Chemistry of Kilauea and Mauna Loa Lava in Space and Time

GEOLOGICAL SURVEY PROFESSIONAL PAPER 735

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By THOMAS L. WRIGHT

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An account of the chemical composition of lavas from Kilauea and Mauna Loa volcanoes, Hawaii, and an interpretation of the processes of partial melting and subsequent fractional crystallization that produced the chemical variability

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CHEMISTRY OF KILAUEA AND MAUNA LOA LAVA IN SPACE AND TIME

By THOMAS L. WRIGHT

ABSTRACT

Kilauea and Mauna Loa, Hawaii's two active shield volcanoes, are composed of tholeiitic basalt having MgO contents ranging from more than 20 percent to less than 4 percent. Most eruptive vents are located either within the central caldera or on two rift zones extending to the east and southwest from each volcano's summit. Mauna Loa also has a few isolated vents on its northwest slope that are apparently unrelated to any rift zone. The chemical variability of Mauna Loa and Kilauea lava having more than about 6.8 percent MgO is principally explained by addition or removal of olivine (olivine control), but other minerals are involved to a lesser degree. The chemical variability of these lavas is described and interpreted in this paper. Lavas having less than 6.8 percent MgO are fractionated by separation of pyroxene, plagioclase, and Fe-Ti oxides in addition to olivine. Fractionated basalt from Kilauea is confined to the rift zones. The rare fractionated lavas from Mauna Loa are also confined to the rift zones and are less fractionated (higher MgO) than those from Kilauea.

The chemistry of nonfractionated lava from single eruptions of Kilauea may be explained by olivine control alone, and this process is consistent with the observation that olivine is the only true phenocryst in unfractionated Kilauea lavas. The chemistry of nonfractionated lava from single eruptions of Mauna Loa can be explained by a more complex mineral control involving olivine, hypersthene, augite, and plagioclase, all being commonly present as phenocrysts. The addition or removal of these minerals is inferred to take place at pressures not exceeding 2 kilobars in shallow magma reservoirs located beneath the two volcanoes.

The chemistry of Mauna Loa lavas shows no correlation with either the time of eruption or location of the eruptive vents. By contrast the lavas erupted at Kilauea summit may be subdivided into three groups—pre-1750, 18th–19th century, and 20th century—on the basis of their chemical composition compared at the same MgO content. The younger lavas are richer in lower melting constituents; for example, K_2O, P_2O_5, and TiO_2. The average composition of Mauna Loa lavas is similar to what one would obtain by extrapolating the Kilauea chemical variation backwards in time. It is possible that the oldest unexposed Kilauea lavas would be similar in composition to Mauna Loa lava. The similarity in the ratio of K_2O:P_2O_5 both within the lavas of each volcano and between the two volcanoes suggests that Kilauea and Mauna Loa originated by partial melting in a mantle of uniform composition and that no processes other than either melting or crystal-liquid fractionation are needed to explain the chemical variations.

The increase in K_2O and P_2O_5 in the more recent Kilauea eruptions suggests that the magma which supplies Kilauea eruptions has been fractionating. The time-related chemical variation can be expressed by two mineral assemblages: (1) olivine-orthopyroxene-plagioclase (An_{60-65}) where the ratio of orthopyroxene to plagioclase equals 2:1 and (2) olivine-aluminous orthopyroxene-aluminous and jadeitic clinopyroxene where the ratio of orthopyroxene to clinopyroxene equals 2:1. Both assemblages indicate relatively high pressure fractionation. Neither of the calculated mineral assemblages is of basalt at high pressure, and it may be that the magmas entirely consistent with recent studies on the crystallization have undergone more than one stage of fractionation.

A model is proposed for the origin of Kilauea which embodies the following points:

1. Generation by partial melting of picritic magmas (20–25 percent MgO) at depths of greater than 60 kilometers.
2. High-pressure fractionation of these magmas during relatively slow ascent to a storage region at 20–30 km depth.
3. Minor fractionation during storage followed by rapid ascent into shallow crustal reservoirs at 2–4 km depth.
4. Settling of olivine during storage at 2–4 km and periodic eruption of the upper parts of these reservoirs, or rarely, the entire reservoir including settled olivine.

INTRODUCTION

Kilauea and Mauna Loa are two active shield volcanoes on the island of Hawaii (fig. 1), which rise to heights above sea level of 1,260 and 4,200 meters, respectively. The undersea part of each volcano is probably composed of overlapping pillow lavas separated by a thin layer of hyaloclastic material from a subaerial section composed of countless thin flows of rather uniform tholeiitic basalt (Moore and Fiske, 1969). At least 10,000 years of geologic time are represented by the section visible above sea level (Rubin and Berthold, 1961; see also Doell and Cox, 1965). Each volcano has erupted lava from its summit and two rift zones. Mauna Loa, in addition, has a number of isolated vents on its northwest slope that are apparently unconnected with any rift zone. The Ninole Hills, on the southeast slope of Mauna Loa, are made of faulted and eroded lavas that have been considered by previous workers to be

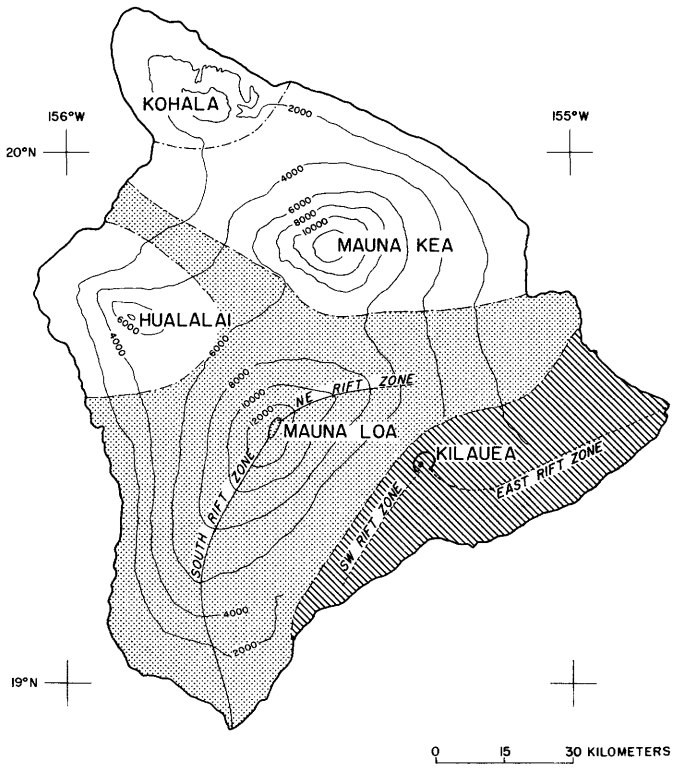

FIGURE 1.—Index map showing the five volcanoes that make up the Island of Hawaii. Contour interval, 2,000 feet. Stippled area, underlain chiefly by lava flows from Mauna Loa; hatched area, underlain chiefly by lava flows from Kilauea.

part of the oldest series of exposed lavas erupted from Mauna Loa.

The general characteristics of Mauna Loa eruptions are similar to those of Kilauea, judging from published descriptions. The frequency of eruption at each volcano has been similar throughout historic time, and the volume of magma erupted from Mauna Loa is approximately equal to that erupted from Kilauea over the same period.

Stearns and Macdonald (1946, p. 131–136) have summarized the ideas of previous observers on the relative ages of Kilauea and Mauna Loa. Their own conclusions, based on field observations, are that Kilauea and Mauna Loa are independent volcanoes, that all lavas exposed in section on the Kilauea shield were erupted from Kilauea, and that the Kilauea shield is younger than the bulk of the Mauna Loa shield.

Petrologic study of Kilauea complements recent geophysical and ground deformation studies which have provided information on the structure of Kilauea Volcano and its mechanism of eruptions. (For example, see Fiske and Koyanagi, 1968; Fiske and Kinoshita, 1969; Kinoshita and others, 1969.) Petrologic interpretation is aided by the extensive knowledge of basaltic crystallization gained from study of the recent lava lakes of Kilauea (Richter and Moore, 1966; Peck and others, 1966; Wright and Weiblen, 1968); there is no comparable knowledge for Mauna Loa.

This paper uses chemical analyses, many of which are previously unpublished, of historic (1750–present; see tables 1 and 2) and prehistoric lavas of both volcanoes to characterize the chemical composition of flows from the summit and rift zones and to develop the following topics:

1. The chemical variation in both time and space of Mauna Loa lava and how it contrasts with the chemical variation in time and space of Kilauea lava.
2. Possible explanations of the chemical differences between Kilauea lavas of different age.

ACKNOWLEDGMENTS

H. A. Powers first introduced the writer to the problems of Kilauea and Mauna Loa chemistry. His encouragement and critical evaluation of this work at many stages has been of great value. The quantitative treatment of differentiation depends on the quality of the chemical data. I would like to extend thanks to L. C. Peck and the individual analysts whose work is included in this paper. The assistance of P. C. Doherty in making computer calculations is gratefully acknowledged. The discussion sections of the paper benefited greatly from communication with R. L. Tuthill, T. N. Irvine, E. D. Jackson, and H. R. Shaw. However, the conclusions expressed are the author's sole responsibility. The paper was reviewed at different stages by R. L. Tuthill, R. S. Fiske, D. A. Swanson, and W. A. Duffield, whose comments are greatly appreciated.

DEFINITIONS AND TERMINOLOGY

Petrologic terminology related to basaltic rocks often carries multiple meanings, so that the following explanations of terms which recur frequently in this report are made to avoid confusion.

THOLEIITE

The term "tholeiite" as used in this report embraces both the definitions of tholeiite (oversaturated) and olivine tholeiite (undersaturated) used by Yoder and Tilley (1962, p. 353–354).

TABLE 1.—*Historic eruptions of Mauna Loa*

[This table is repeated with little modification from Stearns and Macdonald (1946, table, p. 79). Additional data for the eruptions of 1949 and 1950 are from Finch and Macdonald (1951, 1953)]

Date of commencement		Approx duration in days		Location of principal vent(s)	Approx volume of lava [1] (cu m $\times 10^{-6}$)	Tables containing analyses in this paper
Year	Month and day	Summit	Flank			
1832	June 20	21	(?)	Southwest rift	69	---
1843	Jan. 9	5	90	Northeast rift	191	13
1849	May	15	---	Mokuaweoweo	---	---
1851	Aug. 8	21	(?)	----do	69	---
1852	Feb. 17	1	20	Northeast rift	107	10
1855	Aug. 11	---	450	----do	115	10
1859	Jan. 23	1	300	Northwest flank	459	11
1865	Dec. 30	120	---	Mokuaweoweo	---	---
1868	Mar. 27	1	15	Southwest rift	145	9
1872	Aug. 10	60	---	Mokuaweoweo	---	---
1873	Jan. 6	2(?)	---	----do	---	---
1873	Apr. 20	547	---	----do	---	---
1875	Jan. 10	30	---	----do	---	---
1875	Aug. 11	7	---	----do	---	---
1876	Feb. 13	Short	---	----do	---	---
1877	Feb. 14	10	1	----do	---	8
1880	May 1	6	---	----do	---	8
1880	Nov. 1	---	280	Northeast rift	230	10
1887	Jan. 16	---	10	Southwest rift	230	9
1892	Nov. 30	3	---	Mokuaweoweo	---	---
1896	Apr. 21	16	---	----do	---	---
1899	July 4	4	19	Northeast rift	153	10
1903	Oct. 6	60	---	Mokuawcoweo	---	---
1907	Jan. 9	1	15	Southwest rift	77	9
1914	Nov. 25	48	---	Mokuaweoweo	---	---
1916	May 19	---	14	Southwest rift	61	---
1919	Sept. 29	Short	42	----do	268	9
1926	Apr. 10	Short	14	----do	115	9, 13
1933	Dec. 2	17	1	Mokuaweoweo	77	---
1935	Nov. 21	1	42	Northeast rift	122	10
1940	Apr. 7	133	1	Mokuaweoweo	77	8
1942	Apr. 26	2	13	Northeast rift	77	8, 10
1949	Jan. 6	146	---	Mokuaweoweo	59	8
1950	June 1	---	22	Southwest rift	390	9, 13

[1] Includes only lava above sea level. Estimates of lava erupted undersea are given by Stearns and Macdonald (1946, footnotes to table, p. 79) and by Finch and Macdonald (1953; 1950 eruption only).

TABLE 2.—*Historic eruptions of Kilauea*

[For eruptions through 1934, this table is repeated with little modification from Stearns and Macdonald (1946, table p. 111). Data for 1866(?), 1879, and 1889 eruptions are from H. A. Powers (oral commun., 1967; see also Peterson, 1967). Data for eruptions since 1952 are taken from published and unpublished data, Hawaiian Volcano Observatory]

Date of commencement		Approx duration in days	Location of principal vent(s)	Approx volume of lava [1] (cu m $\times 10^{-6}$)	Reference to analyses
Year	Month and day				
1750(?)		---	East rift	15	Wright and Fiske, 1971, table 6.
1790(?)		---	----do	29	Do.
1790	Nov. (?)	---	Kilauea caldera	---	This paper, table 4.
1823	Feb.–July	Short	Southwest rift	12	This paper, table 5.
1832	Jan. 14	Short	Kilauea caldera	?	This paper, table 4.
1840	May 30	26	East rift	216	Wright and Fiske, 1971, table 6.
1866(?)	?	?	Kilauea caldera	---	This paper, table 4.
1868	Apr. 2	Short	Kilauea Iki	?	Do.
1868	Apr. 2(?)	Short	Southwest rift	1	This paper, table 5.
1877	May 4	1(?)	Kilauea caldera	?	This paper, table 4.
1877	May 21(?)	---	Keanakakoi	?	Do.
1879	?	?	Kilauea caldera	---	Do.
1884	Jan. 22	1	----do	?	
1885	Mar.	80(?)	----do	?	
1889	?	?	----do	----	This paper, table 4.

See footnotes at end of table.

TABLE 2.—*Historic eruptions of Kilauea*—Continued

Date of commencement		Approx duration in days	Location of principal vent(s)	Approx volume of lava [1] (cu m $\times 10^{-6}$)	Reference to analyses
Year	Month and day				
1894	Mar. 21	6+	Kilauea caldera	?	
1894	July 7	4(?)	----do	?	
1911–24		---	Halemaumau lava lake	---	This paper, table 4.
1918	Feb. 23	14	Kilauea caldera	1	Do.
1919	Feb. 7	294	----do	26	Do.
1919–20	Dec. 21	221	Southwest rift	48	This paper, table 5.
1921	Mar. 18	7	Kilauea caldera	6.5	This paper, table 4.
1922	May 28	2	East rift	?	
1923	Aug. 25	1	----do	1	Wright and Fiske, 1971, table 6.
1924	May 10	17	Kilauea caldera	---	
1924	July 19	11	Halemaumau	1	This paper, table 4.
1927	July 7	13	----do	2	
1929	Feb. 20	2	----do	1	
1929	July 25	4	----do	3	
1930	Nov. 19	19	----do	6.5	
1931	Dec. 23	14	----do	7.5	This paper, table 4.
1934	Sept. 6	33	----do	7.0	
1952	June 27	136	----do	49	This paper, table 4.
1954	May 31	4	----do	6.5	Do.
1955	Feb. 28	87	East rift	92	Wright and Fiske, 1971, table 5.
1959	Nov. 14	38	Kilauea Iki	39	Murata and Richter, 1966a.
1960	Jan. 13	37	East rift	119	Do.
1961	Feb., Mar., July	1, 22, 7	Halemaumau	13.7	Richter, Ault, Eaton, and Moore, 1964.
1961	Sept. 22	3	East rift	2.5	Do.
1962	Dec. 7	3	----do	.3	Wright and Fiske, 1971, table 6
1963	Aug. 21	1	----do	.8	Do.
1963	Oct. 5	1	----do	7.7	Do.
1965	Mar. 5	10	----do	17.6	Do.
1965	Dec. 24	1	----do	.8	Do.
1967	Nov. 5	238	Halemaumau	81	This paper, table 4.
1968	Aug. 22	4	East rift	.01	
1968	Oct. 7	15	----do	7	
1969	Feb. 22	5	----do	17	
1969	May 24	Continuing	----do	[2]>180	

[1] Includes only lava above sea level. Estimates of lava that flowed into the ocean are given by Stearns and Macdonald (1946, footnotes to table, p. 111).

[2] As of August 1971.

MINERAL CONTROL LINES

A control line is defined by linear variation of the chemical analyses of a suite of rocks plotted on an oxide-oxide plot. If a single-mineral species of limited compositional range is controlling the chemical variation, then it is a necessary but not sufficient condition that the control line extrapolate to the composition of that mineral plotted on the same oxide-oxide diagram. The sufficient condition for single-mineral control is that the control lines on all possible oxide-oxide plots for a given suite of rocks extrapolate to the composition of a single mineral. If the mineral controlling the chemical trends is of variable composition, then the trends will be curved rather than linear. If more than one mineral controls the chemical variation, unique control lines will be defined only if the weight ratios among the minerals removed or added to produce the chemical variation are identical for all the lavas defining the control lines. In general, this situation does not exist, so that it is rarely possible to define quantitatively a multimineral control. However, the sense in which deviations occur from lines that define dominantly a single-mineral control may indicate which additional mineral species is causing the chemical variation.

OLIVINE-CONTROLLED AND DIFFERENTIATED BASALT

Olivine control is a specific type of mineral control (see preceding definition). The best documented example of olivine control on lava compositions was described by Murata and Richter (1966a, b) for the 1959 eruption of Kilauea Iki.

Wright and Fiske (1971) were able to characterize as olivine-controlled lavas all those erupted at the summit of Kilauea and, in general, all Kilauea lavas whose compositions fall within the range of

observed summit lava compositions. They found, empirically, that these olivine-controlled lavas all have 6.8 percent or more MgO; associated lavas having less than 6.8 percent MgO invariably plot well off the extensions of olivine control lines extrapolated to lower MgO contents. These data suggest that 6.8 percent is the minimum MgO content of a liquid which can crystallize only olivine for this suite of rocks; liquids of less than 6.8 percent MgO must have crystallized silicate phase(s) in addition to olivine, and thus their compositions cannot fall on olivine control lines.[1] For lavas erupted from Mauna Loa, a value of 6.8 percent MgO also separates olivine-controlled rocks from those whose compositions cannot be explained by simple addition or removal of olivine. Thus, in this paper, lavas from both volcanoes having less than 6.8 percent MgO are defined as differentiated.

While olivine-controlled lavas of Kilauea and Mauna Loa all have more than 6.8 percent MgO, Hawaiian tholeiitic basalts having more than 6.8 percent MgO can result from processes other than olivine control. Wright and Fiske (1971), for example, describe hybrid lavas in which MgO is greater than 6.8 percent, but such rocks are quite distinct chemically from olivine-controlled lavas having comparable MgO contents.

PREVIOUS WORK

The lavas of Kilauea and Mauna Loa have been recognized as tholeiitic basalts for decades. Cross (1915) summarized early analyses of Kilauea lavas in a normative classification, but he did not further interpret the data. Washington (1923a, b) reported new analyses and petrographic descriptions of Kilauea and Mauna Loa lavas, from which he classified the lavas into three types which would now be called olivine-poor basalt, olivine basalt, and picrite. He also noted the similarity in compositions of Kilauea and Mauna Loa lavas compared with those of lavas from other Hawaiian volcanoes. Powers (1935) dealt briefly with the petrographic character of Kilauea and Mauna Loa lavas, but Macdonald (1949a, b) was the first investigator to describe systematically the lavas of both volcanoes. Both Powers and Macdonald recognized the common presence of olivine as phenocrysts in contrast to the rarity of clinopyroxene phenocrysts. Macdonald pointed out that hypersthene is common in the lavas of Mauna Loa but nearly lacking in the lavas of Kilauea, and he noted that chemical analyses of rocks from the two volcanoes are very similar, although subtle yet systematic compositional differences might be substantiated as new analyses are reported (Macdonald, 1949a, p. 72).

Powers (1955) made an important contribution to understanding the petrogenesis of lavas from Kilauea and Mauna Loa when he recognized that (1) the general chemistry of rocks from each volcano could be explained by differences in olivine content, and (2) systematic chemical differences, particularly in SiO_2 and CaO, exist between the historic lavas of Kilauea and the historic lavas of Mauna Loa. Powers concluded that chemically distinctive lavas, both historic and prehistoric, formed from separate "batches" of magma.

Tilley and Scoon (1961) presented new analyses of the contemporaneous 1868 eruptions of Kilauea and Mauna Loa which confirmed Powers' observation on the lime-silica differences. They also showed that, on a CaO–SiO_2 diagram, a straight line separates hypersthene-bearing basalts (principally from Mauna Loa) from hypersthene-free basalts (principally from Kilauea). Other papers by Tilley (1960a, b; 1961) gave further definition to the hypersthene-bearing basalts and also treated the mechanism of magmatic differentiation at Kilauea.

Aramaki and Moore (1969) supported Powers' (1955) concept of separate batches of magma by proposing that the Kilauea lavas change composition with time in a more or less cyclical manner to explain observed changes in the ratio of K:Na with time.

Recently, Jamieson (1970) has discussed low-pressure fractionation of Kilauea and Mauna Loa lavas from a phase-equilibrium standpoint, and Murata (1970) has proposed a partial-melting model for the origin of Kilauea and Mauna Loa magmas.

METHODS OF STUDY

SAMPLING

Samples were collected from nearly all historic lava flows from both Kilauea and Mauna Loa for which chemical analyses were not already available. Unaltered glassy pumice or spatter clots from source vents were collected where possible, because (1) they show most accurately the relations between preeruptive phenocryst minerals and magma and (2) the Fe_2O_3:FeO ratio of such samples is probably closest to the value which was characteristic of the magma prior to eruption. Samples also

[1] This empirical observation agrees well with the experimental work of Tilley and his co-workers. (See Thompson and Tilley, 1969, for a recent summary.) They show that clinopyroxene appears when the ratio of $(FeO + Fe_2O_3)$ to $(MgO + FeO + Fe_2O_3)$ in the liquid is about 0.625. Kilauea and Mauna lavas in which MgO is 6.8 percent have a ratio of about 0.620.

were collected from many of the freshest and most readily identified prehistoric vents on both Kilauea and Mauna Loa and from the walls of Kilauea caldera, Makaopuhi Crater (Kilauea), and Mokuaweoweo caldera (Mauna Loa).

The localities at which I collected samples are located on topographic maps (U.S. Geol. Survey 7½-min quad. ser.) by latitude and longitude (to the nearest minute) and elevation (table 23). Most localities for historic eruptions are shown on the geologic map of the Island of Hawaii (Stearns and Macdonald, 1946) and are identified by the date of the lava flow. More recent geologic maps which include flows sampled in this study are of the Kilauea Crater quadrangle (Peterson, 1967), Kau Desert quadrangle (Walker, 1969), and the Mauna Loa quadrangle (Macdonald, 1971). Unless otherwise noted, the samples were taken from mapped source vents or cones or from roadcuts. Additional information is given for other samples. The localities of samples taken from the walls of pit craters and calderas, or from the active lava lake in Halemaumau, are self-explanatory. Information on samples not collected by the author is contained in published references which are given in table 23.

In the course of this study, it was found that a few lava flows from Mauna Loa either are not identified or are mismapped on the geologic map of Hawaii (Stearns and Macdonald, 1946), the topographic sheets, or both. Evidence for these errors was initially obtained from study of high-altitude aerial photographs taken in 1954 and from helicopter and ground traverses of flows. Additional evidence was provided from chemical analyses. In all such situations, sufficient information is given in table 23 to enable re-collection at the same locality.

CHEMICAL ANALYSES

Table 23 lists samples of lavas from Kilauea and Mauna Loa which are cited in this paper and for which new analyses are given. Table 24 gives references to published analyses, some of which are included in this paper. All lavas considered in this study were analyzed in the Denver rock analysis laboratory of the U.S. Geological Survey under the direction of L. C. Peck. The estimated precision of the chemical data, precision being expressed as absolute weight percent oxide, is as follows:

$SiO_2 = \pm 0.04 - 0.08$	$Na_2O = \pm 0.02 - 0.045$
$Al_2O_3 = \pm 0.07 - 0.09$	$K_2O = \pm 0.015 - 0.02$
"FeO" [1] $= \pm 0.05 - 0.07$	$TiO_2 = \pm 0.03 - 0.045$
$MgO = \pm 0.05$	$P_2O_5 = \pm 0.005 - 0.01$
$CaO = \pm 0.03 - 0.08$	$MnO = 0.005$

[1] Total iron is calculated as FeO.

These precision figures were obtained empirically by comparing many analyses of single eruptions. The precision figures obtained in this way are somewhat lower than Peck's own estimates (L. C. Peck, 1964, p. 54). The conclusions of this paper rest on the assumption that, if two rocks differ in their chemical composition by more than twice the analytical precision in one or more constituents, the chemical difference must be explained by a petrological process or processes and is not a consequence of errors in the rock analysis.

COMPUTER REDUCTION OF CHEMICAL DATA

Three computer programs have been used in working with the chemical data.

1. Chemical data are plotted on magnesia variation diagrams using a computer-directed plotter. This program is written to plot any number of chemical oxides against a single oxide designated as the abscissa. The abscissa and ordinate scales are specified for each plot, as are the type and size of symbol for each data point. This program is titled "B844: Chemical Plot" and is available from the Computer Center Division, U.S. Geological Survey, Washington, D.C. 20242.
2. Differentiation calculations have been made by a computer program based on least squares and linear programing methods described by Wright and Doherty (1970). The operation of this program is similar to a computer program described by Bryan, Finger, and Chayes (1969) and by Chayes (1968). The program is available as "C129: Mineral Distribution" from the Computer Center Division, U.S. Geological Survey, Washington, D.C. 20242.
3. Mineral control lines for suites of related analyses have been computed using a program entitled "BmDo5R Polynomial Regression," which computes linear regressions of the form $y=ax+b$. (Dixon, 1968)

OBSERVATIONS

The following sections summarize the petrography and chemistry of lavas from Kilauea and Mauna Loa. The chemical data are plotted on MgO variation diagrams. For convenience in comparing different sets of lavas, average control lines have been computed and are plotted in some diagrams in place of the actual analyses. The data for the equation $y=ax+b$ to define these control lines are given in table 3. Figure 2 summarizes the chemical variability of Kilauea and Mauna Loa lavas on magnesia

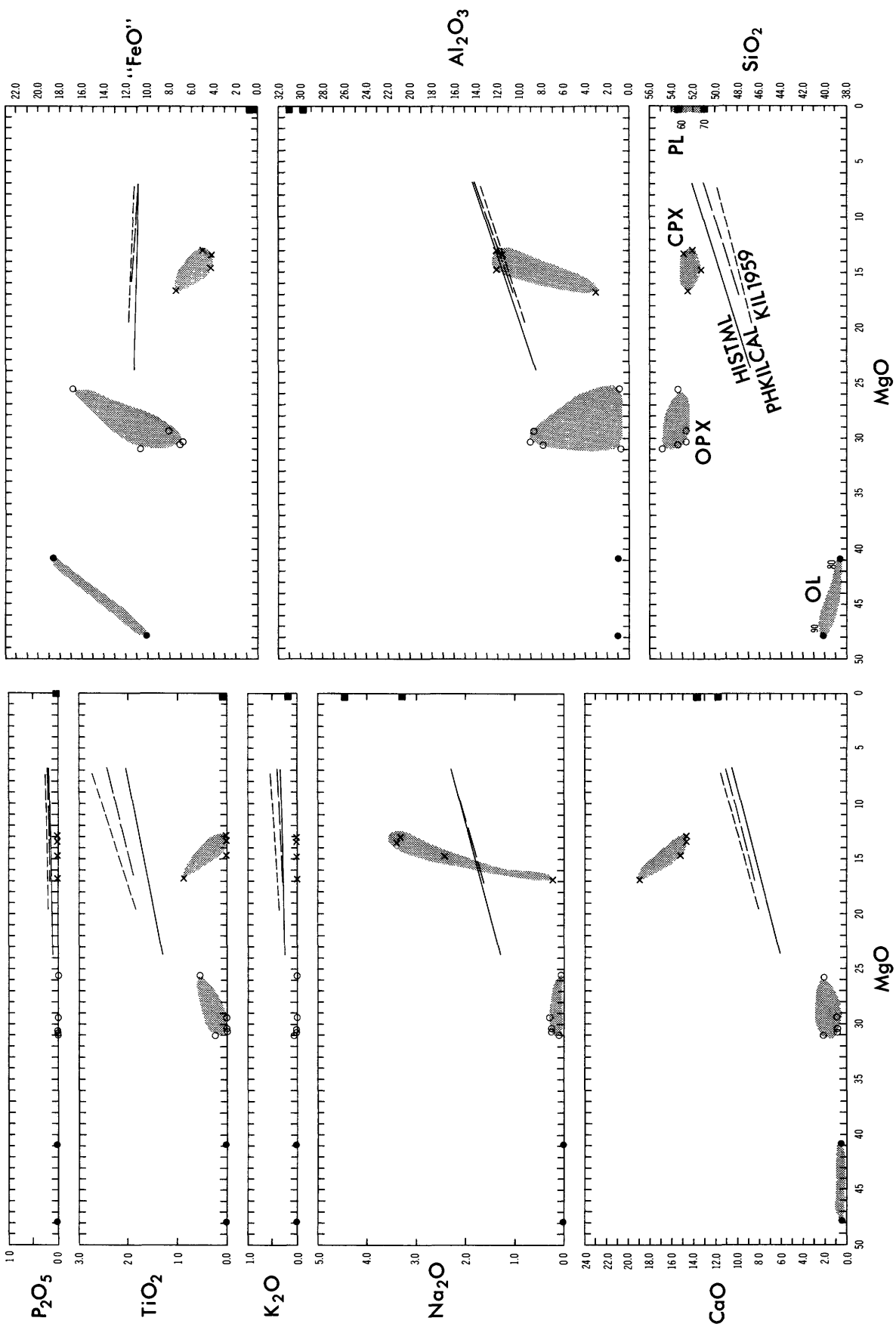

FIGURE 2.—MgO variation diagrams showing Mauna Loa and Kilauea lava flows and minerals that control the chemical variation. Solid line, all historic flows from Mauna Loa (HISTML of table 3); long dash line, prehistoric lavas, Kilauea caldera wall (PHKILCAL of table 3); short dash line, 1959 eruption of Kilauea (KIL1959 of table 3); ●, olivine (numbers give Fo content); ×, clinopyroxene; ■, plagioclase (number gives An content). Shaded area outlines mineral field.

TABLE 3.—*Data for equation* $y = ax + b$ *to define mineral control lines for suites of olivine-controlled lavas from Kilauea and Mauna Loa*

Lava suite	x (MgO mean and range, in parentheses)	y	a	b
Kilauea				
PHKILCAL: Olivine-controlled prehistoric lavas, Kilauea caldera and Hilina sections. 14 analyses are given in table 4.	9.29 (6.80–17.06)	SiO_2	−0.31687 ±.02126	+53.327
		Al_2O_3	−.35384 ±.02785	+16.585
		"FeO"	+.08139 ±.02986	+10.260
		CaO	−.26568 ±.01639	+13.044
		Na_2O	−.06463 ±.00474	+2.753
		K_2O	−.01185 ±.00287	+.497
		TiO_2	−.05665 ±.01244	+2.843
		P_2O_5	−.00502 ±.00139	+.259
PHSWPP: Prehistoric pahoehoe-picrite, southwest rift zone. 11 analyses are given in table 5.	13.76 (6.81–21.98)	SiO_2	−.30625 ±.00752	+53.227
		Al_2O_3	−.35024 ±.00649	+16.635
		"FeO"	+.07281 ±.01239	+10.394
		CaO	−.27761 ±.00833	+12.993
		Na_2O	−.05402 ±.00446	+2.718
		K_2O	−.01543 ±.00204	+.581
		TiO_2	−.06280 ±.00255	+2.868
		P_2O_5	−.00583 ±.00064	+.270
KIL1840: Olivine-controlled lavas of the 1840 eruption, east rift zone. 4 analyses given by Wright and Fiske (1971).	16.38 (14.18–17.54)	SiO_2	−.26643 ±.03596	+52.854
		Al_2O_3	−.34318 ±.00654	+16.359
		"FeO"	+.07719 ±.05572	+9.938
		CaO	−.31560 ±.03702	+13.800
		Na_2O	−.05091 ±.00799	+2.564
		K_2O	−.00468 ±.00546	+.427
		TiO_2	−.05152 ±.02515	+2.851
		P_2O_5	−.00152 ±.00237	+.210
KIL1959: 1959 eruption, Kilauea Iki Crater. 20 analyses are from Murata and Richter (1966a, table 1; unpub. data).	12.36 (7.23–19.55)	SiO_2	−.26637 ±.00469	+51.922
		Al_2O_3	−.32485 ±.00825	+15.945
		"FeO"	+.03520 ±.00297	+11.046
		CaO	−.28376 ±.00975	+13.674
		Na_2O	−.05948 ±.00164	+2.705
		K_2O	−.01458 ±.00142	+.658
		TiO_2	−.07162 ±.00282	+3.263
		P_2O_5	−.00708 ±.00034	+.324
Mauna Loa				
HISTML: All olivine-controlled lava flows of historic age. 33 analyses are given in tables 8–13.	8.75 (6.85–23.64)	SiO_2	−.31233 ±.01025	+54.260
		Al_2O_3	−.33847 ±.00715	+16.527
		"FeO"	+.02494 ±.00581	+10.747
		CaO	−.26347 ±.00501	+12.400
		Na_2O	−.05872 ±.00314	+2.702
		K_2O	−.00568 ±.00180	+.409
		TiO_2	−.04465 ±.00353	+2.380
		P_2O_5	−.00394 ±.00099	+.246

variation diagrams in which mineral compositions are plotted in addition to control lines for different suites of lavas. This figure is meant to aid the reader in following the description and interpretation of variations in lava chemistry.

Values of the ratio of K_2O:P_2O_5 have been computed for all analyses and are entered in the tables of analytical data. This ratio is important in evaluating the processes by which the lavas of each volcano have evolved. (See Anderson and Greenland, 1969, for a discussion of P_2O_5 as an indicator of fractionation.)

KILAUEA

OLIVINE-CONTROLLED LAVAS

PETROGRAPHY

Chromite-bearing olivine is the only phenocryst mineral in most Kilauea lavas. Commonly the lavas contain more than 15 percent modal olivine and are properly termed picrites or oceanites (Macdonald, 1949a). A few lavas contain more than 30 percent modal olivine. Lavas with low magnesia content may contain scarce phenocrysts of plagioclase and even scarcer phenocrysts of augite in addition to olivine. Hypersthene is not a phenocryst mineral in olivine-controlled lavas, but hypersthene phenocrysts are found in some differentiated lavas (Wright and Fiske, 1971), and hypersthene also occurs as a late crystallizing mineral in thick lava flows and intrusive bodies (Evans and Moore, 1968; Murata and Richter, 1961).

The three historic flows erupted in 1823, 1868, and 1919–20 from the southwest rift zone are unusual in having glomeroporphyritic clots of intergrown olivine, augite, and plagioclase. This texture is particularly well developed in the flows of 1823 and 1868. A similar texture also has been observed in lava from the later part of the 1967–68 eruption in Halemaumau lava lake (Kinoshita and others, 1969). The 1968 samples in which this texture was observed are from slow-moving flows that developed where the lava, which had been stored within the lake, oozed to the surface through cracks in the previously solidifed crust. Thus this texture can be attributed to cooling of the melt at shallow depth (that is, within the lake) prior to eruption to the surface. By analogy, the glomeroporphyritic clots in the 1823, 1868, and 1919–20 lavas may also have been caused by cooling and crystallization while stored within either the rift zone or shallow summit magma reservoir prior to eruption on the rift.

The groundmass of Kilauea flows consists of pigmented glass, augite, pigeonite, plagioclase, magnetite, ilmenite, and apatite. Olivine is often partly resorbed in crystallized flows. Olivine and clinopyroxene are zoned from magnesian cores to more iron-rich rims, and plagioclase shows increasing Na_2O:CaO ratios toward the outer parts of the crystals.

CHEMISTRY

Analyses of lavas from Kilauea are given in tables 4 through 6 and are plotted in figures 3 to 6 on MgO variation diagrams after normalization to 100 percent dry weight. "FeO" is total iron expressed as the sum of FeO and 0.9 Fe_2O_3, calculated after normalization of the analyses. The chemical data are

TABLE 4.—*Chemical analyses of olivine-controlled lavas from Kilauea summit*

[Additional sample data are given in table 23]

	Prehistoric														
	Hilina series					Puna series									
Sample	57F–18	57F–15	57F–17	57F–66	57F–97	53P–12	53P–32	53P–33	53P–35	53P–30	HIGS–2	8X002–0	8X038–0	8X067–0	8X078–0
SiO_2	49.63	48.53	49.40	50.59	50.77	50.98	50.52	50.73	50.94	51.47	51.52	51.04	51.11	49.07	47.97
Al_2O_3	13.76	11.15	12.46	13.20	13.46	13.75	13.82	13.74	14.04	14.53	14.10	14.30	14.67	12.28	10.48
Fe_2O_3	3.69	1.15	1.51	1.49	2.07	3.38	3.58	1.83	2.67	1.32	1.70	1.59	1.40	1.16	1.67
FeO	9.31	10.71	10.25	9.92	9.24	8.04	7.90	9.45	8.20	9.08	9.28	9.41	9.02	9.74	10.04
MgO	5.80	15.17	10.96	8.38	8.14	7.18	7.13	7.23	7.24	7.12	6.79	6.93	7.35	13.23	17.03
CaO	10.23	8.94	10.32	10.88	10.76	11.17	11.12	11.22	11.29	11.18	10.92	10.78	11.29	9.75	8.30
Na_2O	2.74	1.76	2.05	2.19	2.23	2.34	2.20	2.20	2.23	2.38	2.34	2.40	2.24	1.89	1.67
K_2O	.61	.33	.38	.39	.38	.43	.44	.46	.40	.39	.42	.46	.33	.30	.31
H_2O+	.20	.14	.25	.32	.07	.01	.26	.14	.11	.08	.08	.23	.05	.08	.14
H_2O-	.08	.03	.01	.04	.01	.05	.06	.02	.04	.01	.03	.04	.03	.04	.04
TiO_2	3.49	1.91	2.21	2.40	2.51	2.52	2.65	2.62	2.46	2.25	2.37	2.43	2.10	2.00	1.98
P_2O_5	.35	.18	.22	.23	.24	.23	.23	.22	.21	.20	.23	.24	.19	.17	.18
MnO	.19	.18	.18	.18	.17	.17	.17	.17	.16	.16	.17	.17	.17	.17	.17
CO_2	.02	.01	.02	.02	.02	.00	.01	.01	.00	.00	.02	.00	.00	.00	.01
Cl	-----	-----	-----	-----	-----	-----	-----	-----	-----	-----	.01	.02	.01	.01	.01
F	-----	-----	-----	-----	-----	-----	-----	-----	-----	-----	.03	.04	.03	.04	.03
Subtotal	-----	-----	-----	-----	-----	-----	-----	-----	-----	-----	100.01	100.08	99.99	99.93	100.03
Less O	-----	-----	-----	-----	-----	-----	-----	-----	-----	-----	.01	.02	.01	.02	.01
Total	100.10	100.19	100.22	100.23	100.07	100.25	100.09	100.04	99.99	100.17	100.00	100.06	99.98	99.91	100.02
$K_2O:P_2O_5$	1.74	1.83	1.73	1.69	1.59	1.87	1.91	2.09	1.90	1.95	1.83	1.92	1.74	1.76	1.82

Date	1790	1832	1866 (?)	1868	1877		1879	1884–85	1889	1911	1917	1918	1919		1921
					Caldera	Keanakakoi							Glass	Flow	
Sample	-----	-----	-----	-----	-----	-----	53P–9	53P–1	53P–2	-----	-----	-----	-----	-----	-----
SiO_2	50.52	50.23	50.57	50.57	50.70	50.46	50.41	50.36	49.97	49.67	50.08	50.02	50.02	50.20	50.04
Al_2O_3	13.35	13.50	14.26	13.88	13.76	13.96	14. 8	14.02	13.69	13.61	13.73	13.87	13.87	14.04	13.68
Fe_2O_3	1.66	3.08	2.18	1.80	5.54	1.84	1.98	2.82	1.38	1.35	1.32	1.23	1.35	1.83	2.29
FeO	10.15	8.06	9.11	9.50	6.21	9.20	9.31	8.68	9.63	9.76	9.79	9.86	9.76	9.50	9.05
MgO	8.29	8.49	6.61	7.37	7.42	7.38	6.88	7.12	8.33	8.84	7.89	7.77	7.45	7.03	7.61
CaO	10.04	10.89	11.19	10.99	10.69	11.29	11.22	11.10	11.23	10.95	11.50	11.42	11.45	11.49	11.38
Na_2O	2.25	2.18	2.41	2.27	2.28	2.26	2.32	2.18	2.21	2.22	2.18	2.23	2.33	2.25	2.24
K_2O	.45	.45	.50	.44	.41	.48	.52	.50	.48	.48	.56	.53	.53	.57	.57
H_2O+	.23	.14	.01	.07	.16	.10	.07	.13	.06	.02	.00	.06	.08	.01	.00
H_2O-	.05	.03	.02	.02	.04	.03	.05	.02	.03	.03	.02	.02	.02	.02	.02
TiO_2	2.63	2.44	2.70	2.46	2.42	2.61	2.78	2.64	2.54	2.63	2.60	2.63	2.70	2.74	2.76
P_2O_5	.25	.24	.26	.25	.23	.25	.26	.25	.23	.25	.26	.26	.26	.27	.27
MnO	.18	.17	.17	.17	.17	.17	.17	.18	.17	.17	.17	.17	.17	.17	.17
CO_2	.01	.04	.03	.01	.01	.01	.00	.00	.00	.00	.01	.02	.02	.02	.06
Cl	.01	.01	.01	.01	.01	.01	-----	.01	.01	.01	.00	.01	.02	-----	-----
F	.04	.04	.04	.04	.04	.04	-----	.04	.03	.04	-----	.04	.04	-----	-----
Subtotal	100.11	99.99	100.07	100.03	100.09	100.09	-----	100.05	99.99	100.03	-----	100.14	100.07	-----	-----
Less O	.02	.02	.02	.02	.02	.02	-----	.02	.01	.02	-----	.02	.02	-----	-----
Total	100.09	99.97	100.05	100.01	100.07	100.07	100.05	100.03	99.98	100.01	100.11	100.12	100.05	100.14	100.14
$K_2O:P_2O_5$	1.80	1.87	1.92	1.76	1.78	1.92	2.00	2.00	2.08	1.92	2.15	2.04	2.06	2.11	2.11

Date	1924	1931–32	1952	1954		1959			1961		November 1967–July 1968				
									February	July[1]					
Sample	-----	1931HM	1952HM	-----	TLW67–42	S–1	S–2	Average[2]	-----	-----	1967HM	HM68–2	HM68–4	HM68–12	HM68–15
SiO_2	49.73	49.71	50.01	50.20	50.09	49.91	50.07	47.90	50.22	50.38	50.24	50.18	50.48	50.24	50.25
Al_2O_3	13.66	13.58	13.83	13.73	13.79	13.00	13.70	10.96	13.64	13.69	13.56	13.63	13.52	13.70	13.61
Fe_2O_3	1.19	2.48	1.85	2.65	1.80	2.56	1.39	11.51	1.29	1.38	1.36	1.66	1.49	1.61	1.49
FeO	9.72	9.03	9.59	8.80	9.59	8.86	10.00		9.63	9.60	9.95	9.72	9.95	9.77	9.86
MgO	8.24	7.46	7.10	7.20	7.31	8.08	7.23	15.42	7.74	7.52	7.59	7.63	7.41	7.58	7.63
CaO	11.60	11.58	11.29	11.56	11.51	11.92	11.55	9.33	11.34	11.34	11.06	11.02	11.08	11.17	11.14
Na_2O	2.26	2.26	2.25	2.25	2.28	2.13	2.30	1.79	2.32	2.33	2.31	2.25	2.31	2.29	2.32
K_2O	.54	.53	.53	.57	.53	.55	.60	.44	.55	.54	.54	.54	.52	.53	.55
H_2O+	.06	.12	.09	.00	.08	.09	.00	-----	.04	.02	.04	.10	.04	.02	.06
H_2O-	.02	.00	.12	.00	.02	.02	.02	-----	.04	.01	.01	.01	.02	.00	.00
TiO_2	2.68	2.78	2.71	2.72	2.68	2.62	2.75	2.16	2.76	2.77	2.65	2.57	2.69	2.62	2.62
P_2O_5	.25	.25	.27	.28	.26	.25	.28	.23	.27	.27	.26	.25	.28	.25	.26
MnO	.17	.17	.17	.17	.17	.17	.17	.18	.17	.17	.17	.17	.17	.17	.17
CO_2	.01	.00	.00	.01	.01	.01	.00	-----	.01	.01	.01	.01	.02	.01	.00
Cl	.02	.02	-----	.02	.01	.02	.02	-----	.02	.02	.01	.01	.01	.01	.02
F	.04	.06	-----	.05	.05	.04	.04	-----	.04	.04	.03	.05	.04	.04	.06
Subtotal	100.19	100.03	-----	100.21	100.18	100.23	100.12	-----	100.08	100.09	99.79	99.80	100.03	100.01	100.03
Less O	.02	.03	-----	.02	.02	.02	.02	-----	.03	.02	.01	.02	.02	.02	.03
Total	100.17	100.00	99.81	100.19	100.16	100.21	100.10	100.00	100.05	100.07	99.78	99.78	100.01	99.99	100.00
$K_2O:P_2O_5$	2.16	2.12	1.96	2.04	2.04	2.20	2.14	1.91	2.04	2.00	2.08	2.16	1.85	2.12	2.11

[1] Average of three analyses (Richter and others, 1964, table 1).

[2] Weighted average of the entire eruption converted to 100 percent dry weight. Data from Murata and Richter (1966a) and Richter and Moore (1966).

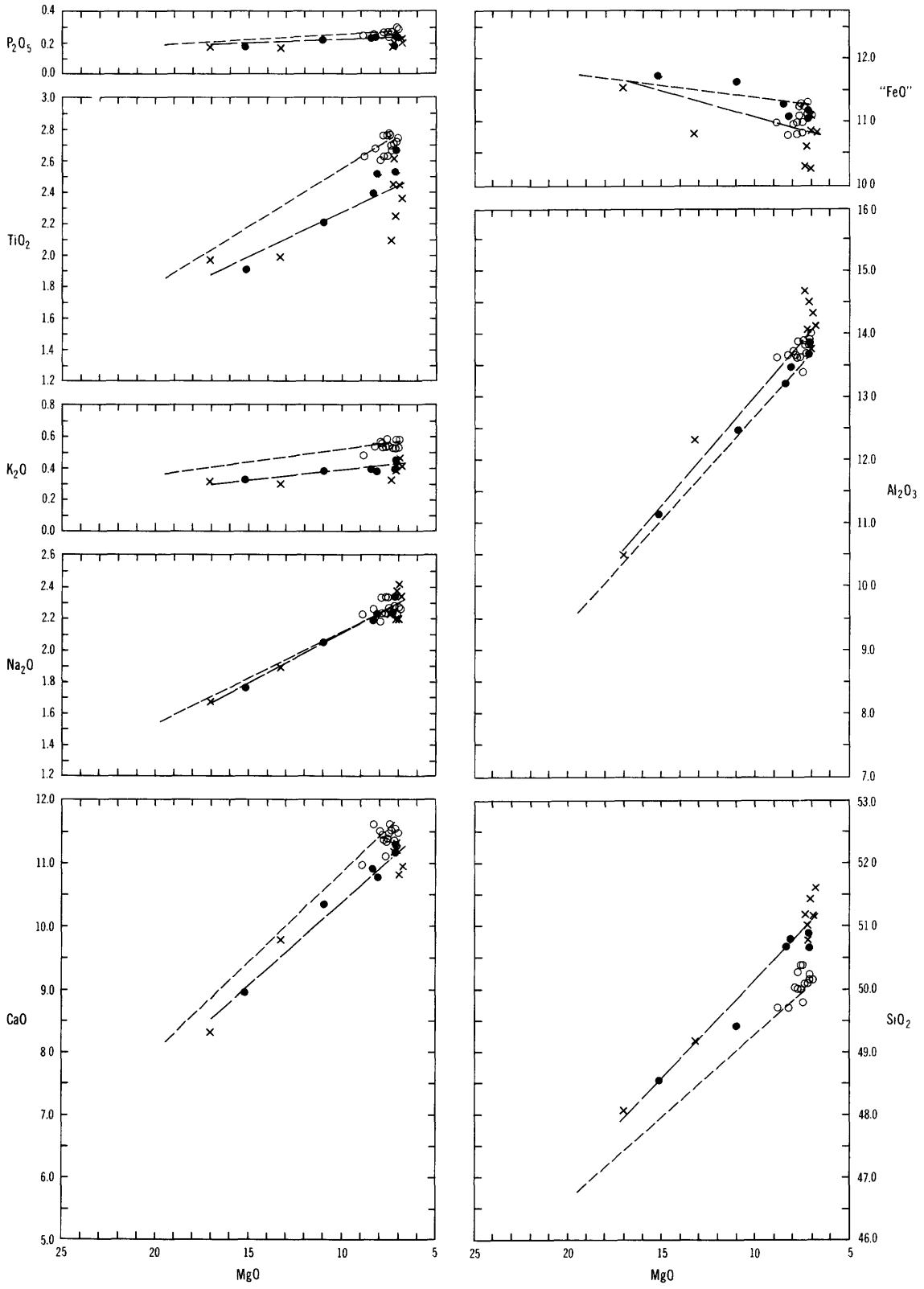

FIGURE 3.—MgO variation diagrams showing lavas erupted at Kilauea summit. Analyses are given in table 4. Control lines are as shown in figure 2. ●, prehistoric lavas, Hilina Pali; ×, prehistoric lavas, Kilauea caldera; ○, 20th century lavas (except 1959), Kilauea caldera. Analyses are plotted after normalization to 100 percent dry weight.

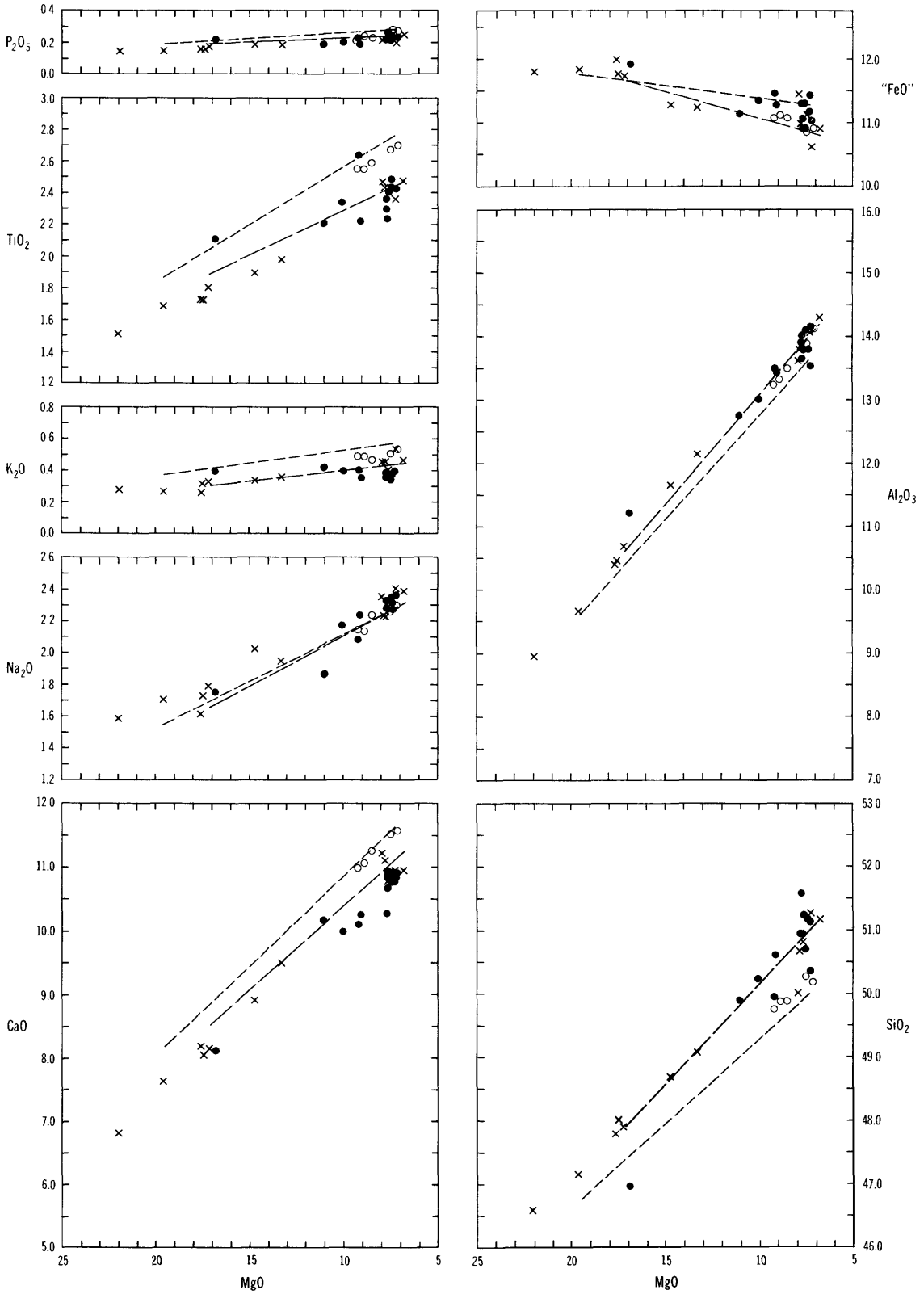

FIGURE 4.—MgO variation diagrams showing lavas erupted from the Kilauea southwest rift zone. Analyses are given in table 5. Control lines are as shown in figure 2. ×, prehistoric regional pahoehoe picrite; ●, younger prehistoric lavas; ○, 1920 lava.

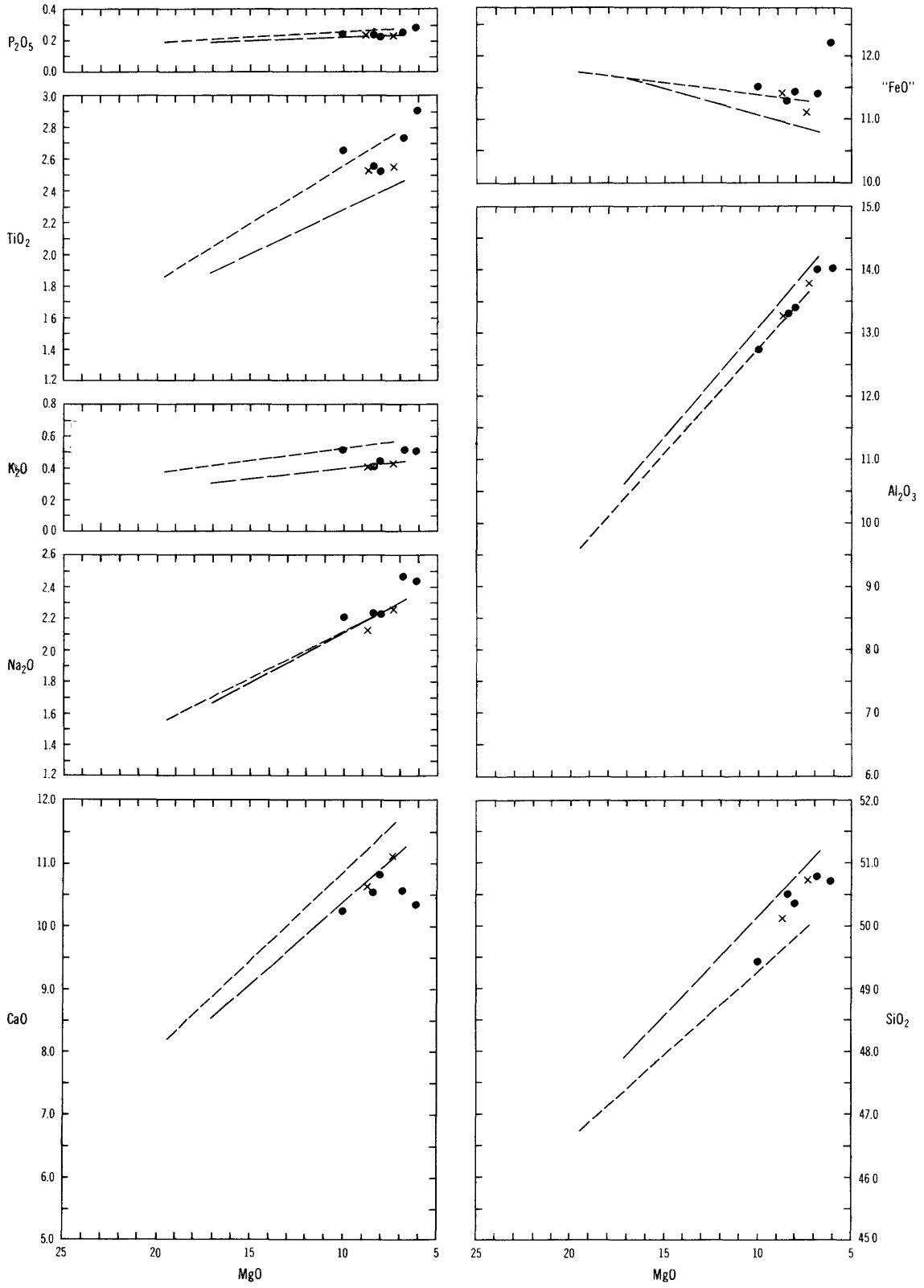

FIGURE 5.—MgO variation diagrams showing lavas erupted from the Kilauea east rift zone. Analyses are given in table 6. Control lines are as shown in figure 2. Analyses of historic eruptions and young submarine eruptions are given in Wright and Fiske (1971). ×, prehistoric Makaopuhi lava lake chill zone (Moore and Evans, 1967); ●, other prehistoric (subaerial) flows.

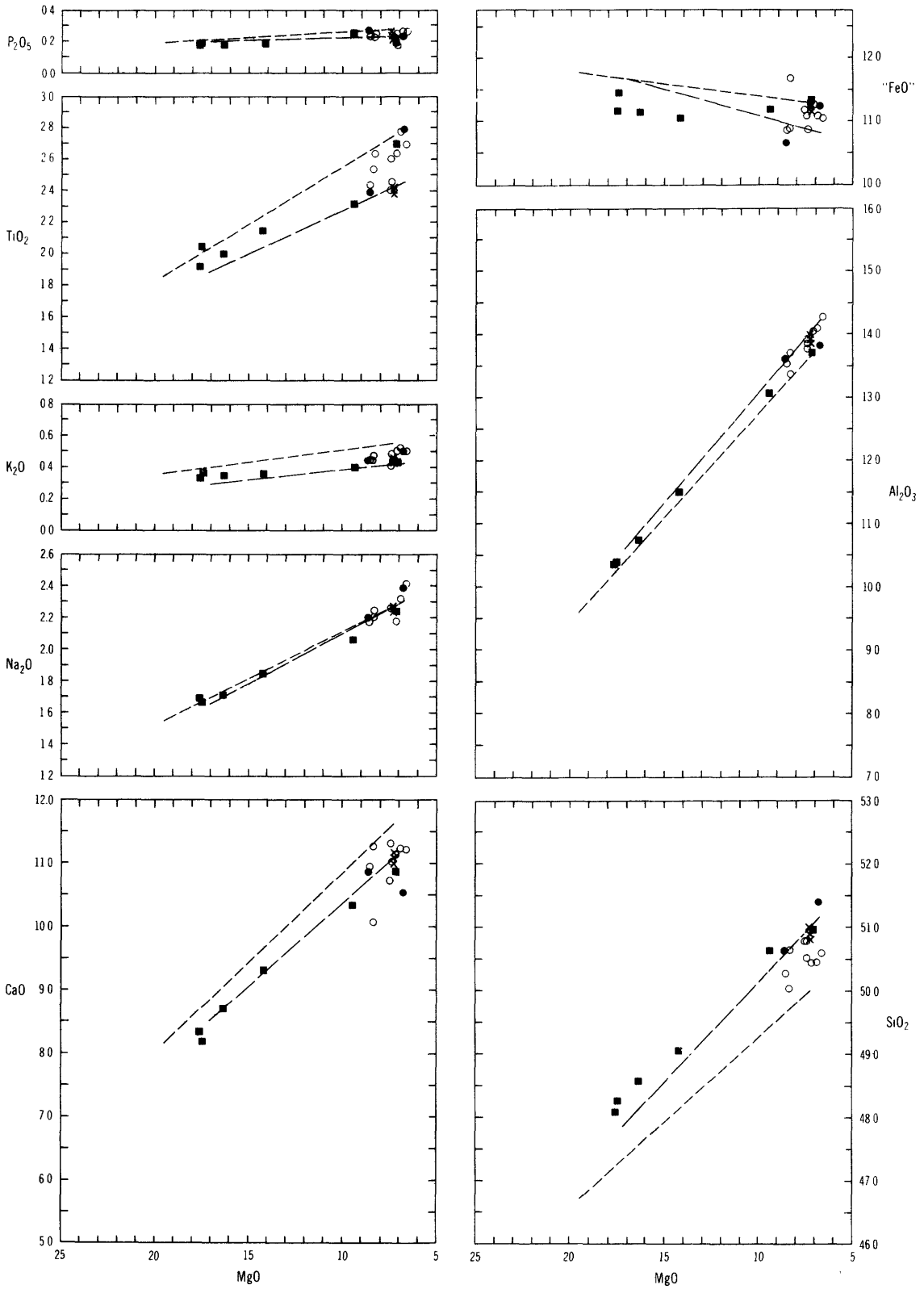

FIGURE 6.—MgO variation diagrams showing Kilauea lavas erupted in 18th and 19th centuries. Analyses are gives in tables 4 and 5 and Wright and Fiske, 1971 (1840 east rift ruption). Control lines are as shown in figure 2. ○, Kilauea caldera 1790–1894; ●, 1868 eruption, southwest rift zone; ×, 1823 eruption, southwest rift zone; ■, 1790 and 1840 eruptions, east rift zone.

TABLE 5.—*Chemical analyses of olivine-controlled lavas from Kilauea southwest rift zone*

[Additional sample data are given in table 23]

	Prehistoric											
					Regional pahoehoe-picrite complex							
Sample	TLW67-138A	TLW67-139	TLW67-140	TLW67-128	TLW67-134	TLW67-136B	TLW67-3	KD-3	KD-32	KD-56	KD-57	KD-91
SiO_2	46.60	49.48	50.05	51.08	51.08	48.60	47.83	51.15	46.57	49.06	47.88	50.21
Al_2O_3	11.12	13.38	12.96	13.76	14.28	11.63	10.39	14.11	8.95	12.14	10.67	13.67
Fe_2O_3	2.84	2.41	1.44	1.37	1.51	1.23	1.43	1.91	1.56	1.06	1.09	1.69
FeO	9.27	9.18	10.00	9.90	9.49	10.14	10.44	8.86	10.38	10.28	10.74	9.95
MgO	16.73	9.11	9.99	7.38	6.80	14.72	17.43	7.20	21.97	13.30	17.20	7.95
CaO	8.05	10.01	9.94	10.78	10.91	8.89	8.01	10.88	6.81	9.50	8.13	11.26
Na_2O	1.74	2.07	2.16	2.32	2.39	2.03	1.73	2.39	1.59	1.95	1.79	2.36
K_2O	.40	.40	.40	.40	.47	.34	.32	.54	.28	.36	.33	.45
H_2O+	.55	.65	.12	.12	.18	.19	.11	.15	.16	.12	.16	.04
H_2O-	.03	.08	.04	.05	.03	.02	.03	.05	.03	.01	.00	.00
TiO_2	2.09	2.62	2.33	2.41	2.48	1.90	1.73	2.36	1.52	1.98	1.81	2.48
P_2O_5	.22	.24	.21	.22	.25	.19	.16	.21	.15	.19	.18	.22
MnO	.17	.18	.17	.17	.17	.17	.17	.16	.17	.16	.17	.17
CO_2	.01	.01	.01	.01	.00	.00	.01	.01	.01	.00	.00	.00
Cl	.01	.01	.01	.01	.01	.01	.01	.00	.01	.00	.00	.01
F	.03	.03	.02	.04	.04	.03	.03	.03	.02	.03	.03	.03
Subtotal	99.86	99.86	99.85	100.02	100.09	100.09	99.83	100.00	100.18	100.14	100.18	100.49
LessO	.01	.01	.01	.02	.02	.01	.01	.01	.01	.01	.01	.01
Total	99.85	99.85	99.84	100.00	100.07	100 08	99.82	99.99	100.17	100.13	100.17	100.48
$K_2O:P_2O_5$	1.82	1.67	1.90	1.82	1.88	1.79	2.00	2.57	1.87	1.89	1.83	2.05

	Prehistoric—Continued												
	Regional pahoehoe-picrite complex—Continued				Regional pahoehoe(-)		Younger flows						
Sample	TLW67-129	KD-143	KD-144	TLW67-10	KD-164	KD-172	KD-45	KD-161	TLW67-16	CC-SW	TLW67-18	TLW67-28	KD-130
SiO_2	47.32	47.69	50.76	50.64	49.83	50.96	51.12	50.54	50.30	51.11	51.15	50.52	50.90
Al_2O_3	9.69	10.38	13.81	13.79	12.72	14.04	14.05	14.05	13.51	13.75	13.52	13.41	13.92
Fe_2O_3	1.34	1.08	1.33	1.38	1.57	1.46	1.23	1.65	11.06	1.25	2.23	1.15	1.24
FeO	10.67	10.98	10.08	9.72	9.72	9.61	9.90	9.61	1.46	9.92	9.18	10.22	9.79
MgO	19.68	17.56	7.64	7.79	11.04	7.70	7.32	7.47	7.28	7.62	7.65	9.10	7.72
CaO	7.66	8.15	10.75	11.10	10.14	10.92	10.85	10.85	10.75	10.63	10.17	10.23	10.87
Na_2O	1.72	1.62	2.27	2.24	1.87	2.26	2.29	2.34	2.36	2.28	2.22	2.24	2.32
K_2O	.27	.26	.42	.46	.42	.39	.40	.34	.40	.41	.36	.36	.41
H_2O+	.06	.16	.24	.07	.18	.00	.07	.32	.07	.13	.47	.14	.00
H_2O-	.00	.03	.02	.02	.01	.00	.01	.01	.02	.06	.26	.05	.04
TiO_2	1.70	1.73	2.40	2.43	2.21	2.30	2.42	2.48	2.36	2.40	2.22	2.22	2.37
P_2O_5	.15	.16	.22	.23	.19	.23	.23	.23	.23	.23	.22	.20	.22
MnO	.17	.17	.17	.17	.17	.17	.17	.17	.17	.17	.16	.17	.17
CO_2	.00	.01	.01	.01	.01	.01	.01	.00	.00	.01	.01	.01	.00
Cl	.00	.00	.01	.01	.01	.01	.01	.01	.00	.01	.01	.01	.01
F	.03	.02	.03	.04	.03	.03	.04	.04	.03	.03	.04	.03	.03
Subtotal	100.46	100.00	100.16	100.10	100.12	100.09	100.12	100.11	100.00	100.01	99.87	100.06	100.01
Less O	.01	.01	.01	.01	.01	.01	.02	.02	.01	.01	.02	.01	.01
Total	100.45	99.99	100.15	100.08	100.11	100.08	100.10	100.09	99.99	100.00	99.85	100.05	100.00
$K_2O:P_2O_5$	1.80	1.63	1.91	2.00	2.21	1.70	1.74	1.48	1.74	1.78	1.64	1.80	1.86

Date	1823			1868		1920				
Sample	A-451	1823-SW	TLW67-24	1868-SW	TLW67-12	1920-231-3	TLW67-1	TLW67-4	TLW67-6	TLW67-9
SiO_2	50.88	50.77	50.87	50.63	51.35	50.18	49.85	49.74	50.21	49.82
Al_2O_3	13.84	13.87	13.88	13.61	13.81	14.12	13.48	13.23	13.87	13.32
Fe_2O_3	.76	2.08	1.36	1.56	1.13	1.17	1.22	1.36	1.24	1.39
FeO	10.50	9.28	9.90	9.27	10.22	9.86	9.97	9.85	9.72	9.86
MgO	7.24	7.27	7.27	8.61	6.78	7.14	8.49	9.21	7.48	8.88
CaO	11.15	11.06	10.93	10.86	10.52	11.57	11.24	10.99	11.50	11.04
Na_2O	2.27	2.27	2.27	2.20	2.39	2.30	2.24	2.15	2.28	2.14
K_2O	.43	.46	.43	.45	.50	.53	.47	.49	.51	.49
H_2O+	.11	.13	.19	.10	.10	.07	.03	.02	.03	.09
H_2O-	.03	.03	.03	.02	.00	.02	.00	.01	.01	.01
TiO_2	2.42	2.41	2.42	2.39	2.80	2.70	2.59	2.55	2.68	2.55
P_2O_5	.24	.24	.22	.27	.24	.26	.23	.23	.25	.24
MnO	.18	.18	.17	.17	.17	.17	.17	.17	.17	.17
CO_2	.01	.01	.01	.01	.01	.01	.03	.00	.01	.01
Cl	.01	.01	.01	.01	.01	.01	.01	.00	.01	.01
F	.03	.04	.04	.03	.04	.04	.04	.04	.04	.04
Subtotal	100.10	100.11	100.00	100.19	100.07	100.15	100.06	100.04	100.01	100.06
Less O	.01	.02	.02	.01	.02	.02	.02	.02	.02	.02
Total	100.09	100.09	99.98	100.18	100.05	100.13	100.04	100.02	99.99	100.04
$K_2O:P_2O_5$	1.79	1.92	1.95	1.67	2.08	2.04	2.04	2.13	2.04	2.04

grouped according to the age of the lava and the location of the vents from which the lava was erupted. Chemical variation within each group of lavas is approximately linear on these plots. The slopes of the lines are negative with the exception of the FeO-MgO plot. The control lines for different groups of lavas have similar slopes, but many of the lines are displaced relative to one another on one or

TABLE 6.—*Chemical analyses of olivine-controlled lavas of prehistoric age from Kilauea east rift zone*

[Additional sample data are given in table 23. Olivine-controlled lavas of historic age were erupted in 1790(-) and in 1840. Analyses of these lavas are given in Wright and Fiske (1971, table 4)]

			Makaopuhi Crater wall			Makaopuhi lava lake chill zone
Sample	TLW67–39	TLW67–40	TLW67–130	TLW67–131	TLW67–132A	MP–57
SiO_2	50.75	50.49	50.57	49.40	50.43	50.02
Al_2O_3	14.00	13.30	14.00	12.74	13.44	13.24
Fe_2O_3	2.13	2.55	2.31	1.50	2.53	3.19
FeO	9.49	9.00	10.10	10.17	9.17	8.55
MgO	6.85	8.45	6.11	10.04	8.09	8.71
CaO	10.54	10.54	10.31	10.23	10.83	10.61
Na_2O	2.47	2.25	2.43	2.21	2.24	2.13
K_2O	.51	.41	.51	.52	.45	.41
H_2O+	.14	.11	.34	.07	.04	.15
H_2O-	.00	.03	.02	.02	.01	.08
TiO_2	2.75	2.56	2.91	2.67	2.53	2.53
P_2O_5	.26	.24	.28	.25	.23	.24
MnO	.18	.17	.18	.17	.17	.18
CO_2	.00	.00	.00	.00	.01	.00
Cl	.01	.00	.01	.01	.00	.01
F	.04	.03	.04	.04	.03	.04
Subtotal	100.12	100.13	100.12	100.04	100.20	100.09
Less O	.02	.01	.02	.02	.01	.02
Total	100.10	100.12	100.10	100.02	100.19	100.07
$K_2O:P_2O_5$	1.96	1.71	1.82	2.08	1.96	1.71

more graphs. Three general time-related chemical groupings are apparent, when compositions at any given MgO content are compared: 1911–present, 1750–1894, and prehistoric (older than 1750). On many of the oxide plots, the 20th century and prehistoric lavas are distinguished with little or no overlapping of data points (figs. 3 and 4). The composition of lavas erupted in the late 18th and throughout the 19th century lies generally between these two groups, but many data points fall within the range of prehistoric or 20th century compositions on one or more of the oxide plots (fig. 6).

There are two exceptions to the general time-related variation. Olivine-rich spatter from Puu Kolekole, a prehistoric cone on the southwest rift zone (TLW 67–138A, table 5, plotted in fig. 4 at MgO equals 16.86), has a chemistry which falls on the 20th century olivine control line on many of the MgO plots. The 1840 eruption on the east rift zone (fig. 6) stands out by having higher SiO_2 and lower FeO than other 19th century lavas and most of the lavas in the prehistoric sections.

Within the three time-groupings, lava chemistry can be compared as a function of vent location. The chemistry of prehistoric lavas erupted at the summit and on the southwest rift zone is sufficiently similar (figs. 3 and 4) that an unambiguous correlation of composition with eruptive vents is not possible. Likewise, historic lavas erupted in the same time span at Kilauea summit and from the southwest rift zone proper have a similar chemistry (figs. 3, 4, and 6). The Hilina-Pali-Kilauea caldera prehistoric lavas and the lavas of the 1959 eruption (fig. 3) are close to the extremes of the time-related chemical variation in olivine-controlled Kilauea lavas.

The relations observed for the southwest rift lavas do not hold for the east rift lavas. Some lavas of prehistoric age and all but two of the historic lavas may be chemically distinguished from lavas erupted at the summit and on the southwest rift zone within the same general time span (Aramaki and Moore, 1969; Wright and Fiske, 1971). The chemistry of east rift lavas is controlled by a complicated differentiation pattern superimposed on the time-related chemical changes. This differentiation pattern is described and interpreted in a separate paper (Wright and Fiske, 1971).

DIFFERENTIATED LAVAS

The composition of typical differentiated lavas from Kilauea is described elsewhere (Wright and Fiske, 1971). Two additional lavas, one of prehistoric and one of historic age (table 4, analysis 57F–18, and table 5, analysis TLW67–12), fit the definition of differentiated lava for the present study (MgO is less than 6.8 percent). TLW67–12 is an exceptionally glassy sample of the 1868 eruption; its chemical composition is related to that of a more normal porphyritic sample of the same eruption by removal of the observed phenocryst assemblage olivine-augite-plagioclase. 57F–18 has a peculiar

TABLE 7.—*Modal data for selected porphyritic lavas from Mauna Loa*

Date	1843			1881		1887		1907	1950
Sample	TLW67-66 [1]	W-A-22 [1]	W-A-23 [1]	TLW67-64 [2]	W-A-6 [2]	TLW67-58 [2]	TLW67-59 [3]	TLW67-56 [3]	TLW67-75 [3]
Phenocrysts:[4]									
Olivine	0	0	0.20	0.35	2.60	0	0	0.05	0.60
Hypersthene	.35	.35	0	.20	1.00	1.95	1.40	.40	.55
Augite	1.35	1.55	.40	0	.45	1.1	2.45	.70	.30
Plagioclase	2.80	3.00	1.25	0	.30	1.05	.55	.65	.05
Total	4.50	4.90	1.85	.55	4.35	4.10	4.40	1.80	1.50
Microphenocrysts:[4]									
Olivine	Trace	0	.60	.05	.05	.85	.45	.10	.55
Hypersthene	0	0	0	.40	.65	.15	0	.10	.05
Augite	1.00	1.80	3.70	.45	3.90	3.95	1.05	6.65	1.05
Plagioclase	.90	3.90	3.90	0	5.95	1.40	1.30	5.05	1.20
Total	1.90	5.70	8.20	.90	10.55	6.35	2.80	11.90	2.85
Glass [4]	.00	.00	86.70	98.15	.00	77.95	84.65	83.40	94.10
Quench [4]	93.60	89.40	3.25	.40	85.10	11.60	8.15	2.90	1.55
Total	93.60	89.40	89.95	98.55	85.10	89.55	92.80	86.30	95.65
Grand total	100.00	100.00	100.00	100.00	100.00	100.00	100.00	100.00	100.00
Number of points (0.3×0.3mm grid)	2785	2700	2000	2000	3000	2000	2000	2000	3000

[1] Chemical analysis given in table 13.
[2] No chemical analysis available for these particular samples. TLW67-64 is probably equivalent in composition to sample (1881–10,000 ft) in table 10; TLW67-58 is probably equivalent in composition to TLW67-59.
[3] Chemical analysis given in table 9.
[4] Modal counting was subdivided as follows:
Phenocrysts: Euhedral crystals generally in excess of 1 mm in the longest dimension which can be inferred to be present in the magma chamber prior to eruption to the surface.
Microphenocrysts: Euhedral crystals smaller than 1 mm in largest dimension which may have grown during ascent of magma to the surface.
Glass: Transparent, isotropic quenched liquid.
Quench: Fine skeletal or fibrous microlites that are presumed to have formed during cooling after extrusion on the surface.

chemistry that cannot be ascribed to processes of either fractionation or mixing of magmas as described by Wright and Fiske (1917). Its origin remains problematical.

MAUNA LOA

OLIVINE-CONTROLLED LAVAS

PETROGRAPHY

Olivine is commonly the dominant phenocryst mineral in lavas from Mauna Loa, and, like Kilauea, modal olivine ranges from trace amounts to more than 30 percent. In contrast to Kilauea, phenocrysts of olivine are generally accompanied by phenocrysts of hypersthene, augite, and plagioclase. Such lavas are especially common on the southwest rift zone. Some glassy samples also contain quench (?) crystals of pigeonite distinguished by a low optic angle, extreme undulatory extinction, and acicular habit. The rims of pyroxene and plagioclase phenocrysts tend to be strongly zoned toward more iron-rich and more sodic compositions, respectively. Modal data for selected porphyritic flows other than picrites are summarized in table 7.

The groundmass of Mauna Loa flows consists of pigmented glass, augite, pigeonite, plagioclase, magnetite, ilmenite, and apatite. Olivine shows irregular, embayed borders against the groundmass. Hypersthene phenocrysts are invariably rimmed by augite (Muir and Long, 1965), even in rapidly quenched glassy samples, and hyersthene is not found as a constituent of the groundmass.

CHEMISTRY

Chemical analyses of olivine-controlled Mauna Loa lavas are given in tables 8 through 12 and are plotted in figures 7 through 10 according to age and location on the volcano.

The Mauna Loa analyses define control lines whose slopes are similar to those defined by analyses of lava suites from Kilauea. MgO also covers approximately the same range as Kilauea, from under

TABLE 8.—*Chemical analyses of olivine-controlled lavas from Mauna Loa summit*

[Additional sample data are given in table 23]

	Prehistoric,					
Sample	7D-014	7D-026	7D-420	7D-428	TLW67-84	TLW67-70B
SiO_2	49.05	51.71	52.02	51.75	48.99	52.03
Al_2O_3	10.60	14.10	14.29	13.76	10.86	14.20
Fe_2O_3	1.34	4.62	2.60	2.34	1.75	1.60
FeO	10.00	6.55	8.69	8.68	9.36	9.25
MgO	16.90	6.70	6.13	7.34	16.22	6.92
CaO	7.97	10.52	10.24	10.20	8.19	10.50
Na_2O	1.70	2.22	2.33	2.32	1.80	2.33
K_2O	.29	.43	.52	.47	.32	.46
H_2O+	.14	.44	.33	.31	.11	.09
H_2O-	.02	.07	.04	.05	.01	.05
TiO_2	1.65	2.16	2.27	2.10	1.75	2.12
P_2O_5	.16	.22	.26	.27	.17	.25
MnO	.17	.17	.17	.17	.17	.17
CO_2	.01	.00	.02	.00	.01	.01
Cl	.00	.01	.01	.01	.01	.01
F	.04	.03	.05	.04	.02	.03
Subtotal	100.04	99.95	99.97	99.81	99.74	100.02
Less O	.02	.01	.02	.02	.01	.01
Total	100.02	99.94	99.95	99.79	99.73	100.01
$K_2O:P_2O_5$	1.81	1.95	2.00	1.74	1.88	1.84

TABLE 8.—*Chemical analyses of olivine-controlled lavas from Mauna Loa summit*—Continued

Date	1877(?)	1880(?)	1940	1942	1949a	1949b
Sample	TLW67-88	TLW67-89	1940ML	TLW67-68	M-56-2	1949ML
SiO_2	52.09	51.26	52.01	51.87	52.16	52.04
Al_2O_3	14.29	12.76	14.09	14.11	14.13	13.94
Fe_2O_3	1.58	1.25	1.46	1.50	1.12	1.58
FeO	9.25	10.08	9.77	9.63	9.90	9.69
MgO	6.84	10.73	7.04	7.11	7.07	7.14
CaO	10.61	9.35	10.74	10.51	10.53	10.63
Na_2O	2.32	2.08	2.23	2.23	2.27	2.25
K_2O	.41	.30	.35	.36	.40	.33
H_2O+	.14	.01	.02	.06	.02	.01
H_2O-	.03	.03	.00	.01	.00	.02
TiO_2	2.01	1.74	2.08	2.03	2.04	2.05
P_2O_5	.23	.23	.24	.21	.21	.26
MnO	.16	.17	.18	.17	.17	.18
CO_2	.00	.01	.00	.01	.00	.00
Cl	.01	.01	.00	.01	-----	.01
F	.03	.02	-----	.04	.02	-----
Subtotal	100.00	100.03	-----	99.86	100.04	-----
Less O	.01	.01	-----	.02	.01	-----
Total	99.99	100.02	100.21	99.84	100.03	100.13
$K_2O:P_2O_5$	1.78	1.30	1.46	1.71	1.91	1.27

TABLE 9.—*Chemical analyses of olivine-controlled lavas from Mauna Loa south rift zone*

[Additional sample data are given in table 23]

	Prehistoric						
	Kahuku Series		Kau Series				Submarine lavas
Sample	E2145	E2146	C819	C820	65MAN-1	65KUH-2	13
SiO_2	51.25	50.87	46.19	48.71	50.26	51.34	48.50
Al_2O_3	13.66	13.12	7.94	15.07	12.00	13.13	10.45
Fe_2O_3	2.33	5.93	6.11	4.11	2.30	2.23	1.69
FeO	8.79	5.53	6.52	8.55	8.82	8.80	9.41
MgO	7.89	9.46	24.20	6.04	13.08	9.92	17.83
CaO	10.22	9.81	5.76	10.19	8.87	9.74	7.72
Na_2O	2.37	2.26	1.23	2.43	1.96	1.95	[1]1.76
K_2O	.44	.30	.28	.36	.34	.37	.32
H_2O+	.32	.17	.14	.84	.13	.10	.52
H_2O-	.09	.07	.05	.39	.02	.03	.05
TiO_2	2.22	2.17	1.24	2.78	1.65	1.82	1.59
P_2O_5	.26	.23	.15	.28	.19	.24	.16
MnO	.17	.17	.17	.18	.17	.17	.17
CO_2	.05	.01	-----	-----	.01	.02	.02
Cl	-----	-----	-----	-----	.01	.01	[1].03
F	-----	-----	.01	.02	.02	.06	-----
Subtotal	-----	-----	99.99	99.95	99.83	99.93	100.21
Less O	-----	-----	.00	.01	.01	.03	.02
Total	100.06	100.10	99.99	99.94	99.82	99.90	100.19
$K_2O:P_2O_5$	1.69	1.30	1.87	1.29	1.79	1.54	2.00

Date	1868					1887
Sample	W-A-6	W-A-7	W-A-8	1868ML	H-19	TLW67-59
SiO_2	51.02	51.23	51.51	46.75	50.58	52.07
Al_2O_3	13.44	13.52	13.51	8.40	12.63	13.97
Fe_2O_3	1.18	1.27	2.23	2.29	1.65	1.37
FeO	9.88	9.76	8.82	9.27	9.35	9.63
MgO	9.30	8.81	9.23	23.58	11.08	7.47
CaO	9.89	10.02	9.86	6.21	9.44	10.26
Na_2O	2.19	2.21	2.14	1.32	2.01	2.22
K_2O	.40	.41	.31	.26	.38	.33
H_2O+	.12	.07	.06	.00	.33	.08
H_2O-	.01	.06	.03	.02	.13	.03
TiO_2	2.01	2.06	1.89	1.34	1.94	1.94
P_2O_5	.22	.23	.18	.14	.21	.19
MnO	.17	.17	.17	.17	.17	.17
CO_2	.01	.00	.00	.01	.01	.02
Cl	.01	.01	.01	.01	.02	.01
F	.03	.03	.03	.02	.03	.03
Subtotal	99.88	99.86	99.98	99.79	99.96	99.79
Less O	.01	.01	.01	.01	.01	.01
Total	99.87	99.85	99.97	99.78	99.95	99.78
$K_2O:P_2O_5$	1.82	1.78	1.72	1.86	1.81	1.74

[1] Na_2O corrected for NaCl contamination is 1.75 percent; Cl corrected for NaCl contamination is 0.01 percent.

TABLE 9.—*Chemical analyses of olivine-controlled lavas from Mauna Loa south rift zone*—Continued

Date	1907	1919			1926
Sample	TLW67-56	TLW67-77	H-34	H-36	TLW67-76
SiO_2	51.76	51.69	51.83	51.89	51.51
Al_2O_3	14.17	14.16	13.95	13.90	13.95
Fe_2O_3	1.24	1.65	1.75	3.24	1.71
FeO	9.77	9.36	9.17	7.88	9.36
MgO	7.17	7.31	7.05	7.21	7.79
CaO	10.44	10.44	10.58	10.61	10.36
Na_2O	2.26	2.25	2.31	2.25	2.21
K_2O	.34	.36	.35	.36	.35
H_2O+	.09	.12	.14	.06	.18
H_2O-	.03	.04	.01	.01	.03
TiO_2	2.04	2.03	2.11	2.10	2.04
P_2O_5	.21	.21	.21	.22	.20
MnO	.17	.17	.17	.18	.17
CO_2	.03	.00	.00	.01	.01
Cl	.01	.01	.02	.01	.01
F	.03	.03	.02	.03	.03
Subtotal	99.76	99.83	99.67	99.96	99.91
Less O	.01	.01	.01	.01	.01
Total	99.75	99.82	99.66	99.95	99.90
$K_2O:P_2O_5$	1.62	1.71	1.66	1.64	1.75

Date	1950				
Sample	TLW67-73	TLW67-74	TLW67-75	TLW67-79	53-2378CD
SiO_2	51.92	51.58	51.34	51.35	51.40
Al_2O_3	14.27	13.84	13.73	13.19	13.27
Fe_2O_3	1.38	1.20	1.37	2.41	2.72
FeO	9.65	9.85	9.70	8.80	8.66
MgO	6.86	8.13	8.70	9.20	9.14
CaO	10.56	10.18	10.07	9.97	10.04
Na_2O	2.29	2.23	2.16	2.15	2.13
K_2O	.37	.36	.36	.36	.31
H_2O+	.02	.07	.06	.00	.04
H_2O-	.04	.01	.00	.04	.00
TiO_2	2.10	2.01	1.94	1.93	1.91
P_2O_5	.22	.21	.20	.21	.22
MnO	.17	.17	.17	.18	.17
CO_2	.02	.02	.01	.01	.00
Cl	.00	.01	.01	.01	-----
F	.03	.03	.03	.03	-----
Subtotal	99.90	99.90	99.85	99.84	-----
Less O	.01	.01	.01	.01	-----
Total	99.89	99.89	99.84	99.83	100.01
$K_2O:P_2O_5$	1.68	1.71	1.80	1.71	1.41

TABLE 10.—*Chemical analyses of olivine-controlled lavas from Mauna Loa northeast rift zone*

[Additional sample data are given in table 23]

Date	Prehistoric	1852	1855		
	Keamoku flow				
Sample	476	TLW67-29	TLW67-61	TLW67-63	W-A-20
SiO_2	50.94	51.92	48.70	50.59	51.34
Al_2O_3	12.97	14.16	10.98	13.22	13.82
Fe_2O_3	1.95	3.49	1.67	1.57	2.18
FeO	8.96	7.52	9.52	9.77	8.87
MgO	10.68	6.98	16.80	9.76	7.92
CaO	9.88	10.50	7.90	9.90	10.26
Na_2O	1.99	2.32	1.69	2.12	2.27
K_2O	.37	.41	.33	.38	.43
H_2O+	.12	.15	.15	.08	.23
H_2O-	.04	.01	.06	.00	.05
TiO_2	1.78	2.10	1.61	2.01	2.09
P_2O_5	.21	.24	.19	.21	.23
MnO	.17	.17	.16	.17	.17
CO_2	.04	.01	.01	.01	.00
Cl	-----	.00	.01	.01	.01
F	-----	.03	.03	.03	.03
Subtotal	-----	100.01	99.81	99.83	99.90
Less O	-----	.01	.01	.01	.01
Total	100.10	100.00	99.80	99.82	99.89
$K_2O:P_2O_5$	1.79	1.71	1.74	1.81	1.87

TABLE 10.—*Chemical analyses of olivine-controlled lavas from Mauna Loa northeast rift zone*—Continued

Date	1881		1899		1935		1942
Sample	10,000 ft	2,200 ft	TLW67-65	W-A-24	TLW67-67	W-A-21	TLW67-62
SiO_2	52.18	52.27	52.05	52.10	51.93	51.85	51.88
Al_2O_3	13.76	13.68	14.13	13.91	14.20	14.14	14.08
Fe_2O_3	3.25	2.31	1.20	1.21	1.34	1.34	1.55
FeO	8.03	9.02	9.88	9.76	9.74	9.77	9.58
MgO	7.95	7.40	7.06	7.67	7.14	7.07	7.20
CaO	10.16	10.24	10.57	10.21	10.56	10.54	10.55
Na_2O	2.06	2.29	2.25	2.25	2.31	2.29	2.29
K_2O	.34	.37	.34	.34	.36	.36	.36
H_2O+	.05	.04	.05	.11	.09	.07	.09
H_2O-	.08	.03	.01	.03	.00	.02	.01
TiO_2	1.95	2.07	2.09	1.94	2.04	2.05	2.06
P_2O_5	.19	.20	.20	.20	.21	.21	.21
MnO	.17	.18	.17	.17	.17	.17	.17
CO_2	.01	.01	.02	.02	.01	.01	.01
Cl	.01	.01	.00	.00	.01	.01	.01
F	.03	.03	.03	.03	.03	.03	.03
Subtotal	100.22	100.15	100.05	99.95	100.14	99.93	100.08
Less O	.01	.01	.01	.01	.01	.01	.01
Total	100.21	100.14	100.04	99.94	100.13	99.92	100.07
$K_2O:P_2O_5$	1.79	1.85	1.70	1.70	1.71	1.71	1.71

7 percent to over 20 percent. Data are given in table 3 for equation $y=ax+b$ to define a set of control lines portraying the composition of all historic flows from Mauna Loa.

Unlike Kilauea, the Mauna Loa lavas do not form chemically distinct groups that can be related to time or location of eruption. This uniformity is shown in figures 7–9, in which the analyses for each group of lavas are compared to the position of the average control line for all historic flows. In terms of entire chemistry, therefore, Mauna Loa lavas are more uniform than Kilauea lavas. On a smaller scale, however, lavas from a single eruption or groups of closely related eruptions show more variation from average control lines than do lavas from individual Kilauea eruptions.

TABLE 11.—*Chemical analyses of olivine-controlled lavas from Mauna Loa northwest slope*

[Additional sample data are given in table 23]

Date	Prehistoric						1859	
	Beach boulder		Puu O Uo		Kokoolau	Puu Koli		
Sample	TLW67-117A	TLW67-78	TLW67-119	TLW67-121	TLW67-123	TLW67-125	65P-2	DPH-77
SiO_2	49.35	51.50	51.91	51.51	51.97	50.50	51.60	51.24
Al_2O_3	11.82	13.65	14.24	14.38	14.23	14.10	13.98	13.72
Fe_2O_3	1.50	1.64	2.49	6.90	1.47	2.04	1.58	2.43
FeO	9.54	9.65	8.39	5.04	9.45	9.14	9.41	8.64
MgO	14.30	8.13	6.69	7.10	6.99	7.80	7.58	7.72
CaO	8.73	10.36	10.31	9.29	10.53	10.35	10.46	10.36
Na_2O	[1] 1.89	2.28	2.22	2.21	2.33	2.36	2.33	[2] 2.45
K_2O	.34	.34	.46	.43	.41	.43	.42	.43
H_2O+	.25	.01	.37	.40	.05	.39	.05	.14
H_2O-	.04	.00	.03	.05	.03	.21	.05	.11
TiO_2	1.69	1.98	2.14	2.17	2.08	2.23	2.16	2.16
P_2O_5	.19	.19	.25	.28	.23	.23	.24	.25
MnO	.17	.17	.16	.18	.17	.16	.17	.17
CO_2	.02	.00	.04	.01	.01	.02	.00	.04
Cl	[1] .03	.00	.00	.01	.01	.01	.01	[2] .18
F	.03	.02	.03	.04	.02	.03	.03	.03
Subtotal	99.89	99.92	99.73	100.00	99.98	100.00	100.07	100.07
Less O	.02	.01	.01	.02	.01	.01	.01	.05
Total	99.87	99.91	99.72	99.98	99.97	99.99	100.06	100.02
$K_2O:P_2O_5$	1.79	1.79	1.84	1.54	1.78	1.87	1.75	1.72

[1] Na_2O corrected for NaCl contamination is 1.88 percent; Cl corrected for NaCl contamination is 0.01 percent.

[2] Na_2O corrected for NaCl contamination is 2.33 percent; Cl corrected for NaCl contamination is 0.01 percent.

TABLE 12.—*Chemical analyses of lavas of prehistoric age from the Ninole Hills, southeast slope of Mauna Loa*

[Additional sample data are given in table 23]

Sample	C817	C818	ID-098-2	ID-214-2	ID-240-2	ID-275-2
SiO_2	48.40	49.47	50.46	47.10	47.26	49.74
Al_2O_3	14.33	14.58	13.84	10.80	11.46	13.42
Fe_2O_3	2.42	3.97	1.47	3.04	2.48	2.36
FeO	9.18	8.10	9.99	9.27	9.52	9.27
MgO	9.78	7.33	7.16	17.30	16.13	9.92
CaO	10.17	9.33	11.07	8.05	8.52	10.14
Na_2O	2.31	1.70	2.30	1.58	1.62	1.99
K_2O	.27	.21	.46	.08	.06	.09
H_2O+	.20	1.78	.15	.38	.43	.35
H_2O-	.07	.87	.05	.34	.42	.36
TiO_2	2.52	2.27	2.68	1.60	1.69	2.04
P_2O_5	.22	.16	.26	.14	.15	.17
MnO	.16	.18	.18	.19	.18	.18
CO_2	-----	-----	.00	.00	.00	.00
Cl	-----	-----	.01	.01	.00	.00
F	.02	.02	.04	.02	.03	.03
Subtotal	100.05	99.97	100.12	99.90	99.95	100.06
Less O	.01	.01	.02	.01	.01	.01
Total	100.04	99.96	100.10	99.89	99.94	100.05
$K_2O:P_2O_5$	1.23	1.31	1.77	.57	.40	.53

Chemical analyses (table 12) of lavas from the Ninole Hills are plotted in figure 10. The Ninole lavas are within themselves extremely variable and are chemically distinct from, and older than, the lavas mapped elsewhere on Mauna Loa.[2] On the average the Ninole lavas differ from the younger lavas of Mauna Loa in having lower SiO_2, higher Al_2O_3, higher "FeO," lower K_2O, and higher TiO_2. Na_2O, CaO, and P_2O_5 are similar. The Ninole lavas may represent remnants of a separate volcano older than Mauna Loa.

[2] One lava flow mapped as Kau Basalt, part of the youngest section of basalts recognized by Stearns and Macdonald (1946), has a composition similar to the lava of the Ninole Hills. This analysis is given in table 9 (C820). The analysis normalized to 100 percent dry weight is plotted in figure 8 at 6.12 percent MgO.

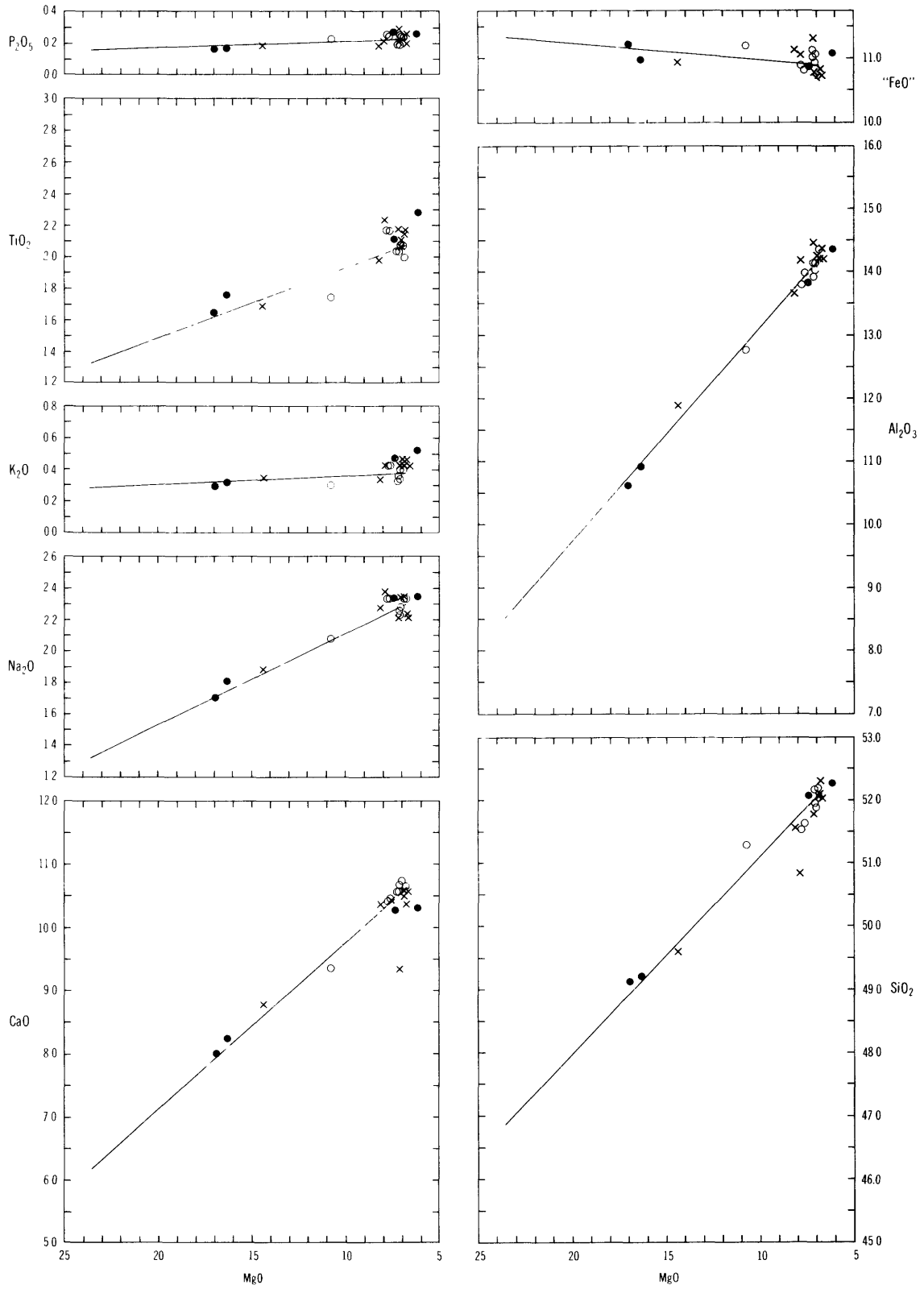

FIGURE 7.—MgO variation diagrams showing lavas from the summit (Mokuaweoweo caldera) and northwest slope of Mauna Loa. Analyses are given in tables 8 and 11. Control lines are as shown in figure 2. ●, prehistoric, summit; ×, prehistoric, northwest slope; ○, 1877–1949 (summit) and 1859 (northwest slope).

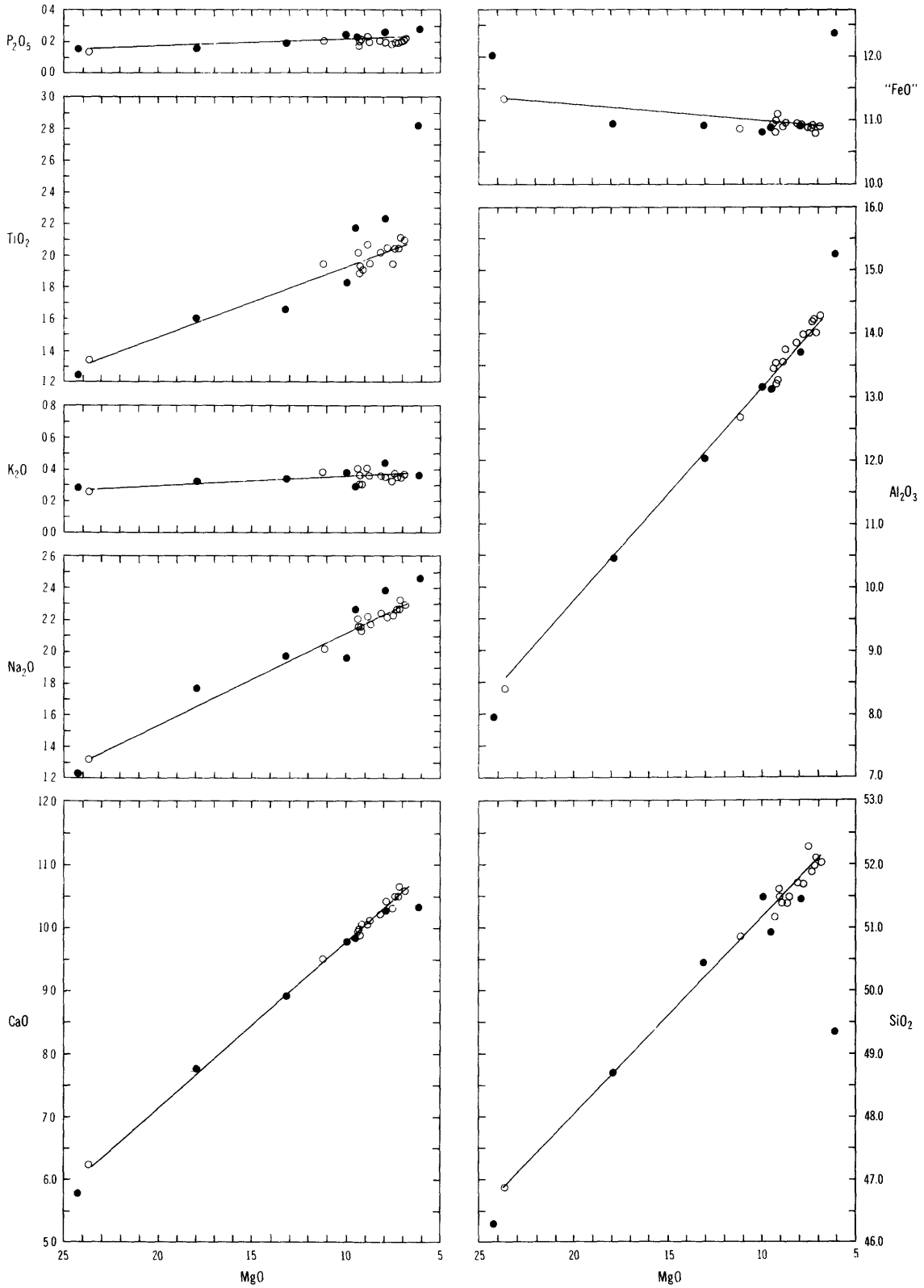

FIGURE 8.—MgO variation diagrams showing lavas from the Mauna Loa southwest rift zone. Analyses are given in table 9. Control lines are as shown in figure 2. ●, prehistoric; ○, 1868–1950.

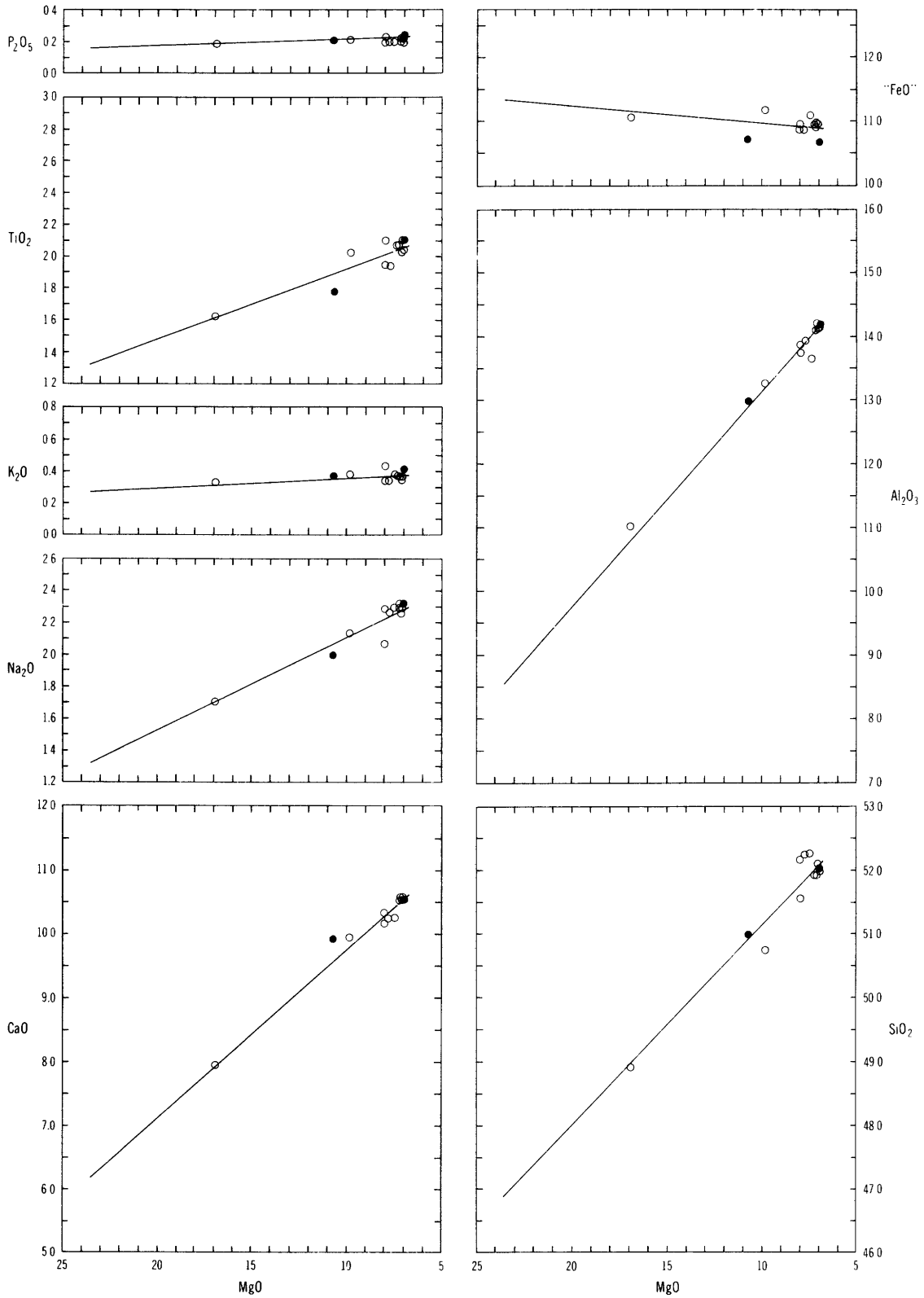

FIGURE 9.—MgO variation diagrams showing lavas from the Mauna Loa northeast rift zone. Analyses are given in table 10. Control lines are as shown in figure 2. •, prehistoric; ○, 1852–1942.

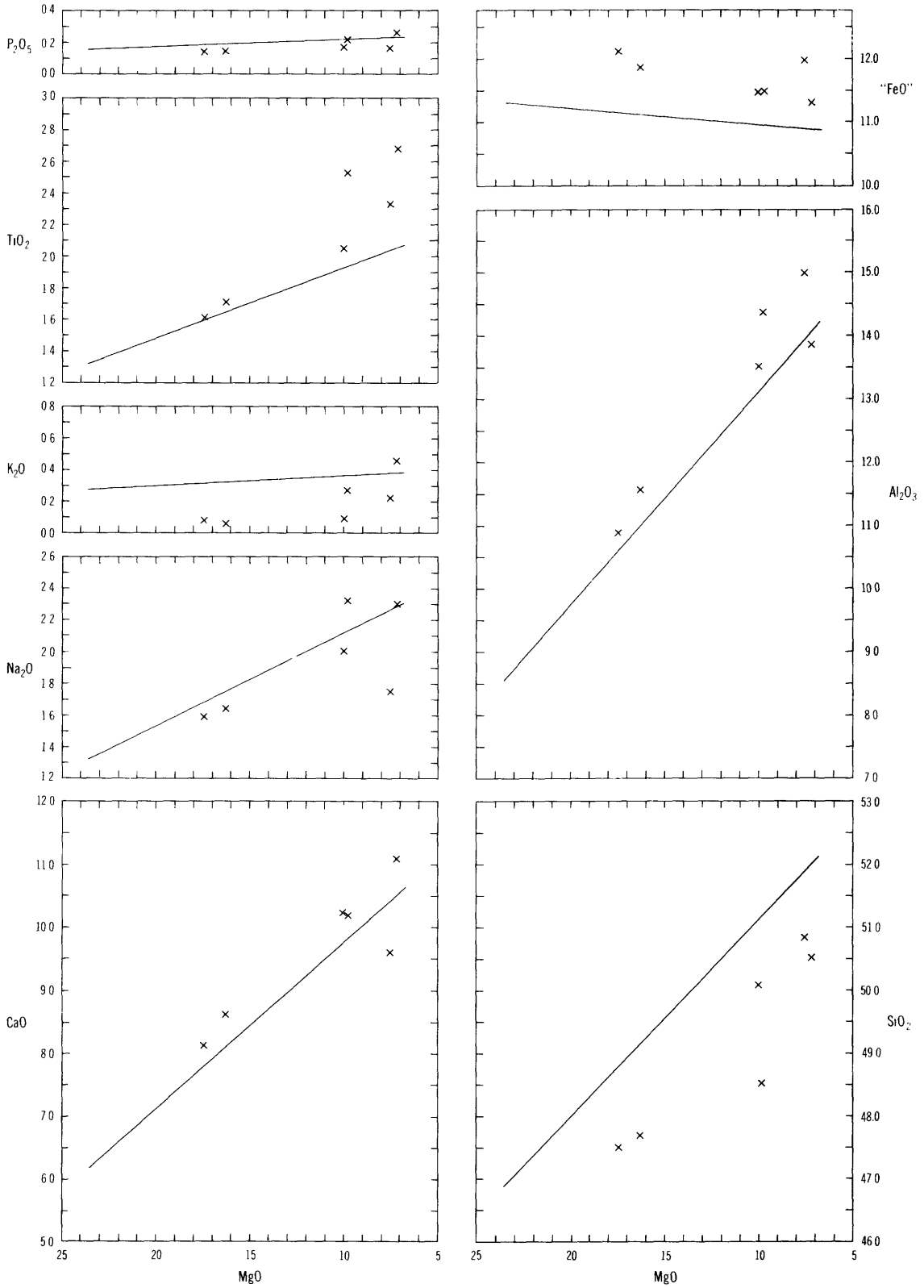

FIGURE 10.—MgO variation diagrams showing lavas from the Ninole Hills, southeast slope of Mauna Loa. Analyses are given in table 12. Control lines are as shown in figure 2. Note that the Ninole lavas (×) plot distinctly away from the control lines for younger Mauna Loa lavas.

DIFFERENTIATED LAVAS

The compositions of differentiated lavas from Mauna Loa are shown in table 13 and plotted in figure 11. The historic differentiates (1843, 1926, and 1950) barely plot off the extension of olivine control lines for the other historic lavas with which they are associated. The submarine sample (9) has a composition more nearly like that of typical Kilauea differentiates.

TABLE 13.—*Chemical analyses of differentiated lavas from Mauna Loa*

[Additional sample data are given in table 23]

Date	Prehistoric	1926	1950			1843	
Sample	9	TLW67-72	TLW67-54	TLW67-54A	TLW67-66	W-A-22	W-A-23
SiO_2	52.12	52.04	52.03	52.09	51.93	51.65	51.89
Al_2O_3	13.41	14.11	14.22	14.19	14.25	14.43	14.30
Fe_2O_3	2.47	1.34	1.48	1.55	1.38	2.56	1.64
FeO	9.45	9.85	9.76	9.70	9.79	8.53	9.23
MgO	5.50	6.68	6.39	6.38	6.66	6.75	6.80
CaO	8.89	10.35	10.26	10.35	10.32	10.48	10.50
Na_2O	[1] 2.97	2.36	2.44	2.50	2.38	2.39	2.41
K_2O	.72	.42	.46	.47	.47	.46	.45
H_2O+	.61	.05	.03	.04	.09	.10	.08
H_2O-	.08	.02	.02	.00	.05	.04	.01
TiO_2	3.17	2.22	2.30	2.28	2.16	2.16	2.16
P_2O_5	.42	.23	.27	.33	.26	.25	.25
MnO	.17	.17	.17	.17	.17	.17	.17
CO_2	.01	.01	.01	.01	.01	.01	.01
Cl	[1] .20	.01	.01	.02	.01	.01	.01
F	.05	.03	.04	.03	.04	.04	.03
Subtotal	100.24	99.89	99.89	100.11	99.97	100.03	99.94
Less O	.07	.01	.02	.01	.02	.02	.01
Total	100.17	99.88	99.87	100.10	99.95	100.01	99.93
$K_2O:P_2O_5$	1.71	1.83	1.70	1.42	1.81	1.84	1.80

[1] Na_2O corrected for NaCl contamination is 2.84 percent; Cl corrected for NaCl contamination is 0.01 percent.

TABLE 14.—*Summary of chemical composition of historic flows from Mauna Loa and of flows of different ages from Kilauea*

[All averages are normalized to 100 percent dry weight after converting all iron to "FeO". Averages are then normalized to 7.0 percent MgO by subtracting chromite-bearing olivine of composition $Fa_{12.5}$ (Mauna Loa) or $Fa_{13.8}$ (Kilauea)]

	Mauna Loa	Kilauea caldera			
	Historic	Prehistoric	1832–89	1911–24	1959 S–2
SiO_2	52.18	51.23	50.77	50.33	50.18
Al_2O_3	14.17	14.14	14.11	14.00	13.79
"FeO"	10.94	10.86	11.06	11.09	11.26
MgO	7.0	7.0	7.0	7.0	7.0
CaO	10.58	11.22	11.27	11.58	11.63
Na_2O	2.29	2.30	2.30	2.28	2.31
K_2O	.37	.41	.48	.55	.60
TiO_2	2.07	2.44	2.61	2.72	2.77
P_2O_5	.21	.22	.25	.27	.28
MnO	.17	.17	.17	.17	.17

CHEMICAL VARIATION WITHIN KILAUEA LAVA AND DIFFERENCE BETWEEN KILAUEA AND MAUNA LOA LAVAS

Figure 2 shows that the lavas of Mauna Loa may be distinguished by their chemistry from any of the lavas of Kilauea. Furthermore, the data indicate that the trend in chemical change (relative to constant MgO or to the position of olivine control lines) between the lavas of Mauna Loa and the prehistoric lavas of Kilauea is similar to that which distinguishes Kilauea's prehistoric lavas from its 20th century lavas. In other words, the extrapolation of the time-related chemical variation of Kilauea lavas backwards in time is toward the average composition of Mauna Loa lavas, as is illustrated in table 14.

DISCUSSION

The following sections aim to explain the observed chemical variation of Kilauea and Mauna Loa in terms of specific petrologic processes. A striking feature of the chemistry of both volcanoes is the uniformity of the ratio $K_2O:P_2O_5$. Anderson and Greenland (1969) have discussed the behavior of P_2O_5 in basaltic melts, and the same principles apply to K_2O in Hawaiian tholeiites. Both oxides are strongly partitioned to the melt until late crystallization of apatite and potassium-rich feldspar. The uniformity of their ratio suggests (1) melting from a mantle of uniform composition with respect to these elements and (2) subsequent crystal-liquid fractionation (or differences in initial degree of melting) as the dominant processes by which magma compositions are determined.

Other processes have been tested and rejected. The process of mixing of magmas, which is important in explaining the composition of Kilauea rift eruptions (Wright and Fiske, 1971), appears to be

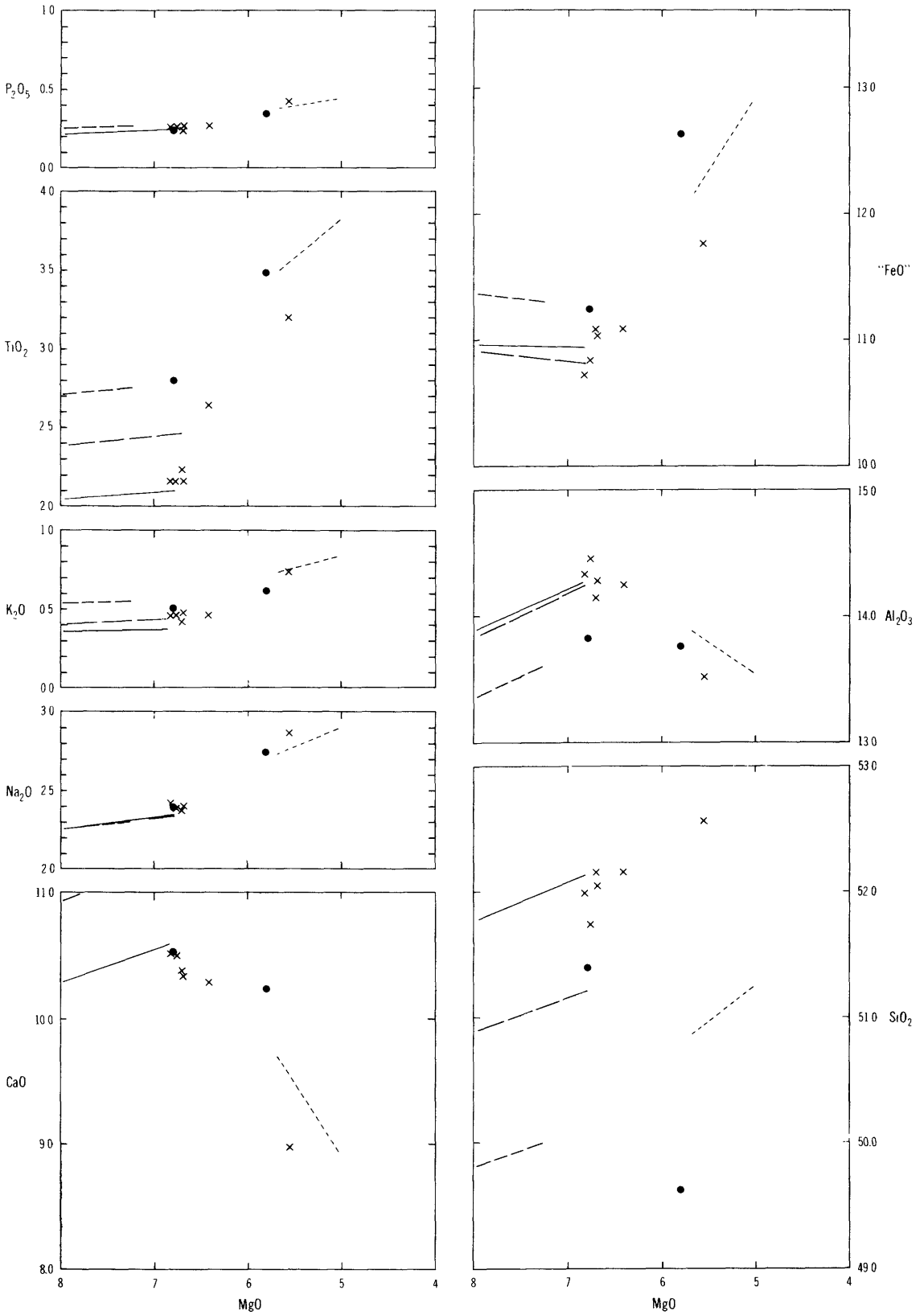

FIGURE 11.—MgO variation diagrams showing differentiated lavas from Kilauea (●) and Mauna Loa (×). Analyses are given in table 13. Control lines are as shown in figure 2 with the addition of control lines for the early part of the Kilauea 1955 eruption (very short dashes between 5 and 6 percent MgO).

of minor importance in explaining the chemistry of lavas erupted either at Kilauea summit or from Mauna Loa. Diffusion of chemical species (for example, alkalies) and reactions with wallrocks cannot be quantitatively treated, but there is no evidence that such processes are important in explaining the chemical variability.

Quantitative fractionation calculations (Wright and Doherty, 1970) are made on the assumption that crystal-liquid fractionation and (or) partial melting are the important processes that result in chemical variability of the lavas. Mineral compositions used in the calculations are given in table 15. The nature of the calculated mineral assemblage

TABLE 15.—*Analyses of minerals used in differentiation calculations*

	Olivine		Chromite	Olivine+chromite		Hypersthene			Augite	
	Fa_{10}	Fa_{30}	KICHRO	KAVOL ($Fa_{13.8}$)	MLAVOL ($Fa_{12.5}$)	KUMLHYP	MP218HYP	STWATHYP	LHZAUG	MP218AUG
SiO_2	40.79	37.67	0.00	39.45	39.70	54.88	53.39	51.50	53.20	52.53
Al_2O_3	-----	-----	[1] 65.00	1.17	.98	.75	.85	1.36	3.00	2.93
"FeO"	9.69	26.78	20.90	13.23	12.08	10.69	16.99	26.40	4.00	7.43
MgO	49.00	35.05	11.60	45.51	46.60	30.99	25.58	18.68	16.50	16.86
CaO	.25	.25	.00	.39	.39	2.14	2.26	1.13	22.50	18.95
Na_2O	-----	-----	.00	.00	.00	.10	.04	.04	.50	.22
K_2O	-----	-----	.00	.00	.00	.04	.00	.01	.00	.00
TiO_2	-----	-----	2.10	.04	.03	.25	.54	.27	.20	.87
P_2O_5	-----	-----	.00	.00	.00	.00	.00	.02	.00	.00
MnO	.29	.29	.20	.22	.22	.16	.37	.59	.10	.22

	Augite—Continued		Jadeite	Ca-Tschermak's molecule	Plagioclase					Ilmenite	Magnetite
	STWATAUG	MPLLAUG			Ab	$An_{59.7}$	$An_{65.8}$	$An_{69.7}$	An	MPILM	MPMAG
SiO_2	51.51	51.49	59.40	27.60	68.29	53.42	52.03	51.01	44.00	0.05	0.07
Al_2O_3	2.30	4.20	25.30	46.70	19.65	29.74	30.08	30.99	36.28	.12	1.90
"FeO"	11.29	7.50	-----	-----	.08	.20	.66	.49	.08	48.99	73.50
MgO	13.53	16.20	-----	-----	.00	.12	.18	.13	.00	1.73	1.03
CaO	20.49	19.00	-----	25.70	.08	11.87	13.00	13.83	19.42	.08	.10
Na_2O	.17	.30	15.30	-----	11.61	4.45	3.64	3.29	.22	.00	.00
K_2O	.01	.01	-----	-----	.28	.19	.35	.20	.00	48.64	23.06
TiO_2	.40	1.10	-----	-----	.01	.07	.07	.06	.00	.00	.00
P_2O_5	.03	.01	-----	-----	.00	.00	.00	.00	.00	.00	.00
MnO	.28	.20	-----	-----	.00	.00	.00	.00	.00	.44	.38

[1] Because Cr_2O_3 was not separately determined in the rock analyses, all Cr_2O_3 has been converted to equivalent Al_2O_3. True percentages are Cr_2O_3, 43.5; Al_2O_3, 13.4.

Olivine—Fa_{10}—Stoichiometric composition based on minor element data for Hawaiian olivines (Murata and others, 1965).
Fa_{30}—Do.
Chromite—KICHRO—Average composition of chromite phenocrysts and inclusions in olivine of the 1959 eruption of Kilauea (B. W. Evans, unpub. data).
Olivine+chromite—KAVOL ($Fa_{13.8}$)—Average composition of olivine (including 1.8 percent chromite) which controls the composition of the 1959 eruption of Kilauea.
MLAVOL ($Fa_{12.5}$)—Average composition of olivine (including 1.5 percent chromite) which controls the composition of the historic flows from Mauna Loa (table 16).
Hypersthene—KUMLHYP—Hypersthene from a prehistoric lava flow, south rift zone of Mauna Loa. Analysis by H. Kuno (1966, table 1, analysis 1).
MP218HYP—Hypersthene from the prehistoric lava lake in Makaopuhi crater, Kilauea (Evans and Moore, 1968, table 3, col. 4, p. 96).
STWATHYP—Hypersthene from the chill zone of the Stillwater Complex, Montana (E. D. Jackson and R. E. Stevens, unpub. data).
Augite—LHZAUG—Average (estimated by T. L. Wright) composition of augite from lherzolite inclusions in Hawaiian basalts. Data of White (1966).
MP218AUG—Augite from the prehistoric lava lake in Makaopuhi crater, Kilauea, coexisting with MP-218HYP (Evans and Moore, 1968, table 3, col. 2, p. 96).
STWATAUG—Augite from the chill zone of the Stillwater Complex, Montana (E. D. Jackson and R. E. Stevens, unpub. data).
MPLLAUG—Augite quenched near the temperature of first appearance from the 1965 Makaopuhi lava lake, Kilauea (P. W. Weiblen and T. L. Wright, unpub. data).
Jadeite—Stoichiometric $NaAlSi_2O_6$.
Ca-Tschermak's molecule—Stoichiometric $CaAl_2SiO_6$.
Plagioclase, from analyses in Deer, Howie, and Zussman (1963):
Ab—Table 13, p. 110, analysis 8.
$An_{59.7}$—Table 16, p. 117, analysis 8.
$An_{65.8}$—Table 16, p. 117, analysis 14.
$An_{69.7}$—Table 17, p. 118, analysis 2.
An—Table 18, p. 120, analysis 7.
Ilmenite—MPILM—Quenched near the temperature of first appearance, from the 1965 Makaopuhi lava lake. (See Wright and Weiblen, 1968, analysis is unpublished.)
Magnetite—MPMAG—Do.

that relates two lavas of different composition gives an idea as to the depth at which fractionation took place. If the assemblage consists only of minerals present as phenocrysts in the lavas, then the fractionation is deduced to be shallow, corresponding to pressures not exceeding 2kb (kilobars).[3] If, however, the calculated mineral assemblage does not match the observed phenocryst assemblage, then the

[3] This is based on a depth of 24 km (kilometers) to Kilauea's shallow magma reservoir (see Eaton and Murata, 1960, Fiske and Kinoshita, 1969).

chemical differences must be inherited from a deeper fractionation or melting event. For Kilauea lavas, hypersthene is a critical mineral. It is absent as a phenocryst, so that fractionation in which hypersthene is a necessary phase is considered to have occurred at pressures greater than 2kb. Since hypersthene does occur as a phenocryst in Mauna Loa lavas, its presence in fractionation calculations is not necessarily indicative of a high-pressure event. However, hypersthene always occurs with equal or greater amounts of plagioclase and augite phenocrysts, so that a preponderance of hypersthene in a fractionation calculation is again taken as a suggestion of a higher pressure event. At higher pressures, melting is taken to be the reverse of fractionation as far as the calculations are concerned. Space-time relations of the lavas suggest whether a fractionation (cooling) or melting event is more likely.

OLIVINE-CONTROLLED CHEMICAL VARIATION IN KILAUEA AND MAUNA LOA LAVAS

Figure 2 shows control lines for some major suites of Kilauea and Mauna Loa lavas plotted together with minerals that might control the observed chemical variation both within and between suites of different lavas. The projection of these control lines shows that addition or removal of olivine is the dominant process explaining the lava chemistry, a conclusion reached by Powers (1955) on the basis of many fewer analytical data. One can ask to what extent the control lines deviate from perfect olivine control and attempt to explain these deviations in a quantitative fashion. The most thoroughly described example of olivine control is the 1959 eruption of Kilauea, for which Murata and Richter (1966b, table 1) calculated the composition of olivine that controlled the major compositional variation of the eruption.[4]

Tilley (1960a) has demonstrated olivine control for the 1921 Kilauea summit lava. Control lines have been calculated for two additional olivine-rich Kilauea eruptions—1840 east rift (Wright and Fiske, 1971, table 4a) and a prehistoric pahoehoe flow unit from the southwest rift (Walker, 1969; this paper, table 5). The results are shown in table 16. The residuals demonstrate nearly perfect olivine control.

TABLE 16.—*Results of differentiation calculations for Kilauea and Mauna Loa control lines*

[Calculations are set up using the calculated composition of the high-MgO (A) and low-MgO (B) ends of the control lines for each lava suite (see table 3) as follows: A = B + olivine (Fa_{10}) + olivine (Fa_{30}) + chromite. Total iron is calculated as FeO]

	Kilauea								
	1840 east rift (KIL1840)			Prehistoric southwest rift (PHSWPP)			Mauna Loa (HISTML)		
	A	B	Residuals (A observed minus A calc)	A	B	Residuals (A observed minus A calc)	A	B	Residuals (A observed minus A calc)
SiO_2	48.18	49.08	0.05	46.52	51.17	−0.06	46.98	52.21	−0.02
Al_2O_3	10.34	11.49	.01	8.96	14.27	−.01	8.56	14.23	−.02
"FeO"	11.29	11.03	−.01	12.01	10.91	.01	11.37	10.95	−.02
MgO	17.54	14.18	−.02	22.00	6.82	.01	23.70	6.89	−.02
CaO	8.26	9.32	−.11	6.90	11.12	.03	6.20	10.62	−.08
Na_2O	1.67	1.84	.03	1.54	2.36	.12	1.32	2.31	−.01
K_2O	.34	.36	.02	.25	.49	−.04	.28	.38	.07
TiO_2	1.97	2.17	.06	1.50	2.45	.01	1.33	2.08	.12
P_2O_5	.18	.19	.02	.15	.24	.01	.16	.23	.03
MnO	.17	.17	.00	.18	.19	−.02	.19	.19	−.01

NOTE.—Solution (weight percent):

	KIL1840	*PHSWPP*	*HISTML*
Olivine	10.66 ($Fa_{14.1}$)	39.01 ($Fa_{14.3}$)	41.81 ($Fa_{12.5}$)
Chromite	.11	.54	.60
B	89.24	60.46	57.60

There are no individual eruptions of Mauna Loa that have as great a range of olivine content as those described from Kilauea. The overall chemical variation, however, is clearly dominated by olivine control. The calculation using the average Mauna Loa control lines (table 3) is also shown in table 16.

Olivine control is inferred to be a shallow process on the basis of the positive correlation between MgO content of a lava and its observed percentage of olivine phenocrysts. Presumably, each subchamber of the shallow reservoir complex inferred to underlie both Kilauea and Mauna Loa is stratified with an olivine-rich lower part and an olivine-poor upper part. The MgO content of a lava then depends on what level or levels of the chamber were tapped.

[4] Their calculated olivine has an abnormally high CaO content. T. L. Wright and D. B. Jackson (unpub. data) explain this by making the 1959 eruption a mixture of two magmas (which differ in CaO relative to MgO), each of which shows virtually perfect olivine-controlled chemical variation.

OLIVINE-PYROXENE-PLAGIOCLASE CONTROL OF MAUNA LOA LAVA COMPOSITIONS

The occurrence of phenocrysts of hypersthene, augite, and plagioclase in Mauna Loa lavas suggests the possibility of a more complex shallow fractionation than the olivine control demonstrated for Kilauea eruptions. This possibility was studied by selecting pairs of Mauna Loa lavas that showed large opposed deviations from the set of average control lines computed for all historic lavas (table 3) and by calculating differences in chemical composition in terms of the observed phenocryst assemblage. Equations of the following form were solved (Wright and Doherty, 1970):

Lava A = lava B ± olivine ± hypersthene ± augite ± plagioclase

where lava A is arbitrarily taken as the lava with the higher content of MgO. The lava pairs include a picrite and a hypersthene-rich lava from each rift zone (southwest rift, 1887 from 1868 picrite parent; northeast rift, 1881 from 1852 picrite parent) and three sets from single rift eruptions (southwest rift, 1868 and 1950; northeast rift, 1899). The composition of olivine (including 1.5 percent chromite) is fixed at $Fa_{12.5}$ from the control lines for all historic Mauna Loa flows (table 16). The composition of plagioclase is fixed at An_{66}, a value within the observed range of phenocryst composition (A. T. Anderson, unpub. data.)

Separate calculations were made for each pair using the three sets of pyroxenes shown in table 15; that is, KUMLHYP and LHZAUG (most magnesian), MP218HYP and MP218AUG and STWATHYP and STWATAUG (most iron-rich). The signs and relative magnitude of the residuals do not vary significantly as a function of assumed pyroxene Mg:Fe ratio. The solutions using pyroxenes of intermediate Mg:Fe ratio are given in table 17.

The results show that minerals in addition to olivine are necessary to balance the chemical differences. The signs of the solution values indicate whether the mineral is relatively enriched (+) or depleted (−) in the sample with higher MgO. The low residuals in the calculations indicate that the chemical differences between lavas can be satisfactorily expressed in terms of minerals present as phenocrysts. However, the observed compositions are probably not simply a result of removal or addition of the mineral assemblage present in the porphyritic lavas. The total amount of calculated silicates other than olivine (5–10 percent, table 17) exceeds by a factor of 2 the observed phenocryst percentages, and augite is a relatively more important component of the observed phenocryst assemblages (table 7). Residuals for K_2O, Na_2O, and TiO_2 tend to exceed the expected analytical error of the rock analyses and are not significantly affected by changing the mineral compositions. It is possible that processes other than shallow crystal-liquid fractionation have contributed to the chemical variation of these Mauna Loa lavas.

TABLE 17.—*Results of differentiation calculations for olivine-controlled lavas from Mauna Loa*

	1887 from 1868 picrite		
	A (ML1868)	B (ML1887)	Residuals (A observed minus A calc)
SiO_2	46.75	52.07	−0.05
Al_2O_3	8.40	13.97	−.05
"FeO"	11.33	10.86	−.06
MgO	23.58	7.47	−.03
CaO	6.21	10.26	−.02
Na_2O	1.32	2.22	.02
K_2O	.26	.33	.07
TiO_2	1.34	1.94	.15
P_2O_5	.14	.19	.03
MnO	.17	.17	−.02

Note.—Solution [1] (weight percent):

Olivine ($Fa_{12.5}$) + chromite	+41.86
Hypersthene (MP218HYP)	−1.65
Augite (MP218AUG)	+.37
Plagioclase ($An_{65.8}$)	−1.62
B	61.07

	1881 from 1852 picrite		
	A	B	Residuals (A observed minus A calc)
SiO_2	48.70	52.18	0.02
Al_2O_3	10.98	13.76	−.05
"FeO"	11.02	10.95	−.07
MgO	16.80	7.95	.00
CaO	7.90	10.16	0.02
Na_2O	1.69	2.06	.06
K_2O	.33	.34	.06
TiO_2	1.61	1.95	.02
P_2O_5	.19	.19	.03
MnO	.16	.17	−.01

Note.—Solution [1] (weight percent):

Olivine ($Fa_{12.5}$) + chromite	+26.07
Hypersthene (MP218HYP)	−6.71
Augite (MP218AUG)	−1.48
Plagioclase ($An_{65.8}$)	−2.34
B	84.49

	1868W-A-6 from ML1868		
	A	B	Residuals (A observed minus A calc)
SiO_2	46.75	51.02	−0.01
Al_2O_3	8.40	13.44	−.03
"FeO"	11.33	10.94	−.05
MgO	23.58	9.30	−.01
CaO	6.21	9.89	−.02
Na_2O	1.32	2.19	.02
K_2O	.26	.40	.03
TiO_2	1.34	2.01	.13
P_2O_5	.14	.22	.02
MnO	.17	.17	−.02

Note.—Solution [1] (weight percent):

Olivine ($Fa_{12.5}$) + chromite	+37.35
Hypersthene (MP218HYP)	+2.69
Augite (MP218AUG)	+1.03
Plagioclase ($An_{65.8}$)	+.65
B	58.30

See footnote at end of table.

TABLE 17.—*Results of differentiation calculations for olivine-controlled lavas from Mauna Loa*—Continued

	1950 (TLW67-75) from 1950 (TLW67-79)		
	A	B	Residuals (A observed minus A calc)
SiO_2	51.35	51.34	0.03
Al_2O_3	13.19	13.73	−.04
"FeO"	10.97	10.93	−.06
MgO	9.20	8.70	.00
CaO	9.97	10.07	−.02
Na_2O	2.15	2.16	.07
K_2O	.36	.36	.02
TiO_2	1.93	1.94	.02
P_2O_5	.21	.20	.02
MnO	.18	.17	.01

Note.—Solution [1] (weight percent):

Olivine ($Fa_{12.5}$) + chromite	+0.11
Hypersthene (MP218HYP)	+1.94
Augite (MP218AUG)	+1.33
Plagioclase ($An_{65.8}$)	−.49
B	97.14

	1899 (TLW67-65) from 1899 (W-A-24)		
	A	B	Residuals (A observed minus A calc)
SiO_2	52.10	52.05	0.03
Al_2O_3	13.91	14.13	−.05
"FeO"	10.85	10.96	−.06
MgO	7.67	7.06	.00
CaO	10.21	10.57	−.01
Na_2O	2.25	2.25	.08
K_2O	.34	.34	.02
TiO_2	1.94	2.09	.01
P_2O_5	.20	.20	.02
MnO	.17	.17	.00

Note.—Solution [1] (weight percent):

Olivine ($Fa_{12.5}$) + chromite	−0.52
Hypersthene (MP218HYP)	+5.83
Augite (MP218AUG)	+.18
Plagioclase ($An_{65.8}$)	+3.66
B	90.88

[1] The sign of the solution value is positive (+) if the more magnesian lava composition (A) is enriched in the components of that mineral phase relative to the lava with less MgO (B). Lava A = lava B ± olivine ± hypersthene ± augite ± plagioclase.

The differentiated lavas of Mauna Loa have been studied by calculations similar to those outlined above. Lava A is taken as a parent with greater than 7 percent MgO; lava B is the differentiate, and ilmenite is added to the list of possible minerals participating in the fractionation process. Table 18 shows the computed amounts of minerals removed from an assumed parent composition to produce the 1843, 1950, and submarine differentiates whose compositions are given in table 13. The two differentiates of historic age can be produced by removal of about 5–15 percent of silicates other than olivine. The prehistoric sample 9 is more strongly differentiated, and the calculations show that 38 percent of silicates in addition to olivine are necessary to produce its composition. The silicates in this case are more iron-rich, as would be expected for a greater degree of fractionation. Removal of iron-titanium oxides is not indicated for any of the differentiates, in contrast to most of the Kilauea differentiates (Wright and Fiske, 1971). Presumably the mechanism for differentiation of these lavas is separation of phenocrysts during flow in conduits, similar to the differentiation mechanism inferred for some Kilauea rift lavas (Wright and Fiske, 1971).

TABLE 18.—*Results of differentiation calculations* [1] *for differentiated lavas from Mauna Loa*

Parent	1852	1950 TLW67-79	1950 TLW67-79
Differentiate	1843 [2]	1950 TLW67-54 [3]	9
Minerals (percent): [4]			
Olivine [5]	25.7 (Fa_{12})	4.9 (Fa_{20})	6.3 (Fa_{13})
Hypersthene	[6] +1.8	[6] +4.9	[7] +8.5
Augite	[6] +0.0	[6] +4.9	[7] +12.7
Plagioclase [8]	+2.0 (An_{66})	+5.1 (An_{71})	+16.6 (An_{69})
Total (except olivine)	3.8	14.9	37.8
Residuals:			
Average	.03	.01	.06
Maximum	.08	.01	.17

[1] Calculations of the form: parent = differentiate + olivine + hypersthene + augite + plagioclase.
[2] Average of the three analyses given in table 13.
[3] A similar solution obtained for the 1926 eruption with TLW67-76 (parent) and TLW67-72 (differentiate). See tables 9 and 13.
[4] The minerals that must be removed from the parent composition to yield the composition of the differentiate. Only silicate minerals are tabulated because in no case were the residuals significantly reduced by inclusion of either ilmenite or titanium-rich magnetite.
[5] Olivine composition derived using Fa_{10} and Fa_{30}.
[6] Hypersthene and augite are MP218HYP and MP218AUG (table 15), respectively.
[7] Hypersthene and augite are STWATHYP and STWATAUG (table 15), respectively.
[8] Plagioclase composition derived using Ab and An (table 15) as input.

HIGH-PRESSURE FRACTIONATION OF KILAUEA LAVA

Perhaps the most difficult problem of Kilauea chemistry is to explain the differences in composition of lavas erupted at Kilauea summit. Two kinds of chemical variation are recognized: (1) Short-term variation in which each summit eruption has a chemical composition distinct from that of every other summit eruption, and (2) a long-term variation defined by the average composition of lavas erupted at different periods in the volcano's history (table 14). The explanation for these chemical variations is crucial to an understanding of the history of Kilauea magma from the time of initial melting to its appearance in the reservoir complex 2–4 km beneath Kilauea summit.

The composition of Mauna Loa lavas (which has not apparently changed composition over the same time interval as the changes of Kilauea lava composition) is chemically an end member to the Kilauea long-term variation (table 14). This observation suggests that the unexposed (submarine) section of Kilauea lavas might have a composition similar to that of present-day Mauna Loa lava.

The chemical differences among Kilauea summit lavas are not explainable by olivine control. The chemical differences in SiO_2 and CaO tend to be opposed, suggesting that orthopyroxene is an important fractionating phase. This in turn indicates a high-pressure origin for the chemical differences, and the calculations below are arranged to show various possibilities for high-pressure fractionation.

LONG-TERM CHEMICAL VARIATION

The younger lavas of Kilauea are richer in low-melting constituents (K_2O, P_2O_5, TiO_2), and this observation leads me to favor some kind of postmelting fractionation model to explain the chemical variation.[5] The calculations that follow are based on such a fractionation model.

The compositions given in table 14 are obviously too poor in magnesia to represent mantle-generated magmas. Murata and Richter (1966a) have analyzed glass from the highest temperature eruptive phase of the 1959 eruption of Kilauea and found it to have 10 percent MgO. The bulk composition of that same eruption is somewhat higher than 15 percent MgO (table 4), and this is considered by the author to represent a reasonable average composition (magma + contained olivine) of magma supplied to the 2- to 4-km-deep reservoir. Thus the initial Kilauea magmas must have had at least 15 percent MgO.

Another approach to initial magma composition arises from application of the hypothesis of Jackson and Wright (1970) to the effect that dunite is the refractory residue after melting of tholeiite. On this hypothesis the bulk composition of the mantle underlying Hawaii should lie on control lines connecting tholeiite and dunite. The composition and a calculated mode of a "Mauna Loa" mantle with 35 percent MgO is given in table 19. Hornblende is used as the potash-bearing phase although similar relations hold if phlogopite is used instead or in addition to hornblende. Cr_2O_3 is assumed to be concentrated entirely in spinel, and TiO_2, in rutile. Bulk pyroxene composition is calculated from the following five end members: $MgSiO_3$, $FeSiO_3$, $CaSiO_3$, $NaAlSi_2O_6$ (jadeite), and Al_2O_3 (Tschermak's components). Actual mantle pyroxenes would contain small amounts of Cr_2O_3 and TiO_2, but these do not significantly affect the calculation of magma compositions. Pyroxene compositions are calculated on the basis of tie line orientations similar to those in coexisting pyroxenes from Hawaiian xenoliths (Beeson and Jackson 1970; M. H. Beeson, unpub. data). The minimum MgO content of tholeiite, assuming all phases except olivine are melted, is 15–20 percent MgO, depending on the composition of olivine used in the calculation. The mantle calculated in table 19 would yield a tholeiite with a minimum MgO of 19 percent. Since olivine must be melted along with other components, a magma with 25 percent MgO is considered reasonable, and this has been used as a parent in the calculations.

TABLE 19.—*Calculated mode and pyroxene composition of a "Mauna Loa" mantle*

	Bulk [1] mantle	Ortho-pyroxene	Clino-pyroxene	Hornblende [2]
SiO_2	43.03	52.33	51.37	40.69
Al_2O_3	4.34	8.76	12.62	14.00
"FeO"	12.67	8.78	5.00	11.29
MgO	35.00	29.13	13.19	13.04
CaO	3.06	.82	14.82	10.35
Na_2O	.65	.18	3.00	3.07
K_2O	.10	---	---	2.07
TiO_2	.60	---	---	4.46
P_2O_5	.06	---	---	---
MnO	.18	---	---	.11
Cr_2O_3	.31	---	---	---
Mode				
Olivine ($Fa_{16.2}$)	60.12	---	---	---
Cr-spinel	1.02	---	---	---
Orthopyroxene	17.72	---	---	---
Clinopyroxene	15.79	---	---	---
Amphibole [2]	4.85	---	---	---
Apatite [3]	.14	---	---	---
Rutile [4]	.37	---	---	---
Total	100.00	---	---	---

[1] Obtained by adding dunite to Mauna Loa (HISTML) composition.
[2] Kakanui hornblende used for K_2O balance.
[3] Apatite used for P_2O_5 balance.
[4] Rutile used for TiO_2 balance in the absence of TiO_2 in pyroxene.

There is no evidence that the average MgO (or potential and actual olivine content) of Kilauea magma supplied to the shallow reservoir has changed as a result of any fractionation process; that is, the incidence of picritic eruptions seems quite as high in the present as any estimates that could be made for earlier lava sections. This also implies that fractionation processes begin with quite MgO-rich magmas and occur at pressures sufficiently high to stabilize other phases with olivine at high liquidus temperatures.

Magma compositions used in the fractionation calculations are shown in table 20. The compositions were constructed from those given in table 14 (PHKILCAL, Kilauea caldera prehistoric; 1959 S–2) and table 4 (1952Hm, 1967–68Hm) by adding olivine ($Fa_{13.7}$) containing 1 percent included Cr-spinel. The younger magmas contain less SiO_2 and more CaO relative to MgO than the prehistoric parent, which suggests that orthopyroxene is an important phase in the fractionation. However, Al_2O_3 decreases slightly and Na_2O remains the same in the younger lavas, which suggests that one or more phases rich in Al_2O_3 and Na_2O must also be important. A simple mineralogy that fits the chemical fractionation is olivine-orthopyroxene-plagioclase (An_{60-65}). This assemblage would be limited by the upper stability limit of plagioclase to 10 kb or less (Green and Ringwood, 1967, Ito and Kennedy,

[5] Murata (1970) has argued that the chemical differences between Mauna Loa and Kilauea are explained by different degrees of melting in a mantle differing with respect to the low-melting constituents. However, Murata did not treat the temporal variation within Kilauea itself.

1968). Sample fractionation calculations are shown in table 21*A*. Two lines of evidence indicate that the orthopyroxene-plagioclase assemblage would not be stable relative to clinopyroxene in rocks of Kilauea bulk composition. Irvine (1969) has analyzed the contrasting cumulate sequences from different layered intrusives. Orthopyroxene-plagioclase cumulates do exist, as for example in the Stillwater Complex (Jackson, 1969), but only in rocks with higher Al_2O_3 than either Kilauea or Mauna Loa. The projections of Jamieson (1970) and the experimental work of Green and Ringwood on compositions similar to but slightly more aluminous than Kilauea indicate that orthopyroxene and clinopyroxene are favored relative to plagioclase at elevated pressures making it highly unlikely that a clinopyroxene-poor fractionation could occur.

If plagioclase is not a possible major phase in the assemblage, then the Na_2O and Al_2O_3 must be concentrated in ferromagnesian minerals. Al_2O_3 can reside in Cr_2O_3-poor spinel, aluminous pyroxenes, or garnet. Na_2O is restricted to a jadeitic clinopyroxene. Table 21*B* summarizes calculations using an assemblage olivine - spinel - orthopyroxene - clinopyroxene. Pyroxene compositions are again calculated from five end members as above. For comparison with the composition of the fractionated pyroxenes the bulk composition of pyroxene in both the parent and the fractionated lava is calculated and shown in table 22. This assemblage, in which pryoxenes are very rich in Al_2O_3 and Na_2O, would be stable at higher pressures, up to about 20 kb in a garnet-free mantle (Ito and Kennedy, 1968, figs. 1 and 2).

As they stand, these calculations are not completely consistent because the bulk Na_2O and Al_2O_3 of the fractionating clinopyroxene exceeds that of the clinopyroxene in PHKILCAL. Presumably with falling temperature the reverse should be true. The Al_2O_3 relations might be modified by consideration of Cr_2O_3 and TiO_2 in pyroxene or by changing the Al:Cr ratio of the spinel, but the Na_2O could only be reversed by making the earlier clinopyroxenes more calcic than the bulk clinopyroxene. The latter would imply both that the CaO in clinopyroxene was decreasing during fractionation and that the ratio orthopyroxene: clinopyroxene was increasing during fractionation, neither of which should occur with falling temperature.

I conclude that there is no single-stage fractionation process that will explain the observed chemical variation. There remains the possibility of a multistage process in which pyroxenes with lower Na_2O and Al_2O_3 than those shown in table 22 are fractionated at high pressure and are joined by a small

TABLE 20.—*Lava compositions*[1] *used in high-pressure fractionation calculations*

	PHKILCAL (25 percent MgO)	1952Hm (20 percent MgO)	1959S–2 (20 percent MgO)	1967–68Hm (20 percent MgO)
SiO_2	46.17	46.81	46.73	47.00
Al_2O_3	7.83	9.30	9.17	9.21
"FeO"	11.36	11.93	11.90	11.88
MgO	25.00	20.00	20.00	20.00
CaO	6.29	7.71	7.86	7.64
Na_2O	1.26	1.51	1.54	1.56
K_2O	.23	.35	.40	.37
TiO_2	1.35	1.82	1.85	1.79
P_2O_5	.12	.19	.19	.18
MnO	.18	.19	.18	.19
Cr_2O_3	.22	.19	.19	.20

[1] Obtained from data of table 4 and table 14 by adding the appropriate amount of olivine ($Fa_{13.7}$) containing 1 percent included Cr-spinel.

TABLE 21.—*Results of high-pressure fractionation calculations for Kilauea summit lavas*

A. Results with olivine-spinel-orthopyroxene-clinopyroxene-plagioclase

Parent / Differentiate	PHKILCAL (25 percent MgO) 1952Hm (20 percent MgO)	PHKILCAL (25 percent MgO) 1959 S–2 (20 percent MgO)	PHKILCAL (25 percent MgO) 1967–68Hm (20 percent MgO)
Fractionated phases:			
Olivine ($Fa_{12.5}$)	19.26	19.29	19.69
Cr-spinel	.39	.39	.35
Orthopyroxene (KUMLHYP)	4.93	5.75	3.70
Clinopyroxene (MP218AUG)	1.91	1.21	1.89
Plagioclase	3.67 ($An_{59.7}$)	4.13 ($An_{59.7}$)	3.62 ($An_{62.1}$)
Total	30.16	30.77	29.25
Residuals:[1]			
SiO_2	.01	.02	.02
Al_2O_3	−.01	.01	.01
"FeO"	.00	.01	.01
MgO	.01	.01	.01
CaO	.01	.01	.01
Na_2O	.04	.01	.00
K_2O	−.02	−.05	−.04
TiO_2	.05	.04	.06
P_2O_5	−.01	−.01	.00
MnO	−.02	−.01	−.02
Cr_2O_3	.01	.01	.01

[1] Observed minus calculated composition of parent.

TABLE 21.—*Results of high-pressure fractionation calculations for Kilauea summit lavas*—Continued

B. Results with olivine-spinel-orthopyroxene-clinopyroxene

Parent Differentiate	PHKILCAL (25 percent MgO) 1952Hm (20 percent MgO)	PHKILCAL (25 percent MgO) 1959 S–2 (20 percent MgO)	PHKILCAL (25 percent MgO) 1967–68Hm (20 percent MgO)
Fractionated phases:			
Olivine ($Fa_{12.5}$)	17.26	16.94	17.36
Cr-spinel	.36	.38	.32
Orthopyroxene	5.35	7.23	4.63
Clinopyroxene	4.30	4.29	4.11
Total	27.27	28.84	26.42
Residuals:[1]			
SiO_2	.02	.02	.02
Al_2O_3	.01	.01	.01
"FeO"	.01	.01	.01
MgO	.01	.01	.01
CaO	.01	.01	.01
Na_2O	.01	.01	.01
K_2O	−.02	−.05	−.04
TiO_2	.03	.04	.04
P_2O_5	−.01	−.01	−.01
MnO	.00	.01	−.01
Cr_2O_3	.01	.01	.01

Calculated composition of pyroxenes

	Orthopyroxene	Clinopyroxene	Orthopyroxene	Clinopyroxene	Orthopyroxene	Clinopyroxene
SiO_2	53.36	52.69	52.59	52.08	52.73	51.29
Al_2O_3	7.85	11.52	8.75	12.01	9.02	12.03
"FeO"	7.02	4.18	8.14	4.95	6.82	4.24
MgO	30.63	13.45	29.38	13.01	30.36	14.75
CaO	.90	14.71	.87	14.63	.83	15.27
Na_2O	.23	3.45	.28	3.32	.23	2.42

[1] Observed minus calculated composition of parent.

TABLE 22.—*Calculated high-pressure solidus assemblage and pyroxene compositions for Kilauea summit lavas*

	PHKILCAL (25 percent MgO)	1952Hm (20 percent MgO)	1959 S–2 (20 percent MgO)	1967–68 (20 percent MgO)
Mode				
Olivine (Fa_{14})	26.21	11.65	11.73	11.07
Cr-spinel	.70	.60	.59	.63
Orthopyroxene	30.19	33.72	32.16	34.03
Clinopyroxene	30.68	35.62	34.77	34.99
Hornblende [1]	11.15	16.96	19.39	17.93
Apatite	.28	.44	.44	.41
Rutile [2]	.84	1.06	.98	.98

Calculated composition of pyroxenes

	Orthopyroxene	Clinopyroxene	Orthopyroxene	Clinopyroxene	Orthopyroxene	Clinopyroxene	Orthopyroxene	Clinopyroxene
SiO_2	51.24	51.04	50.91	50.73	51.28	50.73	51.21	50.96
Al_2O_3	8.30	11.94	7.96	11.72	7.47	11.46	7.58	11.56
"FeO"	13.94	6.96	15.86	7.98	15.77	8.07	15.60	7.94
MgO	25.50	12.26	24.24	11.82	24.48	11.94	24.69	11.75
CaO	.87	14.99	.89	15.11	.83	15.27	.78	15.04
Na_2O	.15	2.84	.15	2.64	.19	2.53	.14	2.75

[1] A hornblende from Kakanui with 4.5 percent TiO_2, 2.1 percent K_2O, and 3.1 percent Na_2O is used for the K_2O balance.
[2] Used for TiO_2 balance in the absence of any TiO_2 in pyroxene.

amount of plagioclase as the magma moves to lower pressure. This process would require a virtually isothermal ascent of magma from the uppermost mantle to the 3-km-deep reservoir in order to move from a field in which plagioclase was stable (at say 8 kb) to the conditions at a depth of 3 km where the magmas lie within the field of olivine just above the stability field of clinopyroxene and plagioclase. (See, for example, Green and Ringwood, 1967, fig. 4, or Ito and Kennedy, 1968, figs. 1 and 2.)

SHORT-TERM CHEMICAL VARIATION

In a previous paper (Wright and Fiske, 1971, app. 2), it is shown that lava from each of the recent (1952 to 1967–68) summit eruptions of Kilauea is uniform in composition but differs from the others in ways that are explainable only by addition or removal of a complex silicate assemblage, generally including hypersthene. The chemical composition of these lavas is shown on an expanded scale in figure 12. The uniformity of each eruption

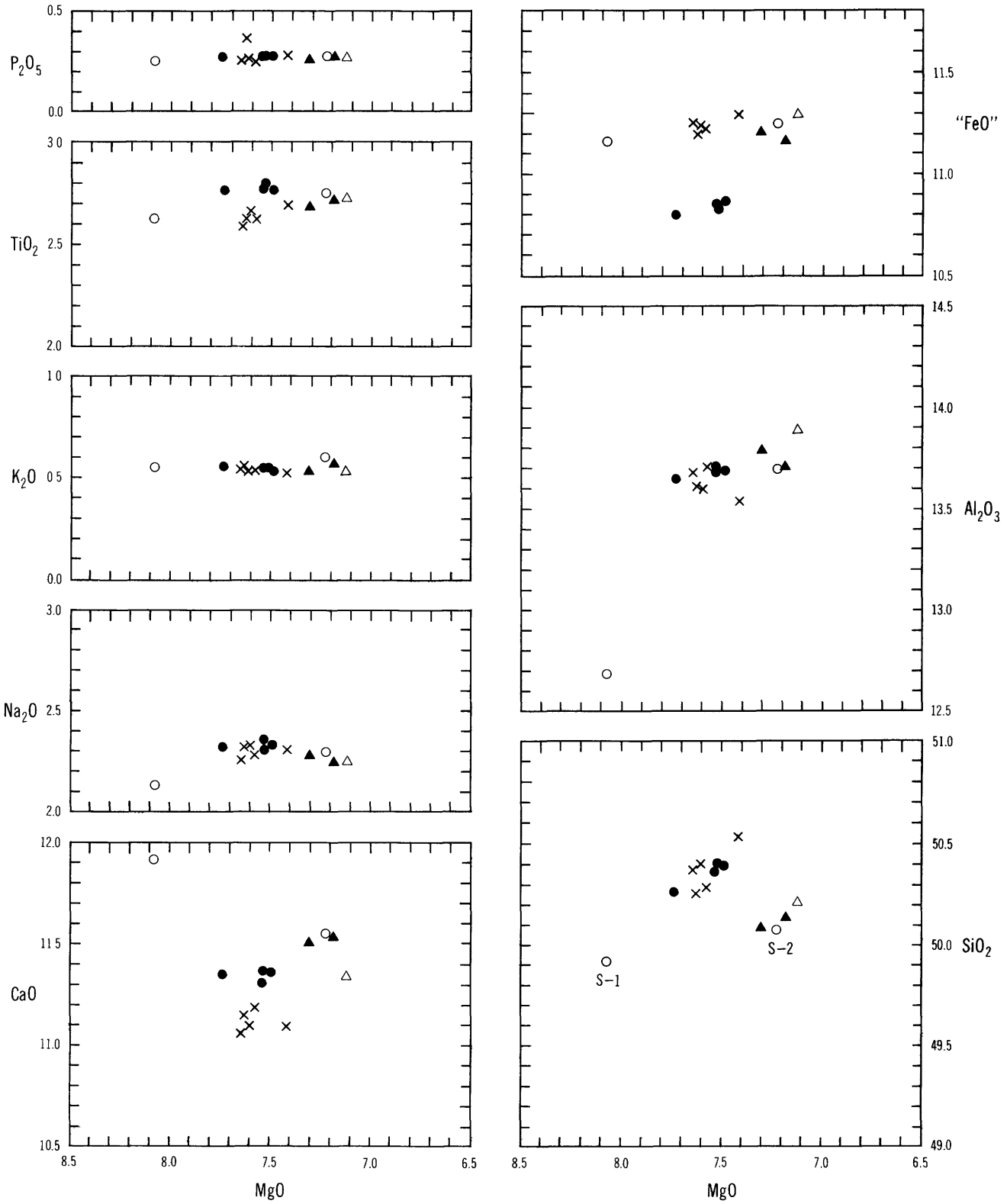

FIGURE 12.—MgO variation diagrams showing Kilauea summit lavas 1952–68. △, 1952—Halemaumau; ▲, 1954—Halemaumau and Kilauea caldera floor; ○, 1959—Kilauea Iki—all samples from the eruption correspond to a mixture of S–1, S–2, and olivine ($Fa_{13.2\text{-}16.8}$); •, 1961—Halemaumau; ×, 1967–68—Halemaumau. Each eruption may be distinguished chemically from every other eruption on one or more of the variation diagrams.

and the necessity for accumulation or removal of hypersthene indicate that these chemical variations are produced at pressures in excess of 2 kb prior to storage of magma in the shallow reservoir complex beneath Kilauea summit. I suggest that these batches are a result of high-pressure fractionation processes similar to those described for the long-term variation and that each batch is produced along a different pressure-temperature-time path in the upper mantle; that is, the original melt is considered to move upward in the mantle along paths where both the rate of cooling and velocity of ascent (equals rate of change of pressure) are variable, and this determines the amount and kind of phases that are fractionated.

MODEL FOR MELTING AND FRACTIONATION OF KILAUEA AND MAUNA LOA MAGMAS

A possible cross section through Kilauea and Mauna Loa is shown at true vertical and horizontal scale in figure 13. The zone of original melting is assumed to be at a depth of at least 60 km (below the deepest recorded earthquakes beneath Kilauea) corresponding to pressures in excess of 20 kb. The amount of melting needed to produce an initial picritic tholeiitic magma with 25 percent MgO is considered to be about 50 percent (see Jackson and Wright, 1970) in order to restrict the range of depth to which the mantle is melted.

There is strong evidence for the existence of an intermediate reservoir in the uppermost mantle, a staging area from which magma is efficiently supplied the 3-km-deep, reservoir. The evidence is contained in the observation that Halemaumau (summit) eruptions are accompanied by only a small collapse of the summit (see for example Kinoshita and others, 1969), implying that magma is resupplied at virtually the same rate as it is erupted (at least $0.3\times10^6 m^3$/day for the 1967–68 eruption).

Thus geophysical observation and the chemical petrology lead me to suggest the following model shown in figure 13.

Depth	*Process(es)*
?–60 km	Melting to produce picritic (20–25 percent MgO) tholeiitic magma.
60–30 km	Upward movement accompanied by fractionation of olivine-spinel and variable amounts of orthopyroxene and clinopyroxene.
30–20 km	Accumulation of magma in separate storage reservoirs which periodically feed the shallow reservoir beneath Kilauea summit. Further removal of olivine and pyroxene and possible fractionation of plagioclase.
20–4 km	Rapid upward transfer of magma during eruption at Kilauea summit and during periods of inflation between eruptions.
4–2 km	Storage of magma prior to eruption. Some cooling and further fractionation of olivine only.

A section through Mauna Loa cannot be specified as closely because there are few geophysical data. The chemistry of the eruptions suggests that there has been relatively little high-pressure fractionation of pyroxenes but significant low-pressure movement of olivine, pyroxene, and plagioclase phenocrysts.

The model of figure 13 is very much like that proposed by O'Hara (1968, p. 95) for derivation of quartz-normative tholeiitic magmas. The model implies that the unmelted part of the upper mantle as well as the lower crust contains excess olivine precipitated from rising picritic magmas. The Kilauea model would imply accumulation of pyroxene as well.

The model proposed here differs in the following respects from that proposed by Murata (1970):

1. The chemical differences between Kilauea and Mauna Loa are explained by fractionation of Kilauea magma, which may have been originally close to the composition of Mauna Loa, instead of by differing degrees of partial melting or by melting in a mantle of variable composition.
2. Orthopyroxene alone is not found sufficient to explain the differences in chemistry either within Kilauea or between Kilauea and Mauna Loa. (Compare the residuals in the calculations of table 21 with those of Murata, 1970, table 2.) It is important to note in this regard that orthopyroxene fractionation alone would yield alkalic basalt whereas Kilauea has remained tholeiitic.
3. I find, in agreement with Murata, an excess of K_2O and TiO_2 in the 1959 Kilauea eruption as compared with Mauna Loa. This is true regardless of what kind of fractionation or melting scheme is proposed. However, these differences are much less accentuated if other recent lavas are compared with Mauna Loa (for example, 1967–68) and are virtually nonexistent if the comparison is made with older lavas of Kilauea.

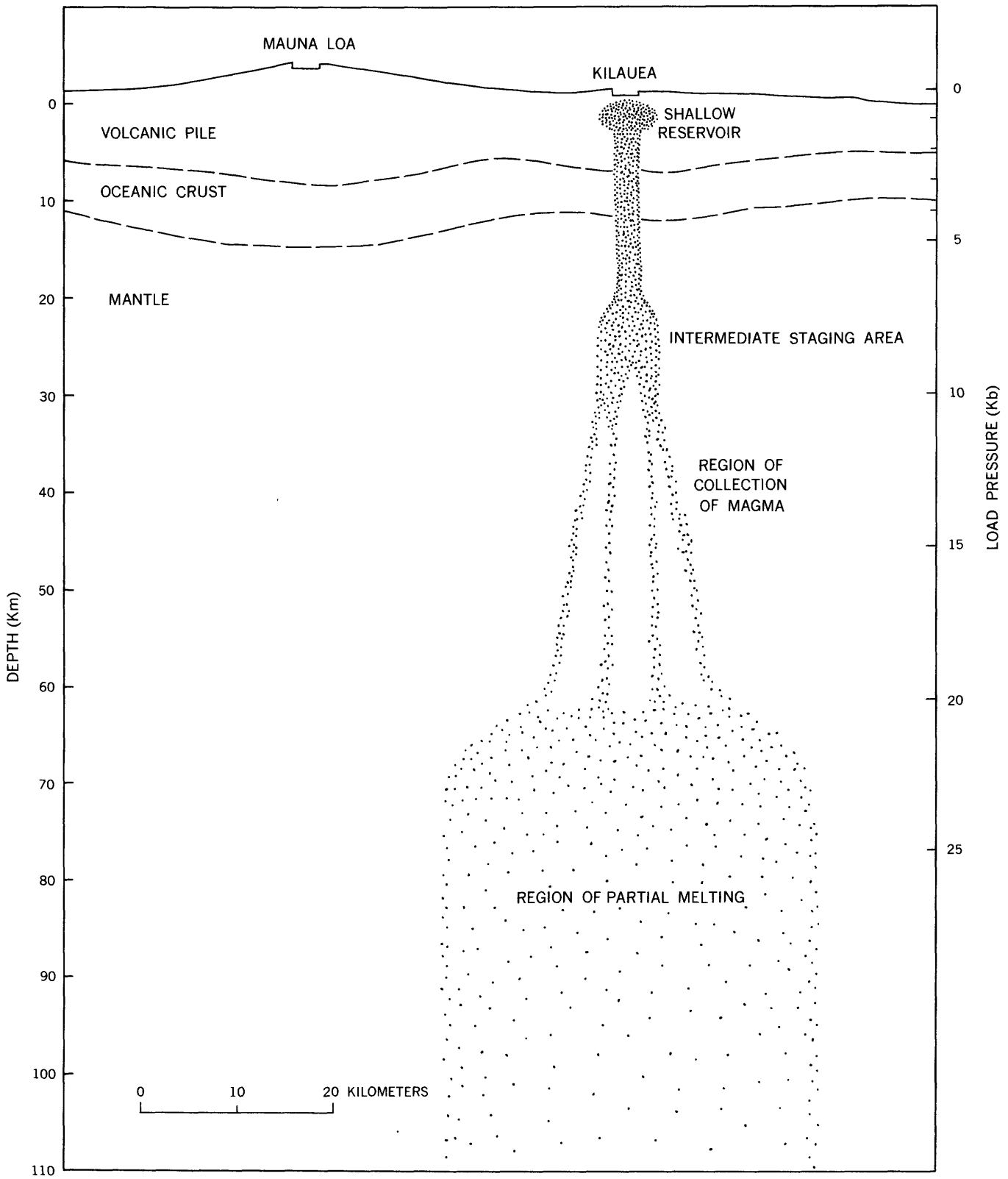

FIGURE 13.—A hypothetical model of Kilauea and Mauna Loa at true scale outlining regions of melting, fractionation, and storage of magma prior to eruption.

TABLE 23.—*Sample data for the chemical analyses of tables 4–6 and 8–13*

All analyses were done in the U.S. Geological Survey under the direction of L. C. Peck; individual analysts are identified as follows: CLP, Christel Parker; DFP, Dorothy Powers; EE, Edythe Engleman; ELM, Elaine Munson; ESD, Ellen Daniels; GOR, George Riddle; JWG, June Goldsmith; LDT, Lois Trumbull; LMK, Lucille Kehl; LNT, Lucille Tarrant; VCS, Vertie Smith]

Field No.	Laboratory No.	Report No.	Analyst	Age	Quadrangle	Lat	Long	Elevation (feet)	Geologic map or other reference	Sample type	Collector
Table 4, lavas from Kilauea summit											
57–F–18	E–2144	IDC–368	JWG	Prehistoric	Kau Desert	19°18′	155°19′	1,965	Walker, 1969	Flow, Hilina Pali section	George Fraser.
15	E–2143	IDC–368	JWG	do	do	19°18′	155°18′	1,100	do	do	Do.
17	E–2147	LDC–368	JWG	do	do	19°18′	155°18′	1,100	do	Multiple dike, Hilina Pali section	Do.
66	E–2148	IDC–368	JWG	do	do	19°18′	155°18′	1,100	do	Dike, Hilina Pali section	Do.
97	E–2149	IDC–368	JWG	do	do	19°18′	155°18′	1,100	do	do	Do.
53P–12	C–812	IDC–237	DFP	do	Kilauea Crater				Peterson, 1967	Northwest wall Kilauea caldera, flow 50 ft above floor.	H. A. Powers.
32	C–814	IDC–237	DFP	do	do				do	Northwest wall Kilauea caldera, flow older than Uwekahuna Ash.	Do.
33	C–815	IDC–237	DFP	do	do				do	do	Do.
35	C–816	IDC–237	DFP	do	do				do	Northwest wall Kilauea caldera, flow resting on Uwekahuna Ash.	Do.
30	C–813	IDC–237	DFP	do	do				do	West rim of Kilauea caldera, flow from quarry at Namakani Paio.	Do.
HIGS–2	D101098	66–DC–7	GOR	do	do				do	East rim of Kilauea caldera, flow near Lua-manu.	Do.
8X002–0	D102182	68–DC–35	CLP	do	do				do	Drill core, flow from northwest wall, Kilauea caldera.	R. R. Doell.
8X038–0	D102183	68–DC–35	CLP	do	do				do	do	Do.
8X067–0	D102184	68–DC–35	CLP	do	do				do	do	Do.
8X078–0	D102185	68–DC–35	CLP	do	do				do	do	Do.
1790	D101973	68–DC–16	EE	1790	do	19°24′	155°17′	3,640	do	Glassy bomb, Kilauea caldera floor	H. A. Powers.
1832	D101756	67–DC–31	EE	1832	do	19°25′	155°16′	3,680	do	Flow, Byron Ledge	T. L. Wright.
1866(?)	D101758	67–DC–31	EE	1866(?)	do	19°25′	155°16	3,540	do	Flow, Kilauea caldera floor	H. A. Powers.
1868	D101422	66–DC–42	GOR	1868	do				do	Flow, wall of Kilauea Iki Crater (covered by 1959 lava).	T. A. Jaggar.
1877 Caldera	D101420	66–DC–42	GOR	1877	do	19°24′	155°16′	3,560	do	Spatter, west wall Kilauea caldera	T. L. Wright.
1877 Keanakakoi	D101421	66–DC–42	GOR	1877	do	19°24′	155°16′	3,470	do	Flow, Keanakakoi Crater floor	Do.
53P–9	C–811	IDC–237	DFP	1879	do	19°24′	155°16′	3,560	do	Flow, Kilauea caldera floor	H. A. Powers.
1	D100044	63–DC–21	DFP	1884–85	do	19°25′	155°17′	3,600	do	Flow, Kilauea caldera floor (covered by 1954 lava).	Do.
2	D100045	63–DC–21	DFP	1889	do	19°25′	155°17′	3,600	do	do	Do.
1911	D101759	67–DC–31	EE	1911	do					Glass from lava lake, Halemaumau Crater.	F. A. Perret.
	CD–53–2284	IDC–122	LNT	1917	do				Macdonald and Eaton, 1955, table 9.	do	T. A. Jaggar.
	D101424	66–DC–42	GOR	1918	do					do	Do.
	D100700	65–DC–17	ESD	1919	do					Glass from lava lake, Halemaumau Crater.	H. A. Powers.
477	CD–53–2283	IDC–122	LNT	1919	do	19°25′	155°17′	3,640	Peterson, 1967 and Macdonald and Eaton, 1955, table 9.	Flow, Kilauea caldera floor	Do.
475	CD–53–2281	IDC–122	LNT	1921	do	19°24′	155°17′	3,670	do	do	Do.
64P–126	D100701	65–DC–17	ESD	1924	do					Glass from lava lake, Halemaumau Crater.	T. A. Jaggar.
1931HM	D102410	69–DC–39	GOR	1931–32	do				Jaggar (Volcano Letter 388, June 1932).	Flow, Halemaumau Crater floor	R. Konishi.
	53–2377CD	IDC–120	LMK	1952	do				Macdonald, 1955, p. 81	Pumice, Halemaumau Crater	G. A. Macdonald.
Kil 1954	B–327	IDC–176	LDT	1954	do	19°25′	155°17′	3,600	Peterson, 1967, and Macdonald and Eaton, 1957, table 1.	Flow, Kilauea caldera floor	Do.
TLW67–42	D101794	67–DC–44	ELM	1954	do	19°25′	155°17′	3,620	Peterson, 1967	do	T. L. Wright.
Feb. 1961	H3562	DC–562	ELM	2/24/61	do				Richter and others, 1964, table 1	Pumice, Halemaumau Crater	D. H. Richter.
July 1961	H3563–5	DC–562	ELM	7/11–16/61	do				do	do	Do.
1967HM	D102012	68–DC–19	GOR	1967	do				Kinoshita and others, 1969, table 2	Pumice, Halemaumau Crater. Erupted Nov. 5, 1967	T. L. Wright.
HM68–2	D102407	69–DC–39	GOR	1968	do					Flow crust, Halemaumau Crater. Erupted May 29, 1968.	D. A. Swanson.
4	D102399	69–DC–29	ELM	1968	do					Flow crust, Halemaumau Crater. Erupted in early July, 1968.	Do.
12	D102408	69–DC–39	GOR	1968	do					Aa flow, Halemaumau Crater. Erupted February 1968.	Do.
15	D102409	69–DC–39	GOR	1968	do					Spatter, Halemaumau Crater. Erupted July 13, 1968.	Do.

TABLE 23.—*Sample data for the chemical analyses of tables 4–6 and 8–13*—Continued

Field No.	Laboratory No.	Report No.	Analyst	Age	Quadrangle	Lat	Long	Elevation (feet)	Geologic map or other reference	Sample type	Collector
Table 5, lavas from Kilauea southwest rift zone											
TLW67-138A	D102009	68-DC-19	GOR	Prehistoric	Pahala	19°11′	155°27′	600	Stearns and Macdonald, 1946	Spatter, Puu Kolekole, Kilauea	T. L. Wright.
139	D102010	68-DC-19	GOR	do	do	19°12′	155°26′	980	do	Spatter, Puu Ulaula, Kilauea	Do.
140	D102011	68-DC-19	GOR	do	do	19°13′	155°25′	1,040	do	Spatter, "lava-plastered cones"	Do.
128	D101967	68-DC-16	EE	do	Wood Valley	19°17′	155°22′	2,260	do	Spatter, Puu Kou	Do.
134	D101954	68-DC-16	EE	do	Kilauea Crater	19°24′	155°18′	3,700	Peterson, 1967	Picrite flow, south wall of Kilauea caldera.	Do.
136B	D101955	68-DC-16	EE	do	do	19°24′	155°18′	3,700	do	do	Do.
3	D101748	67-DC-31	EE	do	Kau Desert	19°22′	155°22′	3,080	Walker, 1969	Picrite flow	Do.
KD-3	D101946	68-DC-16	EE	do	do	19°21′	155°17′	3,200	do	do	G. W. Walker.
32	D101947	68-DC-16	EE	do	do	19°21′	155°20′	2,940	do	do	Do.
56	D101948	68-DC-16	EE	do	do	19°22′	155°19′	3,180	do	do	Do.
57	D101949	68-DC-16	EE	do	do	19°22′	155°19′	3,180	do	do	Do.
91	D101950	68-DC-16	EE	do	Wood Valley	19°16′	155°23′	1,660		do	Do.
TLW67-129	D101951	68-DC-16	EE	do	do	19°16′	155°23′	1,660		do	T. L. Wright.
KD-143	D101952	68-DC-16	EE	do	Kau Desert	19°19′	155°19′	2,700	Walker, 1969	do	G. W. Walker.
144	D101953	68-DC-16	EE	do	do	19°19′	155°19′	2,700	do	do	Do.
TLW67-10	D101742	67-DC-31	EE	do	do	19°22′	155°22′	2,980	do	do	T. L. Wright.
KD-164	D101958	68-DC-16	EE	do	do	19°17′	155°18′	850	do	Picrite flow(?)	G. W. Walker.
172	D101959	68-DC-16	EE	do	Naliikakani Point	19°15′	155°20′	170		do	Do.
45	D101956	68-DC-16	EE	do	Kau Desert	19°20′	155°22′	2,800	Walker, 1969	Flow, south of Mauna Iki, surrounded by 1920 lava.	Do.
161	D101957	68-DC-16	EE	do	do	19°19′	155°21′	2,660	do	Flow from Puu Koae	Do.
TLW67-16	D101751	67-DC-31	EE	do	do	19°21′	155°20′	3,160	do	Bomb, Puu Koae	T. L. Wright.
CC-SW	D101428	66-DC-42	GOR	do	do	19°21′	155°19′	3,140	do	Spatter, Cone Crater	Do.
TLW67-18	D101752	67-DC-31	EE	do	Kilauea Crater	19°23′	155°19′	3,600	Peterson, 1967	Spatter, Cone Peaks	Do.
28	D101750	67-DC-31	EE	do	Wood Valley	19°17′	155°24′	2,000	Stearns and Macdonald, 1946	Kamooalii flow	Do.
KD-130	D101964	68-DC-16	EE	do	Kau Desert	19°19′	155°21′	2,690	Walker, 1969	Flow, hill 2687 northeast of Kamakaia Hills.	G. W. Walker.
A-451	I4175	63-DC-6	DFP	1823	do				Stearns and Macdonald, 1946	Lava ball near Great Crack	J. G. Moore.
1823-SW	D101426	66-DC-42	GOR	1823	do				do	do	J. B. Stone.
TLW67-24	D101747	67-DC-31	EE	1823	Wood Valley	19°15′	155°25′	1,660	do	Spatter, Great Crack	T. L. Wright.
1868-SW	D101423	66-DC-42	GOR	1868	do				do	Flow	T. A. Jaggar.
TLW67-12	D101746	67-DC-31	EE	1868	do	19°19′	155°23′	2,540	do	Spatter, main vent	T. L. Wright.
1920-231-3	D101425	66-DC-42	GOR	1920	Kau Desert	19°21′	155°22′	2,940	Walker, 1969	Glassy toe south of Mauna Iki	H. A. Powers.
TLW67-1	D101749	67-DC-31	EE	1920	do	19°22′	155°21′	3,200	do	Spatter, northernmost vent	T. L. Wright.
4	D101743	67-DC-31	EE	1920	do	19°22′	155°22′	2,980	do	Spatter, Mauna Iki	Do.
6	D101744	67-DC-31	EE	1920	do	19°21′	155°22′	3,020	do	do	Do.
9	D101745	67-DC-31	EE	1920	Wood Valley	19°19′	155°23′	2,560	Stearns and Macdonald, 1946	Aa flow south of Mauna Iki	Do.
Table 6, lavas from Kilauea east rift zone [Analyses of historic flows, Kilauea east rift zone, are given in Wright and Fiske (1971)]											
TLW67-39	D101971	68-DC-16	EE	Prehistoric	Kapoho	19°31′	154°51′	100	Stearns and Macdonald, 1946	Spatter, Kapoho cone	T. L. Wright.
40	D101972	68-DC-16	EE	do	do	19°31′	154°51′	200	do	Spatter, Puu Kea cone near Kapoho	Do.
130	D101968	68-DC-16	EE	do	Makaopuhi Crater					South wall, Makaopuhi Crater; flow.	Do.
131	D101970	68-DC-16	EE	do	do					South wall, Makaopuhi Crater; dike.	Do.
132A	D101969	68-DC-16	EE	do	do					South wall, Makaopuhi Crater; flow.	Do.
MP-57	I4179	63-DC-6	DFP	do	do				Moore and Evans, 1967	Chilled margin, prehistoric lava lake, east pit, Makaopuhi Crater.	J. G. Moore.
Table 8, lavas from Mauna Loa, Mokuaweoweo caldera											
7D-014	D101999	68-DC-19	GOR	Prehistoric	Mauna Loa					Drill core in flow, Mauna Loa, north wall Mokuaweoweo caldera.	R. R. Doell.
026	D102000	68-DC-19	GOR	do	do					do	Do.
420	D102001	68-DC-19	GOR	do	do					do	Do.
428	D102002	68-DC-19	GOR	do	do					do	Do.
TLW67-84	D102003	68-DC-19	GOR	do	Kokoolau	19°31′	155°35′	12,400	Stearns and Macdonald, 1946	Aa flow, summit road	T. L. Wright.
70B	D101830	68-DC-5	CLP	do	Mauna Loa	19°28′	155°37′	13,400	Macdonald, 1971	Flow, west rim, Mokuaweoweo caldera.	Do.
88	D101997	68-DC-19	GOR	1877	do	19°29′	155°36′	13,200	do	Flow, north slope	G. A. Macdonald.
89	D101998	68-DC-19	GOR	1880	do	19°29′	155°35′	13,050	do	Flow near edge of pit crater, Lua Poholo, North Bay.	Do.
1940ML	53-2381CSD	IDC-125	LDT	1940	do				Macdonald and Eaton, 1955	Pumice	Do.
TLW67-68	D101832	68-DC-5	CLP	1942	do	19°29′	155°36′	13,200	Macdonald, 1971	do	T. L. Wright.
M-56-2	C810	IDC-235	LNT	1949	do				Macdonald and Eaton, 1955	Pumice, least oxidized of three samples from main spatter cone.	G. A. Macdonald.
1949ML	53-2382CSD	IDC-125	LDT	1949	do				do	Flow, near South Bay	Do.

Table 9 lavas from Mauna Loa south rift zone

----------	E2145	IDC–368	JWG	Prehistoric	Ka Lae	18°58′	155°42′	500	----------	Kahuku Pali, flow	George Fraser.
----------	E2146	IDC–368	JWG	--do--	----do----	18°58′	155°42′	250	----------	----do----	Do.
----------	C819	IDC–238	LNT	--do--	----------	------	------	--------	Stearns and Clark, 1930	Flow (sample 19)	L. F. Noble.
----------	C820	IDC–238	LNT	--do--	----------	------	------	--------	----do----	Flow (sample 35)	Do.
65MAN–1	D101463	67–DC–9	GOR	--do--	Kealakekua	19°35′	155°57′	1,000	Stearns and Macdonald, 1946	Flow, road to Kailua	E. D. Jackson.
65KUH–2	D101464	67–DC–9	GOR	--do--	Papa	19°11′	155°45′	5,460	----do----	Spatter, cone southeast of Puu Ohohia.	Do.
13	D100695	65–DC–17	ESD	--do--	----------	------	------	--------	Moore, 1965	Submarine basalt, 1200 fathoms	J. G. Moore.
W–A–6	D101852	68–DC–5	CLP	1868	Kahuku Ranch	19°07′	155°41′	3,200	Stearns and Macdonald, 1946; source of flow mapped too low on topographic sheet.	Spatter, uppermost vent, Mauna Loa, south rift zone	A. T. Anderson.
7	D101853	68–DC–5	CLP	1868	----do----	19°06′	155°41′	3,100	----do----	Spatter	Do.
8	D101854	68–DC–5	CLP	1868	----do----	19°04′	155°41′	2,040	----do----	Flow	Do.
1868ML	D102287	69–DC–13	GOR	1868	----do----	19°04′	155°41′	2,040	----do----	Picrite, Mamalahoa Road	T. L. Wright.
H–19	I3836	DC–601	DFP	1868	Puu Hou	18°58′	155°43′	0	Moore and Ault, 1965	Littoral cone	J. G. Moore.
TLW67–59	D101851	68–DC–5	CLP	1887	Puu o Keokeo	19°12′	155°44′	6,000	Stearns and Macdonald, 1946	Spatter, uppermost vents	T. L. Wright.
56	D101850	68–DC–5	CLP	1907	----do----	19°12′	155°45′	6,320	----do----	----do----	Do.
77	D101849	68–DC–5	CLP	1919	Alika Cone	19°16′	155°44′	7,800	----do----	Spatter	Do.
H–34	I3839	DC–601	DFP	1919	Mililii	19°14′	155°54′	0	Moore and Ault, 1965	Glass sand, littoral cone	J. G. Moore.
36	I3840	DC–601	CLP	1919	----do----	19°14′	155°54′	0	----do----	Flow near littoral cone	Do.
TLW67–76	D101844	68–DC–5	CLP	1926	----do----	19°16′	155°45′	7,700	Stearns and Macdonald, 1946	Spatter, lower vents	T. L. Wright.
73	D101846	68–DC–5	CLP	1950	Sulphur Cone	19°23′	155°38′	11,200	----do----	Spatter, vents near Sulphur Cone	Do.
74	D101847	68–DC–5	CLP	1950	Alika Cone	19°21′	155°40′	9,680	----do----	Spatter	Do.
75	D101848	68–DC–5	CLP	1950	----do----	19°18′	155°43′	8,560	----do----	----do----	Do.
79	D102286	69–DC–13	GOR	1950	Kauluoa Point	19°16′	155°53′	1,340	----do----	Flow, southern branch, Mamalahoa Road.	Do.
----------	53–2378CD	IDC–120	LK	1950	----------	------	------	--------	Macdonald and Eaton, 1955	Flow	G. A. Macdonald.

Table 10, lavas from Mauna Loa northeast rift zone

476	53–2282CD	IDC–122	LNT	Prehistoric	----------	------	------	--------	Macdonald and Eaton, 1955	Flow near Olaa	H. A. Powers.
TLW67–29	D101757	67–DC–31	EE	--do--	Wood Valley	19°22′	155°22′	3,000	Stearns and Macdonald, 1946	Keamoku flow, footprints	T. L. Wright.
61	D101831	68–DC–5	CLP	1852	Puu Ulaula	19°34′	155°25′	8,340	----do----	Spatter, source vents	Do.
63	D101834	68–DC–5	CLP	1855	----do----	19°33′	155°28′	10,000	Stearns and Macdonald, 1946. Source not mapped on either geologic map or topographic map. Vents are about 1 mile northwest of Puu Ulaula between the mapped 1899 and 1880–81 flows.	----do----	Do.
W–A–20	D101835	68–DC–5	CLP	1855	Piihonua	19°42′	155°14′	2,800	Stearns and Macdonald, 1946	Flow, Saddle Road	Do.
81–10000	65–M–491	65–DC–36	CLP	1881	Puu Ulaula	19°32′	155°28′	10,000	----do----	Flow. two samples out of five chosen to show extremes of composition variation.	J. G. Moore.
2200	65–M–493	65–DC–36	CLP	1881	Piihonua	19°41′	155°12′	2,200	----do----	----do----	Do.
TLW67–65	D101836	68–DC–5	CLP	1899	Kokoolau	19°31′	155°32′	11,700	Stearns and Macdonald, 1946. The 1899 source mapped about 400 ft too low on both the topographic and geologic map.	Spatter, source vent	T. L. Wright.
W–A–24	D101837	68–DC–5	CLP	1899	Puu Ulaula	19°36′	155°28′	8,000	Stearns and Macdonald, 1946	Flow, road to Mauna Loa Observatory.	Do.
TLW67–67	D101838	68–DC–5	CLP	1935	Kokoolau	19°30′	155°34′	12,520	Stearns and Macdonald, 1946. The 1935 source mapped as 1942 on both the topographic and geologic map.	Spatter source vent	Do.
W–A–21	D101839	68–DC–5	CLP	1935	Puu Oo	19°41′	155°27′	6,300	Stearns and Macdonald, 1946	Flow, Saddle Road	Do.
TLW67–62	D101833	68–DC–5	CLP	1942	Puu Ulaula	19°33′	155°27′	9,200	Stearns and Macdonald, 1946. Source vents extend 100 ft uphill from boundary of flow portrayed on topographic map.	Spatter, source vent	Do.

Table 11, lavas from Mauna Loa, northwest slope

TLW67–117A	D101887	68–DC–10	GOR	Prehistoric	Kiholo	19°51′	155°56′	0	----------	Beach boulder, Kiholo Bay	T. L. Wright.
78	D102004	68–DC–19	GOR	--do--	Hualalai	19°39′	155°46′	5,160	Stearns and Macdonald, 1946	Glassy pahoehoe toe near Ahu a Umi Heiau.	W. E. Banko.
119	D102005	68–DC–19	GOR	--do--	Puu o Uo	19°30′	155°42′	8,800	----do----	Spatter, Puu o Uo	T. L. Wright.
121	D102006	68–DC–19	GOR	--do--	----do----	19°35′	155°38′	8,430	----do----	Spatter, hill 8471, adjacent to lower 1859 vents.	Do.
123	D102007	68–DC–19	GOR	--do--	Kokoolau	19°37′	155°34′	7,960	----do----	Spatter, Kokoolau cone	Do.
125	D102008	68–DC–19	GOR	--do--	Puu Koli	19°38′	155°33′	7,260	----do----	Spatter, Puu Koli	Do.
65P–2	D101093	66–DC–1	CLP	1859	Kokoolau	19°32′	155°37′	11,000	----do----	Pumice, uppermost vent	D. L. Peck.
DPH–17	D101094	66–DC–1	CLP	1859	Kiholo	19°52′	155°55′	10	----do----	Flow	Do.

TABLE 23.—*Sample data for the chemical analyses of tables 4–6 and 8–13*—Continued

Field No.	Laboratory No.	Report No.	Analyst	Age	Quadrangle	Lat	Long	Elevation (feet)	Geologic map or other reference	Sample type	Collector
Table 12, lavas from the Ninole Hills, southeast slope of Mauna Loa											
----------	C817	IDC–238	LNT	Prehistoric	----------	------	------	--------	Stearns and Clark, 1930----------	Flow (sample 25)----------	L. F. Noble.
----------	C818	IDC–238	LNT	--do-------	----------	------	------	--------	----do----------	Flow (sample 34)----------	Do.
ID–098–2---------	D102186	68–DC–35	CLP	--do-------	----------	------	------	--------	Doell and Cox, 1965----------	Drill core, flow----------	R. R. Doell.
214–2---------	D102187	68–DC–35	CLP	--do-------	----------	------	------	--------	----do----------	----do----------	Do.
240–2---------	D102188	68–DC–35	CLP	--do-------	----------	------	------	--------	----do----------	----do----------	Do.
275–2---------	D102189	68–DC–35	CLP	--do-------	----------	------	------	--------	----do----------	----do----------	Do.
Table 13, differentiated lavas, Mauna Loa											
9----------	D100694	65–DC–17	ESD	Prehistoric	----------	------	------	--------	Moore, 1965----------	Submarine dredge sample, 300 fathoms.	J. G. Moore.
TLW67–72-------	D101843	68–DC–5	CLP	1926	Mokuaweoweo------	19°26′	155°37′	12,800	Macdonald, 1971----------	Uppermost vent, Lua Hou--------	T. L. Wright.
54-------	D101845	68–DC–5	CLP	1950	----do----------	19°26′	155°37′	12,800	----do----------	----do----------	R. S. Fiske.
54A-----	D102288	69–DC–13	GOR	1950	----do----------	19°26′	155°37′	12,800	----do----------	----do----------	Do.
66-------	D101840	68–DC–5	CLP	1843	Kokoolau----------	19°32′	155°32′	11,400	Stearns and Macdonald, 1946. The 1843 source vents are exposed within the 1935 flow as portrayed on the geologic map. Vent located about 0.85 miles N. 5° E. from steaming cone.	Source vent----------	T. L. Wright.
W–A–22---------	D101841	68–DC–5	CLP	1843	Puu Oo----------	19°42′	155°30′	6,630	Stearns and Macdonald, 1946-----	Aa flow, Saddle Road----------	Do.
23---------	D101842	68–DC–5	CLP	1843	Puu Koli----------	19°42′	155°30′	6,630	----do----------	Pahoehoe flow, Saddle Road-----	Do.

TABLE 24.—*List of references to published chemical analyses of Kilauea (olivine-controlled) and Mauna Loa flows other than those reported in this paper*

Reference	Volcano and date of eruption	Analyst
Macdonald (1968, table 6)----------	Kilauea, 1832----------	Y. Watanabe.
Do----------	Mauna Loa, prehistoric, 1855, 1880, 1899, 1907-----	M. Chiba, H. Asari.
Macdonald and Katsura (1961, table 1)----------	Kilauea, 1959----------	T. Katsura.
Macdonald and Katsura (1964, table 8)----------	Mauna Loa, 1843, 1859, 1881, 1887, 1926, 1935-----	T. Katsura, K. Ishibashi.
Muir and Tilley (1957, table 2)----------	Kilauea, 1921, prehistoric----------	J. H. Scoon.
Muir and Tilley (1963, table 1)----------	Kilauea, 1921, prehistoric; Mauna Loa, 1887------	Do.
Muir and Tilley (1963, table 5)----------	Kilauea, 1868; Mauna Loa, 1868----------	Do.
Muir and Tilley (1963, table 6)----------	Mauna Loa, 1935----------	Do.
Muir and Tilley (1963, table 8)----------	Kilauea, 1959–60----------	Do.
Tilley (1960a, table 1, 5 analyses)----------	Kilauea, 1921----------	Do.
Tilley (1960b, table 1, 2 analyses)----------	Kilauea, 1959----------	Do.
Tilley (1961, table 1)----------	Mauna Loa, 1887----------	Do.
Tilley and Scoon (1961, table 1)----------	Kilauea, 1868 (southwest rift zone); Kilauea Iki Crater, 1868 (two analyses).	Do.
Tilley and Scoon (1961, table 2)----------	Mauna Loa, 1868 (two analyses)----------	Do.
Tilley and Scoon (1961, table 3)----------	Mauna Loa, prehistoric (three flows), 1887, 1881----	Do.

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