Journal of Volcanology and Geothermal Research, 7 (1980) 189—210

THE 1977 ERUPTION OF KILAUEA VOLCANO, HAWAII

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(Received March 18, 1979; revised and accepted July 16, 1979)

ABSTRACT

Moore, R.B., Helz, R.T., Dzurisin, D., Eaton, G.P., Koyanagi, R.Y., Lipman, P.W., Lockwood, J.P. and Puniwai, G.S., 1980. The 1977 eruption of Kilauea volcano, Hawaii. J. Volcanol. Geotherm. Res., 7: 189—210.

Kilauea volcano began to erupt on September 13, 1977, after a 21.5-month period of quiescence. Harmonic tremor in the upper and central east rift zone and rapid deflation of the summit area occurred for 22 hours before the outbreak of surface activity.

On the first night, spatter ramparts formed along a discontinuous, en-echelon, 5.5-km-long fissure system that trends N70°E between two prehistoric cones, Kalalua and Puu Kauka. Activity soon became concentrated at a central vent that erupted sporadically until September 23 and extruded flows that moved a maximum distance of 2.5 km to the east. On September 18, new spatter ramparts began forming west of Kalalua, extending to 7 km the length of the new vent system. A vent near the center of this latest fissure became the locus of sustained fountaining and continued to extrude spatter and short flows intermittently until September 20.

The most voluminous phase of the eruption began late on September 25. A discontinuous spatter rampart formed along a 700-m segment near the center of the new, 7-km-long fissure system; within 24 hours activity became concentrated at the east end of this segment. One flow from the 35-m-high cone that formed at this site moved rapidly southeast and eventually reached an area 10 km from the vent and 700 m from the nearest house in the evacuated village of Kalapana.

We estimate the total volume of material produced during this 18-day eruption to be 35×10^6 m^3. Samples from active vents and flows are differentiated quartz-normative tholeiitic basalt, similar in composition to lavas erupted from Kilauea in 1955 and 1962. Plagioclase is the only significant phenocryst; augite, minor olivine, and rare orthopyroxene and opaque oxides accompany it as microphenocrysts. Sulfide globules occur in fresh glass and as inclusions in phenocrysts in early 1977 lavas; their absence in chemically-similar basalt from the later phases of the eruption suggests that more extensive intratelluric degassing occurred as the eruption proceeded. Bulk composition of lavas varied somewhat during the eruption, but the last basalt produced also is differentiated, suggesting that the magma withdrawn from the summit reservoir during the rapid deflation has not yet been erupted.

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INTRODUCTION

At 1912 (HST) on September 13, 1977, Kilauea volcano began to erupt from its central east rift zone. The outbreak ended a 21.5-month period of quiescence, the longest in 10 years (Lipman et al., 1978). This report summarizes observations of the eruption and its products by the staff and associates of the U.S. Geological Survey's Hawaiian Volcano Observatory (HVO). A more detailed discussion of geophysical observations prior to and during the eruption is given by Dzurisin et al. (1980).

GEOLOGIC SETTING

Kilauea is one of the world's most active volcanoes, having erupted about 0.9×10^9 m^3 of basalt since 1952. It is the southeasternmost of five large shield volcanoes whose activity has constructed the island of Hawaii (Fig. 1). The summit area of the volcano, which reaches an elevation of 1243 m above sea level, is dominated by a relatively flat-floored caldera, 3 by 5 km in size. Rift zones radiate from the summit caldera to the east and southwest. The east rift zone, which extends 50 km to the east end of the island and continues far below sea level (Moore and Reed, 1963; Fornari et al., 1978), has been the more active during historic time. Eruptions in the vicinity of the 1977 vents occurred most recently in 1961 (Richter et al., 1964), 1963 (Moore and Koyanagi, 1969), and 1968 (Jackson et al., 1975) (Fig. 2). After construction of the Mauna Ulu satellitic shield on the upper east rift zone (Swanson et al., 1971, 1979; Peterson et al., 1976) ended in July 1974, two summit eruptions and an upper southwest rift zone eruption occurred later that year. On November 29, 1975 a M = 7.2 earthquake struck the southeast flank of Kilauea, followed soon after by a brief summit eruption (Tilling et al., 1976). Kilauea did not erupt again until September 13, 1977, although several intrusive events occurred during the intervening period (Dzurisin et al., 1980).

CHRONOLOGICAL SUMMARY OF THE ERUPTION

In contrast to the past observed behavior of Kilauea volcano, no significant inflation of the summit area occurred during the period between the last intrusive event (February 8, 1977) and the onset of eruptive activity on September 13, 1977 (Lipman et al., 1978; Dzurisin et al., 1980). However, dry-tilt measurements in June 1977 detected inflation of the central east rift zone in the vicinity of Heiheiahulu, a late prehistoric satellitic shield (Dzurisin et al., 1980; see Fig. 1).

Seismic activity along the upper east rift zone of Kilauea increased in early September 1977. Short bursts of tremor and shallow microearthquakes were frequent in the Mauna Ulu—Makaopuhi area (Fig. 1). From September 2 to 11 about 250—650 microearthquakes occurred daily within the east rift zone and the adjacent south flank; this activity peaked with a flurry of small shocks

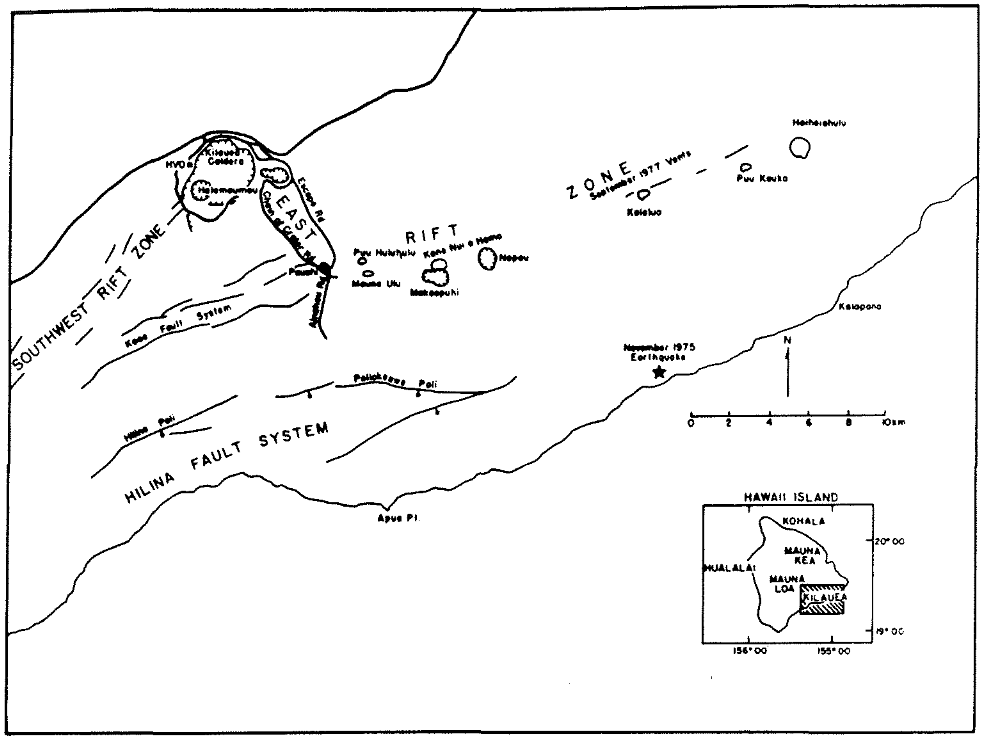

Fig. 1. **Index map of Kilauea volcano, showing general structural features.**

near Makaopuhi from 0400 to 0500 on September 11. After a slight decrease in seismicity, small shocks continued at moderate rates for the next two days.

Beginning of eruption

Harmonic tremor and a swarm of earthquakes, many of which were felt by residents, began at about 2130 on September 12, signalling the underground movement of magma. Rapid summit deflation, by as much as 3 microradians per hour (μrad/hr), began about 15 minutes later (Dzurisin et al., 1980). Tremor and deflation continued without eruption for the next 22 hours. Earthquake epicenters migrated gradually eastward and became concentrated near the prehistoric Kalalua cone in the central east rift zone (Fig. 1). This area is covered by tropical jungle and is readily accessible only by helicopter.

A felt earthquake (M = 3.7) near Kalalua at 1912 on September 13 coincided with the first reports of visible red glow along the east rift zone from residents in Kalapana and from radio-equipped fishermen off the southeast coast of Hawaii. Although visibility was poor, airborne HVO observers saw 25-m-high fountains from en-echelon fissures along at least 1 km of the rift zone, between the prehistoric Kalalua and Puu Kauka cones (Figs. 1 and 2). Subsequent field inspection showed that spatter ramparts as high as 3 m were built along much

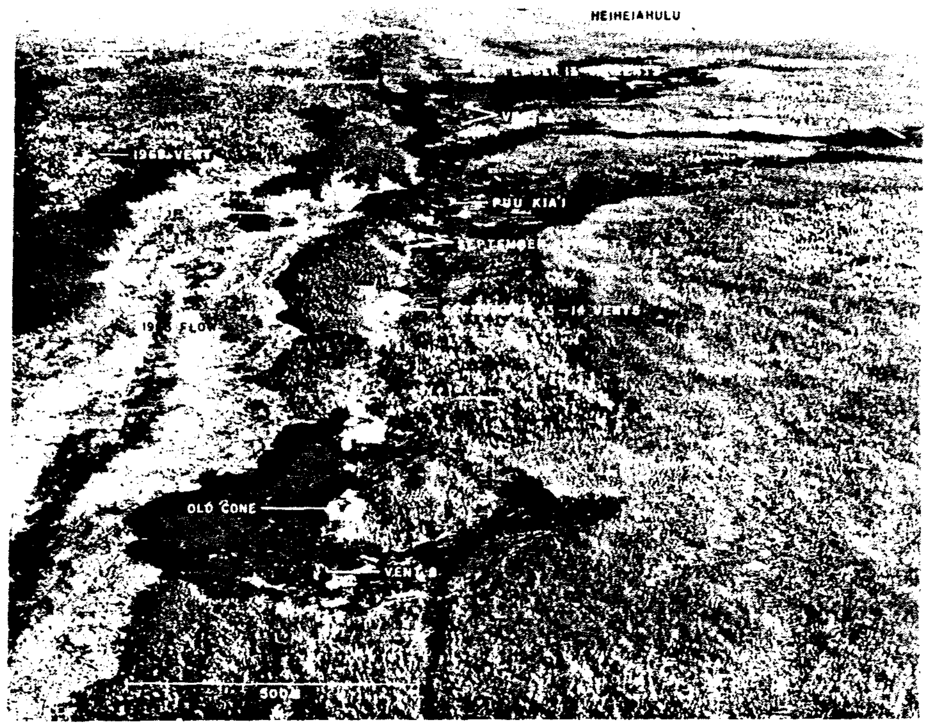

Fig. 2. View east-northeast of central east rift zone of Kilauea, showing features mentioned in text. Photograph by J.P. Lockwood and R.B. Moore, December 23, 1977.

of this segment, and short (50—500 m) flows moved generally east and south of the vents. Some lava drainback and consequent erosion of the fragile spatter ramparts occurred. Faults bounding two pre-existing grabens were reactivated during the eruptive activity, so that new flow and vent materials were displaced by about 1 m near the eastern end of the new fissure system and by as much as 4 m at the western end near Kalalua (Fig. 3). Fountaining temporarily stopped by about 0900 on September 14; Fig. 3 shows the distribution of new spatter ramparts and lava flows at that time.

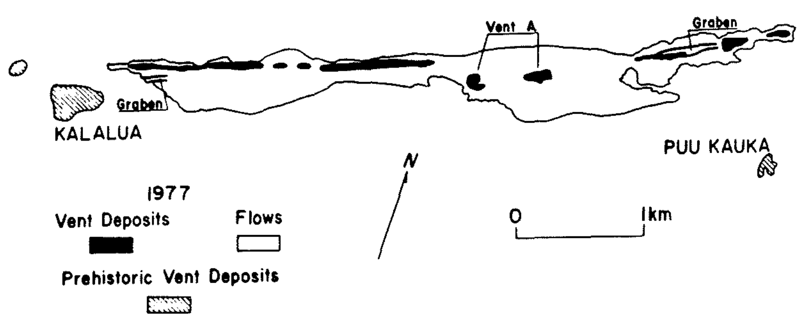

Fig. 3. Distribution of new eruptive products at 0900 on September 14, 1977.

Fountaining resumed at about 1100 on September 14 and became concentrated at vent A (Fig. 3), a fissure about 500 m long near the center of the previous night's activity. Partial burial of vent A by later flows resulted in the separate vent deposits shown in Fig. 3. On September 14, fountains averaged 25—40 m in height, with occasional bursts to 60 m. Pahoehoe and aa flows from vent A moved a maximum distance of 2.5 km east and southeast (Fig. 4), at speeds as high as 170 m/hr. They passed Puu Kauka by 1715 and temporarily threatened a papaya farm and ranch house.

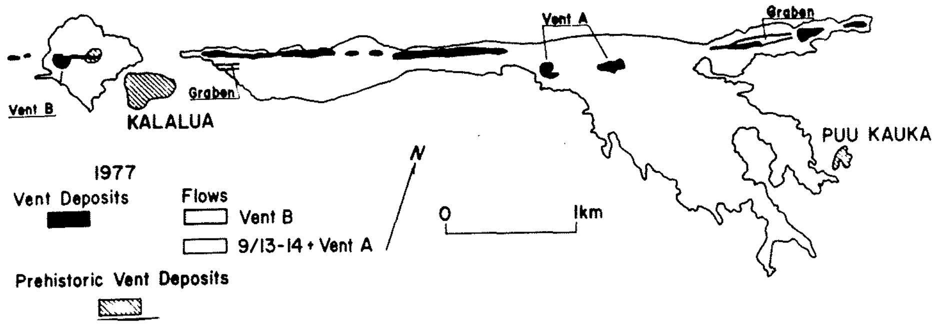

Fig. 4. Distribution of new eruptive products at 1200 on September 20, 1977.

Before dawn on September 15, new intense fuming began from fissures just west of Kalalua; this fuming was a prelude to an eruptive outbreak in this area on September 18. By 0745, fountaining had ceased at vent A, and forward movement of the flows was negligible. Minor fountain activity resumed in the vent A area by 0945, but no flows were extruded. During the day, the rate of summit deflation slowed to 0.3 μrad/hr (Dzurisin et al., 1980) and harmonic tremor, recorded by seismometers near Kalalua and Heiheiahulu, subsided. At 1715 no lava was being erupted from vent A, but 30-m-high fountaining resumed between 1900 and 2210.

Shortly after midnight on September 16, harmonic tremor diminished to nearly zero amplitude on all seismometers. Tremor in the central east rift zone increased at 0415, and by 0519 vent A was erupting again. A new flow moved about 2 km southeast, along the southwest side of the earlier vent A flows, before stagnating during the evening. Vent A fountains were 20—50 m high at 1300.

On September 17, fountaining was low and sporadic, with no significant flow movement. By 2045 harmonic tremor had subsided considerably, and the summit deflation rate, measured by a borehole tiltmeter 5 km southeast of HVO, had dropped to 0.5 μrad/hr, half its morning rate.

Second phase: vent B

Harmonic tremor in the central east rift zone increased slightly at about 0830 on September 18, and by 1015 the fissure system that had started to fume on September 15 began to erupt. The east end of this vent system was about 250 m west of Kalalua (Fig. 4); fissures cut across the north rim of a small prehistoric cone (Fig. 2) and extended west-southwest for 800 m. The earliest activity was not observed, but later field study showed that several spatter ramparts 1—5 m high were constructed discontinuously along the fissure system. Fountaining on the north rim of the old cone formed a small lava pond that covered the old crater floor. Activity soon became concentrated near the center of this new fissure system, where fountains 10—50 m high built a small spatter cone (vent B, Fig. 4). Viscous slab pahoehoe and aa flows moved slowly north, northeast, and southeast. Fountaining at vent B stopped at 1730, resumed briefly at 1850, and by 2200 ceased until the next day.

During the early morning of September 19, an HVO crew near vent B saw occasional flashes of light and heard explosions to the east, probably from the vent A area. That activity ended before dawn.

A felt earthquake (M = 4.1) on the southeast flank of Kilauea at 0902 on September 19 preceded renewal of eruptive activity at vent B by 20 minutes. Fountaining as high as 50 m continued for about 2 hours, but no significant flows were extruded. Harmonic tremor in the Kalalua area continued at moderately high levels for the rest of the day, but no further eruptions occurred until shortly before midnight.

At 2355 on September 19, fountaining began again at vent B. Harmonic tremor along the central east rift zone increased sharply at 0030 on September 20. Vent B erupted fountains as high as 100 m until 0600. Activity resumed at about 1000, but the fountains were then only about 15 m high and soon subsided. Fig. 4 shows the distribution of new vents and flows at the end of this phase of the eruption.

No activity occurred from September 20 until the late evening of September 25, except for some minor eruptions from the west part of vent A on September 23. Harmonic tremor recorded by a seismometer near Kalalua increased slightly at 0730. Beginning at 0930 and ending at 1645, viscous spatter, thrown to a height of 10 m or less, built a small cone nested within the earlier crater of vent A, and a small flow filled the crater.

Third phase: Puu Kia'i

Shortly before midnight on September 25, the third and most important phase of the eruption began. At about 2350, harmonic tremor in the central east rift zone increased markedly, and shortly afterward glow was sighted on the east rift zone from HVO. Aerial inspection at about 0500 on September 26 revealed fountains 60 m high along a 300-m-long fissure between vents A and B, an area that had been inactive since the first night of the eruption (Fig. 5). Heat from the eruption caused moisture from stratus clouds blanketing the east rift zone to rise into a large cumulonimbus dome visible from much of the east side of the island. Fountains and flows from this vent system continued until late morning.

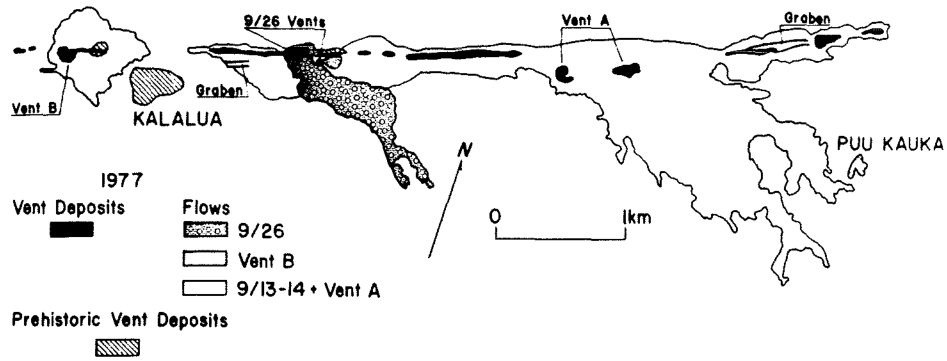

Fig. 5. Distribution of new eruptive products during late afternoon of September 26, 1977.

After a 4-hour hiatus in activity, a new en-echelon vent began erupting at 1440 about 150 m downrift from the spatter rampart built that morning (Fig. 5). This vent continued to erupt spatter and a short pahoehoe flow until at least 1730. Subsequent inspection showed that a small spatter rampart (30 m long, 2 m high) had been constructed, suggesting that activity did not continue long after 1730.

Before 0830 on September 27, en-echelon vents began erupting another 200—400 m downrift, at an elevation of about 570 m. At about 0830, fountaining was concentrated at the east end of the September 26 fissures (vent C, Fig. 6), and minor activity was occurring at several vents to the west. One voluminous lava flow moved east-northeast from vent C and buried small ramparts and short flows emplaced on September 13—14; another flow advanced southeast from a breach in the south rampart of vent C.

Several discrete vents along this latest, most active 250-m-long fissure displayed contrasting eruptive characteristics. A vent at the west end produced fountains about 100 m high that built a steep-sided cone; no significant flow came from this vent. In contrast, at the east end of the fissure, spatter was

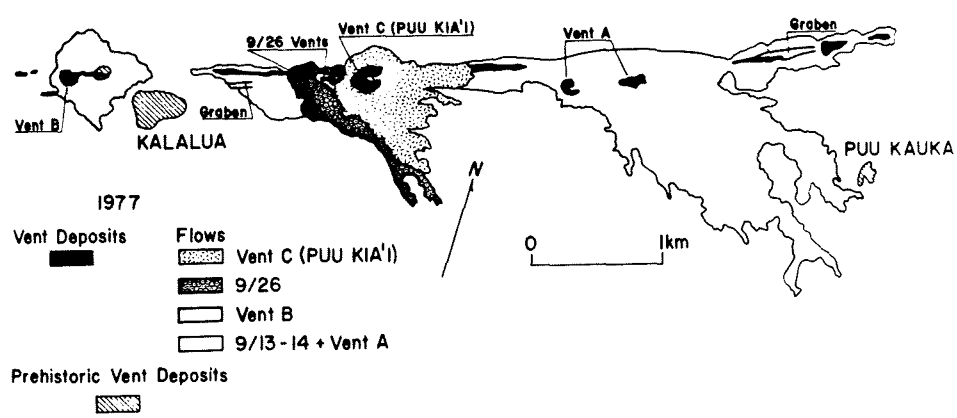

Fig. 6. Distribution of new eruptive products at 2300 on September 27, 1977.

continuously rafted away by the main flow, and no rampart was constructed. Vents between these two erupted fountains 50—100 m high that built a large rampart and fed the main flows. Continued fountaining resulted in coalescence of all these vent deposits to form a large spatter cone, Puu Kia'i (Hawaiian for Guardian Hill).

Shortly after midnight on September 28, the main flow, previously confined to the rift zone, branched about 1 km east of vent C. One stream continued downrift and buried parts of the September 13—14 flows; the other headed southeast toward Kalapana. By 1200 the latter flow front was at 460 m elevation, and by 1530 it had reached 400 m (Fig. 7). Most of this flow, including its advancing distal end, was aa; pahoehoe was confined to the active lava channel that extended from the vent to a few hundred meters above the distal end. In the early afternoon, the breach on the south flank of vent C was healed and the flow heading directly southeast stagnated. Fountaining continued to heights of 50—60 m all day.

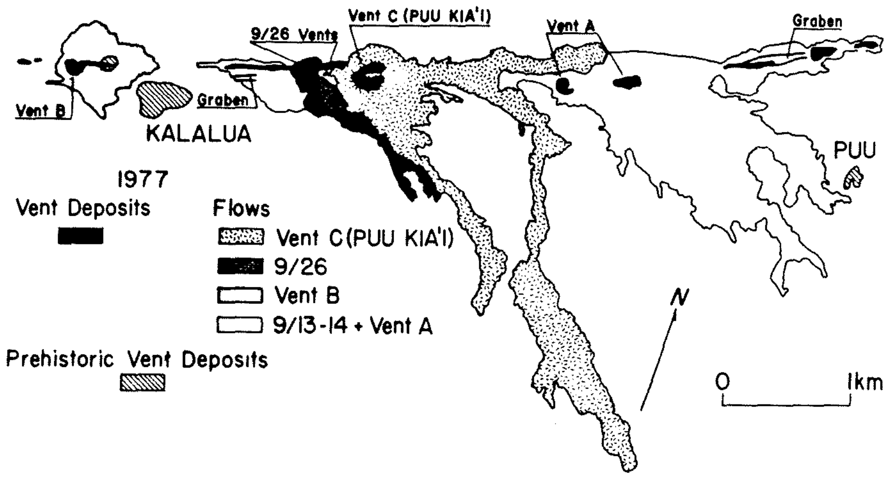

Fig. 7. Distribution of new eruptive products at 1530 on September 28, 1977.

Fountain heights at vent C increased to about 80—100 m on September 29, and residents in Hilo, 30 km to the north, reported visible fountains at 0600. In the early morning, the flow confined to the rift zone cascaded into a 14-m-deep crack, 1.5 km west-northwest of Puu Kauka (Fig. 2), and soon stagnated. Most of the lava remained in the main southeast branch of the flow that advanced toward Kalapana at 20—100 m/hr. This flow front reached 245 m above sea level by 1620. Kalapana was particularly vulnerable because a 12-m-high north-facing fault scarp blocking the slope down which the flow was moving (Fig. 8) may have diverted the lava into the village. Therefore, a partial evacuation was ordered by Hawaii County Civil Defense officials on September 29.

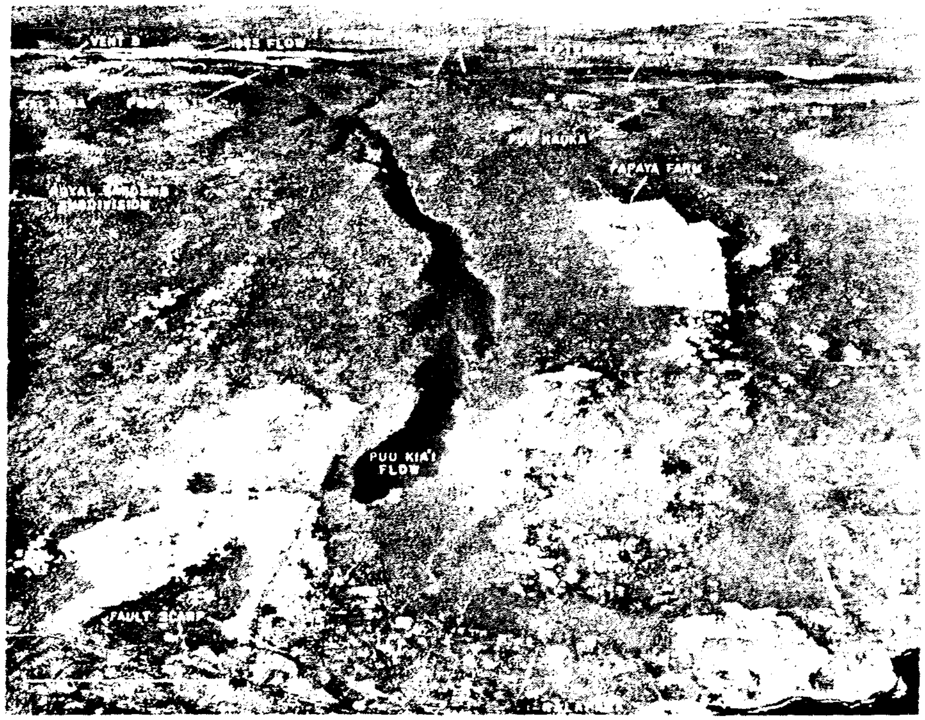

Fig. 8. View northwest of central east rift zone and southeast flank of Kilauea, showing features mentioned in text. Photograph by J.P. Lockwood and R.B. Moore, December 23, 1977.

Fountain heights at vent C fluctuated between 30 and 150 m during most of September 30, although 300-m-high fountains were observed at 2100. As the flow came down the slope 3 km northwest of Kalapana, its channel split into three branches that spread the flow laterally and slowed its advance. Flowage over more gentle slopes, starting at about 70 m above sea level, caused further lateral spreading and thickening. By the end of the day, the flow front was about 50 m above sea level.

During the morning of October 1 eruption of lava from vent C continued at about the same rate (roughly $0.1–0.2 \times 10^6$ m^3/hr) as during the previous four days. Fountain heights ranged generally from 60 to 120 m, although in midmorning, gassy spatter was thrown to a height of about 300 m. The point of transition from pahoehoe to aa in the flow channel, however, migrated upslope from 1 km above the flow front to only about 250 m from vent C and the advance of the flow front northwest of Kalapana slowed from about 40 m/hr at 0200 to only 1 m/hr at 0900. Lateral spreading and, more important, thickening of the lower 1 km of the flow caused this decrease in forward speed. The thickness of the flow 1.5 km above its distal end is about 4 m; thicknesses within 500 m of the distal end range up to 14 m, remarkable for unconfined Kilauea lava flows.

At about 1530 on October 1, the level of harmonic tremor in the central east rift zone dropped abruptly, fountain heights decreased to 30 m, and loud, vigorous degassing began. Eruption of spatter and flow material ceased by 1610.

During the next few days, the flow, though cut off from its source, continued to move forward slowly and to spread laterally because of its weight and the presence of still-molten lava upslope from its distal end. The advance totaled 6 m through October 5 and was negligible thereafter; lateral spreading by about 0.2 m/day continued until mid-October. The flow, whose total length is about 10 km (Fig. 9), reached to within about 700 m of the nearest house in its path.

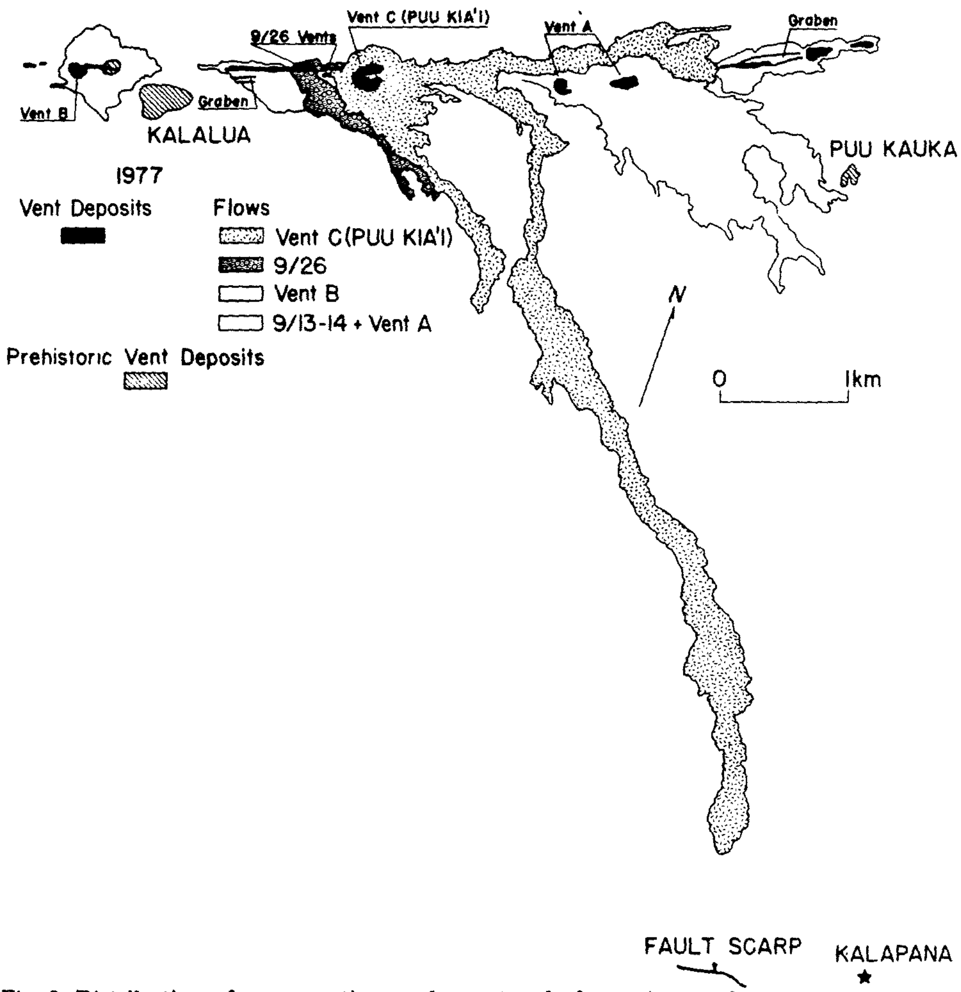

Fig. 9. Distribution of new eruptive products at end of eruption on October 1, 1977.

PETROGRAPHY

Table 1 presents modal data on 12 samples of basalt from the 1977 Kilauea eruption. Plagioclase is the only significant phenocryst; augite, minor olivine, and rare orthopyroxene and opaque oxides accompany it as microphenocrysts (generally smaller than 0.5 mm; phenocrysts listed in Table 1 include microphenocrysts). Cumulophyric clots of plagioclase, augite, and olivine are present in most samples. This phenocryst assemblage, though uncommon in Kilauea lavas, is similar to that of some differentiated basalts erupted from the lower east rift zone in 1955 (Macdonald and Eaton, 1964; Wright and Fiske, 1971).

Examination of the opaque minerals in reflected light suggests that ilmenite is the only stable Fe-Ti oxide phase. Magnetite occurs only as tiny quench-textured microlites in the crystallized mesostasis. In addition to the Fe-Ti oxides, certain samples from the earlier phases of the eruption (samples 1—6, Tables 1 and 2) contain tiny blebs of an immiscible sulfide phase. The largest bleb seen is about 30 μm in diameter; most are 2—5 μm in diameter. They have been observed only in very glassy material or as inclusions in phenocrysts. Where the matrix has crystallized, sulfide is absent. Also, no sulfide has been observed in any scoria recovered from the later phases of the eruption (samples 7—12, Tables 1 and 2), even though the thin sections examined contain more fresh glass than earlier samples.

CHEMISTRY

Table 2 presents wet-chemical analyses and C.I.P.W. norms for the 12 samples for which modal data are shown in Table 1. The samples are fairly uniform in composition: MgO ranges from 5.28 to 5.85% and shows little systematic variation with time.

The variation in SiO_2 content is likewise unsystematic: the extremes in SiO_2 content are represented by spatter ejected from two adjacent vents on the first night of the eruption (samples 1 and 2, Table 2). The former sample has 0.45% more SiO_2 than any previously reported analysis of lava from Kilauea's east rift zone. The significance of this value is uncertain, however, because other samples with comparable MgO content (e.g., samples 2, 3, 7 and 8, Table 2) have noticeably less SiO_2.

Tables 3—6 present microprobe analyses of glass, plagioclase, augite, and olivine, respectively, from basalt erupted on September 13 and 20. The September 20 flow sample was taken from the flow fed by the vent from which sample 5 in Tables 1 and 2 was collected; bulk compositions of the two samples should be similar. All analyses were made by R.T. Helz using an ARL-EMX microanalyser* operated at 15 kV with a sample current of 0.01 μA. All elements were referred to natural glasses and minerals as standards. In addition,

*Any use of trade names in this report is for descriptive purposes only and does not constitute endorsement by the U.S. Geological Survey.

TABLE 1

Modes of 1977 Kilauea basalt*

	1	2	3	4	5	6	7	8	9	10	11	12
Glass or fine-grained groundmass	78.7	60.7	88.2	85.0	86.7	76.6	69.5	84.6	64.0	92.9	82.7	51.6
Olivine phenocrysts	1.1	1.7	0.9	0.5	0.9	1.2	1.6	0.8	1.8	0.7	0.6	1.8
Plagioclase phenocrysts	7.1	19.6	6.9	7.0	7.4	13.1	13.4	10.5	10.8	3.7	5.1	8.7
Clinopyroxene phenocrysts	4.8	2.7	2.3	1.1	2.0	5.2	2.7	3.9	3.1	0.9	1.3	1.0
Orthopyroxene phenocrysts	0.3	—	—	—	—	—	—	—	—	—	—	—
Plagioclase microlites (quench crystals)	7.6	8.6	1.7	6.2	3.0	1.9	12.5	—	10.1	1.8	8.9	13.0
Groundmass pyroxene (quench crystals)	—	6.7	—	—	—	1.3	—	—	10.1	—	—	23.9
Opaque oxide phenocrysts	0.4	—	—	0.2	—	0.7	0.3	0.2	0.1	—	1.4	—

*Sample locations and dates of eruption are given in Table 2. All values in volume percent, based on 1000 data points. Microphenocrysts included with phenocrysts.

TABLE 2

Chemical analyses and normative compositions (in wt. %) of 1977 Kilauea basalt

	1	2	3	4	5	6	7	8	9	10	11	12
SiO_2	51.86	50.75	51.34	50.93	51.11	51.26	51.13	51.22	50.91	50.94	50.89	50.82
TiO_2	3.25	3.44	3.69	3.37	3.36	3.53	3.46	3.48	3.36	3.49	3.32	3.31
Al_2O_3	13.89	13.94	13.65	13.99	13.97	13.90	13.91	13.84	14.00	13.87	13.96	13.97
Fe_2O_3	1.75	2.10	1.86	1.63	1.62	1.79	1.75	1.73	2.37	1.94	1.93	3.61
FeO	9.99	10.18	10.55	10.22	10.21	10.53	10.52	10.55	9.72	10.26	10.04	8.50
MnO	0.17	0.18	0.18	0.17	0.17	0.18	0.18	0.18	0.17	0.17	0.17	0.17
MgO	5.43	5.53	5.28	5.84	5.79	5.39	5.52	5.51	5.75	5.65	5.85	5.84
CaO	9.50	9.57	9.27	10.02	9.95	9.41	9.57	9.55	9.85	9.70	9.94	9.94
Na_2O	2.79	2.73	2.82	2.66	2.68	2.80	2.80	2.79	2.68	2.72	2.65	2.64
K_2O	0.78	0.73	0.79	0.68	0.69	0.76	0.73	0.74	0.69	0.71	0.67	0.66
P_2O_5	0.38	0.38	0.40	0.34	0.35	0.40	0.39	0.40	0.36	0.37	0.35	0.34
H_2O^+	0.07	0.11	0.07	0.06	0.05	0.05	0.06	0.09	0.08	0.11	0.11	0.08
H_2O^-	0.01	0.05	0.0	0.0	0.0	0.0	0.0	0.01	0.01	0.01	0.01	0.02
CO_2	0.01	0.0	0.0	0.01	0.01	0.01	0.01	0.01	0.01	0.01	0.01	0.01
Cl	0.01	0.02	0.01	0.01	0.01	0.01	0.01	0.01	0.01	0.01	0.01	0.01
F	0.06	0.06	0.06	0.05	0.06	0.06	0.06	0.06	0.06	0.05	0.05	0.05
S	0.01	0.08	0.01	0.01	0.02	0.01	0.01	0.01	0.01	0.01	0.01	0.02
Sub-total	99.96	99.85	99.98	99.99	100.05	100.09	100.11	100.18	100.04	100.02	99.97	99.99
Less O	0.04	0.07	0.04	0.03	0.04	0.04	0.04	0.04	0.04	0.03	0.03	0.03
Total	99.92	99.78	99.94	99.96	100.01	100.05	100.07	100.14	100.00	99.99	99.94	99.96
Q	4.6	3.9	4.5	3.2	3.5	4.0	3.5	3.7	4.1	3.7	3.6	5.5
Or	4.6	4.3	4.7	4.0	4.1	4.5	4.3	4.4	4.1	4.2	4.0	3.9
Ab	23.5	23.0	23.8	22.4	22.6	23.6	23.6	23.5	22.6	22.9	22.4	22.3
An	23.1	23.8	22.3	24.3	24.1	23.1	23.2	23.1	24.2	23.6	24.3	24.4
Di-Wo	8.9	8.8	8.7	9.6	9.5	8.6	8.9	8.9	9.2	9.2	9.4	9.4
Di-En	4.6	4.7	4.4	5.1	5.0	4.4	4.6	4.6	5.1	4.8	5.1	5.9
Di-Fs	4.0	3.9	4.1	4.2	4.2	4.0	4.1	4.2	3.8	4.0	4.1	3.0
Hy-En	8.9	9.1	8.7	9.5	9.4	9.0	9.2	9.1	9.2	9.2	9.5	8.7
Hy-Fs	7.8	7.6	8.0	7.9	7.9	8.3	8.3	8.3	6.9	7.7	7.6	4.4
Mt	2.54	3.1	2.70	2.36	2.35	2.59	2.54	2.50	3.4	2.81	2.80	5.2
Il	6.2	6.5	7.0	6.4	6.4	6.7	6.6	6.6	6.4	6.6	6.3	6.3
Ap	0.90	0.90	0.95	0.81	0.83	0.95	0.92	0.95	0.85	0.88	0.83	0.81
Fr	0.05	0.05	0.05	0.04	0.06	0.05	0.05	0.05	0.06	0.04	0.04	0.04
Pr	0.02	0.15	0.02	0.02	0.04	0.02	0.02	0.02	0.02	0.02	0.02	0.04
Cc	0.02	—	—	0.02	0.02	0.02	0.02	0.02	0.02	0.02	0.02	0.02
Hl	0.02	0.03	0.02	0.02	0.02	0.02	0.02	0.02	0.02	0.02	0.02	0.02

1 = spatter, erupted September 13, 1.2 km northeast of Kalalua. 2 = spatter, erupted September 13, 0.9 km northeast of Kalalua. 3 = spatter, erupted September 16, vent A. 4 = spatter, erupted September 19, vent B. 5 = spatter, erupted September 20, vent B. 6 = spatter, erupted September 23, vent A. 7 = spatter, erupted September 26, 0.9 km northeast of Kalalua. 8 = spatter, erupted September 26, 1 km northeast of Kalalua. 9 = spatter, erupted September 28, Puu Kia'i. 10 = spatter, erupted September 29, Puu Kia'i. 11 = spatter, erupted October 1, Puu Kia'i. 12 = pahoehoe flow, erupted October 1, 50 m east of Puu Kia'i.

the sulfur values reported were checked relative to NBS 610, a synthetic standard glass containing 500 ppm S. They appear to be accurate to ± 100 ppm.

The glasses in these three samples are quite uniform in composition where they have not begun to crystallize. Each analysis in Table 3 is the average of three or four points, taken on the clearest glass available, with a beam diameter of 10—15 μm. The glasses from the September 13 and September 20 spatter samples, so defined, are slightly less silicic and aluminous than the corresponding

TABLE 3

1977 Kilauea glasses compared with differentiated glasses from Makaopuhi and Alae lava lakes

	September 13 spatter[1]	September 20 spatter[2]	September 20 flow	Makaopuhi[3]	Alae[4]
SiO_2	51.4	50.7	50.8	50.90	51.4
TiO_2	3.29	3.47	3.86	3.89	4.0
Al_2O_3	13.6	13.7	12.7	12.97	13.0
FeO[5]	12.4	12.0	12.9	13.18	13.6
MnO	0.14	0.18	0.15	0.20	0.17
MgO	5.16	5.76	5.21	5.18	3.0
CaO	9.51	10.0	9.56	9.38	9.6
Na_2O	2.84	2.70	2.74	2.73	3.1
K_2O	0.84	0.68	0.77	0.80	1.0
P_2O_5	0.40	0.39	0.37	0.41	0.45
S	0.04	0.04	0.03	—	0.038
Total	99.6	99.6	99.1	99.64	99.4

[1] Sample 1, Table 2.
[2] Sample 5, Table 2.
[3] Wet-chemical analysis of glass from 1965 Makaopuhi lava lake (sample 69-1-22; Wright and Okamura, 1977, p. 28, table 11).
[4] X-ray fluorescence analysis of glass from Alae lava lake; Skinner and Peck, 1969, p. 311, table 1, column 3. Sulfur analysis by Egon Althaus.
[5] All iron calculated as FeO here and in Tables 4—6.

TABLE 4

1977 Kilauea plagioclases

	September 13 spatter	September 20 flow (vent B)	September 20 spatter (vent B)
SiO_2	54.13	53.19	53.09
TiO_2	0.23	0.18	0.20
Al_2O_3	28.43	28.75	29.29
FeO	1.28	1.04	1.03
MnO	0.02	0.00	0.02
MgO	0.11	0.07	0.08
CaO	11.84	11.99	12.28
Na_2O	4.31	4.25	4.19
K_2O	0.15	0.18	0.16
Total	100.50	99.55	100.34
An	59.7	60.3	61.2
Or	0.9	1.1	0.9
Ab	39.4	38.7	37.8

TABLE 5

1977 Kilauea augites

	September 13 spatter	September 20 flow (vent B)	September 20 spatter (vent B)
SiO_2	50.65	50.28	50.66
TiO_2	1.63	1.56	1.38
Al_2O_3	3.94	3.95	3.44
FeO	9.50	9.38	9.04
MnO	0.28	0.32	0.21
MgO	15.99	16.15	16.16
CaO	17.18	18.38	18.79
Na_2O	0.50	0.23	0.25
Total	99.67	100.25	99.93
En	41.8	41.0	41.0
Wo	38.8	40.3	41.2
Fs	19.4	18.7	17.8

TABLE 6

1977 Kilauea olivines

	September 20 flow (vent B)	September 20 spatter (vent B)
SiO_2	37.25	37.77
TiO_2	0.10	0.06
Al_2O_3	0.02	0.03
FeO	24.77	21.88
MnO	0.51	0.40
MgO	37.36	39.70
CaO	0.41	0.41
Total	100.42	100.25
Fo	72.9	76.4

whole-rock analyses of Table 2, since plagioclase containing more SiO_2 and Al_2O_3 (Table 4) than the glass is the major phenocryst phase. The glass from the September 20 flow sample is more differentiated than the glass from the September 20 scoria, reflecting the fact that the lava was crystallizing as it moved away from the vent.

The analyses of silicate microphenocrysts (Table 4—6) are also averages of 2—5 points, taken with a beam diameter of 1 μm or less. The plagioclases have a uniform core with a narrow, more sodic rim; the analyses of Table 4 are averages of core compositions only. The augites are zoned, sometimes with a conspicuous hourglass structure, so that the average compositions presented in Table 5 may be only rough approximations to their bulk compositions. The olivines (Table 6) are smaller than augites and plagioclases and show little zoning.

To the extent that these probe data are representative, they show that phenocryst compositions vary systematically with the composition of the glass. For example, augite and olivine are more magnesian, and plagioclase and augite more calcic, in glasses with higher MgO and CaO contents. Thus the observed silicate phenocrysts appear to be near equilibrium with their host glasses.

Comparable data on the first compositions of major silicate phases crystallizing initially from other Kilauea lavas are scarce. The only such compositions reported, for minerals other than the olivine phenocrysts (which are typically Fo_{80-90}; Wright, 1971) in the summit lavas are those given by Wright and Weiblen (1967) for the 1965 Makaopuhi lava, only slightly different from a low-MgO summit composition (Wright and Fiske, 1971). Their data compare with the compositions of the 1977 phases as follows:

1965 Makaopuhi	*1977 east rift zone*
An_{67}	An_{60-61}
$Wo_{40}En_{47}Fs_{13}$	$Wo_{41}En_{40}Fs_{19}$
Fo_{80-85}	Fo_{73-76}

The 1977 mineral compositions are in all cases consistent with the differentiated nature of the host lava.

Table 7 shows weight-percent modes for the three samples on which microprobe data are available. These modes were calculated according to the method of Wright and Doherty (1971), by setting up equations of this sort:

ol + cpx + plag + glass = whole rock

Our calculations show that the best-quenched glass in the two spatter samples makes up 96—97% of the corresponding bulk composition, whereas that in the flow sample, collected only a few hundred meters away, has crystallized much more. This result is consistent with the fractionated nature of the melt: it is saturated with respect to all three major silicate phases, so that crystallinity increases rapidly as temperature decreases.

We note that these modes contain much less crystalline material than the modes given in samples 1 and 5 in Table 1. The modes in Table 7, calculated using the freshest glass, would inevitably have fewer crystals than a mode taken over the entire section, which includes less rapidly quenched material. The 3—4% crystals in the calculated modes thus represent more closely the real phenocryst content of the melt prior to eruption than do the crystal contents given in Table 1.

TABLE 7

Modes (in wt. %) for three compositions, calculated from microprobe data in Tables 3—6

	September 13 spatter[1]	September 20 spatter[2]	September 20 flow[2]
Glass	95.6	96.9	83.2
Plagioclase	3.3	2.5	11.3
Augite	1.1	trace	3.3
Olivine	trace	0.6	2.2

[1] Sample 1, Tables 1 and 2.
[2] Sample 5, Tables 1 and 2.

DISCUSSION

The 1977 lavas vs. other Kilauea basalts

The petrographic and chemical data presented above indicate that the lavas extruded during the 1977 east rift zone eruption of Kilauea are all quite differentiated relative to Kilauea summit lava compositions. The 1977 whole-rock and spatter compositions are similar to those of segregation veins found in some historic lava lakes (Wright and Fiske, 1971); these veins correspond to the melt left after removal of 30—60% crystals from a Kilauea summit composition. An analysis of one such vein, from the 1965 Makaopuhi lava lake, is shown in Table 3 for comparison with the spatter analyses.

Differentiated lavas like the 1977 basalts, with their complex phenocryst assemblages, are quite rare on Kilauea and are confined to the rift zones (Wright and Fiske, 1971). Lavas of similar petrographic and chemical character were extruded during the 1955 and 1962 east rift zone eruptions. Specific analyses of lavas from these earlier eruptions (Table 8) are virtually identical to the analyses in Table 2 of samples with similar MgO contents. This resemblance is remarkable, particularly because some notable differences exist between the 1955 and 1977 lavas. For instance, the 1977 lavas are all quite uniform, with compositions varying unsystematically with time. In contrast, the lavas of the 1955 eruption vary much more widely in composition (MgO ranges from 5.02 to 6.69%) and became more magnesian as the eruption proceeded. Also, the phenocrysts in the 1955 lavas are larger and more varied than those in the 1977 lavas. The earlier 1955 lavas contain coarse ilmenite and magnetite in addition to three to four silicate phases, whereas the 1977 lavas contain only sparse microphenocrysts of ilmenite and mafic silicates. Mg/Fe ratios in some individual augite crystals in the 1955 lavas vary greatly, and the later 1955 lavas contain coarse forsteritic olivines (Fo_{79}) and highly calcic plagioclase (An_{73}) (compositions from Anderson and Wright, 1972). The phenocrysts in the 1977 lavas, by contrast, are smaller and appear, from the data available so far, to vary less broadly in composition, although additional microprobe data would be desirable.

TABLE 8

Analyses of other recent Kilauea east rift zone lavas for comparison with data of Table 2

	1	2	3	4	5
SiO_2	51.28	51.00	50.91	51.39	51.13
TiO_2	3.47	3.49	3.60	3.60	3.56
Al_2O_3	13.80	13.85	13.72	13.64	13.81
Fe_2O_3	1.87	2.26	2.65	1.78	2.20
FeO	10.44	10.21	9.87	10.77	9.99
MnO	0.18	0.18	0.18	0.18	0.18
MgO	5.50	5.54	5.64	5.24	5.68
CaO	9.40	9.53	9.58	9.07	9.63
Na_2O	2.82	2.74	2.68	2.83	2.76
K_2O	0.74	0.77	0.74	0.79	0.74
P_2O_5	0.40	0.40	0.40	0.43	0.38
H_2O^+	0.11	0.09	0.01	0.08	0.05
H_2O^-	0.03	0.00	0.02	0.01	0.02
CO_2	0.00	0.01	0.00	0.02	0.02
Cl	0.02	0.02	0.02	0.02	0.02
F	0.07	0.06	0.05	0.06	0.05
Subtotal	100.13	100.15	100.07	99.91	100.22
Less O	0.03	0.03	0.02	0.03	0.02
Total	100.10	100.12	100.05	99.88	100.20

1, 2 = vent E spatter, erupted March 6, 1955. Samples TLW67-41a and TLW67-41b (Wright and Fiske, 1971, p. 16, table 3). 3 = vent S flow, erupted March 14, 1955. Sample 3 (Macdonald and Eaton, 1964, p. 87, table 2). 4 = vent U spatter, erupted March 24, 1955. Sample TLW67-50 (Wright and Fiske, 1971, p. 16, table 3). 5 = Lava of December 1962 eruption near Kane Nui o Hamo. Sample H 301 (Wright and Fiske, 1971, p. 19, Table 4a).

Wright and Fiske (1971) interpreted the differentiated rift zone lavas of Kilauea as the result of a complex process of crystal-liquid fractionation and hybridization. Their model involved magma moving laterally from the summit reservoir into the rift systems, where it cools and fractionates in magma chambers isolated from the summit reservoir, to be erupted when displaced by new magma entering from the summit reservoir, with or without mixing of the differentiated melt with more recently arrived summit magma. Specifically, Wright and Fiske suggested that the later 1955 lavas were formed by mixing of the earliest, most differentiated 1955 lavas with melt of composition similar to that of lavas from the 1952 and 1961 summit eruptions*. They considered the earliest 1955 lavas, for purposes of the mixing calculations, to be pure differentiates of one or more (unknown) parents.

This model may be broadly correct for the 1977 lavas, but it is difficult to quantify. In contrast to the 1955 lavas, evidence of recent hybridization is absent in the 1977 lavas. Bulk composition varied little over the course of the

*The possibility of recognizing magma mixing at Kilauea rests on the observations of Powers (1955) and Wright (1971) that Kilauea summit lavas of different ages are chemically distinct.

1977 eruption. Crystals present are small and appear to be near equilibrium with their host liquids; obvious xenocrysts are absent. If the 1977 lavas are hybrid, magma mixing must have occurred so long before the eruption that evidence of it has been largely obliterated. Therefore, it is impossible that the summit magma which began to move into the east rift zone on September 12, 1977, just before the eruption, was a component of the 1977 lavas.

Without recognizable end members, it is difficult to determine whether the 1977 lavas are hybrids or differentiates of a single batch of summit lava. Since the identity of the parent(s) is unknown, the age of the source is also unknown. The most important observation bearing on both these problems is that the 1977 lavas are virtually identical in composition to melts erupted in 1955 and 1962 (cf. samples 7 and 8, Table 2, with samples 1 and 2, Table 8; or sample 10, Table 2, with samples 3 and 5, Table 8). This observation suggests that: (1) all three sets of lavas may have come from the same source, (2) this source must be rather large to have produced melt of constant composition over a 22-year period, and (3) this source is fairly old relative to the 22-year interval over which the melts have been erupted.

Sulfides in the 1977 lavas

As discussed above, the early 1977 lavas all contain tiny blebs of an immiscible sulfide phase, either in fresh glass or as inclusions in phenocrysts. The presence of this sulfide in phenocrysts implies that it was stable in the magma chamber from which the early (September 13 and 20) lavas ascended. Its absence in more devitrified material suggests that the sulfide was being resorbed, with sulfur entering the vapor phase as SO_2, during the eruption.

Rapid loss of sulfur by evaporation from Kilauea lavas during fountaining and flowage has been documented by Swanson and Fabbi (1973). Evidently, this process occurred during the 1977 eruption as well: microprobe analyses of quenched glasses show 0.03—0.04% S (Table 3). In contrast, the equivalent whole-rock analyses, which include a large volume of more devitrified material, give 0.01—0.02% S (Table 2), except for sample 2, which was coated with sublimate. This contrast in sulfur content between glasses and bulk samples correlates well with the observation that sulfide blebs are preserved only in fresh glass or phenocrysts.

Immiscible sulfides like those in the early 1977 lavas are rare in Kilauea lavas. They have been observed in several sets of differentiated rift zone lavas, including those of the 1955 eruption (Desborough et al., 1968). Also, similar blebs of immiscible sulfide have been found in ooze from Alae lava lake (Skinner and Peck, 1969) and in glassy segregation veins in Kilauea Iki lava lake (R.T. Helz, unpublished data). Of these occurrences, the best documented so far is the sulfide-bearing ooze from Alae.

The question arises as to what factor controls the separation of these immiscible sulfide liquids in Kilauea lavas. In general, exsolution of sulfide liquid from a basaltic liquid, at constant pressure, depends on the sulfur and iron content, oxygen fugacity, and temperature of the basalt (Haughton et al., 1974). The ooze from Alae, which was saturated with sulfide liquid under near-surface pressures, contained 0.038% S and 13.6% FeO, values quite similar to the 0.03—0.04% S and 12.0—12.9% FeO in the 1977 glasses (see Table 3). The range of oxygen fugacities observed for Kilauea lavas is quite limited (Anderson and Wright, 1972). Therefore, if the S and FeO contents, f_{O_2}, and total pressure are all similar for the Alae ooze and the 1977 lavas, and both are sulfide-saturated, the liquidus temperatures should also be similar. The Alae ooze was collected at 1065—1125°C (Wright and Peck, 1978). The 1977 lavas just began to precipitate ilmenite, which suggests, by comparison with the temperature of first appearance of ilmenite in Alae (Peck et al., 1966) and Makaopuhi lava lakes (Wright and Weiblen, 1967), a liquidus temperature of 1070°C for the 1977 lavas. If intratelluric magma chambers at Kilauea are somewhat more oxidizing than the lava lakes, as suggested by Anderson and Wright (1972), the temperature of the 1977 lavas may have been nearer to 1100°C. Graeber et al. (1979) reported temperatures of 1062°C and 1095°C in Puu Kia'i flows on September 27 and 30, 1977. This level of agreement is quite good, considering the number of variables involved.

The overall resemblance between the Alae ooze and the early 1977 lavas allows us to consider the question of why sulfides are absent in the later 1977 (Puu Kia'i) lavas, which otherwise are virtually identical to the earlier lavas, both petrographically and chemically. Clearly, the FeO content, f_{O_2}, and temperature of the basalts did not change significantly. The remaining possibility is that the sulfur content of the later lavas was lower, so that sulfide was not stable even before the eruption. The Puu Kia'i samples are likely not from a different source from the earlier lavas; more probably, their lower sulfur content is due to more extensive intratelluric degassing. Two possible explanations for this are that the immediate source reservoir of the later lavas was shallower than that from which the earlier lavas were derived, or that the feeder system became more open as the eruption proceeded, so that degassing took place at greater depths than was possible before the surface was breached. In either case, the available data suggest that the absence of sulfide in the later 1977 lavas is a secondary feature; that is, the lavas originally contained immiscible sulfide liquids which reacted out over the course of the eruption. The absence of sulfide inclusions in microphenocrysts in the Puu Kia'i spatter, then, implies that these smaller crystals grew during that same time period, perhaps as another result of progressive loss of volatiles from the magma chamber.

SUMMARY

Seismic evidence demonstrates clearly that, despite the absence of summit inflation before the eruption, magma began moving from Kilauea's summit chamber into the east rift zone on September 12, 1977. We believe that this movement of magma triggered the 1977 eruption by forcing to the surface a previously-existing magma body stored within the east rift zone.

Lavas extruded in that eruption are differentiated quartz-normative tholeiites, very similar in composition to some of the early 1955 lavas and to the lava erupted in 1962 near Kane Nui o Hamo. Plagioclase is the dominant phenocryst and is accompanied by minor olivine, augite, orthopyroxene, and opaque oxides. Sulfide globules occur in glass and phenocrysts in the early 1977 lavas; their absence in basalt from Puu Kia'i suggests that intratelluric degassing became more extensive as the eruption proceeded. The last basalt ejected is only slightly less differentiated than the earliest lavas, indicating that primitive summit magma did not reach the surface, either unmixed or as a component in hybrid lavas like the late 1955 lavas described by Wright and Fiske (1971). The recurrence, over a 22-year period, of virtually identical lava compositions suggests that there is a large reservoir of this differentiated liquid within the east rift zone of Kilauea.

The 1977 flows and pyroclastic material cover an area of approximately 8 km^2 and have a volume of 35×10^6 m^3. Since the end of the eruption on October 1, 1977 and the gradual cessation of shallow harmonic tremor near Puu Kia'i a few days later, no consistent pattern of surface deformation of Kilauea volcano has been observed. In November 1978, a slight summit deflation of 9 μrad over 14 days may have caused a local inflation, documented by dry-tilt measurements, in the vicinity of the 1977 vents. Continuing seismicity on the south flank of Kilauea and in the central east rift zone between Napau and Kalalua (Fig. 1) suggests that magma occasionally moves into the latter area.

ACKNOWLEDGEMENTS

Wet chemical analyses were performed by E. Engleman at the U.S. Geological Survey laboratory in Denver, Colo., under the direction of D. Norton. Maurice Sako drafted the figures and J.D. Griggs assisted with photography. D.W. Peterson and D.B. Jackson contributed helpful reviews of the manuscript.

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