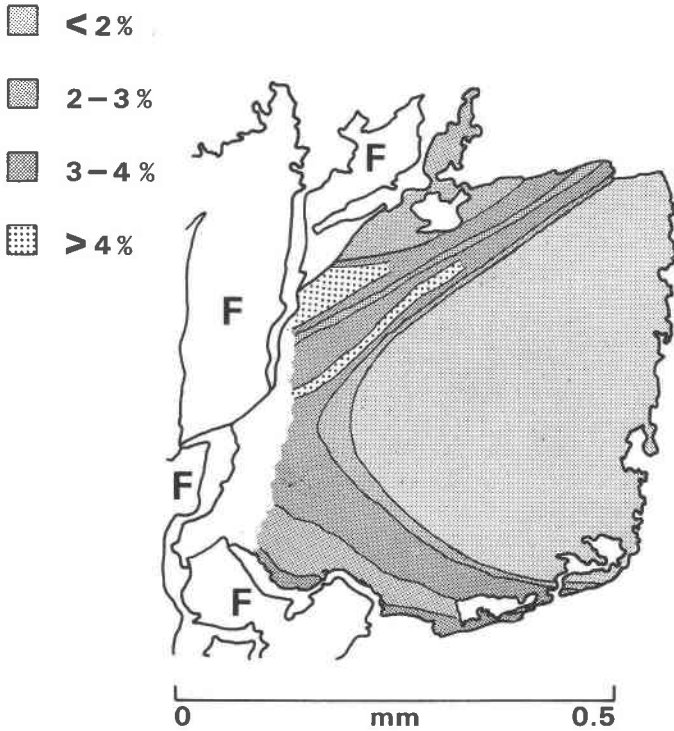


FIG. 3. Map is distribution of TiO₂ (in wt %) in one-half of an "hourglass" zoned pyroxene. The >4% TiO₂ limit corresponds to >9.6% Al₂O₃ and <43.7% SiO₂; the 3-4% TiO₂ zone corresponds to 8.2-9.6% Al₂O₃ and 47.1-43.7% SiO₂; the 2-3% TiO₂ zone corresponds to 5.8-8.2% Al₂O₃ and 50.8-47.1% SiO₂; the <2% TiO₂ limit corresponds to <5.8% Al₂O₃ and >50.8% SiO₂. F denotes feldspar crystals.

pyroxenes in Al₂O₃ and TiO₂ (Table 3) also substantiates a low pressure control of Al₂O₃ and TiO₂. As Verhoogen (1962a) and Le Bas (1962) have shown, it is the silica content of a liquid which appears to be the controlling influence on the incorporation of Ti and Al into a pyroxene structure.

Feldspars. Plagioclase is present in all the lavas as a groundmass constituent and in most as phenocrysts. In three lavas sanidine is found as tiny crystals in the groundmass.

Analyses of the feldspars are given in Table 4. Barium ranges from 0.1 percent (BaO) in the plagioclase to 0.5 percent in the sanidine and increases slightly, in the plagioclase, with increasing potassium content. Iron, reported as Fe₂O₃, ranges from 0.5 to 1.0 percent in the plagioclase

and increases with the albite component; no determination of iron in sanidine was made.

The analytical results given in Table 4 show that the inner zones of the plagioclase phenocrysts are only slightly more calcic (labradorite-bytownite) than those of their associated groundmass plagioclase; thus the estimated average (bulk) compositions of both phases are comparable. The range of zoning appears to be dependent on grain size, since in the finer-grained lavas, plagioclase shows only limited enrichment in albite and orthoclase, whereas in the coarsest lava, the plagioclase is zoned from

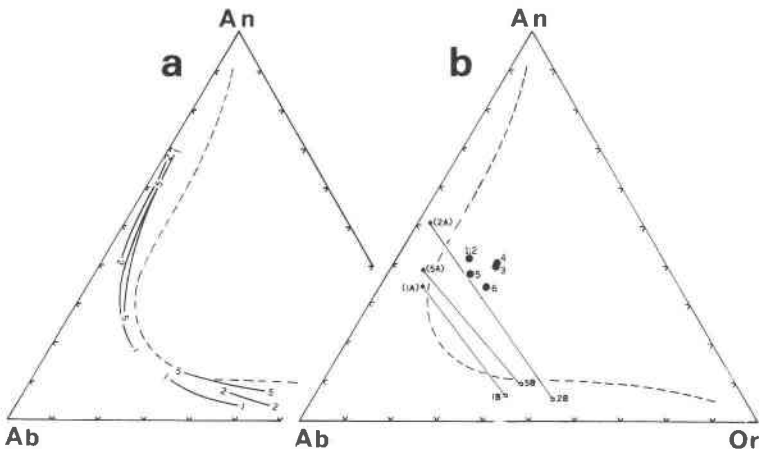


FIG. 4. (a) Extent of zoning (wt %) of feldspar in those trachybasalts which contain plagioclase and sanidine (Nos. 1, 2 and 5; Table 4). Dashed line represents the limit of ternary solid solution in natural feldspars (Smith and MacKenzie, 1958). (b) Average composition (wt %) of sanidines (B) (Table 4) and the outer rims of coexisting plagioclase. Large filled circles are the normative feldspar compositions (Table 6).

labradorite to anorthoclase (Fig. 4a). It is in these coarser lavas that discrete sanidine is found, not unexpectedly in view of the potassic composition of the normative ternary feldspar (Fig. 4b). Although the analyses of sanidine are not extensive, there does seem to be an indication that the more sodic compositions are also richer in calcium (Fig. 4a).

Unfortunately, the direction of zoning in the very small sanidine crystals could not be determined, but the presence of a distinct compositional gap between the outermost rims of the plagioclases and their co-existing sanidines in two of the lavas (Figs. 4a, Nos. 2 and 5) would perhaps argue against the sanidines representing a continuation of the plagioclase crystallization path. Accordingly, the estimated average compositions of the outer rims of the plagioclase and the coexisting san-

idine have been joined in Figure 4b; the composition of the residual glass for one of these feldspar pairs (Table 6, No. 1G) has not been plotted, as the analytical procedure does not determine the $\text{FeO}:\text{Fe}_2\text{O}_3$ content. Unless this is known, it is not possible to calculate the composition of the normative feldspar in compositions which contain normative nepheline. However, in the two limiting cases, namely total iron taken as FeO , and then taken as Fe_2O_3 , the calculated composition of the normative feldspars are more sodic than either the sanidine or the plagioclase.

The normative feldspar compositions (Table 6) of these trachybasalts, which have been plotted in Figure 4b to show their potassic character, do not take account of the 6.5 percent Al_2O_3 (av.) in the pyroxene; allowance for this would reduce the anorthite content of the calculated compositions.

Iron-titanium oxides. Although titanomagnetite occurs both as microphenocrysts and as tiny specks in the glassy or finely-crystalline groundmass of all the lavas, ilmenite is restricted to the coarser grained specimens (Nos. 1 and 5), but only in No. 5 is it found as a microphenocryst. In all cases, the iron-titanium oxides are optically homogeneous, although on occasions, rather variable microprobe results suggest some "incipient" unmixing of the spinel-phase. Titanomagnetite is also found as small included crystals in olivine and pyroxene phenocrysts; these have a similar composition to their associated microphenocrysts, which themselves show little variation within any one specimen. The analyses of the iron-titanium oxides are given in Table 5.

The titanomagnetite (β -phase) (Verhoogen 1962b) phenocrysts in the five trachybasalt range in composition from 74 percent (mole) ulvospinel (Fe_2TiO_4) to 42 percent, the lowest being a chrome-rich spinel. The associated groundmass β -phases only vary by 3.3 percent ulvospinel on average from their microphenocrysts; there is no consistent pattern of relative enrichment, but the microphenocrysts tend to have more MgO , Al_2O_3 and particularly Cr_2O_3 . Even in the absence of more than trace amounts of Cr_2O_3 ($<0.2\%$), these β -phases contain notable amounts of MgO (1.3–5.0%) and Al_2O_3 (1.1%–3.9%) and are quite unlike, in this respect, the titanomagnetites of tholeiitic series (Vincent and Phillips, 1954; Carmichael, 1967b) which contain much less.

The composition of the coexisting β -phase and ilmenite microphenocrysts (No. 5, Table 5) indicate that the oxide phases equilibrated at 1090°C and at an oxygen fugacity of $10^{-9.9}$ (Buddington and Lindsley, 1964). The equivalent data for the coexisting groundmass phases indicates lower temperatures (995°C , No. 1; 980°C , No. 5) and oxygen fugacities ($10^{-11.4}$ and $10^{-11.7}$ respectively). The oxide equilibration data are

close to, but slightly below, oxygen fugacities defined by the assemblage fayalite-magnetite-quartz (Eugster and Wones, 1962) at the appropriate temperatures; this is in accord with other basaltic assemblages (tholeiitic and high-alumina) which have olivine- β -phase assemblages of similar composition (Carmichael, 1967b; Smith and Carmichael, 1968). Temperatures of between 1280°C and 1470°C were obtained for coexisting groundmass olivines and pyroxenes using the nickel geothermometer of Häkli and Wright (1967); these are regarded as unreasonable and suggest, as was pointed out by the authors, that the geothermometer requires recalibration for use with alkaline basaltic lavas.

Two aspects of the iron-titanium oxides are of interest. First, there is an increasing amount of data, particularly for tholeiitic assemblages (Peck *et al.*, 1966; Carmichael, 1967b; Wright and Weiblen 1968) that is concordant to 1030°C–1080°C as a temperature range of either precipitation or equilibration of coexisting iron-titanium oxides. Within this generality, the trachybasalts described above conform, but the order of crystallization of their oxide phases is different; thus a cursory search of the literature indicates that a β -phase is typically the first oxide phase to precipitate in alkaline basalts, whereas in tholeiitic liquids, either ilmenite (α -phase), or α - and β -phases together, crystallize first. Secondly, the β -phases in these trachybasalts are typically more magnesian and more aluminous than those of tholeiitic liquids, and perhaps reflect, or correspond, with this aspect of their associated titanaugites.

Residual glass. Most of the trachybasalts have a dark-brown interstitial glass, which has either partially devitrified, or encloses minute crystals. Only one specimen (No. 1) has glass which is homogeneous enough to analyse with the microprobe, and the analysis is given in Table 6 (No. 1G). The glass is enriched in the normative salic constituents, and iron, but depleted in Ca and Mg in relation to the rock. As the oxidation state of iron is not known, the amount of normative nepheline cannot be calculated; however, for the limiting (minimum) case where all the iron is allotted to normative magnetite, there is slight (0.5%) enrichment of the glass in normative nepheline in comparison to the rock.

Wilkinson (1966) has described an alkaline-basalt with a residual glass with normative corundum. This was attributed to the precipitation of excessive amounts of calcium-rich pyroxene, thus depleting the residual liquid in calcium relative to aluminum. As titaniferous pyroxenes of similar type are found in these Californian trachybasalts without a peraluminous residual liquid, perhaps the explanation lies in the low-temperature leaching of alkalis from the residual glass, such as described by

Lipman (1965); certainly Wilkinson's residual glass is rich in water ($H_2O^+ = 6.99\%$).

CHEMISTRY

The analyses of the trachybasalts are given in Table 6, together with the results of X-ray fluorescence determination of several minor- and trace-elements. The pattern of composition of these lavas (Table 6) is distinctive; although they occur in a continental environment, their TiO_2 contents (2.1–2.7%) places them clearly with the oceanic lavas (Chayes, 1965). In comparison to the oceanic suites, they have a similar alkali content to the Hawaiian mugearites (Fig. 5; Table 7), but they are much more magnesian and calcic, and less siliceous. They have chemical similarities to both the alkali-basalts and trachybasalts of Gough Island (Le Maitre, 1962) and Tristan da Cunha (Baker, *et al.*, 1964), and represent a range of compositions intermediate between those of the two Atlantic-ridge rock types (Fig. 5; Table 7).

The alkalis of these various oceanic series have been plotted against silica in Figure 5; in the lavas of Mt. Pisgah (Nos. 1 to 4) alkalis are highest in the most magnesian rocks (Table 6) and these four lava compositions define a trend of increasing alkali with decreasing silica (Fig. 5). This trend is generally true of all the Californian alkaline-basalts plotted in Figure 5, and, if real, is quite unlike the normal volcanic trends.

The Californian trachybasalts are generally impoverished, with the exception of Zr, in the trace elements Rb, Sr, Ba and the rare earths, when compared to lavas from other alkaline basaltic provinces (Nockolds and Allen, 1954; Le Maitre, 1962; Baker, *et al.*, 1964). The relatively low but variable Rb content of these lavas causes their K/Rb ratios (average 532) to be higher than that observed for most continental basic rock types (Gunn, 1965; Heier *et al.*, 1965; Erlank and Hofmeyer, 1966; Abbott, 1967) but they are appropriately similar to those found for the Hawaiian lavas with < 2 percent K_2O (Lessing, *et al.*, 1963; Hamilton, 1965).

In contrast to the normal distribution of the rare earths in basaltic rocks (Haskin *et al.*, 1966), these lavas do not show any strong enrichment in Ce (or Nd) relative to La. This may indicate that fractionation of the rare earths has occurred. Such fractionation could have resulted from the selective partition of the rare earths among the minerals controlling any fractionated sequence, as was found by Towell, *et al.* (1965) for the San Marcos gabbro, but it could also reflect the source region from which these lavas were derived.

For most igneous rock series trace elements such as Cr and Ni tend to

be richest in the basic members and to decrease with differentiation; in contrast trace elements such as Sr, Ba, Zr, Rb tend to be more abundant in the more differentiated rocks (Nockolds and Allen, 1953, 1954; Taylor, 1966). An odd exception to this appears to be the trachybasalts of Mt. Pisgah (Nos. 1 to 4, Table 6) in which the lavas richest in Sr, Ba, Zr, Rb are also richest in Cr and Ni.

PETROGENESIS

The overall similarity in mineralogy and chemistry between the lavas of the different centers (Mt. Pisgah, Dish Hill, etc.), regardless of whether they contain granitic and/or ultramafic inclusions, suggests a com-

TABLE 6. ANALYSES AND CIPW NORMS OF QUATERNARY LAVAS FROM SOUTHEASTERN CALIFORNIA

	<i>Mt. Pisgah</i>					<i>Amboy Crater</i>	<i>Cima Dome</i>
	1 (256)	1G (256)	2 (255)	3 (258)	4 (254)	5 (253)	6 (252)
Chemical Analysis							
SiO ₂	47.76	59.5	47.65	46.55	46.48	47.41	47.55
TiO ₂	2.27	1.1	2.23	2.46	2.50	2.13	2.71
Al ₂ O ₃	15.94	17.4	16.51	15.88	16.16	15.78	16.38
Fe ₂ O ₃	2.76	1.8 ^a	4.07	3.66	2.95	2.18	2.77
FeO	7.59	4.9 ^a	6.38	6.82	7.56	7.87	7.84
MnO	0.19	0.06	0.17	0.19	0.19	0.18	0.20
MgO	6.97	0.49	7.39	8.05	7.99	8.04	6.40
CaO	10.37	1.6	9.60	9.24	9.20	8.75	8.41
Na ₂ O	3.74	6.9	3.92	4.04	4.36	3.73	4.46
K ₂ O	1.45	5.5	1.50	1.88	1.85	1.72	2.11
P ₂ O ₅	0.49	n.d.	0.51	0.61]	0.64	0.55	0.72
H ₂ O ⁺	0.29	n.d.	0.14	0.57	0.24	0.58	0.57
H ₂ O ⁻	0.14	n.d.	0.06	0.12	0.03	0.28	0.11
CO ₂	0.36	n.d.	tr	0.02	tr	0.10	0.11
Total	100.32	99.1	100.13	100.09	100.15	100.30	100.34
Norm							
Or	8.57	32.8	8.86	11.11	10.93	10.16	12.47
Ab	23.07	45.1	23.63	18.69	16.92	25.01	22.86
An	22.42	0.3	23.02	19.64	19.06	21.23	18.44
Ne	4.65	7.1	5.17	8.39	10.82	3.55	8.06
Di-wo	9.83	—	8.88	9.22	9.35	7.49	7.47
Di-en	6.24	6.7	6.36	6.53	6.25	4.76	4.67
Di-fs	2.97	—	1.72	1.89	2.41	2.25	2.34
ol-fo	7.79	2.7	8.44	9.47	9.56	10.69	7.90
ol-fa	4.09	—	2.52	3.01	4.06	5.57	4.37
Mt	4.00	2.6	5.90	5.31	4.28	3.16	4.02
Il	4.31	2.1	4.24	4.67	4.73	4.05	5.15
Ap	1.16	—	1.21	1.44	1.52	1.30	1.71
Cc	0.82	—	—	0.05	—	0.23	0.25

TABLE 6—(continued)

	1 (256)	2 (255)	3 (258)	4 (254)	5 (253)	6 (252)
Trace metals in p.p.m.						
Rb	15	35	30	35	25	35
Ba	335	310	335	345	150	395
Sr	505	520	625	625	640	545
La	60	50	80	65	70	70
Ce	35	55	75	55	75	80
Pr	— ^b	5	— ^b	5	5	5
Nd	30	30	35	30	35	40
Sm	— ^b	5	— ^b	5	— ^b	— ^b
Y	20	15	20	20	15	20
Zr	185	195	235	240	210	280
Cu	50	45	45	30	45	35
Co	50	55	55	55	55	55
Ni	90	100	135	135	165	90
V	210	240	225	180	200	220
Cr	100	130	140	205	175	175
Zn	105	90	90	100	95	95
K/Rb	800	357	520	440	572	500
Ce/La	0.58	1.10	0.94	0.85	1.07	1.14

Analyses 1–6 by I. S. E. Carmichael and J. Hampel. Analysis IG by A. L. Smith using electron probe.

^a FeO:Fe₂O₃ ratio computed from parent rock 1.

^b Below limit of detection of 3 p.p.m.

mon origin. When discussing their origin, the following theories should be considered:

1. Fractional crystallization in a low pressure (crustal) environment.
2. Partial melting of the mantle (or fractional crystallization in the mantle).
3. Contamination by sialic (crustal) material.
4. Gas transfer.

From his study of Amboy Crater, Parker (1959) concluded that the lavas were related by fractional crystallization. However, on the basis of our calculations using subtraction (Bowen, 1928, p. 78) and phenocryst control diagrams (Powers, 1955) it is considered that the analyses of the lavas (Table 6) cannot be derived one from another *solely* by the subtraction and/or addition of the phenocryst phases.

The presence of ultramafic inclusions (predominantly lherzolites¹ and websterites) in the lavas of Dish Hill and Amboy Crater suggest that these lavas may have been derived by partial melting of the mantle (with

¹ Such inclusions are regarded by White (1966) as more characteristic of nephelinites than of trachybasalts.

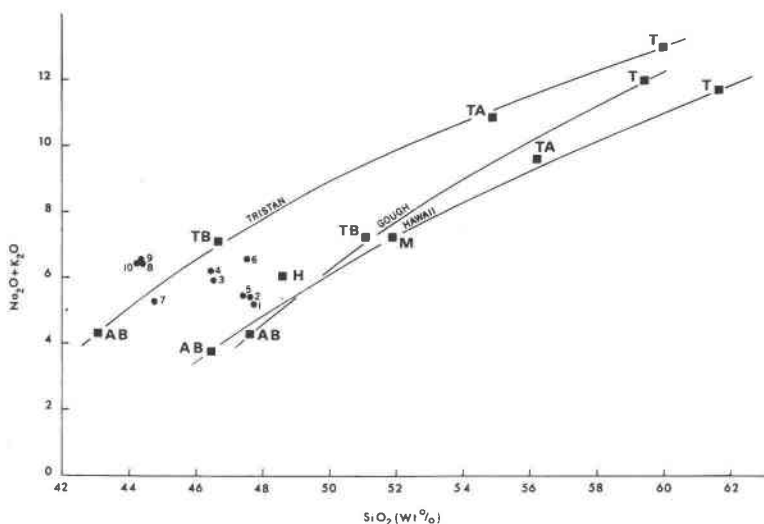


FIG. 5. Total alkalis plotted against silica. The trends of the Hawaiian alkali series, Gough Island (Atlantic) and Tristan da Cunha are taken from Macdonald and Katsura (1964), Le Maitre (1962) and Baker *et al.* (1964) respectively. Filled circles are trachybasalts of southeastern California; Nos. 1 to 6 (Table 6), Nos. 7 to 10 (Dish Hill) are taken from Hess (1955) and Wise (1966). The following abbreviations are used: AB, alkali basalt; TB, trachybasalt; H, hawaiiite; TA, trachyandesite; M, mugearite; T, trachyte.

TABLE 7. COMPOSITION OF SOME ALKALI BASALTS AND TRACHYBASALTS

	1	2	3	4	5	6	7
SiO ₂	47.24	46.46	48.60	47.7	51.1	43.1	46.7
TiO ₂	2.38	3.01	3.16	3.2	2.8	4.1	3.6
Al ₂ O ₃	16.11	14.64	16.49	15.2	17.6	13.1	17.3
Fe ₂ O ₃	3.07	3.27	4.19	2.3	2.8	5.5	3.8
FeO	7.34	9.11	7.40	8.7	6.8	8.5	7.1
MnO	0.19	0.14	0.18	—	—	—	—
MgO	7.47	8.19	4.70	9.7	4.8	9.0	4.7
CaO	9.26	10.33	7.79	8.9	6.9	12.4	9.7
Na ₂ O	4.04	2.92	4.43	2.7	4.0	2.7	4.1
K ₂ O	1.75	0.84	1.60	1.6	3.2	1.6	3.0
P ₂ O ₅	0.59	0.37	0.69	—	—	—	—

1. Average analysis of trachybasalts from S. E. California (analyses 1-6, Table 6)
 2. Average Hawaiian alkali basalt
 3. Average Hawaiian hawaiiite
 4. Average alkali basalt, Gough Is.
 5. Average trachybasalt, Gough Is.
 6. Average alkali basalt, Tristan da Cunha
 7. Average trachybasalt, Tristan da Cunha
- } Macdonald and Katsura, 1964.
 } Le Maitre, 1962.
 } Baker, *et al.*, 1964.

subsequent high pressure fractionation) (White, 1966), as was proposed by Wise (1966, 1967). Calculations of the composition which has to be subtracted to derive one lava from another (even after making allowance for the possible accumulation of ferromagnesian minerals in some lavas) cannot be matched either by the composition of the nodules or their component minerals.

Although "granitic" xenoliths are found in the lavas of Dish Hill, Mt. Pisgah and Cima Dome, from the variation of alkalis with silica (Figure 5), there cannot have been extensive whole-rock assimilation (Wise, 1966). Selective assimilation of minerals could have occurred, since Wise (1966) reports that the feldspars in the inclusions have lost alkalis; also Al-Rawi and Carmichael (1967) indicate that on fusion biotites preferentially lose their salic constituents. Of the minerals in the inclusions only extensive assimilation of biotite and hornblende (both extensively oxidized and rimmed by oxides) could give rise to the observation of alkalis and silica (Fig. 5). It should be noted that biotites are the principal repository of Rb and thus on assimilation the Rb content of the liquid should increase. The high K/Rb ratios (Table 6) observed in these lavas would therefore seem to argue against any extensive assimilation of biotite. Any conclusion of the effectiveness of contamination influencing the compositional variation of the trachybasalts of southeastern California will have to wait until the compositions of the minerals in the inclusions has been determined.

Little can be said about the possibility of gaseous transfer except to comment that preferential enrichment in alkalis, especially potassium, coupled with silica loss could account for the alkali pattern shown in Figure 5. The controlling factor of the origin of the trachybasalts of southeastern California remains obscure since the data are too indecisive to decide between the various possibilities.

ACKNOWLEDGMENTS

The authors are indebted to the National Science Foundation for materially assisting (GA-338 and GA-480) this study. We would also like to thank Professor B. W. Evans and L. K. Burns for their help and advice in the techniques and use of the electron probe and R. N. Jack for instructing the first author in the technique of X-ray fluorescence analysis.

REFERENCES

- ABBOTT, M. J. (1967) K and Rb in a continental alkaline igneous rock suite. *Geochim. Cosmochim. Acta*, **31**, 1035-1041.
- AL-RAWI, Y., AND I. S. E. CARMICHAEL (1967) Natural fusion of granite. *Amer. Mineral.*, **52**, 1806-1814.
- BAKER, P. E., I. G. GASS, P. G. HARRIS, AND R. W. LE MAITRE (1964) The Volcanological Report of the Royal Society Expedition to Tristan da Cunha, 1962. *Phil. Trans. Roy. Soc. London (Ser. A)*, **256**, 439-578.

- BOWEN, N. L. (1928) *The Evolution of the Igneous Rocks*. University Press, Princeton, N.J.
- BRADY, C. F., AND R. W. WEBB (1943) Cored bombs from Arizona and California volcanic cones. *J. Geol.*, **51**, 398-410.
- BUDDINGTON, A. F., AND D. H. LINDSLEY (1964) Iron-titanium oxide minerals and synthetic equivalents. *J. Petrology*, **5**, 310-357.
- CARMICHAEL, I. S. E. (1964) The petrology of Thingmuli, a Tertiary volcano in eastern Iceland. *J. Petrology*, **5**, 435-460.
- (1967a) The iron-titanium oxides of salic volcanic rocks and their associated ferromagnesian silicates. *Contr. Mineral. Petrology* **13**, 36-64.
- (1967b) The mineralogy of Thingmuli, a Tertiary volcano in eastern Iceland. *Amer. Mineral.*, **52**, 1815-1841.
- , AND J. NICHOLLS (1967) Iron-titanium oxides and oxygen fugacities in volcanic rocks. *J. Geophys. Res.*, **72**, 4665-4687.
- CHAYES, F. (1965) Titania and alumina content of oceanic and circumoceanic basalt. *Mineral. Mag.*, **34**, 126-131.
- ERLANK, A. J., AND P. K. HOFMEYER (1966) K/Rb and K/Cs ratios in Karroo dolerites from South Africa. *J. Geophys. Res.*, **71**, 5439-5445.
- EUGSTER, H. P., AND D. R. WONES (1962) Stability relations of the ferruginous biotite, annite. *J. Petrology*, **3**, 82-125.
- EVANS, B. W., AND J. G. MOORE (1968) Mineralogy as a function of depth in the prehistoric Makaopuhi tholeiitic lava lake, Hawaii. *Contr. Mineral. Petrology*, **17**, 85-115.
- GARDNER, D. L. (1940) Geology of the Newberry and Ord Mountains, San Bernardino County, California. *Calif. J. Mines Geol.*, **36**, 257-292.
- GUNN, B. M. (1965) K/Rb and K/Ba ratios in Antarctic and New Zealand tholeiites and alkali basalts. *J. Geophys. Res.*, **70**, 6241-6247.
- HÄKLI, T. A., AND T. L. WRIGHT (1967) The fractionation of nickel between olivine and augite as a geothermometer. *Geochim. Cosmochim. Acta.*, **31**, 877-884.
- HAMILTON, E. I. (1965) Distribution of some trace elements and the isotopic composition of strontium in Hawaiian lavas. *Nature*, **206**, 251-253.
- HASKIN, L. A., F. A. FREY, R. A. SCHMITT, AND R. H. SMITH (1966) Meteoric, solar and terrestrial rare-earth distributions. In: Ahrens L. H., Ed. *Physics and Chemistry of the Earth*, Pergamon Press, N. Y., 167-321.
- HEIER, K. S., W. COMPSTON, AND I. McDOUGALL (1965) Thorium and uranium and the isotopic composition of strontium in the differentiated Tasmanian dolerites. *Geochim. Cosmochim. Acta*, **29**, 643-659.
- HESS, H. H. (1955) The oceanic crust. *J. Marine Res.*, **14**, 423-439.
- HEWITT, D. F. (1956) Geology and Mineral Resources of the Ivanpah Quadrangle, California and Nevada, *U. S. Geol. Surv. Prof. Pap.*, **275**, 1-172.
- KUNO, H. (1964) Aluminum augite and bronzite in alkali olivine basalt from Taka-sima, north Kyuoyu, Japan. In: *Advancing frontiers in geology and geophysics*, Hyderabad, Osmania University Press, 205-220.
- KUSHIRO, I., AND J. F. SCHAIRER (1963) New data on the system diopside-forsterite-silica. *Carnegie Inst. Wash. Year Book* **62**, 95-103.
- LE BAS, M. J. (1962) The role of aluminum in igneous clinopyroxenes with relation to their parentage. *Amer. J. Sci.*, **260**, 267-288.
- LE MAITRE, R. W. (1962) Petrology of volcanic rocks, Gough Island. South Atlantic. *Geol. Soc. Amer. Bull.*, **73**, 1309-1340.
- LESSING, P., R. W. DECKER, AND R. C. REYNOLDS (1963) Potassium and rubidium distribution in Hawaiian lavas. *J. Geophys. Res.*, **68**, 5851-5855.
- LIPMAN, P. W. (1965) Chemical comparison of glassy and crystalline volcanic rocks. *U. S. Geol. Surv. Bull.* **1201-D**.

- MACDONALD, G. A., AND T. KATSURA (1964) Chemical composition of Hawaiian lavas. *J. Petrology*, **5**, 82-133.
- NOCKOLDS, S. R., AND R. ALLEN (1953) The geochemistry of some igneous rock series. *Geochim. Cosmochim. Acta*, **4**, 105-142.
- (1954) The geochemistry of some igneous rock series, Part 2, *Geochim. Cosmochim. Acta*, **5**, 245-285.
- PARKER, R. B. (1959) Magmatic differentiation at Amboy Crater, California. *Amer. Mineral.*, **44**, 656-659.
- (1963) Recent volcanism of Amboy Crater, San Bernardino County, California. *Calif. Div. Mines Geol. Spec. Rep.* **76**.
- PECK, D. L., T. L. WRIGHT, AND J. G. MOORE (1966) Crystallization of tholeiitic basalt in Alae lava lake, Hawaii. *Bull. Volcan.*, **29**, 629-656.
- POWERS, H. A. (1955) Composition and origin of basaltic magma of the Hawaiian Islands. *Geochim. Cosmochim. Acta*, **7**, 77-107.
- SMITH, A. L., AND I. S. E. CARMICHAEL (1968) Quaternary lavas from the southern Cascades, western U. S. A. *Contr. Mineral. Petrol.*, **19**, 212-238.
- SMITH, J. V., AND W. S. MACKENZIE (1958) The alkali feldspars: IV The cooling history of high-temperature sodium-rich feldspars. *Amer. Mineral.*, **43**, 872-889.
- TAYLOR, S. R. (1965) The application of trace element data to problems in petrology. In: Ahrens, L. H., Ed. *Physics and Chemistry of the Earth*, **6**, Pergamon Press, N. Y., 133-213.
- TILLEY, C. E., H. S. YODER, AND J. F. SCHAIRER (1965) Melting relations of volcanic tholeiite and alkali rock series. *Carnegie Inst. Wash. Year Book*, **64**, 69-82.
- TOWELL, D. G., J. W. WINCHESTER, AND R. VOLFOVSKY (1965) Rare-earth distribution in some rocks and associated minerals of the batholith of Southern California. *J. Geophys. Res.*, **70**, 3485-3496.
- TUTTLE, O. F., AND N. L. BOWEN (1958) Origin of granite in the light of experimental studies. *Geol. Soc. Amer. Mem.* **74**.
- VERHOOGEN, J. (1962a) Distribution of titanium between silicates and oxides in igneous rocks. *Amer. J. Sci.*, **260**, 211-220.
- (1962b) Oxidation of iron-titanium oxides in igneous rocks. *J. Geol.*, **70**, 168-181.
- VINCENT, E. A., AND R. PHILLIPS (1954) Iron-titanium oxide minerals in layered gabbros of the Skaergaard intrusion, east Greenland. *Geochim. Cosmochim. Acta*, **6**, 1-26.
- VITALIANO, C. J., AND R. D. HARVEY (1965) Alkali basalt from Nye County, Nevada. *Amer. Mineral.*, **50**, 73-84.
- WHITE, R. W. (1966) Ultramafic inclusions in basaltic rocks from Hawaii. *Contr. Mineral. Petrology*, **12**, 245-314.
- WILKINSON, J. F. F. (1966) Residual glasses from some alkali basaltic lavas from New South Wales. *Mineral. Mag.*, **35**, 847-859.
- WISE, W. S. (1966) Zeolitic basanite from southeastern California. *Bull. Volcan.*, **29**, 235-251.
- (1967) Origin of alkali basaltic magmas of southeastern California: some preliminary results. *Trans. Amer. Geophys. Union*, **48**, 256-257.
- WRIGHT, T. L., AND P. W. WEIBLEN (1967) Mineral composition and paragenesis in tholeiitic basalt from Makaopuhi lava lake, Hawaii. *Progr. Geol. Soc. Amer. Ann. Meet.*, **1967**, 242-243.
- YODER, H. S., AND C. E. TILLEY (1962) Origin of basalt magmas: an experimental study of natural synthetic rock systems. *J. Petrology*, **3**, 342-532.
- YAGI, K., AND K. ONUMA (1967) The join $\text{CaMgSi}_2\text{O}_6$ - $\text{CaTiAl}_2\text{O}_6$ and its bearing on the titanogites. *Jour. Fac. Sci. Hokkaido Univ. Ser. IV*, **8**, 463-483.