

THE 1959-60 ERUPTION OF KILAUEA VOLCANO HAWAII

CHEMISTRY OF
THE LAVAS

GEOLOGICAL SURVEY
PROFESSIONAL PAPER 537-A



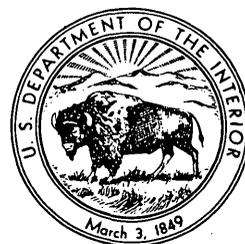
Chemistry of the Lavas of the 1959-60 Eruption of Kilauea Volcano, Hawaii

By K. J. MURATA *and* D. H. RICHTER

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GEOLOGICAL SURVEY PROFESSIONAL PAPER 537-A

*A study of fractional crystallization
of a basaltic magma as revealed by
chronological changes in lava composition
during a major eruption*



UNITED STATES GOVERNMENT PRINTING OFFICE, WASHINGTON : 1966

UNITED STATES DEPARTMENT OF THE INTERIOR

STEWART L. UDALL, *Secretary*

GEOLOGICAL SURVEY

William T. Pecora, *Director*

For sale by the Superintendent of Documents, U.S. Government Printing Office
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ABSTRACT

During the 1959-60 eruption of Kilauea Volcano, the outpouring magma was sampled systematically to obtain detailed information on chronological changes in composition. The temporal variations in composition, when correlated with mineralogy, lava temperature, rate of discharge, and other parameters measured during the eruption, provide new insight into the preeruptional crystallization of basaltic magma, entailing intratelluric depositions of various phenocrysts and migration of rest liquids.

The hottest and most mafic lavas were produced in the 1959 summit phase of the eruption. The compositional variation (7 to 19 percent MgO) among most summit lavas is ascribable solely to fractional crystallization of olivine (Fe_{13}), the first silicate mineral to separate from the primitive magma. A direct relationship between the olivine content of summit lavas and the rate of lava discharge suggests that strong currents of magma erode beds of previously sedimented olivine crystals lying on the bottom of the magma chamber. The coolest, olivine-poor summit lavas contained some small phenocrysts of clinopyroxene and plagioclase as well as olivine. The compositions of these lavas indicated a slight overall accumulation of clinopyroxene, the second mineral to start separating from the cooling magma.

The 1960 flank phase of the eruption involved two magmas of different vintage, the cooler, early-1960 magma representing old material that had not been expelled in the previous flank eruption of 1955 and the hotter, late-1960 magma that had probably just migrated down from the summit region along conduits in the east rift zone. Compositional variations (6.1 to 6.6 percent MgO) among the early-1960 lavas indicated an advanced magma that was fractionally crystallizing plagioclase ($An_{67.1}$), clinopyroxene ($En_{47.3}Fs_{12.2}Wo_{40.5}$), and olivine ($Fe_{23.5}$) in the weight ratio of 11.0:10.0:2.3. This magma had cooled sufficiently to crystallize plagioclase $An_{67.1}$ in some abundance. Its composition lay along the principal line of liquid descent for this stage of basaltic differentiation.

The late-1960 lavas (7 to 13 percent MgO) represented variable amounts of total phenocrysts, consisting of olivine (Fe_{18}) and clinopyroxene ($En_{47.3}Fs_{12.2}Wo_{40.5}$) in a weight ratio of 20.0:3.0, suspended in a rather uniform, moderately differentiated melt. In accord with the very clear petrographic evidence, lava compositions of the intermediate period of the 1960 eruption indicated a mixing of the early- and late-1960 magmas.

Thus, the 1959 summit, the late-1960 flank, and the early-1960 flank magmas clearly showed trends of differentiation resulting

from the separation of various proportions of three major minerals—olivine, clinopyroxene, and plagioclase—at progressively lower temperature.

No lavas representing the stage of chemical transition from the 1959 summit magma to the 1960 flank magmas were obtained. Presumably, the transition took place largely during the subterranean migration of the magma away from the summit region. A plausible mechanism for the transition would be the separation, in an olivine-depleted summit magma, of clinopyroxene ($En_{49.3}Fs_{10.7}Wo_{39.5}$), plagioclase (An_{64}), olivine (Fe_{18}), and magnetite in the weight ratio of 6.00:2.25:0.25:0.50.

The weighted-average composition of the lavas, expelled during the first phase of the 1959 summit eruption, shows 13.9 percent magnesia. The most mafic glass obtained from one of the hottest summit lavas contains 10.0 percent magnesia. These compositions suggest that the primitive Kilauea magma holds at least 10 percent magnesia, but whether it could be even more mafic remains unknown.

INTRODUCTION

The composition and mineralogy of Hawaiian lavas have long been of interest to those concerned with differentiation of basaltic magmas. Basaltic magmas erupted by continental volcanoes are likely to be contaminated by sialic materials of the continental crust, so that compositional changes due to magmatic differentiation may be obscured by those due to assimilation. In Hawaii, however, the possibility of such contamination is slight, so the differentiation of basaltic magmas can be studied there with greater confidence.

Mauna Loa has remained inactive since its eruption in 1950. On the other hand, Kilauea, which was quiet between 1934 and 1952, entered a period of much activity with a summit eruption in 1952; the attention of investigators of basaltic rocks is therefore currently centered on this volcano. The establishment of a well-equipped analytical laboratory at the Observatory on Kilauea in 1958 has greatly facilitated geochemical studies of the recent eruptions.

Data gathered during the 1959-60 eruption of Kilauea have helped to clarify the general relationship between lavas erupted at the summit and those erupted on the flank of the volcano. The 1959 summit lavas showed

limited differentiation from a primitive composition, whereas the 1960 flank lavas represented more advanced stages of differentiation. Primitive magma originates in the mantle of the earth between 40 and 60 kilometers below the summit (Eaton and Murata, 1960). It accumulates in a magma reservoir within the volcanic pile only a few kilometers beneath the summit and may either force its way up vertically to the summit or laterally into the rift zone to erupt eventually from the flank of the mountain.

In breaking to the summit, the magma has to travel only a few kilometers, whereas to erupt on the flank it must migrate laterally as much as 40 km and probably is stored in the rift zone for a variable period of time. Because a crystallizing magma differentiates continuously, summit lavas would probably tend to have a composition more primitive than that of flank lavas.

Kilauea lavas so far studied belong to the tholeiitic type exclusively. The present work, therefore, deals with differentiation of tholeiitic basalt magmas and is not concerned with problems of alkalic basalt magmas, such as those erupted by Hualalai and other older Hawaiian volcanoes.

From a study of the available analyses Powers (1955) concluded that all Kilauea lavas erupted during historic time were derived from a single large batch of magma that was generated in the mantle over a century ago, and he called this magma the historic primitive magma of Kilauea. The less-differentiated lavas of the 1959-60 eruption clearly indicate an affinity to this historic primitive magma. It is to be noted that Powers' hypothesis precludes explaining variations in historic lavas by means of appreciable variations in the fundamental magma; all variants among historic lavas are to be considered as differentiates of a single batch of magma of uniform composition.

ACKNOWLEDGMENTS

The authors are indebted to the staff of Hawaii National Park and to their colleagues of the Hawaiian Volcano Observatory for help in collecting daily samples of lavas and pyroclastic materials during the eruption. The constant stream of background information on seismic activity, ground tilting, lava temperatures, and rates of lava extrusion received from their colleagues throughout the eruption made the authors' work an integral part of an intensely exciting multifaceted investigation. R. T. Okamura helped with the silica determinations throughout the eruption.

The complete analyses of selected samples were made in the laboratories of the U.S. Geological Survey by D. F. Powers, M. C. Lemmon, and E. L. Munson under the supervision of L. C. Peck and by Paul Elmore,

Samuel Botts, Ivan Barlow, and Gillison Chloe under the supervision of W. W. Brannock. Analytical methods used by the first group have been described by L. C. Peck (1964); those used by the second group have been described by Shapiro and Brannock (1962). F. A. Hildebrand made most of the X-ray determinations of olivine, and both he and H. A. Powers kindly made special preparations of certain of the samples prior to analysis so that additional information could be derived. We are also indebted to Marjorie Hooker, who arranged to have the norms of the lavas computed by means of an electronic computer in Washington.

PREVIOUS ANALYSES OF KILAUEA LAVAS AND MINERALS

Chemical analyses of Kilauea lavas made prior to 1949 were compiled and summarized by Macdonald (1949a). Since that time, further analyses have been published by Macdonald (1949b, 1955), Macdonald and Eaton (1955, 1957), Macdonald and Katsura (1961), Muir and Tilley (1957, 1963), Kuno and others (1957), Yoder and Tilley (1957), Tilley (1960a, b), and Tilley and Scoon (1961). Most analyses are of random samples of historic and prehistoric lava flows. They have served to define the limits of compositional variation of Kilauea magmas and to indicate the dominant role of fractional crystallization in the differentiation of the magmas.

Compositional variation among the majority of the previously analyzed samples is rather limited and is due primarily to the separation or accumulation of olivine. The compositions of lavas that issued during the 1955 flank eruption (Macdonald, 1955) are of especial interest because they represent the highest degree of differentiation observed for Kilauea prior to 1960, except for a segregation vein in a prehistoric flow described by Kuno and others (1957). The differentiation of these lavas and of the vein material involved extensive separation of the other major basaltic minerals—clinopyroxene and plagioclase.

In contrast to the lavas, intrusive rocks of Kilauea have been little investigated. A recent study by the authors (Murata and Richter, 1961) of the gabbroic rocks of Uwekahuna laccolith showed that the range of composition represented by the differentiated rocks of this single intrusive was almost as great as that indicated by all previously analyzed samples of lavas from the volcano.

Macdonald (1955) sampled the several flows of lava that were produced during the 1955 eruption and thereby first obtained a series of samples of known chronology for a single eruption of Kilauea. The eight samples showed a decrease in percentage of silica with time,

a fact strongly suggesting that an extensively differentiated body of magma had been expelled in an orderly manner so that the most differentiated upper part emerged first. Systematic sampling of the extruded material was carried out throughout the 1959-60 eruption, with special emphasis on collecting the quickly chilled pumice of the fire fountains.

There are special advantages in studying fresh pumice and lava collected near the vent during an eruption. The time relationship among the samples is known unequivocally, exposure to weathering is at a minimum, and petrochemical data can be correlated with temperature and other geophysical variables measured during the eruption.

Relatively few analyses have been made of the phenocrystic minerals of Kilauea lavas. Analyses are available of phenocrystic olivine from the 1840 flow (Aurousseau and Merwin, 1928), from the Uwekahuna laccolith (Murata and Richter, 1961), and from the 1959 lava pond of Kilauea Iki (Macdonald and Katsura, 1961). The content of total iron (calculated as FeO) in the three olivines lies between 11.8 and 14.2 percent, corresponding to $Fa_{12.2-15.0}$. During the present study, a partial analysis of the sparse olivine phenocrysts in the Kii flow of the 1955 eruption extended the compositional range to $Fa_{23.5}$.

Phenocrysts and microphenocrysts of augites that have been separated from Kilauea rocks and analyzed are tabulated below:

Source	Composition	Reference
Uwekahuna gabbro.	$En_{49.8}Fs_{10.7}Wo_{39.5}$	Muir and Tilley (1957).
1840 picrite-----	$En_{49.0}Fs_{11.0}Wo_{40.0}$	Do.
1921 olivine basalt.	$En_{48.4}Fs_{10.3}Wo_{41.3}$	Muir and Tilley (1963).
1955 basalt-----	$En_{47.6}Fs_{12.1}Wo_{40.0}$	Present study.
1960 basalt-----	$En_{47.8}Fs_{12.3}Wo_{40.1}$	Do.

The meager data suggest that the phenocrystic augites of Kilauea are less variable in composition than phenocrystic olivines.

Orthopyroxene phenocrysts are so scarce and fine grained in Kilauea basalts that only a sample from the gabbro of Uwekahuna laccolith has been analyzed (Muir and Tilley, 1957). Its composition is $En_{73.4}Fs_{21.3}Wo_{5.3}$. No analyses are available for plagioclase phenocrysts nor for opaque minerals occurring either as phenocrysts or as groundmass precipitates. Fractional crystallization is the dominant mechanism for differentiation of Kilauea magmas, and the quantitative treatment of this differentiation is seriously hindered by the dearth of information on the composition of phenocrystic minerals.

METHODS OF SAMPLE COLLECTION AND CHEMICAL ANALYSIS

The eruption at the summit (in Kilauea Iki) was confined to a single vent after the first day, so sample collection was simple. Although most of the material expelled from the vent poured out as a fluid lava flow which accumulated in the crater of Kilauea Iki, a part of it was blown to the southwest by prevailing winds and fell as cinder and pumice. During the first few days of the eruption, silica was determined on several pairs of samples of contemporary pumice and lava, and no significant difference was found. Consequently, nearly all of the later samples consisted of pumice and cinder collected twice daily by spreading a large piece of canvas on the ground downwind from the vent.

The vent system that prevailed during the flank eruption at Kapoho was more complex and variable than that at the summit. One main vent predominated throughout most of the eruption, but from time to time one to five other vents were active. Pumice samples were collected from the main vent whenever possible. During the period February 5 to 12, a shift in wind direction caused the pumice from the main vent to fall mostly on the inaccessible field of fresh lava flows to the east. Most samples of flow lava or spatter were obtained from the westernmost vent, which, in contrast to the main vent, rarely displayed a fountain but instead quietly poured out flows of lava from time to time. As at Kilauea Iki, no significant difference in percentage of silica between contemporary pumice and lava was found. The term "lava" will hereafter be used in a broad sense to include flow lava, spatter material, pumice, cinder, and ash.

Only silica was determined in the samples during the eruption. The determinations were made gravimetrically and involved carbonate fusion of the samples followed by double dehydration with hydrochloric acid. The complete analyses of samples, selected on the basis of their silica content, were made subsequently in the laboratories of the Geological Survey under the direction of L. C. Peck. Some additional samples were analyzed by the rapid-analysis group under the direction of W. W. Brannock. The crystalline and glassy portions of some of the samples were separated by H. A. Powers and analyzed separately.

ANALYTICAL RESULTS

The results of chemical analyses are presented in tables 1, 2, 4, and 6. Table 1 contains the analyses of lavas from the 1959 summit eruption at Kilauea Iki; table 2, analyses of lavas from the 1960 flank eruption

at Kapoho. In both tables the samples are arranged in chronological order of eruption. The analyses of the 1959 summit and 1960 flank lavas are also plotted chron-

ologically in figures 1 and 3 respectively. Concomitant mineralogical changes are described in a separate chapter on the petrography of the lavas.

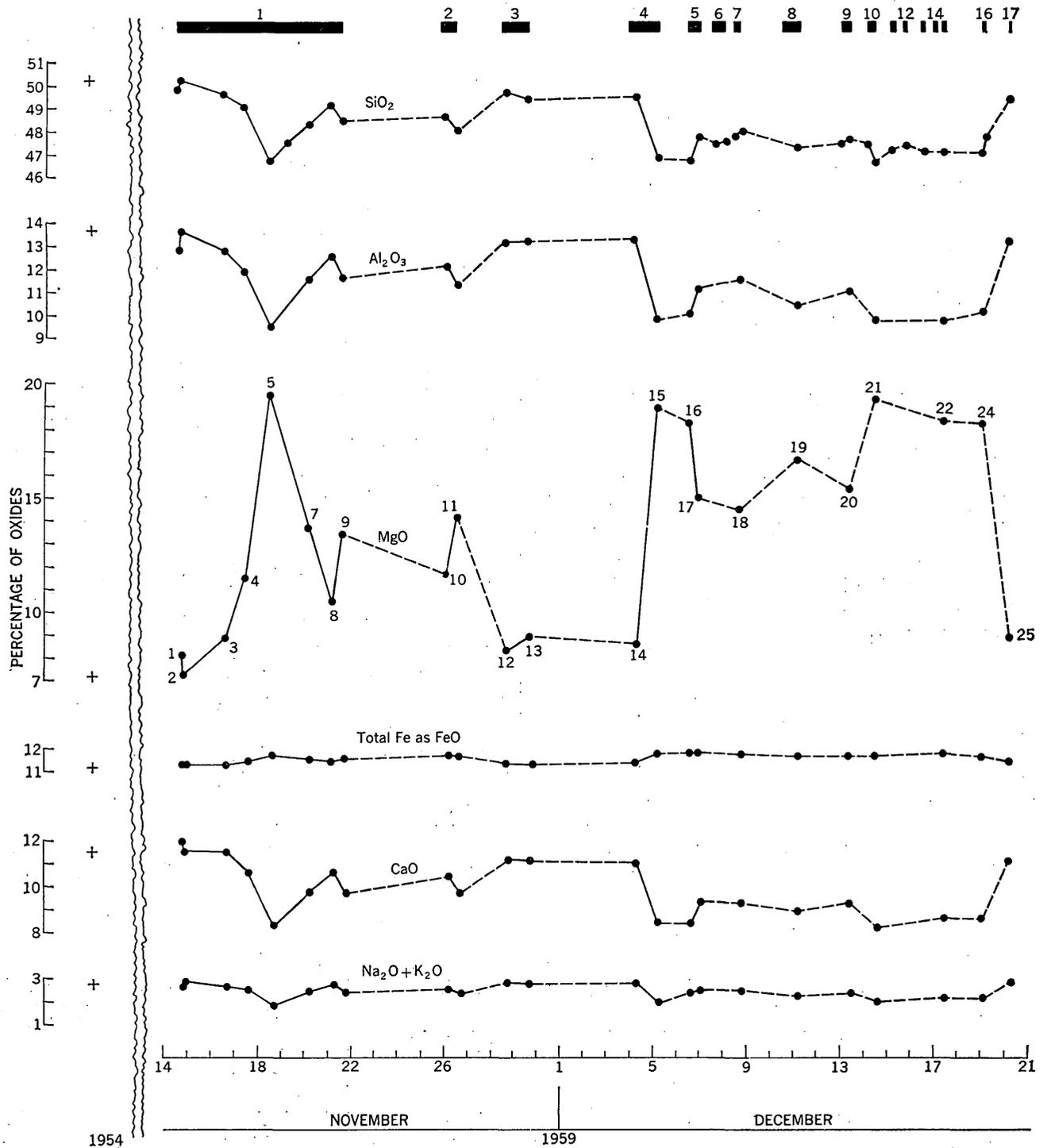


FIGURE 1.—Chronological changes in lava composition during the 1959 summit eruption in Kilauea Iki. Black bars at the top of the figure indicate the time and duration of the 17 phases that characterized this eruption. The composition of the sample obtained during the brief

1954 summit eruption (Macdonald and Eaton, 1957) is plotted on the left side. Numbers along the magnesia curve are the S-series of sample numbers from table 1. Solid lines connect samples of a given eruptive phase; dashed lines, samples of successive phases.

TABLE 1.—Chemical analyses and norms of lavas of the 1959 Kilauea summit eruption

[Analyst: D. F. Powers, unless otherwise noted. Results given in percent; .. indicates constituent not determined or calculated]

	S-1	S-2	S-3	S-4	S-5	S-7	S-8	S-9	S-10	S-11	S-12	S-13	S-14	S-15	S-16	S-17	S-18	S-19	S-20	S-21	S-22	S-24	S-25	
Chemical analyses																								
SiO ₂	49.91	50.07	49.62	48.99	46.68	48.22	49.12	48.41	48.55	47.98	49.56	49.42	49.45	46.82	46.7	47.7	48.0	47.34	47.74	46.74	47.02	46.99	49.44	49.44
Al ₂ O ₃	12.69	13.70	12.82	11.95	9.52	11.56	12.42	11.62	12.09	11.39	13.33	13.22	13.30	9.82	10.0	11.1	11.5	10.47	10.98	9.70	9.86	10.06	13.13	13.13
Fe ₂ O ₃	2.56	1.39	2.70	1.47	1.57	1.36	1.30	1.36	1.40	1.43	2.30	1.75	4.25	1.37	1.5	1.4	1.5	1.69	1.40	1.36	1.24	1.80	2.34	2.34
FeO.....	8.86	10.00	8.82	10.08	10.30	10.31	10.17	10.29	10.44	10.26	9.23	9.72	7.52	10.53	10.4	10.5	10.3	10.08	10.35	10.44	10.53	10.04	9.27	9.27
MgO.....	8.08	7.23	8.85	11.50	19.52	13.67	10.45	13.34	11.61	14.08	8.22	8.92	8.55	18.87	18.2	14.9	14.4	16.59	15.40	19.25	18.26	18.25	8.85	8.85
CaO.....	11.92	11.55	11.49	10.60	8.26	9.68	10.57	9.77	10.40	9.58	11.16	11.05	11.03	8.31	8.3	9.3	9.2	8.92	9.24	8.16	8.46	8.43	10.97	10.97
Na ₂ O.....	2.13	2.30	2.11	2.05	1.52	1.94	2.09	1.94	2.03	1.89	2.22	2.20	2.19	1.57	1.9	1.9	1.9	1.69	1.82	1.55	1.61	1.61	2.18	2.18
K ₂ O.....	.55	.60	.50	.47	.35	.45	.54	.47	.48	.45	.55	.54	.53	.36	.40	.46	.47	.41	.50	.41	.40	.38	.53	.53
H ₂ O.....	.09	.00	.08	.05	.00	.07	.09	.04	.04	.01	.06	.00	.00	.00	.00	.00	.00	.00	.00	.00	.03	.00	.07	.07
H ₂ O+.....	.02	.02	.02	.03	.01	.01	.01	.00	.02	.02	.01	.02	.00	.00	.23	.22	.25	.03	.03	.01	.04	.01	.01	.01
ThO ₂	2.62	2.75	2.55	2.42	1.80	2.27	2.53	2.30	2.40	2.30	2.77	2.68	2.62	1.86	1.9	2.2	2.2	2.15	2.16	1.92	2.03	1.96	2.67	2.67
P ₂ O ₅.....	.25	.28	.26	.23	.18	.23	.23	.25	.24	.23	.27	.26	.26	.19	.22	.25	.25	.21	.21	.19	.20	.20	.26	.26
MnO.....	.17	.17	.18	.18	.17	.18	.18	.17	.18	.17	.17	.18	.17	.17	.17	.18	.18	.17	.18	.18	.18	.18	.17	.18
CO ₂.....	.01	.00	.02	.02	.02	.02	.01	.01	.01	.00	.01	.05	.01	.02	<.05	<.05	<.05	.01	.01	.00	.01	.00	.01	.01
Cl.....	.02	.02	.01	.02	.01	.01	.01	.02	.02	.01	.02	.02	.02	.01	.01	.01	.01	.02	.01	.01	.02	.01	.02	.02
F.....	.04	.04	.03	.03	.02	.03	.04	.03	.03	.03	.03	.03	.03	.02	.02	.02	.02	.02	.03	.02	.02	.02	.03	.03
Cr ₂ O ₃.....	.21						.21																	
Subtotal.....	100.13	100.12	100.06	100.09	99.93	100.01	99.99	100.00	100.11	99.83	99.91	100.06	99.93	99.92	100	100	100	99.80	100.06	99.94	99.91	99.93	99.96	99.96
Less O.....	.02	.02	.01	.01	.01	.01	.02	.01	.01	.01	.01	.01	.01	.01				.01	.01	.01	.01	.01	.01	.01
Total.....	100.11	100.10	100.05	100.08	99.92	100.00	99.97	99.99	100.10	99.82	99.90	100.05	99.92	99.91	100	100	100	99.79	100.05	99.93	99.90	99.92	99.95	99.95

Norms

Q.....	1.58	0.41	0.75	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.65	0.00	2.45	0.00				0.00	0.00	0.00	0.00	0.00	0.00	0.06
Or.....	3.25	3.54	2.95	2.78	2.07	2.66	3.19	2.78	2.84	2.66	3.25	3.19	3.13	2.13				2.42	2.95	2.42	2.36	2.25	3.13	3.13
Ab.....	17.75	19.30	17.53	16.95	12.54	16.09	17.48	16.14	14.88	15.91	18.51	17.86	18.25	12.97				14.03	15.20	13.03	13.35	13.54	18.17	18.17
An.....	23.59	25.37	24.20	22.22	18.29	21.67	23.02	21.75	23.68	21.31	24.93	25.00	25.04	18.85				19.92	20.42	18.34	18.64	19.14	24.62	24.62
Di:																								
Wo.....	14.07	12.48	12.92	11.98	8.94	10.31	11.51	10.46	10.94	10.25	11.91	11.68	11.62	8.78				9.55	9.97	8.69	9.16	8.89	11.67	11.67
En.....	8.83	6.96	8.28	7.60	6.26	6.74	7.12	6.81	6.86	6.78	7.35	7.10	8.20	6.07				6.57	6.68	6.05	6.30	6.22	7.31	7.31
Fs.....	4.37	5.02	3.79	3.62	1.93	2.85	3.71	2.93	3.41	2.74	3.87	3.94	2.42	2.00				2.21	2.55	1.92	2.12	1.92	3.65	3.65
Hy:																								
En.....	11.28	11.04	13.75	12.21	10.68	11.69	12.67	12.14	14.20	11.38	13.12	13.57	13.08	10.71				12.26	10.44	10.11	10.86	11.59	14.72	14.72
Fs.....	5.59	7.96	6.29	5.82	3.29	4.94	6.61	5.22	7.07	4.60	6.92	7.52	3.86	3.52				4.12	3.98	3.21	3.65	3.58	7.36	7.36
Ol:																								
Fo.....	.00	.00	.00	6.18	22.19	10.94	4.36	9.99	5.50	11.84	.00	1.07	.00	21.16				15.75	14.87	22.27	19.83	19.36	.00	.00
Fa.....	.00	.00	.00	3.24	7.53	5.10	2.51	4.74	3.02	5.28	.00	.66	.00	7.67				5.83	6.25	7.79	7.35	6.59	.00	.00
Mt.....	3.71	2.02	3.91	2.13	2.28	1.97	1.88	1.97	2.03	2.07	3.33	2.54	6.16	1.99				2.45	2.03	1.97	1.80	2.61	3.39	3.39
Il.....	4.98	5.22	4.84	4.60	3.42	4.31	4.81	4.37	4.56	4.37	5.26	5.09	4.98	3.53				4.08	4.10	3.65	3.86	3.72	5.07	5.07
Ap.....	.59	.66	.62	.54	.43	.54	.59	.54	.57	.54	.64	.62	.62	.45				.50	.50	.45	.47	.47	.62	.62

S-1. Vent spatter from the most eastern early vent, Nov. 14, 1959.
 S-2. Vent spatter from the most western early vent, Nov. 14, 1959.
 S-3. Lava from main lava river, 2:00 p.m., Nov. 16, 1959.
 S-4. Pumice, 3:00 p.m., Nov. 17, 1959. E. L. Munson, analyst.
 S-5. Pumice, 5:00 p.m., Nov. 18, 1959.
 S-7. Pumice, 7:00 a.m., Nov. 20, 1959.
 S-8. Pumice, 7:10 a.m., Nov. 21, 1959.
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 S-10. Lava flow, 2d eruptive phase, 4:50 a.m., Nov. 26, 1959.
 S-11. Pumice, 2d eruptive phase, 4:00 p.m., Nov. 26, 1959.

S-12. Pumice, 3d eruptive phase, 6:15 p.m., Nov. 28, 1959.
 S-13. Pumice, 3d eruptive phase, 9:00 p.m., Nov. 29, 1959.
 S-14. Slab pahoehoe, 4th eruptive phase, 9:45 a.m., Dec. 4, 1959.
 S-15. Pumice, 4th eruptive phase, 9:30 a.m., Dec. 5, 1959.
 S-16. Pumice, 5th eruptive phase, 4:30 p.m., Dec. 6, 1959. Analysts, rapid analysis group, under the supervision of W. W. Brannock.
 S-17. Pumice, 5th eruptive phase, 12:30 a.m., Dec. 7, 1959. Analysts, rapid analysis group, under the supervision of W. W. Brannock.

S-18. Pumice, 7th eruptive phase, 8:10 p.m., Dec. 8, 1959. Analysts, rapid analysis group, under the supervision of W. W. Brannock.
 S-19. Pumice, 8th eruptive phase, 6:00 a.m., Dec. 11, 1959.
 S-20. Pond lava, 9th eruptive phase, Dec. 13, 1959.
 S-21. Pumice, 10th eruptive phase, 2:00 p.m., Dec. 14, 1959.
 S-22. Pumice, 15th eruptive phase, 2:45 p.m., Dec. 17, 1959.
 S-24. Pumice, 16th eruptive phase, 6:15 a.m., Dec. 19, 1959.
 S-25. Thin pahoehoe, minor 17th eruptive phase, time uncertain, Dec. 20, 1959.

TABLE 2.—Chemical analyses and norms of lavas of the 1960 Kilauea flank eruption
 [Analyst, M. C. Lemon, unless otherwise noted. Results given in percent; ---- indicates constituent not determined or calculated]

	F-1	F-3	F-5	F-6	F-7	F-8	F-9	F-11	F-12	F-13	F-14	F-15	F-16	F-17	F-18	F-19	F-20
Chemical analyses																	
SiO ₂	50.58	50.62	50.76	50.74	50.42	49.87	49.49	49.21	49.34	48.86	49.19	48.4	48.97	48.77	49.31	48.91	49.13
Al ₂ O ₃	13.82	13.76	13.70	13.57	13.51	13.29	12.92	12.34	12.56	11.98	12.24	11.9	11.84	11.55	12.24	11.71	11.96
Fe ₂ O ₃	2.18	1.80	1.68	1.36	2.34	2.13	2.31	1.56	1.78	1.58	2.02	1.7	2.83	1.40	1.31	1.35	1.44
FeO.....	9.52	9.95	10.40	10.63	9.59	9.59	9.43	10.00	9.91	10.06	9.63	10.5	8.93	10.21	10.24	10.33	10.13
MgO.....	6.56	6.43	6.09	6.16	6.97	8.27	9.39	11.27	10.58	12.11	11.28	12.5	12.29	13.13	11.12	12.46	11.82
CaO.....	10.43	10.21	10.01	9.94	10.18	10.24	9.98	9.94	9.80	9.51	9.69	9.3	9.41	9.29	9.85	9.46	9.58
Na ₂ O.....	2.58	2.63	2.71	2.69	2.59	2.41	2.33	2.16	2.24	2.15	2.25	2.1	2.09	2.08	2.22	2.16	2.19
K ₂ O.....	.65	.65	.69	.67	.62	.60	.57	.53	.54	.50	.52	.52	.50	.49	.51	.48	.50
H ₂ O.....	.08	.10	.04	.09	.11	.06	.14	.11	.12	.08	.08	.08	.01	.09	.10	.08	.08
H ₂ O+.....	.01	.00	.03	.00	.00	.03	.00	.00	.00	.03	.03	.28	.03	.02	.01	.01	.00
TiO ₂	3.11	3.20	3.37	3.35	3.17	2.91	2.83	2.59	2.69	2.60	2.69	2.4	2.55	2.42	2.61	2.55	2.65
P ₂ O ₅.....	.35	.35	.36	.37	.34	.33	.31	.27	.28	.31	.28	.29	.26	.26	.28	.28	.27
MnO.....	.18	.18	.18	.18	.18	.18	.18	.17	.17	.18	.18	.17	.18	.18	.17	.18	.18
CO ₂.....	.02	.01	.02	.01	.01	.02	.01	.01	.02	.01	.01	<.05	.02	.02	.01	.01	.00
Cl.....	.02	.02	.02	.02	.02	.02	.02	.02	.02	.02	.01	-----	.02	.01	.02	.02	.01
F.....	.04	.04	.04	.04	.04	.04	.04	.04	.04	.03	.03	-----	.03	.03	.03	.03	.04
Subtotal.....	100.19	99.95	100.10	99.82	100.09	99.99	99.93	100.02	100.09	100.01	100.12	100	99.96	99.94	100.03	100.02	99.98
Less O.....	.02	.02	.02	.02	.02	.02	.02	.02	.02	.01	.01	-----	.01	.01	.01	.01	.02
Total.....	100.17	99.93	100.08	99.80	100.07	99.97	99.91	100.00	100.07	100.00	100.11	100	99.95	99.93	100.02	100.01	99.96
Norms																	
Qr.....	2.69	2.49	2.66	2.46	2.42	0.71	0.00	0.00	0.00	0.00	0.00	-----	0.00	0.00	0.00	0.00	0.00
Or.....	3.84	3.84	4.08	3.96	3.66	3.54	3.37	3.13	3.19	2.95	3.07	-----	2.95	2.89	3.01	2.84	2.95
Ab.....	21.43	21.98	22.53	22.48	21.64	20.00	19.44	18.00	18.56	17.92	18.95	-----	17.29	17.40	18.51	18.00	18.45
An.....	24.58	23.97	23.39	23.12	23.55	23.88	23.26	22.55	22.83	21.71	21.81	-----	21.66	20.84	22.07	20.98	21.37
Di.....	-----	-----	-----	-----	-----	-----	-----	-----	-----	-----	-----	-----	-----	-----	-----	-----	-----
Wo.....	10.31	10.11	9.91	9.85	10.24	10.26	10.03	9.93	9.92	9.74	10.15	-----	9.68	9.77	10.37	10.01	10.10
En.....	5.91	5.59	5.27	5.15	6.01	6.24	6.38	6.33	6.28	6.31	6.63	-----	6.68	6.38	6.50	6.44	6.48
Fs.....	3.94	4.13	4.33	4.43	3.73	3.45	3.01	2.96	3.01	2.76	2.81	-----	2.22	2.72	3.22	2.90	2.95
Hy.....	-----	-----	-----	-----	-----	-----	-----	-----	-----	-----	-----	-----	-----	-----	-----	-----	-----
En.....	10.42	10.42	9.89	10.19	11.34	14.35	16.28	14.76	15.24	14.24	14.59	-----	18.25	13.65	13.73	13.47	13.99
Fs.....	6.94	7.70	8.14	8.77	7.04	7.93	7.68	6.90	7.29	6.24	6.19	-----	6.07	5.82	6.81	6.07	6.35
Ol.....	-----	-----	-----	-----	-----	-----	-----	-----	-----	-----	-----	-----	-----	-----	-----	-----	-----
Fo.....	.00	.00	.00	.00	.00	.00	.50	4.88	3.37	6.73	4.81	-----	3.98	8.87	5.22	7.78	6.28
Fa.....	.00	.00	.00	.00	.00	.00	.26	2.51	1.78	3.25	2.25	-----	1.46	4.17	2.85	3.86	3.14
Mt.....	3.16	2.61	2.44	1.97	3.39	3.09	3.35	2.26	2.58	2.29	2.93	-----	4.10	2.03	1.90	1.96	2.09
Pl.....	5.91	6.08	6.40	6.36	6.02	5.53	5.37	4.92	5.11	4.94	5.11	-----	4.84	4.60	4.96	4.84	5.03
Ap.....	.83	.83	.85	.88	.81	.78	.78	.64	.66	.73	.66	-----	.62	.62	.66	.66	.64

F-1. Slab pahoehoe from an early west vent, 8:10 p.m., Jan. 13, 1960.
 F-3. Pumice from main vent, 7:00 p.m., Jan. 17, 1960.
 F-5. Pumice, 7:00 a.m., Jan. 21, 1960. E. L. Munson, analyst.
 F-6. Pahoehoe ooze from west side of cone, 7:30 a.m., Jan. 21, 1960.
 F-7. Pumice, 7:00 p.m., Jan. 28, 1960.
 F-8. Pahoehoe flow from west side of cone, 10:15 a.m., Jan. 29, 1960.
 F-9. Pumice, 11:00 p.m., Jan. 30, 1960.
 F-11. Pumice, 5:00 a.m., Feb. 1, 1960. D. F. Powers, analyst.
 F-12. Pumice, 8:00 a.m., Feb. 2, 1960. D. F. Powers, analyst.
 F-13. Pumice, 11:30 a.m., Feb. 4, 1960.

F-14. Aa flow to north, Feb. 4, 1960.
 F-15. Spatter from west vent, 11:00 a.m., Feb. 7, 1960. Analysts, rapid analysis group, under the supervision of W. W. Brannock.
 F-16. Pahoehoe, last flow east from main vent, 8:20 a.m., Feb. 12, 1960. E. L. Munson, analyst.
 F-17. Pumice, 7:00 p.m., Feb. 13, 1960.
 F-18. Pumice, 8:30 p.m., Feb. 16, 1960.
 F-19. Pumice, 4:30 p.m., Feb. 18, 1960.
 F-20. Pahoehoe, last flow from west side of cone, Feb. 18, 1960.

THE 1959 SUMMIT LAVAS

The changes in lava composition throughout the 1959 summit eruption are shown in figure 1. The black horizontal bars at the top of the figure indicate the time and duration of the 17 separate phases that characterized this eruption. The weeklong first phase produced about 30 million cubic meters of lava, nearly all of which (excluding the pyroclastics) ponded in Kilauea Iki pit crater. Each of the later eruptive phases involved the expulsion of 2 to 10 million cubic meters of additional lava, most of which drained back into the vent at the end of the phase. The last (17th) phase is not strictly comparable to the others because it produced a very small flow, only a few hundred cubic meters of lava.

The complete range of compositional variation shown by these summit lavas was spanned by materials erupted during the weeklong first phase. The composition of the single sample from the brief 1954 eruption at the summit (Macdonald and Eaton, 1957) is plotted on the

left side of figure 1 and is very similar to that of the early lavas of 1959.

The first materials erupted in 1959, represented by vent spatter of the most eastern and western of the initial vents, were richest in silica (avg. 50.0 percent). During the first 3 days there was a gradual decrease in silica from 50.0 to 49.0 percent. Then silica concentration fell rapidly to a minimum of 46.7 percent and subsequently rose to intermediate percentages toward the end of the first phase. All oxides varied directly with silica except magnesia and total iron oxides, which varied inversely not only during the first phase but throughout the 16 later phases. Silica was determined on many more samples than were analyzed completely; it therefore indicates the compositional variations in greater detail, particularly during the later phases.

As discussed in pages A11-A14, the compositional variations shown in figure 1 are almost entirely due to variations in the amount of phenocrystic olivine present

in the lavas. Olivine is the first silicate mineral to crystallize out of the primitive magma, and because it is heavy relative to the magma, it tends to sink. Therefore, a crystallizing body of primitive magma should be poor in olivine in its upper part and enriched in the mineral in a lower part. The fact that silica-rich, olivine-poor lavas appeared first suggests that the body of magma was erupted, at least during the early part of the first phase, in an orderly manner—that is, its uppermost part was expelled first.

The temperature of the lavas ranged from 1060° to 1190°C (Ault and others, 1961), and, as discussed in the chapter on petrography (Richter and Murata, 1966), varied directly with the concentration of olivine.

SETTLING OF OLIVINE

The settling of olivine phenocrysts to form picritic magmas in Hawaii has been well established by previous investigators, and the process has been quantified chemically in the concept of olivine control of magma compositions (Powers, 1955). Several kinds of observations made prior to and during the 1959 summit eruption throw additional light on the settling process. The question of the distance that olivines settle in the magma and the time required may be considered first.

Lavas of the first part of eruptive phase 1 (Nov. 14 to 18) and those of phase 4 (Dec. 4 and 5) were characterized by a steady increase in temperature and in olivine content with time. A maximum temperature of about 1190°C was observed during both phases when the most picritic lava (19 percent MgO) was being erupted. These data suggest that the most picritic material originated at or near the bottom of the magma reservoir.

During the first part of phase 1 and during phase 4, 8 and 11 million cubic meters of lava, respectively, were produced—an average of about 10 million cubic meters per period. This volume represented only a small part of the total volume of magma in the reservoir, and for our purpose the lava will be considered tentatively to have constituted a vertical sample, cubic in shape, of the reservoir magma. The height of the hypothetical cube is made equal to the thickness of the reservoir magma in order to obtain an order of magnitude of the distance that olivine phenocrysts must settle to reach the bottom if they separated in the uppermost part of the reservoir magma. Under these assumptions, the effective thickness of the reservoir magma is calculated to be about 200 meters.

In calculating the settling rate of olivine phenocrysts, the most uncertain quantity is the viscosity of the basaltic liquid, which is strongly temperature dependent. Hess (1960) reviewed the existing data on viscosity of basaltic liquids at temperatures of about 1100° to

1125°C and concluded that the most probable value is 3×10^3 poises. Two separate determinations of viscosity based on the flow of Hawaiian lavas are of this order of magnitude. Palmer (1927) obtained a result of 1.5×10^3 poises from observations on the 1942 Alike flow of Mauna Loa. During the 1955 Kilauea eruption, Macdonald (1959) found the viscosity of different flows to range from 2×10^3 to 2.6×10^4 poises. The lowest value of 2×10^3 poises was obtained by him for a very hot flow that was coursing through a lava tube near the vent, and this value is adopted for our calculation.

Olivine crystals (diam, 3 mm; density, 3.4) would sink about 50 centimeters per day in a melt with a density of 2.77 and a viscosity of 2×10^3 poises. Thus, about 400 days would be required for such olivines to sink through 200 meters of magma. Tilt measurements in the summit region of Kilauea indicated that the magma reservoir began to fill as early as a year before the 1959 summit eruption (Eaton, 1962; Eaton and Murata, 1960) although a major part of the total charge accumulated during a 2-month period just prior to the eruption. Only olivines from the early increments of magma would have had time to settle through the assumed depth of 200 m to the floor of the magma reservoir.

In addition to simple sedimentation of olivine phenocrysts, the process of two-phase (phenocrysts plus melt) convection very likely operated in the accumulating magma (Grout, 1918; Hess, 1960). The motive force for this process is the slightly greater "aggregate density" of a magma that is crystallizing olivine or other heavy minerals compared to the density of the original melt. The density contrast may be as low as 0.006 g per cc (grams per cubic centimeter), but if the crystallizing magma can move in units a few meters in diameter, a rapid convective motion becomes possible. Thus, a two-phase mass, 1 m in diameter and containing only 1 percent of olivine phenocrysts, could sink over 100 m a day and thereby deliver olivines to the bottom of a magma column even many kilometers high in the time available. Such great speed eliminates the previously imposed limitation of a cubic shape to the 10 million cubic meters of differentiated magma under consideration.

A dense, difficultly mobile sludge of olivine is thought to form at the bottom of the magma column through sedimentation of most of the olivine phenocrysts out of the masses that approach the bottom. The olivine-depleted masses would then be displaced upward by new olivine-bearing masses arriving from above, resulting in a convective pattern that is maintained by density differences in two-phase masses due to differences in concentration of olivine phenocrysts.

Grout (1918) noted that this two-phase convection would operate only during the time crystals were forming locally in the melt and settling through it. That the 1959 Kilauea magma was actively crystallizing olivine is clearly indicated by the fact that the composition of the glassy matrix of the lavas was not uniform but rather was more magnesian (range 7.44 to 10.20 percent magnesia) when the temperature of the lavas was higher.

A relationship exists between the rate of discharge of the 1959 lavas and their content of olivine. In the lower part of figure 2, discharge is plotted against the magnesia (olivine) content of the lava being erupted at any given time. The magnesia content of these lavas is directly related to their olivine content by the previously mentioned mechanism of olivine control of composition. The plot shows that lavas rich in olivine were generally erupted during times of high discharge.

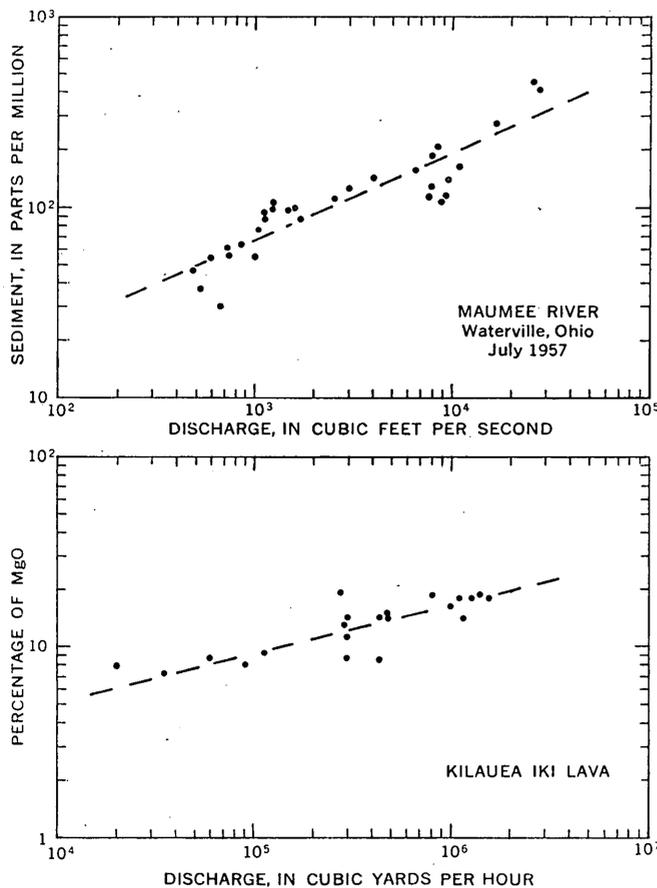


FIGURE 2.—Analogy between discharge and magnesia (olivine) content of the 1959 summit lavas and discharge and sediment content of a river. Data for Maumee River from U.S. Geological Survey (1960).

The olivine phenocrysts also tended on the average to be bigger in the more picritic lavas, as indicated by measurements on the following few samples:

Sample	MgO (percent)	Modal olivine phenocrysts		
		Volume (percent)	Diameter (mm)	
			Maximum	Average
S-14-----	8.55	4	2.0	1.8
3-----	8.85	5	1.1	.6
9-----	13.34	14	7.0	2.5
20-----	15.40	21	4.5	3.5

Thus the abundance and coarseness of olivine phenocrysts in the 1959 lavas were controlled to a significant degree by the rate of lava discharge.

Very similar relationships have been established by hydrologists between discharge of rivers and the amount and coarseness of the suspended matter being transported by the rivers (Linsley and others, 1949). In the upper part of figure 2, the discharge of the Maumee River at Waterville, Ohio (U.S. Geol. Survey, 1960, p. 610), is plotted against its sediment load, and the resultant diagram has a form very similar to the comparable one for the 1959 Kilauea lavas. In analogy to the velocity-dependent transportation or deposition of silt by rivers, during periods of high discharge magma currents with abnormally high velocities may scour beds of sedimented olivines at the bottom of the magma reservoir to yield picritic lavas. Fluctuations in the magnesia (olivine) content of the 1959 lavas, shown in figure 1, thus may have been largely related to the waxing and waning of such magma currents.

In summary, data from the 1959 eruption suggest that the primitive magma starts crystallizing olivine in the shallow reservoir beneath the summit and deposits the olivine at the bottom of the reservoir primarily by the mechanism of two-phase convection. During eruption, upward-trending magma currents not only oppose the general tendency for deposition of olivine but at times of high discharge erode beds of previously deposited olivine.

THE 1960 FLANK LAVAS

The chronological changes in composition of the lavas that were produced during the flank eruptions of 1955 and 1960 are shown in figure 3. This figure shows the great similarity between the early-1960 (January 13 to 21) lavas and the 1955 lavas. The 1955 lavas (Macdonald, 1955) are of a relatively highly differentiated type that is scarce on Kilauea, so the similar material of the succeeding flank eruption of early 1960 probably is closely related. Such a conclusion would mean that about 40 million cubic meters of magma failed to erupt in 1955 and remained in storage for 5 years until expelled early in the next eruption.

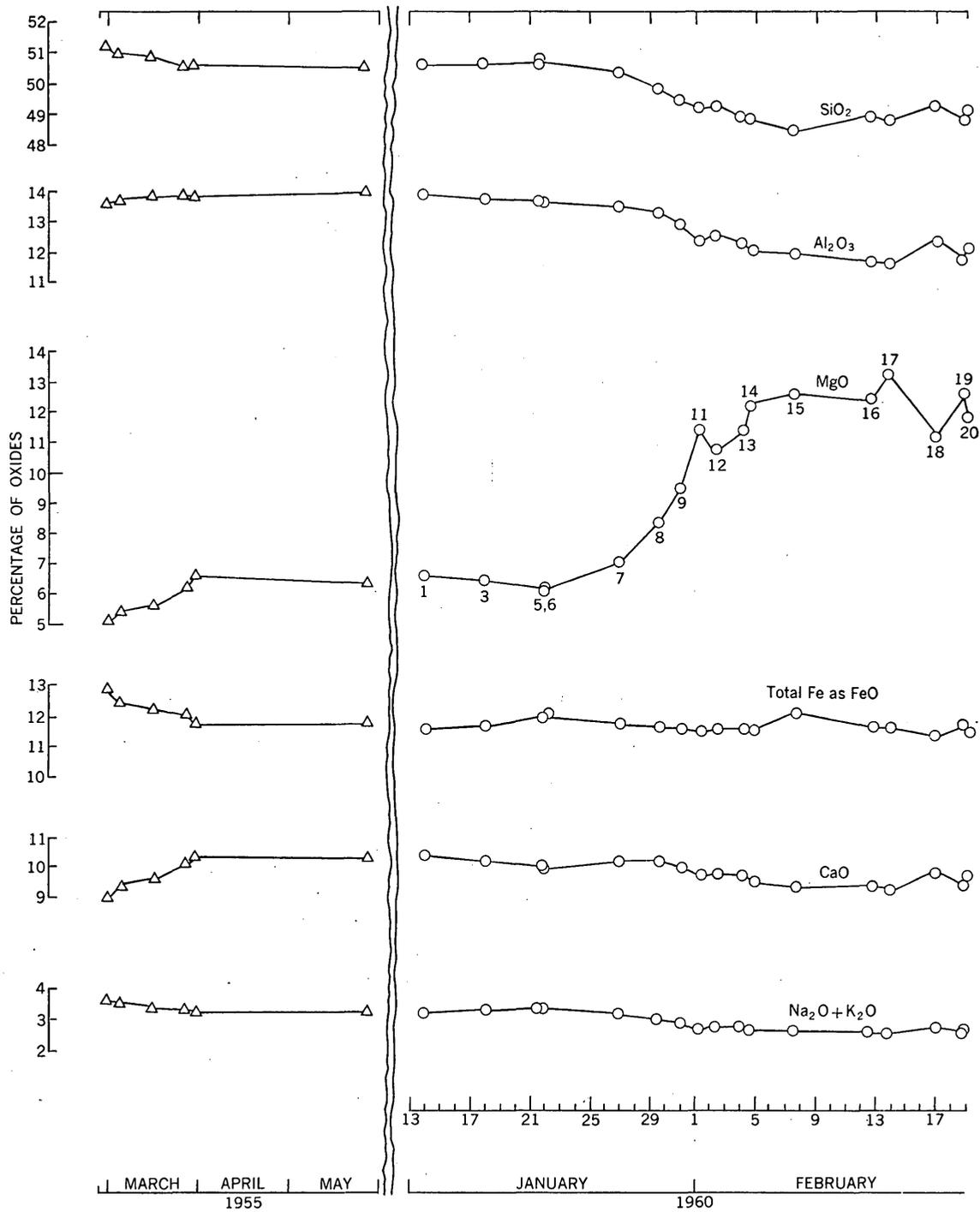


FIGURE 3.—Chronological changes in lava composition during the 1955 and 1960 flank eruptions in the Puna district. Data on the 1955 lavas are from Macdonald (1955). The 1955 time scale is smaller than the 1960 scale. Numbers along the magnesia curve are the F-series of sample numbers from table 2. Note the chronological trend toward a generally more magnesian composition among the 1955 lavas and the slight reversal of this trend among the early-1960 lavas (samples 1 to 6).

The petrography of the lavas also indicates the close similarity between the early-1960 and the 1955 lavas. In sharp contrast to the 1959 summit lavas, nearly all of which contained olivine as the sole phenocrystic mineral, the flank lavas under consideration had plagioclase and clinopyroxene as the dominant phenocrysts, accompanied by minor olivine and traces of hypersthene. The more mafic later lavas of 1960 (February 1 to 18) resembled the 1959 summit lavas in having abundant phenocrysts of olivine but differed in containing notable amounts of phenocrystic clinopyroxene and plagioclase. The petrography of the lavas of the middle period of the 1960 eruption (January 26 to 31) clearly shows them to be mixtures of the early and late magmas.

The first four samples of the 1960 eruption, plotted in figure 3, show a minor trend of all the oxides that is opposite to that manifested in the 1955 lavas. This trend leads to a curious reversal in the variation diagrams that will be discussed in detail in a following section.

The order in which the several minerals separate from the primitive Kilauea magma has been established both through petrographic studies of 1959-60 lavas of known eruption temperatures (Richter and Murata, 1966) and by laboratory quenching experiments on samples of two other Kilauea lavas (Yoder and Tilley, 1957, 1962). The order of the first appearance of the minerals in the cooling primitive melt is as follows: chromian spinel (minor amount typically embedded in olivine), olivine, clinopyroxene, plagioclase, and hypersthene (minor). All the silicate minerals separate from the melt throughout a considerable range of temperature, the mafic minerals being more ferroan and the plagioclase generally more sodic the lower the temperature of separation.

TRENDS OF DIFFERENTIATION

The composition of the 1959-60 Kilauea lavas are shown in figure 4 in the form of a magnesia-variation diagram, previously used by Powers (1955) for lavas in Hawaii. The magnesia percentages decrease from left to right along the abscissa, which thus corresponds to the increasing percentage of silica in the conventional silica-variation diagram. The curves for the various oxides in the figure closely resemble those obtained when the analyses are plotted on the silica-variation diagram. The reasons for selecting magnesia as the reference constituent for establishing the compositional sequence of the samples are twofold:

1. Magnesia shows the greatest range of concentration among major constituents, its highest concentration being 3.2 times its lowest. The highest silica concentration, on the other hand, is only 1.1 times its lowest. Because the precision of analytical de-

termination is about the same for both constituents, the ordering of samples into a sequence will be far more certain and precise if the greater ranging magnesia is used rather than the silica.

2. The effects of the separation of different phenocrystic minerals on magmatic composition may be seen with unusual clarity in the 1959-60 lavas. In emphasizing this particular type of compositional control, it is desirable to indicate explicitly the composition of the phenocrystic minerals on one or more variation diagrams. For this purpose, clinopyroxene and plagioclase should plot as widely separated as possible. The silica (and calcium oxide) content of these two minerals is similar, whereas their content of magnesia is quite different; thus, the desired separation is ensured on the magnesia-variation diagram. Murata (1960) proposed the use of an alumina-silica-variation diagram with the same objective of separating clinopyroxene-rich and plagioclase-rich compositions on the diagram. Like the one based on silica, the alumina-silica-variation diagram does not have the precision of the magnesia-variation diagram for these Kilauea magmas because of the more limited variation of alumina and silica.

Before the trends of variations shown in figure 4 are discussed, brief comments on certain of the constituents are desirable. Potassium is a constituent that is least likely to be removed from the liquid during fractional crystallization, and it continuously accumulates to the highest degree in the residual melt (Holmes, 1930). Its trend of variation thus serves as a criterion for judging the behavior of the other constituents. Following are tabulated the ratios of maximum to minimum percentages of several oxides whose concentrations generally increased with decreasing magnesia in the several glasses of 1950-60 lavas:

Constituent	Ratio, maximum to minimum percentages
K ₂ O	1.50
P ₂ O ₅	1.62
TiO ₂	1.43
Na ₂ O	1.27

Ratios lower than that of K₂O indicate a relative loss of the constituent through separation of one or more minerals from the magma. The ratio of P₂O₅ is probably the same as that of K₂O within the error of determination. K₂O, however, is not perfectly inert because very small amounts of it are also precipitated as a component, about 0.2 percent, of plagioclase and as a component, about 0.03 percent, of clinopyroxene. Therefore, its slightly lower ratio relative to that of P₂O₅ in the preceding tabulation may be real. TiO₂ content in

clinopyroxene phenocrysts is known to be about 1 percent and to be major in titaniferous magnetite, while Na₂O is a major constituent of plagioclase.

The wide scatter of points for FeO and Fe₂O₃ appears to be largely due to erratic oxidation of FeO in the hot lava by air. Following are tabulated all samples from both the summit and flank eruptions that contain more than 2.0 percent Fe₂O₃:

Sample	MgO (percent)	Fe ₂ O ₃ (percent)	Material
S-1	8.08	2.56	Vent spatter.
3	8.85	2.70	Flow in main channel.
12	8.22	2.30	Pumice.
14	8.55	4.25	Flow, slabby pahoehoe.
25	8.85	2.34	Flow, thin pahoehoe.
F-1	6.56	2.18	Flow, slabby pahoehoe.
7	6.97	2.34	Pumice.
8	8.27	2.13	Flow.
9	9.39	2.31	Pumice.
13	11.28	2.02	Flow.
16	12.29	2.83	Flow, shelly pahoehoe.

There are twice as many flow samples represented in the tabulation as pumice samples. Lava flows moving over the surface of the land are more likely to be oxidized than pumice fragments that are quickly chilled as they are ejected from the vent. This general difference between flows and pumice is analogous to the difference in oxidizability between aa and pahoehoe types of lava (Washington, 1923). The 1955 lavas (Macdonald, 1955) plotted in figure 4 were all samples of flows, ranging in form from slab pahoehoe to aa, and three-fourths of them contained more than 2.0 percent Fe₂O₃.

Even within flows there is a striking difference in the oxidation of iron between the quickly chilled glassy selvage and the more slowly cooled crystalline interior, as shown by the following examples:

Sample	Fe ₂ O ₃ , in percent	
	Flow interior	Glassy selvage
S-3	2.70	1.82
14	4.25	2.65
25	2.34	1.94

There is a suggestion in figure 4 that samples with magnesia percentages smaller than about 12 (corresponding to silica percentages greater than about 49) are more likely to be oxidized. A check of the samples with magnesia percentages greater than 12, however, shows that they fortuitously consist of pumice or dense pahoehoe—forms that are most difficult to oxidize. It would therefore appear that the original magmatic state of oxidation of both the summit and flank materials is completely obscured by posteruption oxidation by air. Total iron (calculated as FeO), however, varies in a very regular manner, reflecting changes in magma composition that took place prior to eruption.

Manganese oxide, which was not included in figure 4, shows a poorly defined tendency to rise from 0.17 to 0.18 percent in the direction of decreasing magnesia (or increasing total iron oxide). In the tholeiitic magma of Dillsburg, Pa. (Hotz, 1953), which had a much greater range of composition than these Kilauea lavas, a close direct relationship between manganese oxide and total iron oxide is evident.

THE 1959 SUMMIT LAVAS

In figure 4, all constituents of the 1959 summit lavas (except for ferric and ferrous oxides) generally lie along well-defined straight lines, the olivine-control lines of Powers (1955). According to Powers, these olivine-control lines, the high-magnesia ends of which terminate at the composition of the pertinent olivine, "indicate the straight-line variation that would result from changing the amount of olivine in any plotted rock composition through which the lines are drawn." Two compositions, one at 19.00 and the other at 8.00 percent magnesia, have been read off the olivine-control lines in figure 4 (and from table 1 for the uncharted constituents) and are given in the following columns A and B as an aid to those who may wish to reproduce the lines. Composition A lies in the range of highly picritic basalt, whereas composition B represents an olivine-poor basalt.

	A	B	B:A	C=1.418A	D=C-B	D:0.4163
SiO ₂	46.85	49.75	1.062	66.43	16.68	40.07
Al ₂ O ₃	9.70	13.42	1.383	13.75	.33	.79
FeO (total Fe)	11.75	11.32	.963	16.66	5.34	12.83
MgO	19.00	8.00	.421	28.94	18.94	45.49
CaO	8.20	11.35	1.384	11.62	.27	.65
Na ₂ O	1.58	2.23	1.411	2.24		
K ₂ O	.38	.54	1.421	.54		
H ₂ O+	.07	.11	1.571	.10		
H ₂ O-	.02	.02	1.000	.03		
TiO ₂	1.92	2.72	1.417	2.72		
P ₂ O ₅	.19	.27	1.421	.27		
MnO	.17	.17	1.000	.04	.07	.17
CO ₂	.02	.02	1.000	.03		
Cl	.02	.02	1.000	.03		
F	.02	.03	1.500	.03		
Subtotal	99.89	99.97		141.60	41.63	100.00
Less O	.01	.01		.02		
Total	99.88	99.96		141.58	41.63	100.00

NOTE.—Differences between columns C and B less than ±0.02 percent are within the error of chemical determination and are not given.

Constituents that are not incorporated in olivine—such as the oxides of sodium, potassium, titanium, and phosphorous—should concentrate in the residual melt during the period when olivine is separating from the magma. These constituents are uniformly about 1.418 times (range 1.411 to 1.421) more concentrated in composition B than in A. For a quantitative test of the hypothesis of olivine control, composition A may be multiplied by this factor of 1.418 to obtain the product in column C. Then, composition B is subtracted from

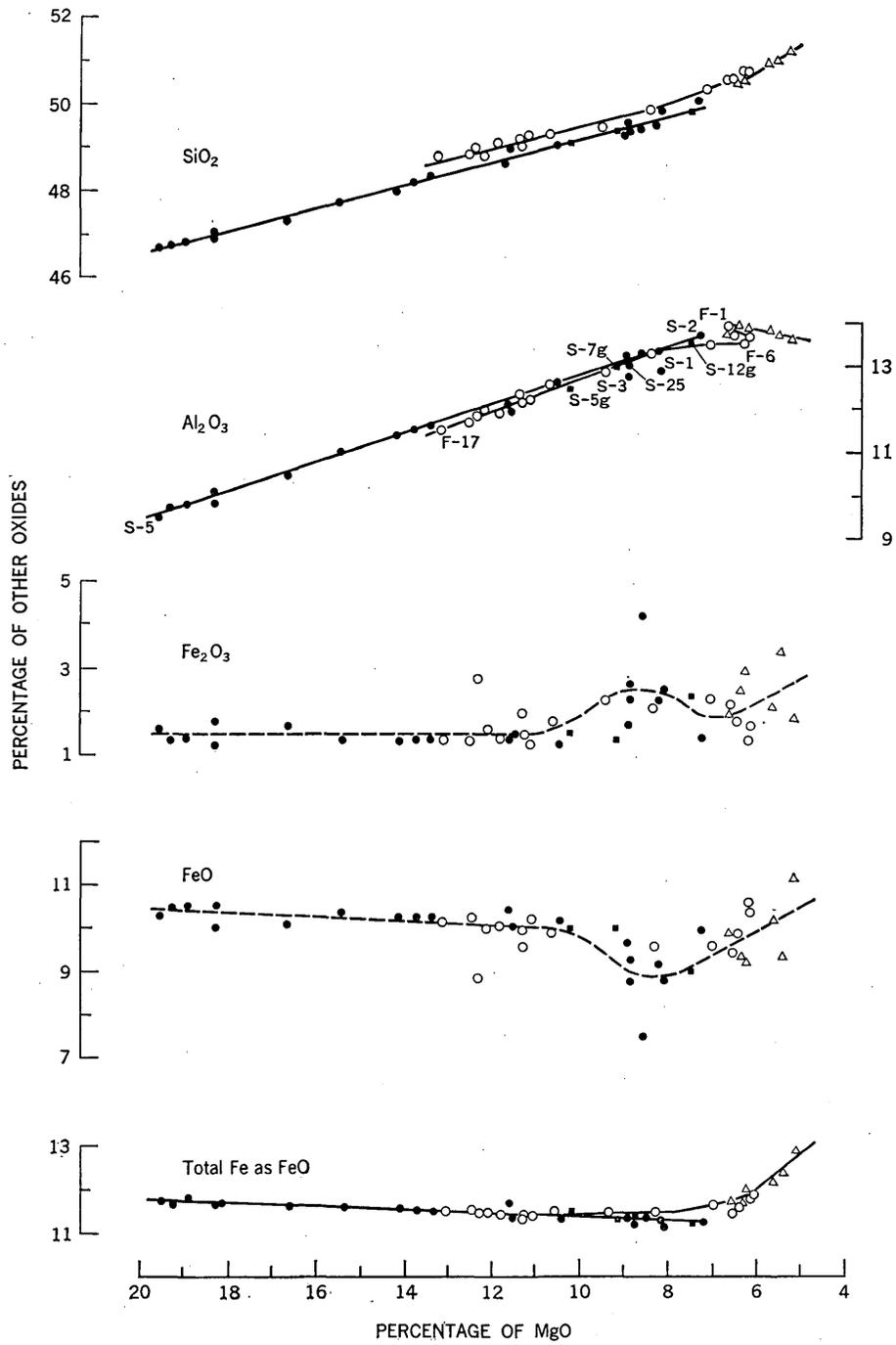


FIGURE 4.—Magnesia variation diagram for the 1959 summit lavas (solid circles), the 1960 flank lavas (open circles), and the 1955 flank lavas (open triangles). The three black squares denote glasses separated from the 1959 summit lavas. The straight lines defined by the constituents of the 1959 summit lavas denote compositional variations due solely to separation of phenocrystic olivine (Fa₁₃) from the primitive magma. Other lines of variation defined by the constituents of the 1960 and 1955 flank lavas

the product to yield the composition in column D. The last column gives the composition of column D scaled up to 100 percent, and it is a good representation of the composition of the major type of olivine in the 1959 summit lavas. In terms of finite quantities of lava, the calculation indicates that if 142 g of lava A is compared with 100 g of lava B, they are found to differ only because the former contains 42 g more of an olivine having the composition (Fa₁₃) given in the last column.

The percentages of alumina and calcium oxide in the last column are slightly high for olivine, but the calculations do tend to magnify any error of analysis. Partial analyses of three samples of olivines separated from the 1959 lavas gave an average FeO percentage of 12.05 ± .04, somewhat lower than the 12.83 percent shown in the last column. A few tenths of a percent of Fe₂O₃, not revealed in the FeO determination, is probably present in the olivine and would reduce the discrepancy. A part of the alumina and a small part of the ferrous oxide are also probably assignable to the small amount of a dark spinel commonly present in Kilauea olivines. Aside from these minor uncertainties, the preceding calculations amply demonstrate that the straight lines, along which the compositions of most of the 1959 summit lavas lie, are indeed lines of olivine control of composition.

Sample S-2 (table 1), one of the earliest products of the eruption, is of special interest because it seems to mark the low-magnesia terminus of the olivine-control lines. Lavas of very similar composition have been erupted repeatedly at the summit. Analyses of six samples with this common composition are compiled in table 3; they constitute a remarkably uniform group. The amount of olivine phenocrysts in this kind of lava is always 1 percent or less, and small amounts of clinopyroxene and plagioclase microphenocrysts are commonly present. The composition apparently represents the stage of differentiation at which the bulk of the olivine had settled out of the rest magma but no effective movement of plagioclase or clinopyroxene crystals had taken place.

Like sample S-2, low-magnesia samples S-1 and S-3 (table 1) were among the earliest and coolest lavas of the eruption, but they differ from sample S-2 in that their compositions definitely lie off the olivine-control lines of figure 4 by showing an excess of CaO and a deficiency of most of the other constituents. The direction in which their compositions deviate from the olivine-control lines indicates a moderate accumulation of clinopyroxene phenocrysts relative to that of plagioclase. Samples S-1 and S-3 thus represent a differen-

tiation stage slightly beyond that of sample S-2 because they point to a certain amount of gravitative separation of the newly crystallized clinopyroxene and plagioclase phenocrysts. These samples presage a type of differentiation, especially well shown in the 1955 and early-1960 lavas, in which composition is mainly controlled by the separation of clinopyroxene and plagioclase phenocrysts.

TABLE 3.—Composition, in percent, of a type of lava commonly found in summit eruptions of Kilauea

	1	2	3	4	5	6	7
Norm of the average composition of column 7:							
Q.....	1.20						
Or.....	3.34						
Ab.....	18.86						
An.....	25.85						
Di.....							
Wo.....	12.18						
En.....							7.10
Fs.....							4.49
Hy.....							
En.....							11.20
Fs.....							7.26
Mt.....							2.78
Pl.....							5.17
Ap.....							.67
SiO ₂	50.08	50.20	50.04	50.01	50.20	50.07	50.10
Al ₂ O ₃	13.73	14.04	13.68	13.83	13.73	13.70	13.78
Fe ₂ O ₃	1.32	1.83	2.29	1.85	2.65	1.39	1.89
FeO.....	9.79	9.50	9.05	9.59	8.80	10.00	9.46
MgO.....	7.89	7.03	7.61	7.10	7.20	7.23	7.34
CaO.....	11.50	11.49	11.38	11.29	11.56	11.55	11.46
Na ₂ O.....	2.18	2.25	2.24	2.25	2.25	2.30	2.25
K ₂ O.....	.56	.57	.57	.53	.57	.60	.57
H ₂ O ⁺00	.01	.00	.09	.00	.00	.02
H ₂ O ⁻02	.02	.02	.12	.00	.02	.03
TiO ₂	2.60	2.74	2.76	2.71	2.72	2.75	2.71
P ₂ O ₅.....	.26	.27	.27	.27	.28	.28	.27
MnO.....	.17	.17	.17	.17	.17	.17	.17
CO ₂.....	.01	.02	.06		.01	.02	.02
Cl.....					.02	.02	.02
F.....					.05	.04	.04
Subtotal.....					100.21	100.12	100.13
Less O.....					.02	.02	.02
Total.....	100.11	100.14	100.14	99.81	100.19	100.10	100.11
Total iron oxides (as FeO).....	10.98	10.69	11.11	11.25	11.18	11.25	11.16

1. Lava of 1917, splash from lava lake at Halemaumau. L. N. Tarrant, analyst (Macdonald and Eaton, 1955).
2. Lava of 1919, near northeast edge of Kilauea caldera. L. N. Tarrant, analyst (Macdonald and Eaton, 1955).
3. Lava of 1921, near south edge of Kilauea caldera. L. N. Tarrant, analyst (Macdonald and Eaton, 1955).
4. Pumice ejected on June 27, 1952 at Halemaumau. L. M. Kehl, analyst (Macdonald, 1955).
5. Pahoehoe flow on caldera floor northeast of Halemaumau, erupted May 31, 1954. Lois Trumbull, analyst (Macdonald and Eaton, 1957).
6. Analysis of S-2 in table 1.
7. Average of analyses in cols. 1-6.

According to the petrographic data, sample S-25 (table 1), from a minor outflow of lava that constituted the final phase of the summit eruption, also contained phenocrysts of pyroxene, plagioclase, and olivine; but its composition, like that of sample S-2, lies on the olivine-control lines. This relationship suggests that, although the particular magma had cooled to the crystallization temperatures of clinopyroxene and plagioclase, no removal or accumulation of the phenocrysts of these minerals had yet taken place.

Thus, materials erupted in 1959, besides showing the dominance of olivine control in the first stage of differentiation of the primitive magma, also reveal in some detail the very beginning of differentiation due to separation of clinopyroxene and plagioclase.

TABLE 4.—Chemical analyses, in percent, of basaltic glasses

(D. F. Powers, analyst. The glasses have numbers corresponding to those of the lavas (listed in tables 1 and 2) from which they were separated)

	S-5g	S-7g	S-12g	F-3g	F-12g	F-11g	F-19g	Average of F-11g, F-12g, F-19g
Chemical analyses								
SiO ₂	49.08	49.42	49.85	50.69	50.44	50.45	50.46	50.45
Al ₂ O ₃	12.48	13.06	13.50	13.51	14.09	14.00	13.94	14.01
Fe ₂ O ₃	1.59	1.42	2.41	1.87	1.62	1.74	1.40	1.58
FeO.....	10.05	10.06	9.09	10.70	9.83	9.63	9.81	9.76
MgO.....	10.20	9.15	7.44	5.74	6.58	6.72	6.95	6.75
CaO.....	11.05	10.95	11.41	9.72	10.70	10.80	10.78	10.76
Na ₂ O.....	2.04	2.12	2.27	2.60	2.50	2.48	2.53	2.50
K ₂ O.....	.48	.53	.55	.72	.62	.59	.60	.60
H ₂ O+.....	.09	.11	.01	.08	.13	.08	.08	.08
H ₂ O-.....	.00	.01	.03	.00	.00	.00	.01	.01
TiO ₂	2.48	2.59	2.81	3.56	3.02	2.95	2.95	2.97
P ₂ O ₅.....	.24	.26	.27	.39	.31	.30	.30	.31
MnO.....	.18	.17	.18	.18	.17	.17	.17	.17
CO ₂.....	.01	.01	.00	.00	.00	.01	.01	.01
Cl.....	.02	.02	.02	.02	.03	.03	.02	.02
F.....	.03	.03	.03	.04	.04	.04	.04	.04
Subtotal.....	100.02	99.91	99.87	99.82	100.08	99.99	100.05	100.02
Less O.....	.01	.01	.01	.02	.03	.03	.02	.02
Total.....	100.01	99.90	99.86	99.80	100.05	99.96	100.03	100.00
SiO ₂ (whole lava) ..	46.68	48.22	49.56	50.62	49.34	49.21	48.91	-----
MgO (whole lava) ..	19.52	13.67	8.22	6.43	10.58	11.27	12.46	-----
Refractive index....	1.613	1.610	1.607	1.604	1.604	1.604	1.602	1.603

Norms								
Q.....	0.00	0.00	1.61	3.83	1.92	2.07	1.20	1.73
Or.....	2.84	3.13	3.25	4.25	3.66	3.49	3.54	3.56
Ab.....	16.99	17.66	19.05	21.84	20.92	20.63	21.13	20.89
An.....	23.62	24.70	25.10	23.15	25.51	25.51	25.05	25.36
Di:								
Wo.....	12.31	11.60	12.36	9.31	10.58	10.81	10.96	10.78
En.....	7.59	6.94	7.48	4.83	5.86	6.10	6.15	6.04
Fs.....	4.00	4.06	4.20	4.25	4.31	4.26	4.37	4.31
Hy:								
En.....	12.36	13.27	11.04	9.46	10.52	10.63	11.15	10.77
Fs.....	6.51	7.77	6.19	8.31	7.73	7.42	7.93	7.69
Ol:								
Fo.....	3.82	1.81	.00	.00	.00	.00	.00	.00
Fa.....	2.22	1.16	.00	.00	.00	.00	.00	.00
Mt.....	2.31	2.06	3.49	2.71	2.35	2.52	2.03	2.30
Il.....	4.71	4.92	5.34	6.76	5.74	5.60	5.60	5.65
Ap.....	.67	.62	.64	.92	.73	.71	.71	.72

The composition of the glassy parts of three 1959 summit lavas (S-5g, -7g, -12g) is presented in table 4. Such glassy parts of lavas represent magmatic liquid that was quenched during eruption. The composition of glasses S-7g and S-12g plots well on the lines of olivine control defined by the whole lavas in figure 4; these glasses therefore offer direct proof that these lines, excepting the parts representing olivine accumulates, constitute lines of descent of the residual melt. Glass S-5g deviates somewhat from the olivine-control lines and will be discussed further.

The magnesia content of the three summit glasses varied directly with the olivine content of the whole lavas; and, were it not for the fact that the glasses were carefully separated from all crystalline materials, this variation might be attributed to contamination of the glasses by phenocrystic olivine. The magnesia content also varied directly with the temperature of the lavas, and the most mafic glass (S-5g) was from one of the hottest lavas of the summit eruption (1190°C). It

would appear that melts into which much olivine had settled represented the lower and hotter parts of the magma body, parts that had not yet crystallized much olivine. Olivine-poor lavas, on the other hand, represented higher and cooler parts of the magma body which had fractionally crystallized much olivine, so that the melt was correspondingly poorer in magnesia. The least mafic glass (S-12g in table 4) is close in composition to the previously mentioned type of lava (table 3) that marks the low-magnesia end of the olivine-control lines.

Glass S-5g, extracted from the most picritic lava of the first eruptive phase, deviates slightly from the olivine-control lines in the same sense as do lava samples S-1 and S-3, discussed previously. The amount of the deviation corresponds to about 1.5 percent enrichment with respect to clinopyroxene. No clinopyroxene phenocrysts were observed in lava S-5, as they were in S-1 and S-3, and the slight excess of clinopyroxene is localized in the glass.

In the magma column that was involved in the first eruptive phase, the settling olivines were apparently accompanied by some clinopyroxene phenocrysts that did not survive the high temperatures prevailing at the bottom of the column and that melted completely. In a subsequent section dealing with the late lavas of the 1960 flank eruption, examples will be given of cooler picritic magmas that contained substantial amounts of clinopyroxene phenocrysts along with the olivine.

THE 1960 FLANK LAVAS

The trends of compositional variation manifested in the 1960 flank lavas (fig. 4) are more complicated than those of the 1959 summit lavas and reflect the more advanced and complex preruptional history of the magmas. As previously mentioned, petrographic data clearly point to the involvement of two magmas of different vintage in the eruption. In analyzing the 1960 compositional trends, the early-1960 lavas (along with those of 1955) and the late-1960 lavas will be treated as two separate magmatic systems, and lavas of the middle period of the eruption will be considered as mixtures of the early and late systems.

The compositions of early-1960 and 1955 lavas (total range of magnesia, 5 to 7 percent) define a trend that is controlled primarily by the simultaneous separation of clinopyroxene and plagioclase along with minor olivine (Murata, 1960; Tilley and Scoon, 1961). In figure 4, the decrease in calcium oxide and alumina and the increase in all other constituents with decreasing magnesia in this range are due to the simultaneous separation of these minerals.

The chronological trend of lava composition during the 1955 eruption (Macdonald, 1955) was in the direction of increasing magnesia, calcium oxide, and alumina (fig. 3), reflecting either (1) an accumulation of clinopyroxene, plagioclase, and olivine phenocrysts in the deeper parts of a magma body, analogous to the settling of olivine in the 1959 summit magmas, or (2) a vertical gradient in temperature and melt composition in a magma body that was separating these minerals largely in the form of a coherent crystal meshwork attached to the walls of the magma chamber. In general, a fractionally crystallizing body of basaltic magma would be expected to have a relatively less dense magnesia-depleted rest liquid in its upper part and more dense and more magnesian parental and accumulate magmas in its lower part. Ordinarily, the upper rest liquid would be erupted first, so a chronological trend toward more magnesian compositions, as seen in the 1955 eruption, would be considered normal.

As previously stated, early-1960 lavas (samples F-1 to F-6) are considered to represent old magma that failed to be expelled in the 1955 eruption. Figures 3 and 4 show that these early-1960 lavas manifested an abnormal chronological trend toward less magnesian compositions. Petrographically, the content of clinopyroxene, plagioclase, and olivine phenocrysts was virtually uniform in these lavas, apparently ruling out an explanation of the abnormal trend on the basis of a variation in the amount of these phenocrysts. The problem, thus, is one of suitably expelling a melt, which is presumed to be richer in magnesia in its lower part than in its upper part, so that the chronological trend toward less magnesian compositions is realized.

Of the several possible solutions, the simplest and preferred one, which was suggested to us by H. A. Powers, calls for tapping the lower part of the pocket of old 1955 magma and draining the contents laterally to 1960 vents at a lower elevation. Spatially, this is possible, because the last active vents of the 1955 eruptions were 16 km uphill from the 1960 vents, at elevations more than 300 m higher. Such a mode of expulsion of the magma would very simply explain the unusual chronological trend toward less magnesian compositions seen in the early-1960 lavas.

Further discussion of the compositional trends in the 1960 flank lavas will be undertaken through the use of enlarged variation diagrams for alumina and calcium oxide, shown in figure 5.

Three of the variation trends among the flank lavas ($D-E$, $D-F$, and $D-G$) plot as straight lines in figure 5, while the fourth (trend of the intermediate-1960 lavas) describes an arc, which starts near E and meets line $D-F$ near its middle. Straight-line trends, as already exem-

plified by the olivine-control line $B-A-C$ of the 1959 summit lavas, are readily amenable to treatment in terms of separation of one or more phenocrystic minerals from appropriate magmas.

The phenocrystic minerals present in flank lavas have been identified microscopically (Richter and Murata, 1966), and sufficient data on their chemical composition have been obtained to justify a quantitative treatment of the straight-line trends among the flank lavas. The general procedure has been to start with a lava or a glass that marks one end of a given trend line and calculate the composition of the lava or glass at the other end by adding or subtracting appropriate amounts of the several phenocrystic minerals. Trial calculations were carried out until a satisfactory agreement was obtained between the derived composition and the known composition of the terminal lava or glass.

The 1955 and early-1960 magmas (lines $D-G$ and $D-E$, respectively, in fig. 5) have been considered together up to this point and will continue to be so considered, but the variation lines of certain constituents, such as alumina and soda (figs. 4 and 5), suggest a second-order difference between the compositional trends of the two magmas. Because the difference is so minor, it is not thought necessary to treat the two trends separately, and only the early-1960 trend ($D-E$) will be discussed in detail.

Point D in figure 5 is a key point of reference for establishing the interrelationship among flank magmas. This point is obtained as an average composition (table 4, last column) for very similar glasses separated from three samples of late-1960 lavas (samples F-11g, -12g, and -19g of table 4). With respect to these lavas, the glass of point D represented an essentially homogeneous liquid which served as a suspension medium for olivine and clinopyroxene phenocrysts. It occupied a terminal position in the variation trend of the late-1960 lavas analogous to the position held by lava C in the olivine-control trend of the 1959 summit lavas.

The composition of glass D may also be attained by only a slight extrapolation of either the 1955 or early-1960 trends of variation to a higher percentage of magnesia (line $G-D$ or $E-D$, fig. 5). These trends undoubtedly represent lines of liquid descent for Kilauea magmas in this advanced stage of differentiation. The melt of point D can be thought of as having a parental relationship to the 1955 and early-1960 magmas and would be hotter than these magmas. It then serves as a connecting link between these magmas and the late-1960 magma ($F-D$, fig. 5). As will be seen later, it further constitutes a connecting link between flank magmas in general and the more primitive 1959 summit magmas.

The process of fractional crystallization of the early-1960 magma (line *D-E*) can be examined quantitatively by comparing the composition of glasses *D* and *E*, under the assumption that the latter represents a residual liquid obtained by partial crystallization and removal of crystals from the former. Before the required calculations can be discussed, the compositions of the several phenocrystic minerals involved must be presented in table 5. Mineral compositions given in the table are to be considered as averages for phenocrystic minerals with somewhat variable composition. Clinopyroxene (augite) phenocrysts were separated from the earliest 1960 lava (F-1) and also from a 1955 flow, and their compositions are given in columns 2 and 3 of the table. Because the compositions are very similar, the average of the two, given in column 4, is used in the calculations. The average composition of plagioclase phenocrysts, given in column 5, was obtained by making trial calculations with several compositions in the petrographically determined range of An_{72-56} and selecting the one ($An_{67.5}$) that best fit the chemical data.

The olivine composition ($Fa_{23.5}$), column 6 of table 5, is based on a chemical determination of 21.60 percent FeO for a concentrate of olivine phenocrysts separated from the same 1955 lava that furnished the clinopyroxene (augite) of column 3 and on unpublished data on minor elements in Kilauea olivines (Harry Bastron, written commun., 1963). A similar olivine concentrate prepared from sample F-1 of 1960 contained 19.67 percent FeO. The higher percentage of FeO was selected because petrographic studies showed that these concentrates consisted of two different kinds of olivine

with compositions Fa_{17} and Fa_{24} and further showed that the more fayalitic olivine was the one in equilibrium with the melt.

Trend *D-E* can now be calculated by starting with 123.30 g of glass *D* (table 5, col. 1) and abstracting a mixture of minerals consisting of 10.00 g of clinopyroxene (col. 4), 11.00 g of plagioclase (col. 5), and 2.30 g of olivine (col. 6). The aggregate composition of the abstracted mixture of crystals is shown as *E'* in figure 5. The 100.00 g remainder has the composition given in column 7, which agrees tolerably well with the analysis of glass *E* (col. 8). Thus, trend *D-E* can be quantitatively described in terms of a separation of the previously listed weights of the several minerals from each 123.30 g of glass (melt) *D* to yield 100.00 g of a residual melt with composition close to glass *E*.

A similar treatment of the variation trend in the late-1960 lavas (line *F-D*, fig. 5) involves phenocrysts of clinopyroxene (table 5, col. 4) and of olivine. Olivines isolated from lavas F-9, F-16, and F-17 were found to contain 12.64 ± 0.17 percent FeO ($Fa_{13.3}$) by partial chemical analysis, and this average FeO content has been used as the basis to derive the olivine composition given in column 11 of table 5. Point *F* in figure 5 represents the most mafic of the late-1960 lavas (sample F-17), and the calculation of trend *F-D* consists in determining how much olivine and clinopyroxene must be added to glass *D* to obtain point *F*. The magma that provides the olivine and clinopyroxene is discussed in a later section; it is presumed to be hotter and more magnesian in composition than melt *D*.

TABLE 5.—Compositions of minerals, glasses, and a lava and calculated compositions of a glass and a lava

[Complete analyses for cols. 2 and 3 are given on p. A25; compositions given in percent; volatile-free basis; total iron expressed as FeO]

	1955 and early-1960 magma							Late-1960 magma					
	1	2	3	4	5	6	7	8	9	10	11	12	13
SiO ₂	50.61	51.43	51.44	51.44	51.16	38.44	50.75	50.96	50.61	51.44	40.10	48.92	48.95
Al ₂ O ₃ +Cr ₂ O ₃	14.05	3.93	3.75	3.84	31.29	.30	13.50	13.58	14.05	3.84	.30	11.57	11.59
FeO.....	11.21	7.39	7.34	7.37	-----	21.60	12.60	12.45	11.21	7.37	12.64	11.35	11.51
MgO.....	6.77	16.42	16.62	16.52	-----	39.24	5.78	5.77	6.77	16.52	46.54	13.47	13.18
CaO.....	10.79	19.20	19.33	19.26	13.86	.25	9.84	9.77	10.79	19.26	.25	9.28	9.32
Na ₂ O.....	2.51	.34	.31	.32	3.69	-----	2.65	2.60	2.51	.32	-----	2.05	2.09
K ₂ O.....	.60	.03	.02	.03	-----	-----	.74	.72	.60	.03	-----	.49	.49
TiO ₂	2.98	1.08	1.01	1.04	-----	-----	3.57	3.58	2.98	1.04	-----	2.45	2.43
P ₂ O ₅.....	.31	-----	-----	-----	-----	-----	.38	.39	.31	-----	-----	.25	.26
MnO.....	.17	.18	.15	.18	-----	.17	.19	.18	.17	.18	.17	.17	.18
Total.....	100.00	100.00	100.00	100.00	100.00	100.00	100.00	100.00	100.00	100.00	100.00	100.00	100.00
Amount taken.....	123.30	-----	-----	10.00	11.00	2.30	100.00	-----	100.00	3.00	20.00	123.00	-----

1. Glass *D* from table 4, last column.
2. F-1 cpx, clinopyroxene phenocrysts ($En_{47.5}Fs_{12.3}Wo_{40.1}$) separated from 1960 lava sample F-1. D. F. Powers, analyst.
3. Clinopyroxene phenocrysts ($En_{47.5}Fs_{12.1}Wo_{40.4}$) separated from a sample of the 1955 Kil flow on roadcut on highway into Kapoho, Hawaii. D. F. Powers, analyst.
4. Average of cols. 2 and 3, $En_{47.5}Fs_{12.2}Wo_{40.0}$.
5. Theoretical composition of plagioclase $An_{67.5}$. This composition, lying within the petrographically determined range of An_{72-56} , best fits the chemical data.
6. Olivine (1), composition of olivine ($Fa_{23.5}$) in 1955 lavas, computed from the determination of FeO by R. Okamura and of CaO, MnO, Al₂O₃, and Cr₂O₃ by Harry Bastron.
7. Glass *E*, calculated composition, obtained by subtracting 10.00, 11.00, and 2.30

8. Glass *E*, composition from sample F-3g of table 4.
9. Glass *D*, repeated from col. 1.
10. Clinopyroxene composition, repeated from col. 4.
11. Olivine (2), composition of average olivine ($Fa_{13.3}$) in late-1960 lavas; computed from the average FeO content of three samples partially analyzed by R. Okamura. The percentages of CaO, MnO, Al₂O₃, and Cr₂O₃ are assumed to be the same as in col. 6.
12. Lava F-17, calculated composition, obtained by adding 3.00 and 20.00 parts of the minerals in cols. 10 and 11, respectively, to 100.00 parts of glass *D* in col. 9.
13. Lava F-17, composition from table 2.

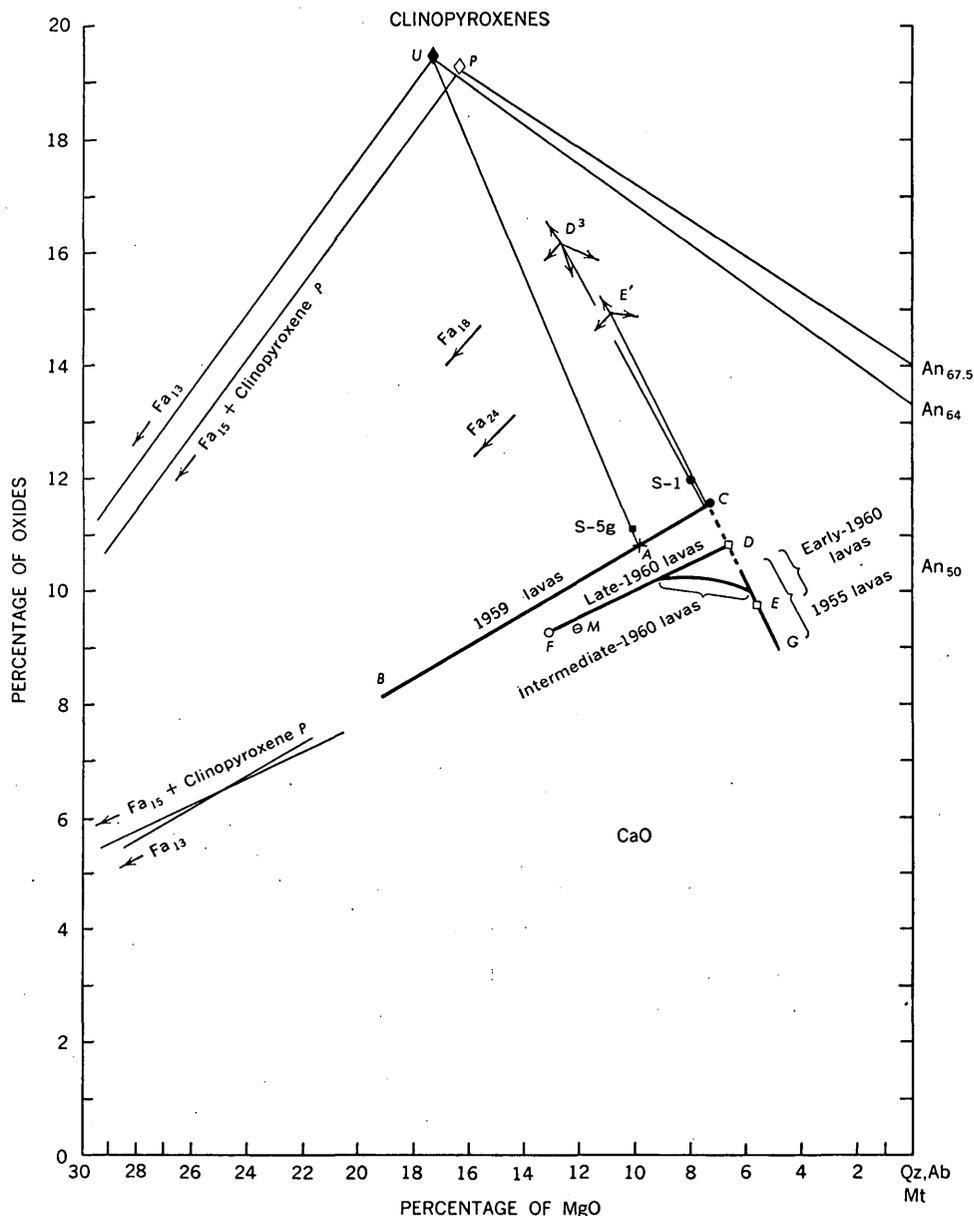


FIGURE 5.—Variation diagram of calcium oxide and alumina showing trends of compositional variation of the lavas relative to key lavas (circles) and glasses (squares) and to the compositions of the separating minerals. Heavy solid lines denote compositions directly indicated by analyzed lavas or glasses. Broken lines denote compositional trends deduced from the fractional crystallization sequence of Kilauea magma.

Explanation for figure 5

- A. Basaltic glass, probably very close in composition to the primitive melt (table 8, col. 2).
- B. Most magnesian lava of the 1959 summit eruption (sample S-5, fig. 4 and table 1).
- C. Average low-magnesia lava of the type commonly produced in summit eruptions of Kilauea (table 3, col. 7). Includes the least magnesian 1959 summit lava (sample S-2, fig. 4 and table 1).
- B-A-C. The olivine-control line of variation defined by the 1959 summit lavas.
- D. Average glassy fraction of the late-1960 flank lavas (table 4, last column). This glass occupies a key position in the differentiation of the 1955 and 1960 flank magmas, as well as in the transition from summit to flank magmas.
- E. Glassy fraction of the least magnesian early-1960 flank lavas (sample F-3g, table 4).
- F. Most magnesian late-1960 flank lava (sample F-17, fig. 4 and table 2).
- G. Least magnesian 1955 flank lava (Macdonald, 1955, table 13, col. 2; triangular point to the extreme right in fig. 4 of this paper).
- C-D. Possible mode of transition from summit magma to flank magma (table cols. 1 to 8).
- D³. Possible composition of the mixture of minerals that separated from magma C to produce the transition C-D. The arrows radiating from D³ point to the compositions of the four minerals involved—clinopyroxene U, An₆₄, Fa₁₈, and Mt (table 7, explanation of col. 7).
- D-E. Differentiation trend of the early-1960 flank magma.
- E'. Composition of the mixture of minerals separating out of magma D to produce trend D-E. The arrows radiating from E' point to the compositions of the three minerals involved—An_{67.5}, clinopyroxene P, and Fa_{23.5} (table 5, cols. 1 to 7).

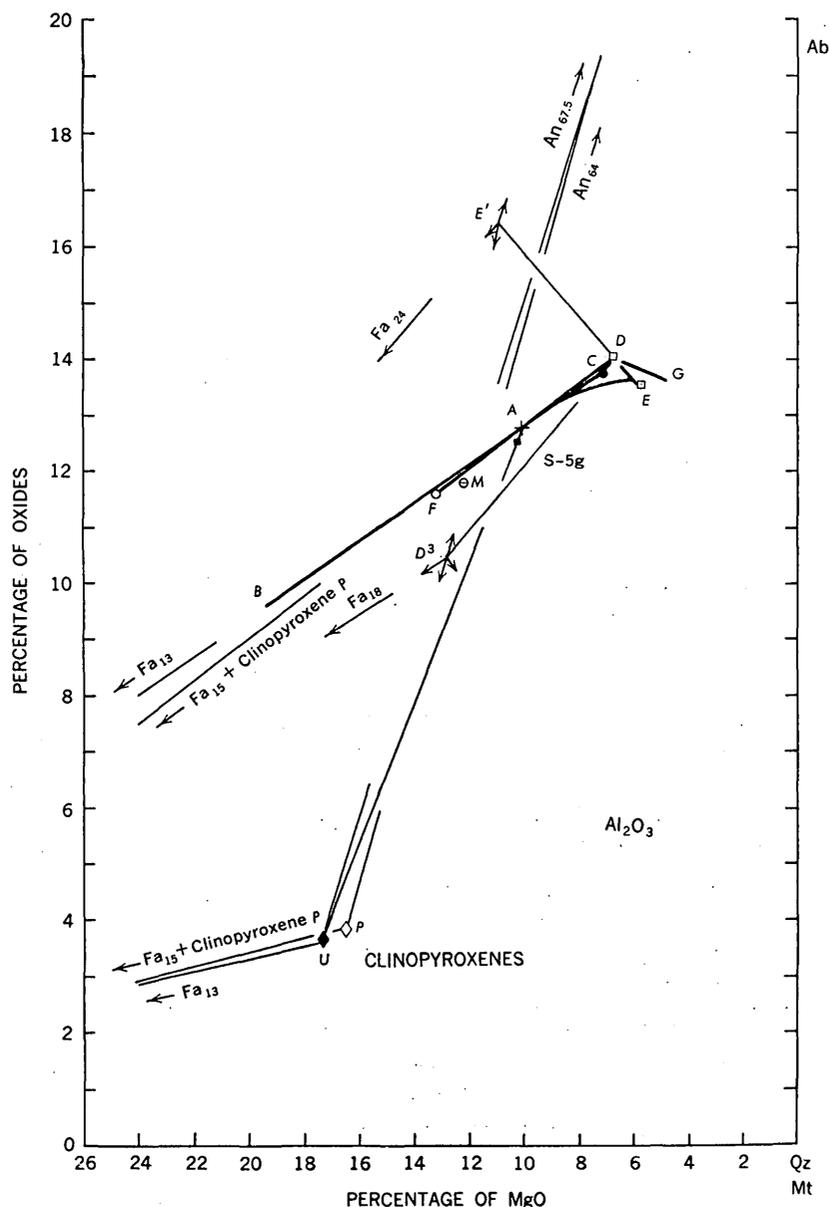


FIGURE 5.—Continued

Explanation for figure 5—Continued

D-G. Differentiation trend of the 1955 flank lavas.

U. Clinopyroxene from the Uwekahuna laccolith of Kilauea (Muir and Tilley, 1957; table 7, col. 1 of this paper).

P. Average clinopyroxene in the 1955 and early-1960 lavas (table 5, col. 4).

M. Composition of lava erupted 8 miles downhill from the summit (Shepherd, 1938, p. 336).

As shown in columns 9 to 12 of table 5, the addition of 3.00 g of clinopyroxene and 20.00 g of olivine No. 2 to 100.00 g of glass D produces 123.00 g of a mixture with the composition listed in column 12, which closely approximates the composition of lava F-17. The calculated composition is only a little low in FeO and a little high in MgO. This discrepancy suggests that the average olivine of the late-1960 lavas was about 1 percent richer in FeO and correspondingly poorer in MgO than the example given in column 11. The calculation

indicates that the late-1960 lavas corresponded chiefly to suspensions of variable amounts of olivine and clinopyroxene in a rather uniform melt, with the weight ratio of olivine to clinopyroxene fixed at 20:3.

This ratio of olivine to clinopyroxene, deduced from the variation trend of the late-1960 lavas as a whole, may be compared with the relative amounts of phenocrysts of the two minerals in individual lava samples. Petrographic determinations of the ratio in several samples are given by Richter and Murata

(1966), and ratios close to 20:3 are reported for the most picritic samples.

A chemical method of determining the relative amounts of phenocrystic minerals is based on analyses of concentrates of crystals prepared from samples F-11 and F-12 of late-1960 lavas. The analyses are listed in table 6, columns 1 and 6. Because the aim was to retain all crystals in their original proportions, these concentrates were not purified to a high degree and thus were contaminated by substantial amounts of glass. Nevertheless, any increase in the crystals-to-glass ratio over that in the original lava accentuates the contrast in composition between crystals and glass and thereby helps to fix the total composition of the crystals more precisely. The analyses of the crude concentrates are corrected by means of the known compositions of the pertinent glass (table 4) under the assumption that all potassium oxide belongs to the glass. Columns 2 and 7 in table 6 contain the corrected compositions of the pure crystalline fractions of lavas F-11 and F-12, respectively. In the further calculations, the composition of the olivine was left as a variable instead of assuming it to be that given in column 11 of table 5. It appears as a remainder in columns 5 and 10 of table 6.

For both crystalline fractions, a satisfactory solution could not be obtained without allowing a small amount of plagioclase. This result is in accord with the petrographic observation in late-1960 lavas of progressively decreasing amounts of remnant plagioclase crystals inherited from the early-1960 magma. Plagioclase $An_{67.5}$ was unstable in the late-1960 magma and played no significant role in its differentiation. The residual com-

positions in table 6, columns 5 and 10, fit the mineral olivine very closely, and they both indicate about 14.0 percent FeO ($Fa_{14.8}$) for the olivine of the late-1960 lavas. It will be recalled that the calculation of the general variation trend for these lavas (table 5) also suggested such an FeO content, in contrast to the average chemically determined percentage of 12.64 ($Fa_{13.3}$). Muir and Tilley (1963) reported an optically determined composition of Fa_{14-15} for the olivine in the last flow of the 1960 eruption. It is possible that during the purification of gram quantities of some olivine phenocrysts for chemical analysis, the practice of magnetically removing fractions that are contaminated by glass or ore minerals may tend to remove the more fayalitic grains as well and thus introduce a bias toward a somewhat less fayalitic composition.

The ratio of olivine to clinopyroxene in lavas F-11 and F-12, according to the above calculations, was 20:2.79 and 20:2.76, respectively, in agreement with the general ratio of 20:3 derived in table 5 for the late 1960 magma.

In summary, two separate magmas were erupted during the 1960 flank eruption, and the cooler early magma manifested a compositional trend that can be defined in terms of separation of clinopyroxene ($En_{47.8}Fs_{12.2}Wo_{40.0}$), plagioclase ($An_{67.5}$), and olivine ($Fa_{23.5}$) in the weight ratio of 10.0:11.0:2.3 from a melt (*D*), whose composition is given in table 5, column 1. The hotter late-1960 magma can be represented by variable amounts of total phenocrysts, consisting of olivine ($Fa_{14.8}$) plus the above clinopyroxene in the ratio of 20:3, suspended in the same melt *D*. This magma had not cooled to the

TABLE 6.—Calculated compositions, in percent, of the crystalline fraction of two late-1960 flank lavas and their contained olivines

[Volatile-free basis; total iron expressed as FeO]

	1	2	3	4	5	6	7	8	9	10
SiO ₂	45.76	41.37	51.16	51.44	39.71	44.17	41.33	51.16	51.44	39.80
Al ₂ O ₃ + Cr ₂ O ₃	7.59	1.72	31.29	3.84	.73	5.22	1.26	31.29	3.84	.56
FeO.....	12.20	13.07	-----	7.37	14.16	12.51	13.04	-----	7.37	13.96
MgO.....	24.50	40.65	-----	16.52	44.95	30.73	41.46	-----	16.52	45.37
CaO.....	6.59	2.73	13.86	19.26	.15	5.08	2.57	13.86	19.26	.13
Na ₂ O.....	1.22	.06	3.69	.32	-----	.79	.03	3.69	.32	-----
K ₂ O.....	.28	-----	-----	.03	-----	.19	-----	-----	.03	-----
TiO ₂	1.52	.21	-----	1.04	.10	1.02	.13	-----	1.04	-----
P ₂ O ₅.....	.16	-----	-----	-----	-----	.11	-----	-----	-----	-----
MnO.....	.18	.19	-----	.18	.20	.18	.18	-----	.18	.18
Total.....	100.00	100.00	100.00	100.00	100.00	100.00	100.00	100.00	100.00	100.00
Relative amount.....	190.90	100.00	2.00	12.00	86.00	144.44	100.00	1.00	12.00	87.00

1. F-11x, original crystal-rich fraction separated from lava F-11; contaminated with glass F-11g of table 4. D. F. Powers, analyst.
2. F-11x, pure crystalline fraction of col. 1 calculated free of glass, assuming that all K₂O belongs in the glass.
3. Theoretical composition of plagioclase $An_{67.5}$.
4. Composition of average phenocrystic clinopyroxene from table 5, col. 4.
5. Remainder left after deducting plagioclase and clinopyroxene from the crystalline fraction of col. 2. The composition is that of olivine.

6. F-12x, original crystal-rich fraction separated from lava F-12; contaminated with glass F-12g of table 4. D. F. Powers, analyst.
7. F-12x, pure crystalline fraction of col. 6 calculated free of glass, assuming that all K₂O belongs in the glass.
8. Plagioclase composition repeated from col. 3.
9. Clinopyroxene composition repeated from col. 4.
10. Remainder left after deducting plagioclase and clinopyroxene from the crystalline fraction of col. 7. The composition is that of olivine.

crystallization temperature of plagioclase $An_{67.5}$. Melt D was a residual liquid in the hotter late-1960 magma and a parental liquid for the cooler early-1960 magma.

Lavas of the intermediate period (samples F-7 to -9), which describe curved rather than straight trends on the variation diagrams, were mixtures of the early and late magmas.

THE TRANSITION FROM SUMMIT MAGMA TO FLANK MAGMA

The problem of the way in which 1960 flank magmas were derived from the 1959 or an even earlier primitive magma will be discussed in some detail because it affords an opportunity to summarize many aspects of fractional crystallization of the primitive magma. This problem will be examined in terms of attaining the composition of the key glass D (an average composition of glasses separated from three samples of late-1960 lava (fig. 5; table 5, col. 1)) from some composition on the olivine-control line of the 1959 summit lavas. The course of the olivine-control lines for these lavas ($B-A-C$, fig. 5) indicates that the separation of olivine alone cannot effect the transition to glass D , as is especially well shown by the variation lines of calcium oxide.

The distinctly lower content of calcium in glass D than in summit lavas of similar magnesia content clearly calls for a separation of either or both clinopyroxene and plagioclase. We are, however, faced with the fact that the most silicic 1959 lava ($S-2$) contained only 50.1 percent silica, whereas Kilauea clinopyroxenes have 51.3 to 51.7 percent silica and labradorite ranges between 50.5 and 55.6 percent silica. The higher silica content of glass D (50.6 percent in comparison with 50.1 percent of lava $S-2$) cannot be attained by separation of either or both clinopyroxene and labradorite without the accompaniment of other phases poorer in silica, such as olivine, magnetite, or bytownite.

That clinopyroxene predominated among the separated phases is strongly suggested by the fact that it is the next mineral after olivine to be crystallized by the cooling magma; a minor accumulation of this mineral was actually observed among the coolest of the 1959 lavas (samples $S-1$ and $S-3$). Also, when clinopyroxene and plagioclase separate together in approximately equal amounts, as in the early-1960 magma (trend $D-E$, fig. 5), the alumina content of the residual liquid drops steadily. In the transition from any composition on the olivine-control line of the 1959 lavas to glass D , however, the rise in the concentration of alumina in the residual liquid indicates that the separation of plagioclase must have been minor relative to clinopyroxene.

Given an appropriate set of cooling conditions, the transition to glass D , in principle, can start from any

composition on the olivine-control line. However, it is already clear that the primitive summit magma can rapidly differentiate into an olivine-rich lower part and an olivine-poor upper part and that the transition to glass D probably involved the low-magnesia rest liquids of the upper part. For our purpose, the average low-magnesia summit lava given in table 3 is used as the starting magma for the transition to glass D . Calculated residual compositions based on the abstraction of several combinations of minerals from this magma are given in table 7. For each combination, trial calculations were not carried out exhaustively but only to the extent necessary to discover the general merit of the combination.

Optical determination (Richter and Murata, 1966) of the clinopyroxene phenocrysts in summit lavas $S-1$ and $S-3$ gave a composition of approximately $En_{50}Fs_{10}Wo_{40}$. This composition differs somewhat from that of the analyzed clinopyroxenes (average of $En_{47.8}Fs_{12.2}Wo_{40.0}$ as given in table 5, col. 4) separated from an early 1960 and a 1955 lava. It more closely approximates the composition of clinopyroxene $En_{47.8}Fs_{12.2}Wo_{40.0}$ as given in table 5, col. 4) separated Uwekahuna laccolith of Kilauea by Muir and Tilley (1957), so the composition of the Uwekahuna clinopyroxene, U , as given in table 7, col. 1, is used in the calculations.

TABLE 7.—Calculation of the transition from a summit magma to a key flank magma

[Results in percent; volatile-free basis; total iron given as FeO]

	1	2	3	4	5	6	7	8
SiO ₂	51.59	52.04	39.31	50.21	50.08	50.10	50.35	50.61
Al ₂ O ₃ +Cr ₂ O ₃	3.63	30.69	.30	13.80	14.71	14.07	14.13	14.05
FeO.....	6.75	-----	16.95	11.18	11.58	11.69	11.25	11.21
MgO.....	17.41	-----	43.02	7.85	6.44	6.83	6.86	6.77
CaO.....	19.43	13.17	.25	11.48	10.77	10.99	11.05	10.79
Na ₂ O.....	.32	4.10	-----	2.25	2.42	2.33	2.34	2.51
K ₂ O.....	.01	-----	-----	.57	.62	.62	.62	.60
TiO ₂.....	.72	-----	-----	2.72	2.91	2.91	2.93	2.98
P ₂ O ₅	-----	-----	-----	.27	.29	.29	.29	.31
MnO.....	.14	-----	.17	.17	.18	.17	.18	.17
Total.....	100.00	100.00	100.00	100.00	100.00	100.00	100.00	100.00

1. Clinopyroxene $U(En_{47.8}Fs_{12.2}Wo_{40.0})$ of Uwekahuna laccolith at the summit of Kilauea volcano. J. H. Scoon, analyst (Muir and Tilley, 1957, table 4, No. 1a).
2. Theoretical composition of phenocrystic plagioclase An_{64} that was found in the 1959 summit lavas $S-1$ and $S-3$.
3. Assumed composition of olivine Fa_{18} that was found in the 1959 summit lavas $S-1$ and $S-3$.
4. Common type of low-magnesia lava produced in summit eruptions of Kilauea. Average composition given in table 3, col. 7.
5. Residual liquid D' obtained by subtracting 9 parts of clinopyroxene U from 109 parts of the summit magma of col. 4.
6. Residual liquid D'' obtained by subtracting 8.50 parts of total crystals, consisting of 6.00 parts of clinopyroxene U , 2.25 parts of An_{64} , and 0.25 part of Fa_{18} , from 108.50 parts of the summit magma of col. 4.
7. Residual liquid D''' obtained by subtracting 9.00 parts of total crystals, consisting of 6.00 parts of clinopyroxene U , 2.25 parts of An_{64} , 0.25 part of Fa_{18} , and 0.50 part of FeO (for magnetite), from 109.00 parts of the summit magma of col. 4.
8. Key flank magma, glass D from table 5, col. 9.

Plagioclase phenocrysts observed in summit lavas $S-1$ and $S-3$ were determined optically to have the composition An_{64} , which is given in table 7, column 2. The composition of olivine Fa_{18} , observed in the same lavas,

has been constructed from the available data on minor elements in other Kilauea olivines and from the theoretical formula and is listed in column 3. The composition of the summit magma that was selected as the starting substance for the transition to flank glass *D* is listed in column 4 and denoted by point *C* on figure 5.

The abstraction of 9.00 parts of clinopyroxene *U* alone from 109.00 parts of the summit magma yields a residual liquid *D'* with the composition given in column 5, which should be compared with the composition of glass *D* in column 8. This liquid is too low in silica and magnesia and too high in alumina and ferrous oxide. Clinopyroxene is richer in calcium oxide than plagioclase An_{64} or olivine, so the fact that separation of clinopyroxene alone only lowers the concentration of calcium oxide down to that in glass *D* shows that the possibilities of involving the other minerals are very restricted. The excessive amount of alumina in liquid *D'* calls for removal of some plagioclase as well as clinopyroxene, but the low percentage of soda is a severe limitation, unless recourse is taken to plagioclase compositions more anorthitic than An_{64} .

By separating 6.00 parts of clinopyroxene *U*, 2.25 parts of plagioclase An_{64} , and 0.25 part of olivine Fa_{18} from 108.50 parts of the summit magma, residual liquid *D''*, with the composition given in column 6, is obtained. Compared to residual liquid *D'*, *D''* agrees better with glass *D* with regard to alumina and magnesia but is still too low in silica and too high in ferrous oxide. If, in addition to the 8.50 parts of the several minerals deducted above, 0.50 part of ferrous oxide (representing equivalent magnetite) were removed from a total of 109.00 parts of the summit magma, the resultant liquid *D'''* would have the composition given in column 7. This composition attains a tolerable overall agreement with glass *D*. An even closer fit is obtained if a more calcic plagioclase (up to An_{50}) is substituted for An_{64} , but petrographic observations do not support such a substitution.

The calculations show the degree to which clinopyroxene predominates over the other minerals separated from the summit magma *C*. The weight ratio of clinopyroxene, plagioclase, olivine, and magnetite to one another is 10.0:3.8:0.4:0.8. The transition from the summit magma to glass *D* is the only step in the differentiation of Kilauea magma in which an intratelluric crystallization of magnetite is suggested. Presumably crystallization of magnetite could be caused by the rise in partial pressure of oxygen due to the high stand of the particular magma in the magma chamber or conduit, where it could have become contaminated by air.

Analyses of two samples of low-magnesium lavas

produced in the small 1868 eruption in Kilauea Iki (Tilley and Scoon, 1961) show contents of total iron both lower and higher than those indicated by the olivine-control line for their percentages of magnesia. The low-iron sample (their sample 2, their table 1) appears to illustrate the depletion of iron from a magma whose composition originally lay on the olivine-control line, whereas the high-iron sample (their sample 3, their table 1) has a general composition more like those of flank lavas of similar magnesium content. Very likely the 1868 lavas, like the first ones of 1959, represented the uppermost and coolest portion of a column of summit magma which was separating clinopyroxene, plagioclase, and minor olivine and magnetite and producing a residual liquid like glass *D*. The previously discussed fractional crystallization of about 8 percent of magma *C* to achieve compositions approaching glass *D* seems to be the most advanced stage of differentiation possible for summit magmas under the current eruptive regimen.

Although melts approaching glass *D* in composition have been erupted occasionally at the summit, the far more common type of summit rest magma is that described in table 3 (also point *C*, fig. 5). As discussed previously, this magma represents the terminal composition on the variation trend due to olivine control and has not yet started separating any other mineral. It thus appears that the transition *C-D* of figure 5 to glass *D* takes place largely during the movement of the supernatant rest magma away from the summit region along subterranean conduits in the rift zone. If so, clinopyroxene and other minerals separated in the differentiation would be deposited mostly in conduits and chambers in the rift zone. Such a removal of the separated phases would explain both the consistent manifestation of simple olivine-control in summit magmas, only rarely complicated by the separation of other minerals, and also the commonly more advanced compositions of flank magmas. The composition of the lava that was erupted in 1923 near Makaopuhi (Shepherd, 1938), only 8 miles down the east rift zone from the summit, is illustrated by the percentage of CaO and Al_2O_3 in figure 5, and the indicated affinity is clearly with the flank type of magma rather than with the summit type.

With decreasing temperature, progressively larger amounts of plagioclase would separate from the flank rest magma until plagioclase and clinopyroxene would be depositing in nearly equal proportions, giving rise to trend *D-G* or *D-E* of the 1955 and early-1960 lavas. The total of about 150 million cubic meters of lava produced in 1955 and early 1960 contained no picrites. Their absence in such a major outpouring of magma on

the Kilauea flank seems unusual and may be due to the derivation of these particular flank magmas from the magnesia-depleted liquid *C* of the summit column of magma.

If, however, rest magma *D* in the rift zone were joined by primitive magma escaping from the lower part of the summit magma column, the resultant mixed magma would crystallize substantial amounts of olivine. The fractional crystallization of such a mixed magma has not been worked out in detail, but because its temperature would be lower than that of the primitive magma, it would be expected to crystallize olivine and clinopyroxene that are somewhat more ferroan. The accumulate picrites would differ from typical summit picrites by containing phenocrysts of clinopyroxene interspersed among the olivines. The late-1960 olive-rich basalts (trend *D-F*, fig. 5) appear to have been derived from such a mixed magma.

In principle, a charge of primitive magma injected into the rift zone could have produced the late-1960 magma through appropriate separation of olivine, clinopyroxene, plagioclase, and magnetite. However, the spatial and thermal conditions of separation that must be postulated would then be so complex that it seems simpler to invoke a mixing of the primitive magma with an appropriate rest liquid such as glass *D*.

Lavas of the intermediate period of the 1960 eruption (samples F-7 to F-9) illustrate a further intermingling of the late-1960 magma, already a mixed magma, with the 1955 and early-1960 magma representing the principal line of liquid descent (*D-G* and *D-E*).

The several stages of differentiation of Kilauea magma revealed in the lavas of the 1959-60 eruption are summarized in the following table. The composition of the primitive magma is assumed to be that of glass S-5g, as corrected on page A24 and in table 8, column 2. The extent of crystallization of the magma at each stage of differentiation has been derived from the series of fractional crystallizations previously calculated.

Stage of differentiation (See fig. 5)	Percentage of—			Major minerals previously crystallized
	MgO	SiO ₂	Crystals removed	
A. Primitive magma (table 8, col. 2).	10.00	49.20	0	None.
C. End of major olivine crystallization (table 3, col. 7).	7.34	50.10	6.4	Olivine.
D. Start of main feldspar crystallization (table 4, col. 8).	6.75	50.45	14.1	Pyroxene, olivine.
E. Most differentiated glass in early-1960 lavas (table 4, col. 4).	5.74	50.69	30.3	Plagioclase, pyroxene, olivine.
G. Most differentiated 1955 lava (Macdonald, 1955).	5.12	51.24	36.5	Plagioclase, pyroxene, olivine.

The table shows that after crystallization of over a third of the original primitive magma, the silica percentage

rises only from 49.20 to 51.24 percent. The amount of quartz-rich granophyric differentiate with more than 60 percent silica that could be derived from Kilauea magma would thus be very small.

COMPOSITION OF THE PRIMITIVE KILAUEA MAGMA

Practically all lavas erupted by Kilauea volcano are somewhat differentiated. What the composition of the original undifferentiated magma that rises from great depth might be is a question of abiding interest. Macdonald (1949a) arrived at a possible composition by averaging all analyses of Kilauea lavas available in 1949 (table 8, col. 3). Powers subsequently (1955) obtained a primitive composition that was somewhat less mafic (table 8, col. 4). Because the 1959-60 eruption of Kilauea was studied in much detail geochemically and geophysically, an attempt was made to derive a primitive composition from the data on this eruption. As previously mentioned, the 1959 summit lava S-2 and similar materials of earlier eruptions (table 3) represent the low-magnesia terminus of the variation trend due to olivine control. The problem of deriving the composition of the primitive magma is largely one of determining how much olivine becomes separated to produce this low-magnesia magma.

As shown in figure 1, the 1959 eruption at Kilauea Iki was complicated by a peculiar spasmodic behavior, which, from the 2d to the final (17th) phase, involved repeated eruption and withdrawal of 1.5 to 10 million cubic meters of lava. For the present purpose, only materials erupted during the weeklong first phase will be considered. The ground-tilt data indicate a general deflation of the summit region during the first phase as though a single charge of magma was being expelled in an orderly manner.

The composition and quantity of lava that ponded in Kilauea Iki during the first eruptive phase are known with an accuracy rarely attained in studies of volcanic eruptions. The minor amount of pumice deposited outside of Kilauea Iki during the first phase represents the only deficiency in the data. An average composition of the lava of the first phase, weighted according to the quantities of lava discharged, is given in table 8, column 1. This composition is very similar to that of lavas S-7 and S-9 (table 1), which raises the possibility that magma of primitive composition was reaching the surface during the latter part of phase 1. It is a surprisingly mafic composition with nearly 14 percent magnesia. It can be argued that this material is so mafic because it contains olivine that had been left behind in the magma chamber by an earlier magma, perhaps that of 1954.

TABLE 8.—*Calculated compositions and norms, in percent, of the primitive Kilauea magma*

	1	2	3	4
Calculated composition				
SiO ₂ -----	48.21	49.20	49.80	50.08
Al ₂ O ₃ -----	11.37	12.77	12.42	12.93
Fe ₂ O ₃ -----	1.50	1.50	1.53	1.51
FeO-----	10.18	10.05	9.91	9.95
MgO-----	13.94	10.00	10.31	8.66
CaO-----	9.74	10.75	10.32	10.96
Na ₂ O-----	1.89	2.12	1.96	2.20
K ₂ O-----	.44	.51	.45	.50
H ₂ O+-----	.04	.09	-----	-----
H ₂ O-----	.01	.02	-----	-----
TiO ₂ -----	2.24	2.57	2.68	2.69
P ₂ O ₅ -----	.22	.25	.29	.29
MnO-----	.18	.17	.13	-----
CO ₂ -----	.02	.02	-----	-----
Cl-----	.02	.02	-----	-----
F-----	.03	.02	-----	-----
Subtotal-----	100.03	100.06	99.80	99.77
Less O-----	.02	.01	-----	-----
Total-----	100.01	100.05	99.80	99.77
Norms				
Q-----	0.00	0.00	0.00	.36
Or-----	2.22	2.78	2.22	2.78
Ab-----	16.24	17.82	16.24	18.34
An-----	21.41	23.91	24.19	23.91
Di:				
Wo-----	10.90	11.95	10.56	11.95
En-----	7.20	7.40	6.60	7.10
Fs-----	2.90	3.83	3.30	4.22
Hy:				
En-----	10.80	12.10	19.20	14.50
Fs-----	4.49	6.34	9.50	8.58
Ol:				
Fo-----	11.76	3.92	.14	.00
Fa-----	5.30	2.24	.20	.00
Mt-----	2.09	2.09	2.09	2.09
Il-----	4.26	5.02	5.02	5.17
Ap-----	.34	.34	.67	.67

1. Weighted average composition of lava produced during the first eruptive phase at Kilauea Iki, Nov. 14 to 21, 1959.
2. Most mafic glass S-5g found among lavas of the 1959 summit eruption at Kilauea Iki, corrected for clinopyroxene as explained in the text (p. A24).
3. Average of 24 analyses of Kilauea rocks (Macdonald, 1949, p. 74).
4. Average historic Kilauea magma (Powers, 1955, p. 85).

Another indication of the composition of the primitive magma can be derived from the composition of the glassy parts of the lavas. The most mafic glass found among 1959 lavas has the composition given for sample S-5g in table 4. Evidence for its containing a slight excess of dissolved clinopyroxene has been presented (p. A15). A graphical subtraction of this excess is made by projecting a line in figure 5 from clinopyroxene *U* through the composition of the glass onto point *A* (10.00 percent MgO) on the olivine-control line. The corrected composition, read off the olivine-control lines in figure 4 at the magnesia percentage of 10.00, is given in table 8, column 2. It is somewhat less mafic than the composition of column 1 and is fairly close to the primi-

tive composition derived by Macdonald (1949) as given in column 3.

The most mafic Kilauea glass would seem to be the best sample of the primitive magma, but it too is not free of ambiguity. If the primitive melt had a certain amount of superheat, it could melt olivine phenocrysts that settled into it and thereby become more mafic than it was originally. The corroded outline of some olivine phenocrysts in summit picrites may be due to such a process of remelting. However, such remelting of olivine must take place only to a limited extent because the maximum lava temperatures seem to be close to the liquidus of the primitive magma.

Uncertainty as to what actually transpired underground during the spasmodic later phases of Kilauea Iki eruption obscures the significance of the chemical compositions of the later lavas. If all lavas erupted during the 2d through the 17th phases are considered to be new materials reaching the surface for the first time, the overall average composition based on a total discharge of 100 million cubic meters would be substantially more mafic than that in table 6, column 1, perhaps having as much as 17 percent magnesia. Such an ultramafic lava (corresponding to magma with about 25 percent dissolved olivine) is generally thought to form through gravitative settling of olivine phenocrysts. In recent years, however, the question of the existence of such ultramafic primitive magmas has been raised by Drever and Johnston (1957) and by Wyllie (1960). The general picture of magmatism developed through the years by investigators in Hawaii clearly indicates the efficacy of settling of olivine phenocrysts for producing ultramafic lavas. Existing information seems to favor a content of roughly 7 percent of dissolved olivine (Fa₁₃) in the primitive magma, corresponding to about 10 percent magnesia. The possibility of more mafic magmas, however, is not entirely excluded by the data now available.

DATA PERTINENT TO THE GENESIS OF COMPOSITE INTRUSIONS

For those concerned with problems about intrusive bodies of basaltic composition, the rapid fluctuations in the composition of the 1959 summit lavas are interesting to ponder. As shown in figure 1, the composition may become more mafic or less mafic with time. However, if the trend toward less mafic composition is related to a waning of magmatic pressure, as figure 2 suggests, then the opposite trend is probably more pertinent to the problem of forceful intrusion of magma into a cold country rock. Using samples S-2 to S-5 of figure 1 as an example, it is conceivable that a less mafic magma could form the leading edge or finger of a growing intrusive and chill against the wall rock. If the intrusive

were thin enough, the chilled early material would not be remelted by, and mix with, the more mafic magma that soon followed it. There would then result a seemingly anomalous intrusive body whose core was more mafic than the chilled border zone.

In the west wall of the caldera of Kilauea is a small composite vertical dike about a foot thick. Its outer zone consists of aphanitic basalt, while its core is highly picritic, with no chill relationship between the two parts. The zonation of this dike was probably due to a previously established compositional gradient in the intruded magma rather than to any differentiation following emplacement.

COMPOSITION OF TWO KILAUEA CLINOPYROXENES

For the purpose of the calculations outlined in table 5, the composition of a clinopyroxene isolated from an early-1960 lava and that of another from a 1955 lava were given on a volatile-free basis, with total iron expressed as FeO and with chromium oxide combined with alumina. The original analyses in percent are given as follows:

Oxides	Elements based on six oxygen atoms				
	1	2			
SiO ₂	51.34	51.43	Si.....	1.893	1.892
Al ₂ O ₃	2.85	2.86	Al.....	.107	.108
Fe ₂ O ₃	1.36	1.40	Total.....	2.000	2.000
FeO.....	6.16	6.08	Al.....	.016	.016
MgO.....	16.40	16.62	Ti.....	.030	.028
CaO.....	19.17	19.33	Fe ³⁺038	.039
Na ₂ O.....	.34	.31	Cr.....	.031	.025
K ₂ O.....	.03	.02	Mg.....	.901	.911
H ₂ O ⁺08	.08	Fe ²⁺190	.187
H ₂ O ⁻03	.00	Mn.....	.006	.006
TiO ₂	1.08	1.01	Ca.....	.757	.762
MnO.....	.18	.18	Na.....	.024	.023
Cr ₂ O ₃	1.08	.89	K.....	.001	.001
Total.....	100.10	100.21	Total.....	1.994	1.998
			Mg.....	47.6	47.9
			Fe.....	12.3	12.1
			Ca.....	40.1	40.0

¹ Fe = Fe²⁺ + Fe³⁺ + Mn.

1. Chromian augite, phenocrysts separated from sample F-1 of table 2. D.F. Powers, analyst.
2. Chromian augite, phenocrysts separated from a sample of the 1955 Kilauea flow collected in the cut on highway to Kapoho. D.F. Powers, analyst.

REFERENCES

Ault, W. U., Eaton, J. P., and Richter, D. H., 1961, Lava temperatures in the 1959 Kilauea eruption and cooling lake: *Geol. Soc. America Bull.*, v. 72, no. 5, p. 791-794.

Aurousseau, M., and Merwin, H. E., 1928, Olivine—I, From the Hawaiian Islands; II, Pure forsterite: *Am. Mineralogist*, v. 13, no. 11, p. 559-564.

Drever, H. I., and Johnston, R., 1957, Crystal growth of forsteritic olivine in magmas and melts: *Royal Soc. Edinburgh Trans.*, v. 63, pt. 2, p. 289-315.

Eaton, J. P., 1962, Crustal structure and volcanism in Hawaii, in *The crust of the Pacific basin*: *Am. Geophys. Union Mon.* 6, p. 13-29.

Eaton, J. P., and Murata, K. J., 1960, How volcanoes grow: *Science*, v. 132, no. 3432, p. 925-938.

Grout, F. F., 1918, Two-phase convection in igneous magmas: *Jour. Geology*, v. 26, no. 6, p. 481-499.

Hess, H. H., 1960, Stillwater igneous complex, Montana: *Geol. Soc. America Mem.* 80, p. 148-149.

Holmes, Arthur, 1930, *Petrographic methods and calculations*: London, Thomas Murby, 515 p.

Hotz, P. E., 1953, *Petrology of granophyre in diabase near Dillsburg, Pennsylvania*: *Geol. Soc. America Bull.*, v. 64, no. 6, p. 675-704.

Kuno, Hisashi, Yamasaki, Kazuo, Iida, Chuzō, and Nagashima, Kozo, 1957, Differentiation of Hawaiian magmas: *Japanese Jour. Geology and Geography*, v. 28, p. 179-218.

Linsley, R. K., Jr., Kohler, M. A., and Paulhus, J. L. H., 1949, *Applied hydrology*, 1st ed.: New York, McGraw-Hill Book Co., Inc., 689 p.

Macdonald, G. A., 1949a, Petrography of the island of Hawaii: *U.S. Geol. Survey Prof. Paper* 214-D, p. 51-96.

——— 1949b, Hawaiian petrographic province: *Geol. Soc. America Bull.*, v. 60, no. 10, p. 1541-1595.

——— 1955, Hawaiian Islands, Pt. 3 of *Catalogue of the active volcanoes of the world including solfatara fields*: Naples, Italy, *Internat. Volcanol. Assoc.*, 37 p.

——— 1959, The activity of Hawaiian volcanoes during the years 1951-56: *Bull. Volcanol. [Italy]*, v. 22, p. 3-70.

Macdonald, G. A., and Eaton, J. P., 1955, Hawaiian volcanoes during 1953: *U.S. Geol. Survey Bull.* 1021-D, p. 127-166.

——— 1957, Hawaiian volcanoes during 1954: *U.S. Geol. Survey Bull.* 1061-B, p. 17-72.

Macdonald, G. A., and Katsura, Takashi, 1961, Variations in the lava of the 1959 eruption in Kilauea Iki: *Pacific Sci.*, v. 15, no. 3, p. 358-369.

Muir, I. D., and Tilley, C. E., 1957, The picrite-basalts of Kilauea, Pt. 1 of *Contributions to the petrology of Hawaiian basalts*: *Am. Jour. Sci.*, v. 255, no. 4, p. 241-253.

——— 1963, The tholeiitic basalts of Mauna Loa and Kilauea, Pt. 2 of *Contributions to the petrology of Hawaiian basalts*: *Am. Jour. Sci.*, v. 261, no. 2, p. 111-128.

Murata, K. J., 1960, A new method of plotting chemical analyses of basaltic rocks: *Am. Jour. Sci.*, v. 258-A (Bradley volume), p. 247-252.

Murata, K. J., and Richter, D. H., 1961, Magmatic differentiation in the Uwekahuna laccolith, Kilauea Caldera, Hawaii: *Jour. Petrology [Oxford, England]* v. 2, no. 3, p. 424-437.

Palmer, H. S., 1927, A study of the viscosity of lava: *Hawaiian Volcano Observatory Monthly Bull.*, v. 15, no. 1, p. 1-4.

Peck, L. C., 1964, *Systematic analysis of silicates*: *U.S. Geol. Survey Bull.* 1170, 89 p.

Powers, H. A., 1955, Composition and origin of basaltic magma of the Hawaiian Islands: *Geochim. et Cosmochim. Acta*, v. 7, nos. 1-2, p. 77-107.

Richter, D. H., and Murata, K. J., 1966, Petrography of the lavas of the 1959-60 eruption of Kilauea Volcano, Hawaii: *U.S. Geol. Survey Prof. Paper* 573-D.

Shapiro, Leonard, and Brannock, W. W., 1962, Rapid analysis of silicate, carbonate, and phosphate rocks: *U.S. Geol. Survey Bull.* 1144-A, p. A1-A56.

Shepherd, E. S., 1938, The gases in rocks and some related problems: *Am. Jour. Sci.*, 5th ser., v. 35-A, p. 311-351.

Tilley, C. E., 1960a, Differentiation of Hawaiian basalts—some variants in lava suites of dated Kilauean eruptions; chemical analysis by J. H. Scoon: *Jour. Petrology [Oxford, England]*, v. 1, no. 1, p. 47-55.

——— 1960b, Kilauea magma 1959-60: *Geol. Mag. [Great Britain]*, v. 97, no. 6, p. 494-497.

- Tilley, C. E., and Scoon, J. H., 1961, Differentiation of Hawaiian basalts—trends of Mauna Loa and Kilauea historic magma: *Am. Jour. Sci.*, v. 259, no. 1, p. 60-68.
- U.S. Geological Survey, 1960, Quality of surface waters of the United States 1957. Pts. 1-4: U.S. Geol. Survey Water-Supply Paper 1520, p. 1-610.
- Washington, H. S., 1923, The formation of aa and pahoehoe, Pt. 4 of *Petrology of the Hawaiian Islands*: *Am. Jour. Sci.*, 5th ser., v. 6, p. 409-423.
- Wyllie, P. J., 1960, The system CaO-MgO-FeO-SiO₂ and its bearing on the origin of ultrabasic and basic rocks: *Mineralog. Mag.* [London], v. 32, no. 249, p. 459-470.
- Yoder, H. S., Jr., and Tilley, C. E., 1957, Basalt magmas in Geophysical Laboratory [rept.]: Carnegie Inst. Washington, Year Book 56, 1956-57, p. 156-161.
- 1962, Origin of basalt magmas—an experimental study of natural and synthetic rock systems: *Jour. Petrology* [Oxford, England], v. 3, no. 3, p. 342-532.

