SOLIDIFICATION OF ALAE LAVA LAKE, HAWAII

CRYSTALLIZATION AND DIFFERENTIATION OF THE ALAE MAGMA

GEOLOGICAL SURVEY
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Crystallization and Differentiation of the Alae Magma, Alae Lava Lake, Hawaii

By THOMAS L. WRIGHT *and* DALLAS L. PECK

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An account of the crystallization history and chemical differentiation of tholeiitic basalt from one of Kilauea's lava lakes

UNITED STATES DEPARTMENT OF THE INTERIOR

CECIL D. ANDRUS, *Secretary*

GEOLOGICAL SURVEY

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METRIC-ENGLISH EQUIVALENTS

Metric unit		English equivalent
Length		
millimeter (mm)	=	0.03937 inch (in)
meter (m)	=	3.28 feet (ft)
kilometer (km)	=	.62 mile (mi)
Area		
square meter (m²)	=	10.76 square feet (ft²)
square kilometer (km²)	=	.386 square mile (mi²)
hectare (ha)	=	2.47 acres
Volume		
cubic centimeter (cm³)	=	0.061 cubic inch (in³)
liter (L)	=	61.03 cubic inches
cubic meter (m³)	=	35.31 cubic feet (ft³)
cubic meter	=	.00081 acre-foot (acre-ft)
cubic hectometer (hm³)	=	810.7 acre-feet
liter	=	2.113 pints (pt)
liter	=	1.06 quarts (qt)
liter	=	.26 gallon (gal)
cubic meter	=	.00026 million gallons (Mgal or 10⁶ gal)
cubic meter	=	6.290 barrels (bbl) (1 bbl=42 gal)
Weight		
gram (g)	=	0.035 ounce, avoirdupois (oz avdp)
gram	=	.0022 pound, avoirdupois (lb avdp)
tonne (t)	=	1.1 tons, short (2,000 lb)
tonne	=	.98 ton, long (2,240 lb)
Specific combinations		
kilogram per square centimeter (kg/cm²)	=	0.96 atmosphere (atm)
kilogram per square centimeter	=	.98 bar (0.9869 atm)

Metric unit		English equivalent
Specific combinations—Continued		
cubic meter per second (m³/s)	=	35.3 cubic feet per second (ft³/s)
liter per second (L/s)	=	.0353 cubic foot per second
cubic meter per second per square kilometer [(m³/s)/km²]	=	91.47 cubic feet per second per square mile [(ft³/s)/mi²]
meter per day (m/d)	=	3.28 feet per day (hydraulic conductivity) (ft/d)
meter per kilometer (m/km)	=	5.28 feet per mile (ft/mi)
kilometer per hour (km/h)	=	.9113 foot per second (ft/s)
meter per second (m/s)	=	3.28 feet per second
meter squared per day (m²/d)	=	10.764 feet squared per day (ft²/d) (transmissivity)
cubic meter per second (m³/s)	=	22.826 million gallons per day (Mgal/d)
cubic meter per minute (m³/min)	=	264.2 gallons per minute (gal/min)
liter per second (L/s)	=	15.85 gallons per minute
liter per second per meter [(L/s)/m]	=	4.83 gallons per minute per foot [(gal/min)/ft]
kilometer per hour (km/h)	=	.62 mile per hour (mi/h)
meter per second (m/s)	=	2.237 miles per hour
gram per cubic centimeter (g/cm³)	=	62.43 pounds per cubic foot (lb/ft³)
gram per square centimeter (g/cm²)	=	2.048 pounds per square foot (lb/ft²)
gram per square centimeter	=	.0142 pound per square inch (lb/in²)
Temperature		
degree Celsius (°C)	=	1.8 degrees Fahrenheit (°F)
degrees Celsius (temperature)	=	[(1.8×°C)+32] degrees Fahrenheit

CRYSTALLIZATION AND DIFFERENTIATION OF THE ALAE MAGMA, ALAE LAVA LAKE, HAWAII

By Thomas L. Wright and Dallas L. Peck

ABSTRACT

The 15-m-thick lake of lava, which erupted into Alae pit crater in August 1963, has been sampled by core drilling through the crust and by emplacing ceramic probes in the melt. Temperature profiles were obtained by inserting thermocouples in open drill holes. Petrographic studies of pumice and drill cores, combined with chemical analyses of crust, melt, filter-pressed liquids (oozes), and mineral and glass separates, show the sequence of crystallization in a tholeiitic basalt.

Olivine (Fo_{80}) is the first mineral to crystallize at about 1,190°C, followed closely by augite($Wo_{40}En_{48.8}Fs_{11.2}$) at 1,180°–1,185°C and plagioclase (An_{70}) at 1,165°–1,170°C. Ilmenite ($Ilm_{90}Hem_{10}$) first appears at 1,070°C, followed by pigeonite (composition unknown) at about 1,050°C, magnetite at about 1,030°C, and apatite at 1,010°C. The solidus is 980°C.

Plagioclase changes composition during crystallization from An_{70} in the pumice to an average composition of An_{59} in the crystallized basalt. Traces of sodic plagioclase and alkali feldspar were detected during the separation of the residual glass for analysis. Bulk clinopyroxene in the crystallized basalt is calculated to have an "FeO"/MgO ratio of 1.3. Olivine was zoned to at least Fo_{45} before it ceased crystallizing at about 1,100°C.

The Alae basalt is a tholeiite that has a very uniform bulk composition as follows: SiO_2=50.47; Al_2O_3=13.67; Fe_2O_3=1.30; FeO=9.80; MgO=7.55; CaO=11.11; Na_2O=2.38; K_2O=0.54; TiO_2=2.74; P_2O_5=0.27; MnO=0.17. During crystallization of silicates, but before the appearance of Fe-Ti oxides, the liquid changes composition with, overall, a slight decrease in SiO_2 and decreases in Al_2O_3, MgO, and CaO, and increases in "FeO," Na_2O, K_2O, P_2O_5, and TiO_2. Following the appearance of opaque phases, Al_2O_3 shows little change, MgO and CaO continue to decrease, SiO_2, Na_2O, K_2O, and P_2O_5 increase; TiO_2 and "FeO" reach a maximum, then decrease. P_2O_5, which is progressively enriched in the liquid throughout most of the crystallization, eventually goes into apatite. Among minor elements, Cr and Ni are depleted and Ba, Cu, Li, Nb, Rb, Y, Yb, and Zr are enriched in successively lower temperature liquids. Sr remains nearly constant, Ga shows a slight increase in late liquids, and V reaches a maximum and then is depleted in lower temperature liquid. The residual liquid, represented by a colorless glass making up about 6 percent by weight of the crystallized basalt, con-tains more than 75 percent SiO_2 and can be calculated to consist of more than 95 percent quartz plus feldspar. Its composition corresponds to a calc-alkaline rhyolite.

Liquids (oozes) that flow into open drill holes were found to have brought in less than 10 percent crystals from the enclosing partly crystalline crust. Within this crystal fraction the plagioclase/pyroxene ratio tends to be higher than in the host rock, suggesting that plagioclase and pyroxene were separated during flow.

Extensive use has been made of "chemical modes," the computation of mineral and liquid proportions from knowledge of the chemical composition of a rock and its constituent phases. It is shown that optical modal data for Alae basalt are grossly in error; pyroxene is overestimated by 20 percent and opaque minerals by a factor of two, and plagioclase is correspondingly underestimated. Using the chemical modal data, the crystallization curve is shown to be S-shaped and to have a horizontal discontinuity at the temperature of the crust-melt interface.

INTRODUCTION

The eruption of Kilauea Volcano in August 1963 ponded a basaltic flow in the bottom of Alae Crater, forming a stagnant lava lake. Six days after the eruption we drilled a hole 0.9 m into the crust, an estimated 8 cm less than the thickness of the crust. The following day we measured a temperature profile in that drill hole. During 1963 and 1964 we drilled 11 additional holes from which 17 kg of core were recovered. Additional samples of molten basalt were collected in ceramic combustion tubes and on thermocouples. Repeated temperature measurements were made in the open drill holes during 1963 and 1964 while the lake solidified and for another three years while the lake continued to cool. The center of the lake reached ambient temperature by August 1967. Petrographic, mineralogical, and chemical studies of samples of melt, drill core, and quenched samples of pumice provide data that contribute to our knowledge of the crystallization and, particularly, differentiation of tholeiitic basalt.

The following preliminary reports describe aspects of the cooling history. Peck and others (1964) report temperature measurements in the lake through February 1964; Peck and others (1966) describe the crystallization of basalt in the lake; and Decker and Peck (1967) give an account of infrared temperature measurements in the lake. Skinner and Peck (1969) report on an immiscible sulfide liquid found in one sample of melt. Recently Shaw and others (1977) and Peck and others (1977) report results of finite-element modeling of the cooling history.

In October 1968 the floor of Alae Crater was overrun by new lava. Subsequently, beginning in May 1969, the crater was filled by lava from the long-lived Mauna Ulu eruption (Swanson and others, 1971). As of this writing, the spot once marked by Alae Crater now stands high as part of the Mauna Ulu shield volcano.

This report is the third of a series of chapters on the solidification of Alae lava lake. Chapter A (Peck and Kinoshita, 1976) describes the eruption and the formation of surface features of the lake. Chapter B (Peck, 1978) presents and interprets temperature measurements made in the drill holes, the density and vesicularity of recovered core, and also the results of repeated level surveys of the lava surface, all of which provide information on the pattern of solidification of the lake.

The present report extends the field studies of crystallizing basalt in Kilauea lava lakes and benefits significantly from earlier study of the two lava lakes, one prehistoric and one historic, in Makaopuhi pit crater (Wright and Okamura, 1977). A general summary of studies of Kilauea lava lakes, including an annotated bibliography, is given by Wright and others (1976).

ACKNOWLEDGMENTS

METHODS OF STUDY

DRILLING

Holes were bored in the solidified crust of the lava by means of a portable core drill with tungsten

TABLE 1.—Record of drill holes in Alae lava lake

Date	Drill hole No.	Depth of interval drilled (ft)	
8/29/63	[1]1	0 – 2.83	
9/3/63	1	2.67– 3.75	
9/6/63	1	3.62– 4.6	(to base of crust)
	[2]2	0 – 2.15	
9/17/63	1	4.20– 5.58	
10/1/63 and 10/2/63	[3]3	0 – 9.33	(to base of crust)
10/24/63	3	7.80–11.40	(to base of crust)
11/7/63	3	9.9 –13.40	(to base of crust)
11/20/63	[4]4	0 –15.3	(to base of crust)
11/27/63	4	11.3 –15.3	(to base of crust)
12/16/63	[5]5	0 –29.2	(through 2 ft of melt, lower crust and base of lake at approximately 28.5 ft)
1/29/64	5	17.5 –21.0	(plug of ooze)
4/1/64 and 4/2/64	[6]6	0 –32.25	(through 6 ft of melt into lower crust)
4/15/64	6	17.75–42.8	(through plug of ooze and lower crust to near base of lake)
4/22/64	6	19.4 –35	(through plug of ooze)
4/22/64	[7]7	0 – 0.83	(mast hole)
4/29/64	7	0 –20	
6/4/64	7	19.7 –21.8	
6/10/64	7	21.35–23.4	
6/17/64	[8]8	0 –20.75	
6/18/64	8	20.75–28.65	(through 1 ft of melt into lower crust)
7/28/64	[9]9	0 –11.7	
7/29/64	9	11.7 –12.7	(EX hole to 24.5 ft)
9/11/64	9	12.7 –22.7	(SP hole 24.5–34.5 ft)
9/14/64	9	22.7 –34.5	(through partly molten center of lake into lower crust)
10/20/64	9	34.5 –52.9	(through base of lake at approximately 48.0 ft and into 1840 lava (cored from 48–50 ft))
10/22/64	[10]10	0 –16	
	[11]11	0 – 9	
11/17/64	11	9 –16	
	[12]12	0 –15.7	
11/19/64	12	15.7 –47	(through base of lake at approximately 44.5 ft)

FIGURE 1.—Index map of Alae lava lake, showing topographic contours at the base and margin of the lake and location of the numbered drill holes.

carbide bits. The drill was powered by a 9-horse-power gasoline engine. Most of the holes were 2.86 cm in diameter, but the upper part of one hole (drill hole 9) was cut to 3.8-cm diameter by means of EX bits. During the first 15 months after the eruption 12 holes were drilled. Dates and depths of drilling are listed in table 1, and the locations of the numbered drill holes are plotted on figure 1.

All except the first two holes were made with a drill mounted on a portable mast anchored in the crust. The bits were cooled with water pumped through the drill pipe by a portable 3¼-horsepower gasoline engine. The water was fed through hoses from the rim of the crater and stored in a 50-gallon (190-L) steel drum near the drilling site. About 10 gallons of water were used for each linear foot of drilling. The first two holes were drilled by holding the drill manually and pouring water into the hole by hand.

A core barrel was used during the drilling, except

near the base of the crust, where the barrel impeded the flow of the cooling water and had to be removed. For most of the drilling, the drill stem was pulled at 1- or 2-foot (30- or 60-cm) intervals and the core was collected. Core samples were numbered consecutively in each hole; thus sample A-9-5 is the fifth core sample from drill hole 9 in the Alae flow. Core recovery averaged between 25 and 50 percent for all holes. Typically, recovery was good from that part of the crust that was at temperatures of 700°C or less before drilling. In several holes, however, recovery was poor from the cavernous and highly vesicular zone between depths of 0.3–1.2 m. Core recovery was also poor from the interval of crust that was at temperatures between 700°C and 950°C before drilling, apparently because some cores shattered when quenched by the drilling water. Fortunately, abundant core was recovered from the interval of crust that had been at temperatures of 950°C and 1,070°C, the interval spanning the zone of crystallization. No core was recovered from lava that was at temperatures of more than 1,070°C, before drilling.

TEMPERATURE MEASUREMENTS

Temperatures in drill holes were measured on 47 different days during the four-year study of the cooling lake. Most measurements were made with thermocouples of chromel-alumel, and, a few with thermocouples of platinum-platinum plus 10 percent rhodium, using a portable millivolt potentiometer and a 0°C reference junction in an ice-filled vacuum bottle. Most of the temperature measurements have an accuracy of ± half a percent at 500°C and ±1 percent at 1,000°C. Details of thermocouple construction and calibration are given in chapter B.

In several drill holes, temperatures were measured both in the crust and in the underlying melt. This was done by pushing a ceramic probe into the melt through the bottom of a drill hole after boring through the base of the crust. Temperatures were measured with a thermocouple inserted in the probe. Probes as long as 3 m were constructed from 91.5-cm lengths of 2.54-cm OD mullite tubes (the lower tube closed at one end), joined with 10.16-cm sleeves cemented with silica cement. The probe was attached to the drill steel with a machined fitting. The whole probe unit was placed in the completed drill hole and the temperature was then measured at the bottom of the hole. After the temperature had reached 1,065°C to 1,070°C,[1] the unit could be pushed slowly on into the melt. Sometimes, but not always, it could also be pulled out. Excessive pressure caused

the ceramic probes to crack, allowing melt to enter. An unbroken probe was not emplaced in the melt until December 2, 1963. Six attempts were unsuccessful during the preceding three months. Later work in the 1965 lava lake in Makaopuhi Crater has shown that stainless steel probes can be used successfully for long periods in the melt, and can be emplaced with less hazard of breakage.

Several different methods were used to estimate the temperature of core samples immediately before drilling. Sometimes the temperatures of cores recovered from drill holes adjacent to existing holes were determined by measuring the gradient in the existing holes immediately before drilling. Other times the holes were deepened only a few inches at a time, particularly in the zones of crystallization; and the core temperatures were estimated by extrapolating the gradient measured in these holes before renewed drilling. In other holes, the temperatures were estimated from a plot of the depth of isotherms versus the square root of time (see fig. 10, chapter B), extrapolating the depths of isotherms back to the time of drilling from a plot of temperatures measured in each hole over a period of time after drilling. Temperature intervals assigned to cores from the upper crust of the lake in the range 500°C to 1,070°C are probably accurate to ±2 percent, estimated from the uncertainty in reconstructing isotherms for a single drill hole (see fig. 10, chapter B). Temperatures assigned to cores in the range below 500°C are less accurate, perhaps ±10 percent, because of greater differences between holes, marked effect of rainfall, and slower thermal recovery after drilling. Temperatures assigned to cores from the lower margins of the lake are highly interpretive and may be in error by as much as ±20 percent. Table 2 is a complete list of all samples collected and an estimate of their temperatures at collection.

LABORATORY STUDIES

All drill cores were inspected under a binocular microscope, and a thin section from each core interval was examined under the petrographic microscope. Modal counts were made with a point counter. Selected pieces of core were analyzed chemically by the rock analysis laboratory of the Geological Survey in Denver, Colo. A total of 22 standard and 48 partial

[1] This temperature marks the interface between crust and melt in all of the lava lakes. The transition from crust to melt takes place when the lava is approximately 50 percent crystallized, and is marked by an abrupt change in physical properties—particularly shear strength—of the basalt. Below the transition temperature, the basaltic crust behaves as a rigid solid. Above the transition temperature, the melt, either in a liquid or supercooled form, gives little resistance to either a drill or a blunt-ended probe pushed by hand.

TABLE 2.—*Drill cores from Alae lava lake*

Drill hole No. 1

Sample No.	Depth (ft)	Date	Estimated temperature of collection (°C)	Weight of core (g)	Comments
A- 1-1 __	0.8 - 1.2	8/29/63	520- 650	11	
2 __	2.7 - 3.1	9/ 3/63	880- 950	4	May include ooze from 2.7-2.8 ft (temperature= 1,040°- 1,060°C).
3 __	3.1 - 3.75	do	950-1,040	27	
4 __	3.75	do	1,040	5	
5 __	3.8 - 4.0	9/ 6/63	995-1,015	7	
6 __	4.25- 4.6	do	1,040-1,075	7	
7 __	4.8 - 5.0	9/17/63	960- 980	7	
8 __	5.0 - 5.2	do	980-1,000	18	

Drill hole No. 2

Sample No.	Depth (ft)	Date	Estimated temperature of collection (°C)	Weight of core (g)	Comments
A- 2-1 __	0 - 0.5	9/ 6/63	190	33	
2 __	.5 - 1.0	do	350	62	
3 __	1.0 - 1.3	do	490	15	
4 __	1.3 - 1.5	do	580	23	
5 __	2.0 - 2.15	do	720	8	

Drill hole No. 3

Sample No.	Depth (ft)	Date	Estimated temperature of collection (°C)	Weight of core (g)	Comments
A- 3-1 __	0 - 0.8	10/ 1/63	50- 280	18	
2 __	.8 - 2.8	do	280- 620	63	
3 __	2.8 - 3.8	do	620- 740	25	
4 __	4.8 - 5.8	do	850- 940	12	
5 __	6.8 - 7.8	do	1,020-1,075	16	
6 __	7.5 - 9.75	10/24/63	950-1,080	<1	
ooze	9.9	11/ 6/63	1,040	<1	Contaminated from old drill pipe.

Drill hole No. 4

Sample No.	Depth (ft)	Date	Estimated temperature of collection (°C)	Weight of core (g)	Comments
A- 4-1 __	0 - 0.25	11/20/63	50- 70	19	
2* __	.25- .8	do	70- 130	56	
3 __	.8 - 2.1	do	130- 290	5	
4 __	2.1 - 3.05	do	290- 410	20	
5* __	3.05- 4.45	do	410- 580	38	
6* __	4.45- 5.95	do	580- 715	57	
7 __	5.95- 6.95	do	715- 790	7	
8* __	9.9 -10.9	do	970-1,010	33	
10* _	10.9 -12.0	do	1,010-1,040	28	
11 __	12.0 -12.85	do	1,040-1,060	3	
12* _	14.0	11/21/63	1,067	19	Ooze on thermocouple.
13* _	14.2 -20.5	12/ 2/63	1,065-1,125	500	Filled ceramic combustion tube.

Drill hole No. 5

Sample No.	Depth (ft)	Date	Estimated temperature of collection (°C)	Weight of core (g)	Comments
A- 5-1 __	0 - 0.35	12/16/63	40- 70	116	
2 __	.35- .55	do	70- 90	73	
3 __	.55- .7	do	90- 100	61	
4 __	0 - .2	do	40- 55	17	
5 __	.2 - 1.0	do	55- 130	23	
6 __	1.0 - 2.0	do	130- 220	27	
7 __	2.0 - 3.0	do	220- 320	34	
8 __	3.0 - 5.1	do	320- 510	177	
9 __	6.1 - 7.1	do	590- 660	30	
10 __	10.2 -11.2	do	840- 890	26	
11 __	11.2 -12.2	do	890- 940	45	
12 __	13.2 -14.2	do	980-1,010	30	
13 __	14.2 -16.2	do	1,010-1,060	89	
14 __	18.2 -20.2	do	1,070	10	
15 __	20.2 -22.2	do	1,070-1,040	40	
16 __	22.2 -23.2	do	1,040-1,020	9	
17 __	26.2 -28.2	do	940- 870	15	Ooze on thermocouple.
18 __	28.2 -29.2	do	870- 840	11	
19 __	17.8 -18.3	12/30/63	1,050±2	23	
20* _	19.0 -20.0	do	1,045±5	55	Do.
21 __	ca. 18.5	do	1,050±	<1	Do.

See footnote at end of table.

TABLE 2.—*Drill cores from Alae lava lake*—Continued

Drill hole No. 6

Sample No.	Depth (ft)	Date	Estimated temperature of collection (°C)	Weight of core (g)	Comments
A- 6-1 __	0 - 0.4	4/ 1/64	40- 50	127	
2 __	.4 - .5	do	50	72	
3 __	.5 - .7	do	50- 60	29	
4 __	.7 - .9	do	60	89	
5 __	0 - 1.0	do	40- 60	89	
6 __	1.0 - 2.0	do	60- 90	12	
7 __	2.0 - 3.0	do	90- 140	34	
8 __	3.0 - 5.0	do	140- 250	13	
9 __	5.0 - 6.0	do	250- 320	66	
10 __	6.0 - 7.0	do	320- 410	65	
11 __	8.0 -10.0	do	480- 610	144	
12 __	10.0 -11.0	do	610- 670	62	
13 __	11.0 -12.0	do	670- 730	100	
14 __	13.0 -15.0	do	790- 890	112	
15 __	15.0 -16.0	do	890- 930	42	
16 __	16.0 -17.0	4/ 2/64	930- 970	21	
17* _	19.0 -20.0	do	1,030-1,050	75	
18 __	22.0 -23.0	do	1,060-1,070	17	
19* _	23.0 -24.0	do	1,070?	33	
20 __	24.0 -25.0	do	1,070?	9	
21* _	25.0 -26.0	do	1,070?	27	
22 __	27.0 -28.0	do	1,070?	<1	
23 __	28.0 -29.0	do	1,060-1,070	26	
24* _	31.0 -32.0	do	1,030-1,010	30	
25* _	19.0 -19.7	4/15/64	1,010-1,030	23	Ooze.
26 __	20.0 -27.5	do	1,030-1,060	52	
27 __	35.0 -40.0	do	970- 900	61	
28 __	19.4 -21.0	4/22/64	1,000-1,020?	17	
29* _	25.0 -29.0	do	1,060-1,050	38	Ooze.
30* _	29.0 -31.0	do	1,050-1,020?	28	Ooze.
31 __	23 -28?	4/ 3/64	1,045-1,060?	19	Ooze on thermocouple.

Drill hole No. 7

Sample No.	Depth (ft)	Date	Estimated temperature of collection (°C)	Weight of core (g)	Comments
A- 7-1 __	0 - 0.4	4/22/64	40- 60	159	
2 __	.4 - .6	do	60- 70	121	
3 __	.6 - .8	do	70- 80	85	
4 __	0 - .7	4/29/64	50- 75	14	
5 __	.7 - 2.0	do	75- 120	28	
6 __	2.0 - 3.0	do	120- 150	89	
7 __	3.0 - 4.0	do	150- 190	127	
8 __	4.0 - 5.0	do	190- 230	93	
9 __	5.0 - 6.0	do	230- 290	88	
10 __	6.0 - 7.0	do	290- 360	95	
11 __	7.0 - 8.0	do	360- 430	140	
12 __	8.0 - 9.0	do	430- 500	172	
13 __	9.0 -10.0	do	500- 560	47	
14 __	10.0 -10.6	do	560- 600	50	
15 __	12.0 -13.0	do	640- 700	64	
16 __	13.0 -14.0	do	700- 770	46	
17 __	15.0 -16.0	do	820- 870	24	
18 __	17.0 -18.0	do	910- 950	92	
19 __	18.0 -19.0	do	950- 990	140	
20 __	19.0 -20.0	do	990-1,020	66	
21 __	19.7 -20.0	6/ 4/64	945- 955	<1	
22 __	20.0 -21.0	do	955- 990	127	
23 __	21.0 -21.8	do	990-1,010	53	
24 __	21.8 -22.7	6/10/64	995-1,015	3	
25* _	22.7 -23.4	do	1,015-1,030	47	

Drill hole No. 8

Sample No.	Depth (ft)	Date	Estimated temperature of collection (°C)	Weight of core (g)	Comments
A- 8-1 __	0 - 2.0	6/18/64	40- 100	56	
2 __	2.0 - 4.0	do	100- 170	211	
3 __	4.0 - 6.0	do	170- 260	122	
4 __	6.0 - 7.45	do	260- 340	59	
5 __	8.0 -10.0	do	370- 470	72	
6 __	10.0 -12.0	do	470- 570	166	
7 __	13.9 -14.9	do	670- 720	26	
8 __	14.9 -15.9	do	720- 770	12	
9 __	20.75-21.85	6/19/64	960- 990	20	
10* _	22.85-23.35	do	1,020-1,030	20	
11 __	23.85-24.85	do	1,040-1,050	25	
12 __	24.85-25.85	do	1,050-1,060	8	
13 __	25.85-26.85	do	1,060-1,070	9	
14 __	26.85-27.85	do	1,060-1,050	24	

Drill hole No. 9

Sample No.	Depth (ft)	Date	Estimated temperature of collection (°C)	Weight of core (g)	Comments
A- 9-1c __	0 - 0.3	7/28/64	40- 60	137	
1a __	.3 - .55	do	60- 70	102	
1b __	.55- .85	do	70- 90	141	
2 __	0 - 1.6	do	40- 110	90	±50°
3 __	1.6 - 2.3	do	110- 130	62	
4 __	2.3 - 3.55	do	130- 170	16	
5 __	4.55- 5.55	do	200- 240	172	
6 __	5.55- 6.7	do	240- 290	217	

TABLE 2.—*Drill cores from Alae lava lake*—Continued

Drill hole No. 9—Continued

Sample No.	Depth (ft)	Date	Estimated temperature of collection (°C)	Weight of core (g)	Comments
A- 9-7 __	6.7 - 7.7	do	290– 360	134	
8 __	7.7 - 8.6	do	360– 410	88	
9 __	8.6 - 9.7	do	410– 470	146	
10 __	9.7 -10.7	do	470– 520	249	
11 __	10.7 -11.7	do	520– 570	150	
12 __	11.7 -12.7	7/29/64	570– 610	273	
13 __	12.7 -13.7	9/11/64	560– 600	155	
14 __	13.7 -14.2	do	600– 620	37	
15 __	14.2 -15.7	do	620– 670	427	
16 __	15.7 -16.7	do	670– 710	135	
17* _	16.7 -17.7	do	710– 750	161	
18 __	17.7 -18.7	do	750– 780	130	
19 __	18.7 -19.1	do	780– 800	32	
20 __	19.1 -20.1	do	800– 830	44	
21 __	20.7 -21.7	do	850– 870	35	
22 __	24.5 -26.0	9/14/64	940– 970	114	
23* _	26.0 -27.0	do	970– 990	47	
24 __	28.8 -30.0	do	1,000–1,010	13	
25* _	30.0 -31.0	do	1,010±	24	
26 __	32.0 -33.0	do	1,010– 990	115	
27 __	42.0 -45.0	10/20/64	900– 860±	144	
28 __	48.0 -50.0	do	810– 770±	8	1840 lava.

Drill hole No. 10

Sample No.	Depth (ft)	Date	Estimated temperature of collection (°C)	Weight of core (g)	Comments
A-10-1 __	0 - 0.10	10/27/64		29	
2 __	.1 - .55	do	30– 80	216	
3 __	.55- .70	do	do	78	
4 __	.7 - .80	do	do	41	
5 __	.8 - .95	do	do	73	
6 __	.95- 1.10	do	do	45	
8 __	0 - 2.0	do	30– 125	125	
9 __	2.0 - 3.0	do	125– 180	92	
10 __	3.0 - 4.0	do	180– 230	88	
11 __	4.0 - 5.0	do	230– 285	112	
12 __	5.0 - 6.0	do	285– 340	159	
13 __	6.0 - 7.0	do	340– 395	159	
14 __	7.0 - 8.0	do	395– 445	118	
15 __	8.0 -10.0	do	445– 540	228	
16 __	10.0 -12.0	do	540– 620	213	
17 __	12.0 -14.0	do	620– 685	155	
18 __	14.0 -16.0	do	685– 745	69	

Drill hole No. 11

Sample No.	Depth (ft)	Date	Estimated temperature of collection (°C)	Weight of core (g)	Comments
A-11-1 __	0 - 0.5	10/27/64	30– 75	222	
2 __	.5 - .7	do	do	119	
3 __	.7 - .8	do	do	27	
4 __	0 - 2.0	do	30– 150	110	
5 __	2.0 - 4.0	do	150– 255	275	
6 __	4.0 - 5.4	do	255– 320	195	
7 __	5.4 - 7.0	do	320– 390	244	
8 __	7.0 - 9.0	do	390– 460	226	
9 __	9.0 -10.0	11/17/64	455– 485	108	
10 __	10.0 -12.0	do	485– 550	228	
11 __	14.0 -16.0	do	610– 675	89	

Drill hole No. 12

Sample No.	Depth (ft)	Date	Estimated temperature of collection (°C)	Weight of core (g)	Comments
A-12-1a __	0 - 0.1	11/17/64	40– 150	18	
1b __	.1 - 0.3	do	do	69	
1c __	.3 - 0.7	do	do	186	
1d __	.7 - 0.9	do	do	110	
2 __	0 - 1.0	do	40– 150	54	
3 __	1.0 - 3.0	do	150– 280	73	
4 __	3.0 - 5.0	do	280– 375	51	
5 __	5.0 - 7.0	do	375– 465	182	
6 __	7.0 - 9.0	do	465– 545	322	
7 __	9.0 -11.0	do	545– 610	171	
8 __	11.0 -13.0	do	610– 675	272	
9 __	13.0 -15.0	do	675– 725	250	
10 __	15.0 -19.0	11/19/64	725– 815	380	
11 __	19.0 -23.0	do	815– 880	425	
12 __	23.0 -27.0	do	880– 905	38	
13 __	27.0 -31.0	do	905– 895	212	
14 __	31.0 -35.0	do	895– 860	263	
15 __	35.0 -39.0	do	860– 810	222	
16 __	39.0 -43.0	do	810– 750	398	

* Samples have complete chemical analyses (table 3).

analyses were made of core; and four additional complete analyses were made of samples of pumice, spatter, and crust.

The constituent minerals and glass in two samples of pumice and one core sample were separated after grinding to −400 mesh size, using heavy liquids, an ultrasonic vibrator, a magnetic separator, and an elutriator. The separates were studied under the microscope in oil immersion, by X-ray diffraction, and by chemical analysis. Glass from the pumice samples was separated by repeated centrifuging in BR-DMF (Bromoform-Dimethylforamide) mixtures of specific gravity 2.74± and 2.78. The specific gravity of the glass was determined as 2.761±0.005. The purity of the glass was first tested by studying the separates on an X-ray diffractometer and comparing the resulting pattern with previously calibrated mixtures of glass and known amounts of plagioclase, pryroxene, and olivine. The calibration showed that is little as 2 percent of plagioclase or olivine and as little as 3 percent of pyroxene could be detected as crystalline contamination of a glass. The final separates showed no X-ray diffraction peaks for the three silicate phases. Next, a standard mixture of 1-percent crystals in crystal-free glass was prepared as an optical standard. The crystal content of the separated glasses was estimated to be less than that of the standard and hence the glasses submitted for chemical analysis were considered to be 99+ percent pure.

Plagioclase from the pumice was concentrated (but could not be purified) by flotation in a BR-DMF mixture of specific gravity 2.71.

Separation of olivine and clinopyroxene from glass in samples of pumice was achieved by first collecting the −270 to +400 mesh fraction which sunk in methylene iodide (MI) diluted with DMF to a density of 3.20. This sample was then resieved and put on a Frantz magnetic separator. When a side slope of 15° and a forward slope of 20° were used, the olivine was found to be magnetic at 0.65 amperes, and the pyroxene to be nonmagnetic at 0.67 amperes. Final purification of the pyroxene was achieved by crushing the nonmagnetic fraction to −400 to +500 mesh and centrifuging in MI-DMF mixtures, the specific gravity of which was increased from 3.20 in steps of 0.01 until the sink fraction consisted of essentially glass-free clinopyroxene as determined by inspecting it in oils with a petrographic microscope. Pyroxene separated in this way was submitted for chemical analysis. The composition of olivine (not more than 90 percent pure) was determined using the X-ray diffractometer and the calibration of Murata and others (1965).

One sample of core collected at subsolidus temperatures was crushed and sieved to -400 to $+500$ mesh for separation of residual glass and plagioclase. Pyroxene could not be separated effectively because of its included opaque phases. The plagioclase was separated by repeated centrifuging in BR-DMF liquids of specific gravity 2.725 and 2.671. Because of the fine grain size, further magnetic separation was not attempted. Plagioclase submitted for chemical analysis was estimated from optical examination to be essentially free of glass and pyroxene but to contain a small but unknown percentage of opaque mineral as inclusions.

The residual glass was separated after elutriation of the -400 to $+500$ mesh sample that formed the float fraction in the liquid of specific gravity 2.671. The elutriation produced size fractions estimated to be -44 to $+25$ microns (μ) and -25μ to $+10\mu$. These were then centrifuged in BR-DMF mixtures of specific gravity 2.515, 2.400, 2.345, and 2.285. The specific gravity of the glass was found to be between 2.285 and 2.345. The following fractions were collected for chemical analysis:

25–44μ _____ 2.400 < sp gr < 2.515
10–25μ _____ 2.400 < sp gr < 2.515
10–44μ _____ 2.345 < sp gr < 2.400
10–44μ _____ 2.285 < sp gr < 2.345

All samples showed some admixture of feldspar both optically and by X-ray diffraction. No further attempt was made to purify the glass because of the small grain size and the small quantity of separate.

PETROLOGY OF ALAE BASALT

Solidified crust from the lake at depths below 1.5 m consists of homogeneous gray basalt containing sparse olivine microphenocrysts in a fine-grained intergranular groundmass. The surface crust contains as much as 35 percent of augite and plagioclase in addition to olivine in a base of brown glass. Pumice is brown and has a crystallinity of less than 15 percent. The average modal composition of solidified crust, calculated as weight percent, is as follows: 3.3 percent olivine, 41.7 percent clinopyroxene, 42.7 percent plagioclase, 4.6 percent ilmenite, 1.1 percent magnetite, 0.6 percent apatite, and 6.0 percent clear, residual glass.

Clinopyroxene appears as equant subhedral grains averaging 0.1 mm in diameter. Most is augite which has an estimated $2V$ of about 50°; however, a small fraction of the smaller grains are pigeonite which has a $2V < 10°$. Plagioclase is mainly An_{60} (α index=1.558) but shows some zoning toward An_{70} in the cores. The plagioclase appears as tabular crystals averaging 0.2 mm long and 0.04 mm thick. Olivine (Fo_{80} to Fo_{70}) is found mostly as corroded wedge-shaped tabular crystals 0.4 mm long and 0.1 mm thick. However, the drill core also contains a trace of olivine in roughly equant microphenocrysts 0.5 mm in diameter. The opaque minerals consist mainly of an ilmenite-rich phase (estimated from X-ray method of Lindsley, 1962, as $ilmenite_{90}$ $hematite_{10}$) in bladed crystals 0.5 mm long and 0.01 mm thick. Subordinate magnetite having the estimated composition $magnetite_{60}$ $ulvospinel_{40}$ (X-ray method, Lindsley, 1962) appears as equant crystals about 0.01 mm in diameter. Apatite forms as minute needles 0.01 mm long and scattered through the interstitial glass.

The refractive index of glass varies from 1.61 in samples of pumice to 1.492 in the residual glass (see Peck and others 1966, fig. 5.).

BULK CHEMICAL COMPOSITION

Major- and trace-element analyses of drill core from the lava lake are given in table 3. The chemical composition is remarkably uniform even for Kilauea lavas. Averages have been computed for the two samples of pumice and samples collected above and below the solidus temperature. The averages do not differ significantly from each other or from the overall average published earlier (Peck and others, 1966, table 1, p. 20) except for the ratio of Fe_2O_3 to FeO, which is higher in samples collected below the solidus and in pumice oxidized by contact with air. One reason for the chemical uniformity is the low content and small size of olivine in the erupted lava. Of the 2 percent olivine present on eruption, less than half is found as crystals large enough to settle at an appreciable rate through the magma (that is, more than 1 mm in diameter). The rest of the olivine appears as small skeletal crystals that were growing at the time of quenching.

The chemical uniformity is an advantage in studying the sequence of crystallization in the lava lake, as one need not consider the effects of variable olivine content so evident in other Kilauea eruptions (see Powers, 1955; Murata and Richter, 1966; Moore and Evans, 1967; Wright, 1971, 1973; Wright and Fiske, 1971).

Analyses of differentiated samples are given in table 3B. These include one natural segregation (A–9–23), three "oozes" that flowed into drill holes and were later cored (A–6–25, A–6–30, and A–6–29), and three samples collected on thermocouples or

TABLE 3.—*Chemical analyses of undifferentiated (A) and differentiated (B) samples, Alae lava lake*

A. Undifferentiated samples

	H-186, pumice[2] (1,165)	DPH-77, spatter[2] (1,140)	A-4-2, drill core[2] (70-130)	A-4-5, drill core[2] (70-130)	A-4-8, drill core[2] (410-580)	A-4-6, drill core[2] (580-715)	A-4-10, drill core[2] (1,010-1,040)	A-6-1,[1] drill core[3] (40-50)	A-6-4,[1] drill core[3] (60)	A-6-7,[1] drill core[3] (90-140)	A-6-10,[1] drill core[3] (320-410)	A-6-13,[1] drill core[3] (670-730)	A-6-17, drill core[2] (1,030-1,050)
Oxides (weight percent)													
SiO_2	50.41	50.45	50.45	50.47	50.40	50.40	50.39	50.56	50.48	50.50	50.32	50.63	50.47
Al_2O_3	13.66	13.60	13.58	13.63	13.71	13.77	13.69	13.87	13.76	13.85	13.80	13.84	13.70
Fe_2O_3	1.30	1.63	2.21	2.70	1.40	1.25	1.14	2.64	1.65	1.92	4.18	1.23	1.36
FeO	9.68	9.43	8.93	8.32	9.77	9.76	9.86	8.60	9.45	9.25	7.12	9.75	9.70
MgO	7.50	7.48	7.51	7.62	7.44	7.64	7.66	7.49	7.54	7.54	7.51	7.64	7.55
CaO	11.09	11.11	11.10	11.18	11.06	11.17	11.11	11.11	11.08	11.11	11.10	11.23	11.14
Na_2O	2.41	2.41	2.33	2.38	2.48	2.43	2.39	---	---	---	---	---	2.43
K_2O	.56	.54	.55	.54	.57	.55	.54	---	---	---	---	---	.53
[4]H_2O^+	.15	.11	.19	.08	.06	.02	.02	---	---	---	---	---	.03
TiO_2	2.72	2.77	2.75	2.67	2.79	2.63	2.73	2.73	2.70	2.72	2.73	2.70	2.71
P_2O_5	.27	.28	.28	.27	.27	.26	.27	---	---	---	---	---	.28
MnO	.17	.17	.17	.16	.17	.17	.17	---	---	---	---	---	.17
CO_2	.03	.01	.03	.02	.01	.00	.00	---	---	---	---	---	.00
Cl	.03	.02	.03	.02	.02	.03	.02	---	---	---	---	---	.02
F	.06	.04	.04	.04	.04	.04	.04	---	---	---	---	---	.04
Subtotal	100.04	100.05	100.15	100.10	100.19	100.12	100.03	97.00	96.66	96.89	96.76	97.02	100.13
Less O	.03	.02	.02	.02	.02	.02	.02	.0	.0	.0	.0	.0	.02
Total	100.01	100.03	100.13	100.08	100.17	100.10	100.01	97.00	96.66	96.89	96.76	97.02	100.11
Trace elements[5] (ppm)													
Ba	270		230	240	220	200	240						
Cr	370		310	350	350	320	380						
Cu	130		140	150	130	110	110						
Ga	21		22	21	20	18	24						
Li	4		---	4	4	4	4						
Nb	16.2		---	18.4	16.4	16.6	19.3						
Ni	130		110	140	150	90	140						
Rb	20		---	<10	<10	<10	<10						
Sr	380		340	350	320	310	310						
V	340		270	340	330	250	360						
Y	40		40	40	40	30	40						
Yb	4		3	3	4	3	4						
Zr	150		160	160	150	130	150						

A. Undifferentiated samples—Continued

	A-6-19, drill core (1,070 (?))	A-6-21, drill core (1,070 (?))	A-6-24, drill core (1,030-1,010)	A-7-25, drill core (1,015-1,030)	A-8-6,[1] drill core (470-570)	A-8-8,[1] drill core (720-770)	A-8-10, drill core (1,020-1,030)	A-9-17, drill core (710-750)	A-9-25, drill core (1,010)	A-12-16T, drill core (810-750)	Averages[6] (1)	(2)	(3)
Oxides (weight percent)													
SiO_2	50.32	50.46	50.47	50.44	50.38	50.51	50.51	50.48	50.50	50.39	50.52	50.46	50.45
Al_2O_3	13.82	13.70	13.69	13.66	13.72	13.80	13.59	13.82	13.59	13.77	13.65	13.69	13.72
Fe_2O_3	1.27	1.27	1.11	1.21	3.69	2.19	1.11	1.27	1.21	1.30	1.47	1.20	1.69
FeO	9.81	9.90	9.88	9.90	7.65	8.95	9.90	9.77	9.85	9.72	9.57	9.84	9.38
MgO	7.49	7.32	7.58	7.49	7.60	7.56	7.63	7.55	7.59	7.56	7.50	7.57	7.56
CaO	11.11	11.00	11.17	11.10	11.11	11.15	11.20	11.05	11.15	11.11	11.12	11.14	11.11
Na_2O	2.39	2.39	2.41	2.39	---	---	2.34	2.33	2.33	2.36	2.41	2.38	2.39
K_2O	.53	.59	.54	.56	---	---	.53	.55	.53	.52	.55	.54	.55
[4]H_2O^+	.06	.03	.00	.01	---	---	.03	.04	.00	.04	---	---	---
TiO_2	2.73	2.85	2.71	2.78	2.77	2.78	2.79	2.70	2.73	2.78	2.75	2.74	2.72
P_2O_5	.27	.28	.27	.28	---	---	.27	.26	.27	.25	.28	.27	.26
MnO	.16	.17	.17	.17	---	---	.17	.17	.17	.17	.17	.17	.17
CO_2	.00	.03	.00	.01	---	---	.03	.02	.03	.01	---	---	---
Cl	.02	.02	.02	.02	---	---	.03	.01	.02	.01	---	---	---
F	.04	.04	.04	.04	---	---	.04	.04	.04	.03	---	---	---
Subtotal	100.02	100.05	100.06	100.06	96.92	96.94	100.17	100.06	100.01	100.02	---	---	---
Less O	.02	.02	.02	.02	.0	.0	.02	.02	.02	.01	---	---	---
Total	100.00	100.03	100.04	100.04	96.92	96.94	100.15	100.04	99.99	100.01	---	---	---
Trace elements[5] (ppm)													
Ba	210										270	210	226
Cr	260										370	260	342
Cu	100										130	100	128
Ga	16										21	16	21
Li	4										4	5	4
Nb	18.3										16.2	18.3	17.7
Ni	85										130	85	126
Rb	<10										20	<10	<10
Sr	300										380	300	326
V	320										340	320	310
Y	30										40	30	38
Yb	3										4	3	3.4
Zr	130										150	130	150

See footnotes at end of table.

TABLE 3.—*Chemical analyses of undifferentiated (A) and differentiated (B) samples, Alae lava lake*—Continued

B. Differentiated samples

	Type of sample and (in parentheses) temperature (°C)									
	H-186GL, glass[7] (1,165)	DPH-77GL, glass[7] (1,140)	A-4-13, ooze[2] (1,065-1,125)	A-4-12, ooze[2] (1,067)	A-6-25, ooze[2] (1,010-1,030)	A-6-30, ooze[2] (1,050-1,020)	A-6-29, ooze[2] (1,060-1,050)	A-9-23, segregation[8] (970-990)	A-5-20, ooze[2] (1,045)	A-5-19,[1] ooze[3] (1,050)
Oxides (weight percent)										
SiO_2	50.92	50.91	50.25	50.62	50.72	51.34	51.73	51.68	53.30	53.42
Al_2O_3	14.15	14.19	12.76	12.85	12.91	12.44	12.28	12.44	12.37	13.25
Fe_2O_3	1.24	1.64	1.24	1.31	1.80	2.00	2.18	1.94	1.37	1.13
FeO	9.81	9.82	12.56	12.24	12.19	12.29	12.31	12.51	13.05	13.34
MgO	6.39	6.06	5.66	5.46	4.79	4.39	4.03	3.88	3.10	3.08
CaO	10.98	10.69	9.66	9.42	8.82	8.44	8.14	8.08	7.28	7.25
Na_2O	2.49	2.56	2.62	2.65	2.77	2.80	2.83	3.10	3.26	---
K_2O	.57	.60	.80	.88	.96	1.07	1.16	1.17	1.57	---
[9]H_2O+	.11	.05	.06	.06	.00	.06	.06	.06	.10	---
TiO_2	2.88	3.04	3.77	3.74	4.28	4.39	4.23	4.25	3.36	3.28
P_2O_5	.28	.29	.43	.45	.49	.56	.62	.63	.88	---
MnO	.17	.17	.20	.20	.21	.20	.21	.20	.20	---
CO_2	.00	.00	.02	.03	.00	.00	.00	.00	.04	---
Cl	.02	.02	.03	.03	.03	.03	.04	.03	.05	---
F	.05	.05	.06	.06	.06	.07	.09	.09	.12	---
Subtotal	100.06	100.09	100.12	100.00	100.03	100.08	99.91	100.06	100.05	94.75
Less O	.03	.03	.03	.03	.03	.04	.05	.04	.06	.0
Total	100.03	100.06	100.09	99.97	100.00	100.04	99.96	100.02	99.99	94.75
Trace elements[6] (ppm)										
Ba			390	360	420	430	480	530	520	
Cr			220	900	110	34	37	9	58	
Cu			200	210	200	270	290	230	340	
Ga			24	21	23	26	30	35	30	
Li			9	6	7	7	8	---	11	
Nb			30.1	29.9	38.7	43.8	44.3	---	47.4	
Ni			78	690	110	37	35	33	45	
Rb			20	10	10	20	20	---	30	
Sr			340	380	320	390	360	370	300	
V			390	400	450	330	340	420	270	
Y			50	40	60	60	60	50	70	
Yb			4	4	6	5	5	4	5	
Zr			240	210	280	280	320	350	340	

[1] Partial analyses: Al_2O_3 value includes P_2O_5.
[2] Analyses by C. L. Parker.
[3] Analyses by E. L. Munson.
[4] H_2O^- analyses: H-186 (0.06), DPH-77 (0.03), A-4-2 (0.02), A-4-5 (0.02), A-4-6 (0.01), A-4-8 (0.02), A-4-10 (0.02), A-6-17 (0.01), A-6-19 (0.02), A-6-21 (0.04), A-6-24 (0.04), A-6-25 (0.05), A-7-25 (0.02), A-8-10 (0.02), A-9-17 (0.02), A-9-25 (0.01), A-12-16T (0.00).

[5] All trace elements except Nb analyzed spectrographically by J. C. Hamilton. Nb analyses by L. B. Jenkins (D. Gottfried, written commun., 1966).
[6] Averages: (1)=pumice, (2)=partially molten core collected above 1,000°C, (3)=crystalline core collected below 1,000°C.
[7] Analyses by V. C. Smith.
[8] Analyses by G. O. Riddle.
[9] H_2O^- analyses: A-4-13 (0.01), A-4-12 (0.01), A-6-25 (0.05), A-6-30 (0.02), A-6-29 (0.03), A-9-23 (0.01), A-5-20 (0.00).

sampling tubes while still molten (A-4-13, A-4-12, A-5-20). The oozes collected while still molten are affected by reaction with the drilling steel. The iron in the samples is reduced relative to the least oxidized drill core (table 3A), and heavy trace-element contents (for example, Cr, Ni, Cu) are increased. Oozes drilled out at temperatures less than 1,065°C are not affected by reaction with drilling steel. However, two of the three artificially segregated oozes (A-6-30 and A-6-29) show some evidence of oxidation. This oxidation probably took place because residual air-contaminated drilling water was present when the ooze was segregated.

Analyses of mineral and glass separates are listed in table 4. Composition of the plagioclase and olivine in the two pumices (H-186 and DPH-77) was estimated by optical and X-ray methods, respectively, to be An_{70} and Fo_{82}. The olivine in DPH-77 is zoned to compositions as fayalitic as Fo_{62}, as shown by broadening of the (310) reflection.

The two pumice glasses and the plagioclase separate from A-12-10, -11 were submitted to two different laboratories for analysis. The Denver rock analysis laboratory analyzed these by conventional gravimetric methods devised by Lee C. Peck (Peck, 1964). These analyses are comparable in precision with the rock analyses listed in table 3. A second laboratory analyzed the separates by micrometric methods. The same methods were used to analyze the remaining samples, which were separated in quantities too small to be analyzed by conventional gravimetric methods. The interlaboratory agreement is excellent, in general, although small but consistent biases are evident for Al_2O_3, CaO, alkalis, and P_2O_5. These biases are sufficiently small, however, that the remaining mineral analyses may be applied with confidence in the calculations using the bulk rock analyses.

TABLE 4.—*Chemical analyses, in weight percent, of mineral and glass separates, Alae lava lake*

[Sample data : H–186, pumice from the earliest phase of the eruption collected from trees adjacent to Alae crater. DPH–77, pumice from the latest phase of the eruption in back of the main vent on the floor of the Alae crater. A–12–10, –11, drill core from the central part of Alae lake, 15–23 ft in drill hole 12. Analysts : Vertie C. Smith (columns 1, 3, and 7), Denver rock analysis laboratory using methods outlined in L. C. Peck (1964). John Marinenko (columns 2, 4, 5, 8, 11, 12), Washington rock analysis laboratory using microchemical methods. Robert Meyrowitz (columns 6, 9, 10), Washington rock analysis laboratory using microchemical methods]

Oxide	H–186 glass		DPH–77 glass		H–186 augite	DPH–77 augite	A–12–10, –11 plagioclase		A–12–10, –11 glass			
									GLP–1	GLP–2	GLP–3	GLP–4
SiO2	50.92	50.9	50.91	50.8	49.3	49.78	53.67	53.7	67.08	66.52	71.5	79.9
Al2O3	14.15	14.4	14.19	14.5	5.5	5.66	28.29	28.7	14.15	14.09	11.5	8.7
Fe2O3	1.24	1.1	1.64	1.3	2.0	1.78	.65	.73	.55	.49	---	---
FeO	9.81	10.1	9.82	10.2	6.5	6.51	.36	.22	1.48	1.11	²1.51	²1.4
MgO	6.39	6.4	6.06	6.1	15.9	15.24	.18	.14	.25	.20	.18	.25
CaO	10.98	11.2	10.69	10.8	18.1	17.18	11.76	11.8	4.15	4.15	1.9	2.2
Na2O	2.49	2.45	2.56	2.44	.6	.56	4.52	4.33	4.07	4.13	3.2	2.5
K2O	.57	.50	.60	.51	.06	.08	.36	.34	4.31	4.37	5.2	2.3
TiO2	2.88	2.92	3.04	2.95	1.68	1.63	.17	1.8	.68	.60	.63	.49
P2O5	.28	.30	.29	.33	.05	.05	.05	.07	1.59	1.62	1.02	.29
MnO	.17	.11	.17	.11	---	.16	.01	< .01	---	---	---	---
Cl	.02	---	.02	---	---	---	.00	---	---	---	---	---
F	.05	.08	.05	---	---	---	.01	< .02	.18	.18	< .2	< .2
H2O+	.11	---	.05	---	---	---	.00	---	---	---	---	---
H2O-	.00	³.12	.03	³.18	---	³.13	.02	³.09	³.29	³.56	³.8	---
Subtotal	100.06	100.58	100.12	---	---	---	100.05	---	98.78	98.02	---	---
Less O	.02	.03	.03	---	---	---	.01	---	.08	.08	---	---
Total	100.04	100.55	100.09	100.22	99.69	¹98.76	100.04	100.30	98.70	97.94	97.44	98.03

Mineral formulas

	H–186 augite	DPH–77 augite			Plagioclase A–12–10, –11	
Si	1.8231	1.8419	Si		9.7514	9.7259
Al^{IV}	.1769	.1581	Al		6.0580	6.1263
Total	2.0000	2.0000	Fe^{+3}		.0889	.0995
Al^{VI}	.0628	.0888	Total		15.8983	15.9517
Ti	.0467	.0454	Ti		.0232	.0245
Fe^{+3}	.0557	.0496	Mg		.0487	.0378
Cr	----	.0167	Fe^{+2}		.0547	.0333
Mg	.8764	.8405	Na		1.5923	1.5205
Ni	----	----	Ca		2.2893	2.2898
Cu	----	.0017	K		.0834	.0786
Zn	----	.0041	Total		4.0916	3.9845
Fe^{+2}	.2010	.2014	Total of all cations (to 32 O)		19.9899	19.9362
Mn	----	.0050	An		57.7	58.9
Ca	.7171	.6811	Ab		40.2	39.1
Na	.0430	.0402	Or		2.1	2.0
K	.0028	.0038				
Total	2.0055	1.9781				
Total of all cations (to 6 O)	4.0055	3.9781				
Ca	40.0	39.5				
Mg	48.8	48.8				
Fe^{+2}	11.2	11.7				

¹ Additional oxides in DPH–77 augite; $Cr_2O_3=0.57$; $ZnO=0.15$; $CuO=0.06$.
² Total iron as FeO.
³ Total H2O.

Analyses of the concentrates of residual glass (GLP–1 to GLP–4, table 4) show that plagioclase and apatite are removed from the residual glass as the specific gravity of the separating liquid is decreased from 2.515 to 2.345. Surprisingly, the composition of the lowest specific gravity fraction indicates that potash-soda feldspar was removed in addition to apatite when the specific gravity of the separating liquid was reduced to 2.285.

GLP–3 shows very weak reflections for plagioclase on its X-ray pattern and is considered to be the most nearly representative sample of the residual glass, containing 2 percent apatite and an undetermined amount of alkali feldspar. This analysis, after removal of all P_2O_5 and an equivalent amount of CaO as apatite, is given in table 5 with a single electron microprobe analysis of residual glass from the same

TABLE 5.—*Composition, in weight percent, of residual glass, Alae lava lake*

Sample No.	A–12–10, –11 (wet chemical [1])	A–12–9 (electron-microprobe [2])
SiO2	75.8	75.9
Al2O3	12.2	11.9
Fe2O3	.43	----
FeO	1.21	³1.1
MgO	.19	.05
CaO	.60	.54
Na2O	3.4	3.37
K2O	5.5	5.99
TiO2	.67	.24
P2O5	----	----
MnO	----	----
Total	100.00	99.2

[1] Glass separate GLP–3 (this paper, table 4) recalculated to 100 percent after removing P_2O_5 and equivalent CaO as apatite.
[2] Analyst : R. T. Helz.
³ Total iron as FeO.

drill hole. The small differences between analyses reflect the presence of small amounts of plagioclase

and Fe-Ti oxide as impurities in the separated glass. The analyses are similar to electron microprobe analyses of residual glass from the prehistoric lava lake exposed in the East Pit of Makaopuhi Crater (Evans and Moore, 1968, table 8).

CHEMICAL MODES

The term "chemical mode" is used in this paper to describe mineral and glass percentages in a rock as they are calculated from the bulk chemical composition of the rock using compositions of glass and mineral phases (see Wright and Doherty, 1970). The mixing equations, one for each major oxide,[2] are formulated as follows:

Parent=Differentiate (glass or ooze)+olivine+
    augite+plagioclase+pigeonite+ilmenite+
    apatite.   (1)
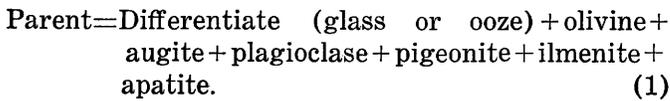
On the assumption that the various chemical data are accurately known, the chemical modes provide a close approximation to the true modal composition (in weight percent) of either a holocrystalline rock or partly molten lava quenched at liquidus temperatures. Such modes may be used in the same way as modal data obtained by conventional petrographic methods to estimate order of appearance of phases and rates of crystallization as a function of temperature. As pointed out in the next section, we consider the chemical modes far more accurate than the

[2] SiO_2, Al_2O_3, Fe_2O_3, FeO, MgO, CaO, Na_2O, K_2O, TiO_2, P_2O_5, MnO.

petrographic modes obtained for fine-grained basalt.

Table 6 summarizes the results of chemical mode calculations. Modes for H-186 and DPH-77 were made by using the rock analyses (table 3), the analyzed glasses (table 4), and the analyzed or optically determined mineral compositions (table 4).

In order to fix accurately the amount of liquid (differentiate), P_2O_5 was weighted high to ensure an exact match between the observed P_2O_5 in the parent and that calculated from the mixture of minerals and liquid. This procedure assumes that P_2O_5 is partitioned to the liquid [3] with the exception of a small amount partitioned to augite (see analysis of DPH-77 augite, table 4). Later calculations of trace-element abundance (table 8) suggest that plagioclase may also contain a small amount of P_2O_5 and thus the liquid percentages given in table 6 represent a maximum value. The residuals in all calculations are less than 0.1 percent. The rest of the calculations were made using the mineral compositions given in table 7, and the analyses of differentiated liquids given in table 3B. All of these calculations have residuals of 0.01 or less in all oxides, virtually an exact match to the bulk composition. The solution values in the calculation using the residual glass (A12-10, -11) represent the modal abundance of phases in the basalt collected at sub-

[3] See Anderson and Greenland (1969) for discussion of the usefulness of P_2O_5 as a fractionation index and its use in evaluating fractionation in Alae lava lake.

TABLE 6—*Computer-calculated chemical modes, Alae lava lake*

[All mineral proportions in weight percent]

Parent (table 3)	Sample No. and type									
	H-186, glass pumice	DPH-77, glass pumice	Alae average [1]							
			A-4-13, ooze-molten	A-4-12, ooze-molten	A-6-25, ooze-drilled	A-6-30, ooze-drilled	A-6-29, ooze-drilled	A-5-20, ooze-molten	A-12-10, -11, residual glass	A-9-23, segregation vein
Olivine (Fo80)	2.3	2.2	2.0	2.7	3.5	4.3	4.5	3.1	3.9	3.5
Augite[2]	3.4	8.5	17.8	19.4	22.5	24.4	21.0	29.3	31.7	25.6
(MgO/(MgO+FeO))	(.66)	(.65)	(.67)	(.62)	(.59)	(.56)	(.56)	(.57)	(.45)	(.58)
Plagioclase[3]	0.3	2.7	16.1	17.3	19.1	22.8	24.8	29.2	43.2	24.2
(An content)	(70)	(70)	(61.5)	(61.6)	(61.9)	(61.3)	(60.4)	(59.8)	(56.1)	(61.3)
Pigeonite[4]										
(En55.3 Fs34.5 Wo10.2)	---	---	2.9	1.9	1.2	.8	1.1	5.8	9.3	3.9
Ilmenite[5]	---	---	.30	.58	.33	.79	1.28	2.72	4.74	1.26
Magnetite[5]	---	---	---	---	---	.06	.10	.23	.42	.12
Apatite	---	---	---	---	---	---	---	---	.6	---
Total minerals crystallized	6.0	13.4	39.2	41.8	46.5	53.1	57.7	70.4	93.9	58.6
Liquid	94.0	86.6	60.8	58.2	53.5	46.9	42.3	29.6	6.1	41.4
Enrichment factor[6]	1.064	1.155	1.645	1.718	1.869	2.132	2.364	3.378	16.529	2.415
Fe_2O_3/(Fe_2O_3 + FeO)[7]										
Observed	.112	.143	.084	.097	.129	.140	.150	.095	.262	.134
Calculated	---	---	.118	.121	.129	.134	.133	.132	---	.132

[1] Average (2) given in table 3A.
[2] Augite compositions used as input: H-186 (H-186 augite, table 4); DPH-77 augite, table 4); A-4-12 through A-9-23 (mixtures of DPH-77 and Fe Aug R, table 7).
[3] Plagioclase assumed as An70 for H-186 and DPH-77, and calculated for the remaining samples as a mixture of An50 and An70 (table 7).
[4] Pigeonite 13-13P (table 7) used in all calculations.
[5] Ilmenite (ILM) and magnetite (TIMAG) from table 7 used in all calculations.

[6] Enrichment factor calculated as 100÷weight percent liquid. This factor is fixed by P_2O_5 in the mode calculations and represents the expected maximum enrichment of the least compatible element or oxide during crystallization.
[7] Fe_2O_3 and FeO of each sample were adjusted for purposes of the calculation in order to give realistic ilmenite/magnetite ratios and also to fit the actual ratios of the least oxidized drilled samples.

TABLE 7.—*Mineral analyses used in mixing calculations*

[Microprobe analyses made by P. W. Weiblen: of augite (Fe Aug R) and pigeonite with F_2O_3 assumed; of ilmenite and magnetite with Fe_2O_3 calculated from stoichiometry]

	A	B	C	D	E		F	
	Olivine, Fa₂₀	Augite		Pigeonite, 13–13P	Plagioclase		Ilmenite, ILM	Magnetite, TIMAG
		DPH–77	Fe Aug R		An₇₀	An₅₀		
SiO_2	38.72	50.48	49.52	54.64	50.74	55.71	0.05	0.06
Al_2O_3	.87	5.74	1.28	1.66	31.53	28.19	.12	1.65
Fe_2O_3	----	.88	.89	1.01	----	----	9.66	23.63
FeO	17.80	7.55	16.58	19.55	----	----	39.81	50.68
MgO	42.06	15.46	13.05	17.60	----	----	1.72	1.00
CaO	.29	17.42	17.66	4.53	14.19	10.26	.08	.08
Na_2O	----	.57	----	----	3.37	5.67	----	----
K_2O	----	.09	----	----	.21	.21	----	----
TiO_2	.02	1.66	.50	.52	----	----	48.14	22.52
P_2O_5	----	.06	----	----	----	----	----	----
MnO	.27	.17	.50	.51	----	----	.44	.37

Nature of samples:
A. Stoichiometric Fa₂₀ with 1.5 percent Cr-spinel included. 0.3 percent CaO included as Ca₂SiO₄.
B. Analyzed augite (see table 4). Fe₂O₃ and FeO adjusted (see text).
C. Most iron-rich augite from Makaopuhi lava lake.

D. Pigeonite from Makaopuhi lava lake.
E. Stoichiometric NaAlSi₃O₈ and CaAl₂SiO₄ with 0.5 percent K₂O included as KAlSi₃O₈.
F. Ilmenite and magnetite from Makaopuhi lava lake.

solidus temperatures. The calculation is very sensitive to Fe_2O_3/FeO ratios used in the pyroxene, glass, and bulk rock composition. The $Fe_2O_3/(Fe_2O_3+FeO)$ contents in the pyroxenes and the differentiates were adjusted to fit the following two assumptions:

1. The parent was taken as the average composition showing the least oxidation in table 3 (see average (s), table 3A; $Fe_2O_3=1.20$, FeO$=9.84$). This represents the composition of the lava before subsolidus oxidation took place (see Sato and Wright, 1966, and Wright and Okamura, 1977, for further discussion of oxidation).

2. Magnetite was assumed to appear at a lower temperature than ilmenite and the magnetite/ilmenite ratio was assumed to increase slightly during crystallization.

Two consequences of these assumptions are, first, that the $Fe_2O_3/(Fe_2O_3+FeO)$ ratio in the analyzed DPH–77 augite is too high to fit the calculations for the least oxidized bulk composition. We need values of $Fe_2O_3=0.88$ and FeO$=7.55$ compared with analyzed values of $Fe_2O_3=1.78$, FeO$=6.51$. The calculated mineral formula (table 4) for DPH–77 shows a cation deficiency relative to six oxygens and this imbalance could be improved by reducing the amount of Fe_2O_3. Thus we feel this analysis is probably in error; an adjusted analysis that fits the rock composition is given in table 7. The second consequence of the assumptions is that A–6–25 is the only ooze that has an analyzed $Fe_2O_3/(Fe_2O_3+FeO)$ ratio consistent with its degree of crystallization if one assumes no subsolidus oxidation. The calculated and observed $Fe_2O_3/(Fe_2O_3+FeO)$ ratios are shown at the bottom of table 6. They show that samples A–4–13, A–4–12, and A–5–20 are reduced

relative to what is predicted from the chemical mode calculation. This is consistent, as noted above, with the environment of collection where the molten ooze was collected in contact with drill steel or thermocouple sheathing. A–6–30 and A–6–29 are slightly oxidized relative to their predicted value, which is also consistent with their appearance in thin section. These samples and A–6–25 were drilled out when solid. The slight oxidation may have taken place because of the presence of air-contaminated drilling water when the ooze flowed into the drill hole. A–9–23, a natural segregation, is essentially unoxidized.

The mineral percentages calculated in table 6 are generally consistent with the inferred paragenesis, except for the inclusion of pigeonite and ilmenite in samples A–4–13 and A–4–12. TiO_2 is lower in these samples than would be predicted on the basis of crystallization of silicates only. If ilmenite is removed from the calculation, a TiO_2 residual of 0.15 results, far too high to ascribe to analytical error in the rock, ooze, or pyroxene. Pigeonite is probably an artifact of ilmenite being included in the calculation and is taken in order to balance the SiO_2. Calculations made without pigeonite have a SiO_2 residual of about 0.2 if Na_2O is balanced to give the same plagioclase composition. We do not know the reason for the anomalous compositions. Two possibilities are (1) reaction with steel resulting in loss of TiO_2 (and FeO?) or (2) admixture of lower temperature ooze during collection. The latter seems more likely as samples in Makaopuhi lava lake that were collected in stainless steel picked up small amounts of iron and showed no TiO_2 gain or loss.

Mineral compositions change in a regular way as

crystallization increases. (Note: These represent the average composition of each phase crystallized before collection of the ooze or glass sample. As the minerals are normally zoned, the calculated compositions of feldspar and mafic silicates are more calcic and magnesian, respectively, than the actual composition of the mineral in contact with the liquid represented by the glass or ooze. Electron microprobe study would be necessary to specify the exact compositions of coexisting mineral-liquid pairs.) Olivine and pigeonite are taken as fixed compositions so that the changing composition of the mafic assemblage is represented by the $MgO/(MgO+FeO)$ ratio calculated for augite and given in parentheses in table 6. These range from 0.66 in the pumice (H-186) to 0.45 in the subsolidus assemblage (A-12-10, -11). Plagioclase changes composition from An_{70} in the pumice to An_{56} in the subsolidus assemblage.

In summary, the data of table 6 represent a nearly quantitative representation of changing mineral proportions and compositions during crystallization of Alae lava lake. These data are plotted in figures 2 and 3.

Trace-element content also varies along the liquid line of descent. Unfortunately, the collection of melt samples and ooze in proximity to drilling steel contaminated some samples, especially with regard to Cr and Ni. The overall variation in trace-element content is less regular than for major elements (see table 3), precluding an accurate assessment of distribution coefficients between silicates and liquid along the liquid line of descent. Table 8 summarizes data on relatively incompatible elements. The values for an undifferentiated bulk composition are taken from average (3), table 3A. Maximum enrichment factors, assuming that each element is totally partitioned to the liquid, are calculated from the results of mixing calculations given in table 6. For example, sample A-6-29 represents 57.7 percent crystallization and a consequent maximum enrichment factor

of $1 \div (1-0.577) = 2.364$. The mixing calculations of table 6 assume that P_2O_5 was the most incompatible minor element.

The data of table 8 indicate the following:

1. Nb is the most incompatible of the trace elements during silicate crystallization; in fact, it appears to be anomalously enriched in oozes A-6-25 and A-6-30 beyond what is possible by complete partitioning to the liquid. One possible explanation is that P_2O_5 is partitioned in part to phases other than augite or liquid (for example, plagioclase). A very small amount of P_2O_5 in plagioclase would increase the enrichment factors to a point where the Nb data would fit. Nb is well determined (D. Gottfried, written commun., 1966), yet it still varies over a 10 percent range in the undifferentiated samples and even in the pumice. Also, Nb may possibly be redistributed by a process as yet unrecognized for any other element in the lava lakes. At lower temperatures Nb is concentrated by ilmenite and magnetite, and the rest of the samples show depletion of Nb relative to the maximum calculated enrichment.

2. Li and K_2O show parallel variation indicative of slight partitioning to plagioclase at high temperatures, increasing toward lower temperatures.

3. Zr is not well determined but shows significant partitioning to crystallizing phases (probably pyroxene) in the two lowest temperature samples.

Other trace elements show significant partitioning to crystallizing phases at high temperatures and either remain constant or are depleted in lower temperature samples.

PETROGRAPHY

The modal composition of Alae lava lake has been summarized in an earlier paper (Peck and others, 1966, fig. 4, p. 635–641). For the present study, new thin sections were cut for several samples of partly molten core. Counts of 1,500 points were made on these and the older sections, using a 0.3×0.3-mm grid. All modal data, obtained in volume percent,

TABLE 8.—*Comparison of observed and calculated values of relatively incompatible trace elements in Alae lava lake*

[Calculated results are obtained by multiplying the trace-element values for average (3) in table 3A by the maximum enrichment factor given in table 6]

Sample No.	K_2O (weight percent)		Li (ppm)		Nb (ppm)		Zn (ppm)	
	Obs.	Calc.	Obs.	Calc.	Obs.	Calc.	Obs.	Calc.
A-4-13	0.80	0.90	9	6.6	30.1	26.6–31.7	240	247
4-12	.88	.95	6	6.9	29.9	27.8–33.2	210	258
6-25	.96	1.03	7	7.5	38.7	30.3–36.1	280	280
6-30	1.07	1.17	7	8.5	43.8	34.5–41.1	280	320
6-29	1.16	1.30	8	9.5	44.3	38.3–45.6	320	355
5-20	1.57	1.86	11	13.5	47.4	59.7–65.2	340	507

[1] Range calculated from the maximum variation in Nb in undifferentiated core (table 3A).
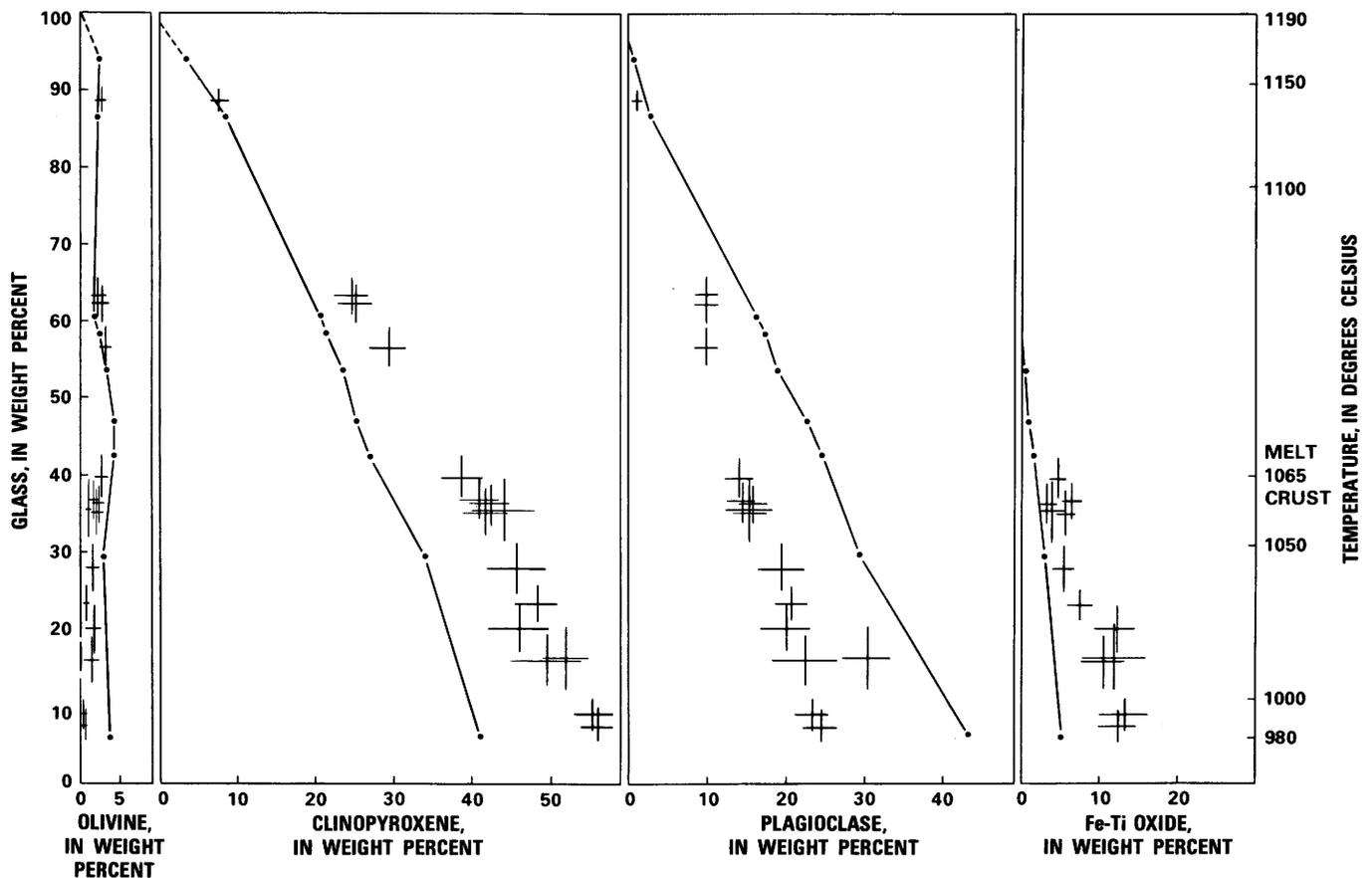
FIGURE 2.—Graph showing modal data for Alae lava lake. Crosses show modal data obtained in transmitted light converted to weight percent (see text). The length of the bars represents the estimated counting error of the mode according to the method of Van Der Plas and Tobi (1965). The dots (●) indicate weight percent modes calculated from analyzed glasses and oozes (data of table 6) and represent the modal abundances consistent with the bulk chemistry. Note that pyroxene and opaque minerals are overcounted and plagioclase undercounted in the optical modes.

were converted to weight percent by assuming the following specific gravity for minerals: olivine and pyroxene (sp gr=3.3); opaque phases (sp gr=4.5). The specific gravity of glass used in the conversion from volume to weight percent was estimated from the refractive index of the glass, assuming linear variations between the refractive index (R.I.) and specific gravity (sp gr) for the separated glasses: (sp gr=2.3, R.I.=1.488; sp gr=2.76, R.I.=1.602). The new modal data are summarized in figure 2 along with the curves defined by the chemical modes. An important finding is that there is significant bias in the optical modes relative to the chemical modes, marked by high values for pyroxene and opaque phases and by low values for plagioclase. This is evidently the result of the fine grain size of the basalt, in particular the very thin (less than 0.01 mm) laths of plagioclase. From figure 2, we

can calculate that the pyroxene is consistently overestimated by approximately 24 percent and the opaque minerals by 50 percent. If these percentages are subtracted from the optical estimates of pyroxene and opaque mineral, respectively, and are added to the plagioclase percentage estimated optically, a close approximation to the chemical mode is obtained.

The glass content is estimated satisfactorily by optical methods. Figure 3 shows the modal percentage of glass plotted against temperature, using the chemical modes and all of the optical modes of partly molten samples for which accurate temperature data were available. A single curve can be drawn through most of these data, indicating that the optical estimate of glass content is satisfactory.

Serious discrepancies exist for two samples of ooze for which chemical modes were calculated
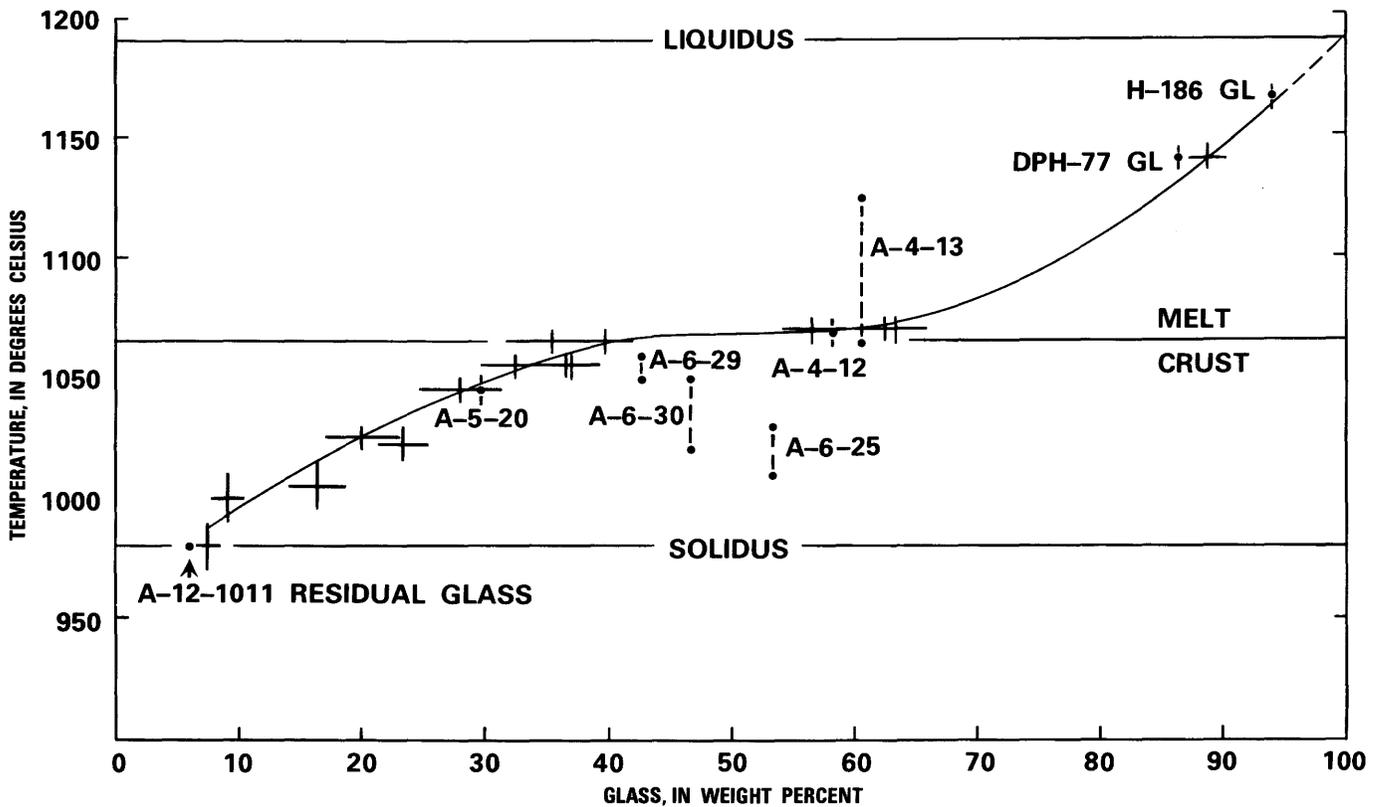
FIGURE 3.—Graph showing weight percent glass plotted against temperature. The S-shaped line is a best-fit by eye, drawn with the modal data for undifferentiated samples in figure 2. Data for glass content of differentiated samples (for example, A–6–25) are taken from table 6 and plotted against temperature of collection. Discrepancies for samples A–6–25 and A–6–30 are discussed in the text.

(A–6–25 and A–6–30). Both samples suggest a temperature of formation higher than the temperature at the time of collection. Drill hole 6 was the first hole to penetrate the lower crust of the lake (tables 1, 2). The samples A–6–25 through A–6–30 were samples of core that filled the open drill hole adjacent to the partly molten crust between the two 1,000°C isothermal surfaces. The easiest way to rationalize the temperature discrepancy shown on figure 3 is to infer that all the ooze came in from near the hottest zone (1,070°C, see table 2) and moved up or down the drill hole as it flowed in. Thus A–6–29 was collected at a depth corresponding to the maximum temperature in the hole and close to where it entered the drill hole; and A–6–25 and A–6–30 were collected at depths respectively above and below where the ooze entered the drill hole. Hence the estimated temperatures at the depth of collection are too low.

The temperatures of the pumices (H–186 and DPH–77) were estimated from temperature measurements made during the eruption. The liquidus temperature of the whole rock (100 percent liquid) is estimated from the Mg/Fe ratio using the method of Tilley and others (1964). The shape of the curve that relates glass content to temperature is very similar to that obtained for Makaopuhi lava lake, for which a broader range of temperature data is known (Wright and Okamura, 1977; Wright and others, 1976, fig. 12). The temperatures obtained using figure 3 are also shown on figure 2. Figures 2 and 3 together give a quantitative description of crystallization of the liquid line of descent (fig. 4) for Alae lava lake.

Petrographic modes of selected samples of ooze are given in table 9. Some of these (for example, A–5–20 and A–4–12) contain less than 10 percent crystals, commonly clotted together, placing an upper limit on the amount of previously crystallized material brought in with the liquid. Other oozes, notably those from drill hole 6 (A–6–25, A–6–29, and A–6–30), are highly crystalline because they

TABLE 9.—*Petrographic modes for selected oozes, in volume percent, from Alae lava lake*

[A, crystals brought in with liquid; B, crystals growing in the liquid]

Mineral	A-4-12	A-6-25		A-6-30		A-6-29		A-5-20	
		1	2	1	2	1	2	1	2
Olivine:									
A	----	----	0.1	----	0.1	0.0	0.0	0.0	0.0
B	---	---	---	---	----	---	----	----	----
Total	0.0	0.0	.1	0.0	.1	.0	.0	.0	.0
Pyroxene:									
A	3.0	4.8	3.6	6.4	4.4	3.0	2.7	2.7	2.7
B	----	26.9	28.7	26.1	29.0	18.9	12.9	.4	.3
Total	3.0	31.7	32.3	32.5	33.4	21.9	15.6	3.1	3.0
Plagioclase:									
A	4.4	3.1	3.0	5.8	4.0	4.0	2.7	1.5	1.2
B	----	11.2	12.8	14.3	12.9	8.1	5.9	2.0	1.1
Total	4.4	14.3	15.8	20.1	16.9	12.1	8.6	3.5	2.3
Ilmenite:									
A	----	.7	----	.8	----	.8	----	.7	1.0
B	1.3	13.6	15.8	13.4	14.1	11.4	6.9	.4	1.0
Total	1.3	14.3	15.8	14.2	14.1	12.2	6.9	1.1	2.0
Magnetite:									
A	----	----	----	----	----	----	----	----	----
B	.1	.2	.9	2.7	7.4	1.0	1.8	----	----
Total	.1	.2	.9	2.7	7.4	1.0	1.8	.0	.0
Glass [1]	91.2	39.6	34.7	30.3	28.1	52.8	67.1	92.4	92.7
Total	.100.0	100.0	100.0	100.0	100.0	100.0	100.0	100.0	100.0
Total A	7.4	8.6	6.6	13.0	8.4	7.8	5.4	4.9	4.9
Number of points (0.3×0.3-mm grid)	1,583	420	900	1,000	1,000	1,000	713	1,000	1,428

[1] Includes fresh and devitrified or oxidized glass.

were collected 2 to 3 weeks after drilling (see table 2) during which time they cooled and crystallized. This is further evidence that these oozes initially flowed into the hottest part of drill hole 6 and moved to cooler parts of the hole where they crystallized before the collection time. These also have glomerophyric clots which we interpreted as having been associated with the liquid before its entry into the drill hole, whereas we interpret the isolated crystals forming the bulk of the ooze as the products of crystallization in the time interval before collection and after the ooze entered the drill hole. The best evidence that the glomeroporphyritic clots did not form in the drill hole is the presence in them of resorbed olivine. It is known from study of all the lava lakes that magnesian olivine is no longer stable at the temperatures at which the oozes are formed.

DISCUSSION

MINERAL PARAGENESIS

The data presented in table 6 and plotted in figures 2, 3, and 4 yield the best estimate of the crystallization of Alae lava lake along its liquid line of descent. The first appearances of pigeonite and magnetite are not closely specified and have not been checked by electron probe as they were for

Makaopuhi lava lake (Wright and Weiblen, 1967). The chemical modes of oozes shown in table 6 are an exact match to the bulk composition of the lava lake. The appearance of magnetite in the calculations is controlled by assumptions regarding $Fe_2O_3/(Fe_2O_3+FeO)$ ratios in the oozes. Overall, the sequence and temperature of crystallization of all phases are consistent with those observed in Makaopuhi lava lake.

Tilley and others (1967, table 6, p. 265) determined the silicate paragenesis in a sample of basalt from Alae lava lake. They obtained temperatures of first appearance for augite (1,190°C), olivine (1,180°C), and plagioclase (1,155°C). The range of temperatures is in satisfactory agreement with the data of figure 2, particularly as the liquidus temperature of Alae has been estimated from the $(FeO+Fe_2O_3)/(MgO+FeO+Fe_2O_3)$ in the bulk composition using the calibration of Tilley and others (1964, fig. 23, p. 95). The experimentally observed order of appearance of olivine and pyroxene is different from that inferred from the presence of large olivine phenocrysts in the Alae pumice, assumed to be the earliest mineral to crystallize. This discrepancy may be apparent because of the uncertainties in the experimental techniques and in the extrapolation of data in figure 2.
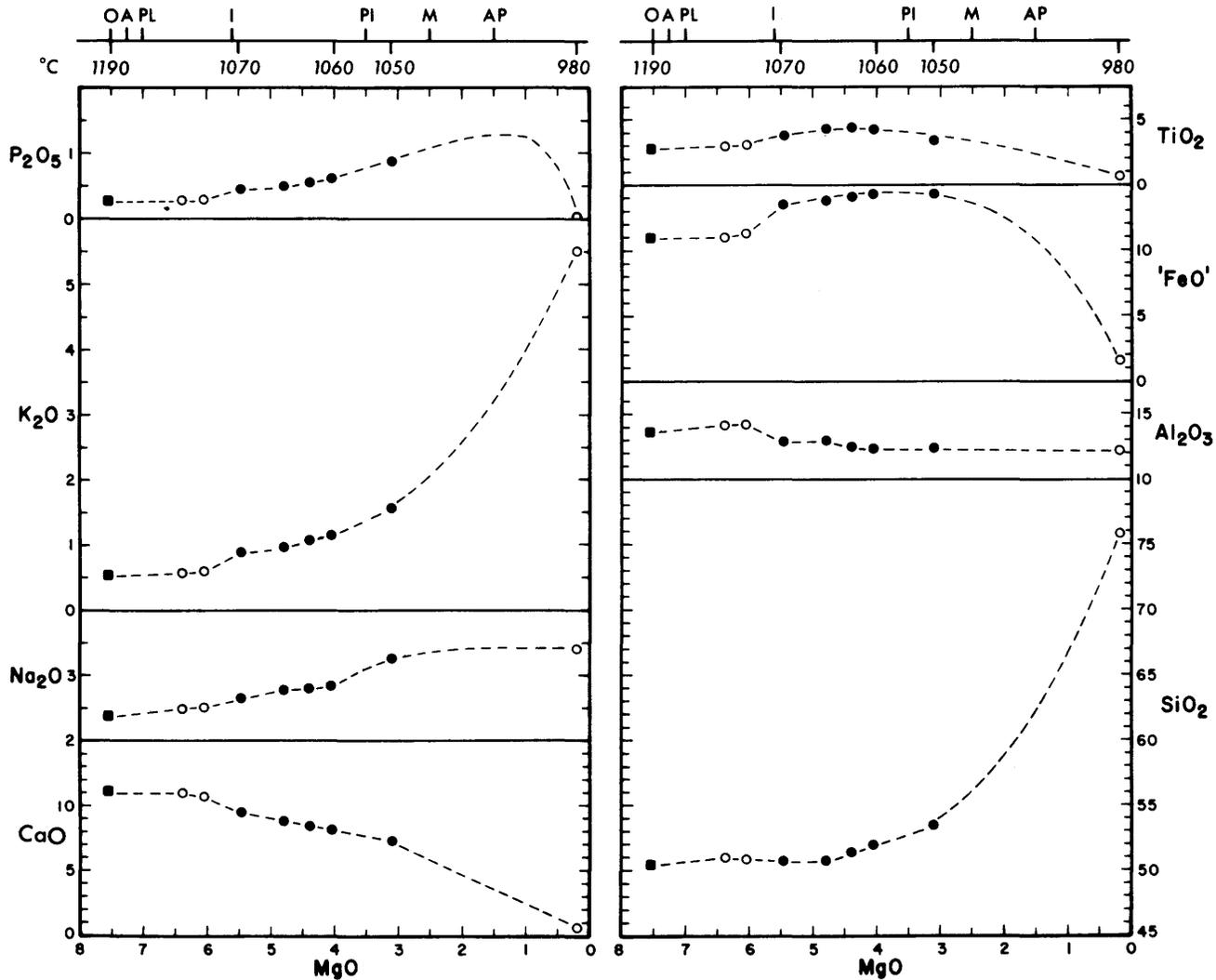
EXPLANATION

|			
O	Olivine	M	Magnetite
A	Augite	AP	Apatite
PL	Plagioclase	■	Bulk composition
I	Ilmenite	○	Separated and analyzed glasses
PI	Pigeonite	●	Naturally filter-pressed oozes

FIGURE 4.—MgO variation diagram showing liquid line of descent for Alae lava lake. Chemical data from table 3A (bulk composition), table 3B (oozes), and table 4 (glasses). The approximate correlation between liquid temperature and composition is shown at the top of the diagram, along with the approximate temperatures of first appearance of minerals on the liquidus. Liquidus = 1,200°C, solidus = 980°C. Figure modified from Wright and Fiske (1971, fig. 3).

RATES OF CRYSTALLIZATION OF MINERALS

Figure 3 shows the rate of crystallization of the basalt as a function of temperature. The pronounced S shape indicates low crystallization rates near the liquidus and solidus and a very rapid crystallization rate at and below the temperature of the crust-melt interface. A similar crystallization curve has been obtained for Makaopuhi lava lake, where reliable temperature measurements extend to 1,160°C (Wright and Okamura, 1977).

VARIATION OF LIQUID COMPOSITION DURING CRYSTALLIZATION

The analyses of glass and oozes from Alae lava lake approximate a liquid line of descent for tholeiitic basalt from Kilauea and thus define the chemical composition of possible differentiates produced either by settling of early formed crystals, or by filter pressing of late liquids. The variation of major element chemical data for Alae as temperatures decrease may be described in three distinct stages (see fig. 4):

1. *Crystallization of olivine in magnesian lavas (T>1,190°C).*—Where olivine is the only mineral crystallizing, successive liquid compositions will lie along olivine control lines. The best description of an eruption in which the changing composition of lavas was controlled by olivine is that of 1959 (Murata and Richter, 1966; Wright, 1973). Removal of olivine results in depletion of the liquid in magnesia, Cr, and Ni, and to a small extent in iron; but it also results in enrichment of the liquid in every other chemical constituent.

2. *Crystallization of pyroxene and plagioclase in addition to olivine (1,180°C>T>1,070°C).*—Once pyroxene and plagioclase begin to crystallize, the liquid is depleted in CaO and SiO_2 in addition to MgO and is further enriched in TiO_2 and alkalis relative to the olivine control lines of stage 1.[4] Total iron begins to increase markedly. The variation of Al_2O_3 in the liquid depends on the ratio of plagioclase to pyroxene. Generally the Al_2O_3 decreases once plagioclase begins to crystallize in significant amount.

Among the trace elements, Ba, Sr, and Ga are partitioned to plagioclase, and Cu, Y, and Yb are partitioned to pyroxene. All of these elements are eventually depleted in liquids collected at temperatures below 1,070°C.

The bulk composition of Alae lies near the low-magnesia terminus of olivine control. As shown in figures 2 and 4, all three silicate phases appear very close on the liquidus. Nonetheless, the differences between the H–186 and DPH–77 glasses and the bulk composition show the effects of olivine control, particularly in Al_2O_3 and SiO_2, as well as the lesser effect of removal of pyroxene and plagioclase (mainly lower CaO).

3. *Crystallization of oxides (1,070°C>T>980°C).*—Once ilmenite begins to crystallize, the rate of increase of total iron and TiO_2 in the liquid dimin-

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[4] The analyzed plagioclase and pyroxene from Kilauean basalts, including those from Alae lava lake, are always more siliceous than the bulk composition of the magma.

ishes. As crystallization continues, maximum values for TiO_2 and "FeO" are reached, after which both oxides decrease markedly in the liquid throughout the rest of the crystallization history; CaO and MgO continue to decrease. SiO_2 and alkalis, particularly K_2O, continue to increase. P_2O_5 is enriched in the liquid to slightly beyond the point where apatite begins to crystallize. V and Nb, and perhaps Zr, are concentrated in the Fe-Ti oxides but are enriched in the lowest temperature liquid (A–5–20) over their initial value. The residual liquid, formed as the end product of tholeiitic differentiation, is of rhyolitic composition; 95 percent of the chemical components are those of feldspar and quartz. The analyses of the residual liquid from A–12–10, –11, recalculated in table 5, can be calculated to the following mineral assemblage:

	Percent
Fe-rich pyroxene	1.2
Magnetite	1.3
Ilmenite	0.7
Feldspar ($Or_{50}Ab_{47}An_3$)	63.3
Quartz	33.5

This assemblage is like that found in a hedenbergite granophyre or in an anhydrous rhyolitic pitchstone.

NATURAL DIFFERENTIATES OF KILAUEAN THOLEIITE

The known natural differentiates of Kilauean tholeiite all correspond in their chemistry to those low-temperature filter-pressed differentiates that are similar to the Alae oozes (Wright and Fiske, 1971, appendix 3). Commonly these appear as fracture fillings (segregation veins).

The natural differentiates generally correspond to liquids produced near the boundary separating stages 2 and 3 of the liquid line of descent outlined above. Differentiation temperatures range from about 1,040° to 1,065°C. Two factors are believed to operate in restricting the temperature range of formation. First, below 1,065°C the crystal mush provides a stable framework through which the liquid can move. Secondly, open fractures are restricted to the brittle crust and cannot penetrate deeper than the crust-melt interface. Hence, the pressure differential necessary to trigger filter pressing of liquid is lacking at temperatures higher than that of the crust-melt interface.

Although the filter-press mechanism is well established, the differentiates produced by this mechanism will vary in composition according to the efficiency of the filter press in separating liquid from crystals. Many natural differentiates show the effects

of incomplete separation of liquid and crystals and separation of minerals in a ratio differing from their abundance in the host rock.

One example is the natural segregation vein from drill hole 9 (A-9-23, table 6). The chemical mode for A-9-23 may be compared with the ooze A-6-29 in which the calculated amount of liquid is approximately the same (41.4 percent, 42.3 percent). The calculated An content of plagioclase and the Mg/(Mg+Fe) content of augite are greater in A-9-23 than in A-6-29. This is interpreted as the result of small amounts of sodic plagioclase and Fe-rich pyroxene being brought in with the liquid.

The data of table 9 show that the higher temperature Alae oozes brought in crystal aggregates which have a higher ratio of plagioclase to pyroxene than was in the liquid before filter pressing. This "plagioclase" effect, and any other differences in the ratios of minerals brought in with the liquid to those available in the liquid, produce a differentiate which does not, strictly speaking, lie on a "liquid line of descent." This must be taken into account in postulating a parent magma for any basaltic differentiate. At the lowest temperature (1,045°C) and highest crystallinity (70 percent) of any Alae ooze (A-5-20), the plagioclase effect apparently did not operate. Perhaps in this case, the crystal mush was sufficiently tight that fragments of the crystal framework were brought in directly with no opportunity for differential movement of plagioclase and pyroxene.

SUMMARY

Study of Alae lava lake provides information on changing amounts and composition of liquid and crystals during crystallization. Modes computed from chemical data are more accurate than modes obtained optically in transmitted light. Mineral proportions and compositions vary in a regular and predictable manner. Likewise, the composition of liquid in terms of both major and trace elements also varies smoothly. Among the trace elements, Nb, Li, and Zr are partitioned to the liquid at high temperatures and are increasingly partitioned to crystals at lower temperatures. Cr and Ni are depleted at high temperatures by concentration in olivine and spinel. The rest of the trace elements (Ba, Sr, V, Y, Yb) are partitioned between crystallizing phases and liquid at all temperatures but all tend to become slightly enriched in the low-temperature liquids relative to their value in the bulk composition.

Differentiation takes place by filtration of liquid through a crystal mush with variable but small retention of the crystal framework in the separated differentiated liquid.

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