The October 1963 Eruption of Kilauea Volcano Hawaii

GEOLOGICAL SURVEY PROFESSIONAL PAPER 614-C

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By James G. Moore and Robert Y. Koyanagi

ABSTRACT

The eruption of October 5–6, 1963, occurred along an 8-mile section of the central part of the east rift zone of Kilauea Volcano. About 9 million cubic yards of lava was erupted from more than 30 fissures which show a slight right-offset en echelon pattern; the new lava covered an area of 1.3 square miles.

A few hours before the actual outbreak, the summit of Kilauea began to subside, and strong harmonic tremor and earthquakes commenced at both the summit and the site of the later activity near Napau Crater. These phenomena were apparently caused by subsurface flow of magma from the summit reservoir through the rift zone conduits to the eruptive vents 8 miles distant.

The lava of the eruption is a tholeiitic basalt with an average of 5.6 percent olivine. In general, lavas that erupted toward the eastern end of the eruptive zone are richer in olivine. These lavas, like others that erupted in historic times on the rift zone, show a slight differentiation when compared with lavas that erupted from the summit. The differentiation, apparently caused by cooling and crystallization within the rift zone, can be measured by the ratio ($CaO/FeO+0.9\ Fe_2O_3$), which is greater than 1 for summit lavas and which decreases systematically for lavas that erupted progressively eastward along the rift zone.

INTRODUCTION

Kilauea Volcano erupted on its upper east rift zone (fig. 1) on October 5–6, 1963, just 43 days after the last eruption, which occurred at Alae Crater 3 miles west of the region affected in this eruption. The eruption occurred along an 8-mile section of the central part of the rift zone extending from near Napau Crater eastward to Kalalua Crater. This activity is the fourth consecutive small eruption along the east rift zone during the past 2 years, and it marks a curious departure from the usual pattern of one or more summit eruptions followed by a flank eruption.

During the eruption, lava flowed from more than 30 fissures that are arranged in a right-offset en echelon pattern. Some flows are more than half a mile wide, and the total area covered by new lava is 1.3 square miles. The volume of the erupted lava is about 9 million cubic yards (disregarding lava which flowed back down cracks). Although this volume exceeds that of the previous three flank eruptions (September 1961, December 1962, and August 1963), it is small compared with earlier flank eruptions.

The eruption occurred in a remote area distant from roads and overgrown with dense tropical vegetation. Most of the observations during the eruptive activity were made from the air, and subsequent fieldwork was limited owing to the inaccessible terrain. Sampling of the flow was accomplished with the aid of a light helicopter.

This report includes a summary of observations and data collected by the staff of the Hawaiian Volcano Observatory, whose contributions and help are gratefully acknowledged. The Hawaii Army National Guard provided air reconnaissance support, and personnel of Hawaii Volcanoes National Park contributed data and observations.

DISTRIBUTION OF VOLCANIC ACTIVITY ON THE EAST RIFT ZONE

Most of the mapping shown on plate 1 has been done with the aid of aerial photographs, because roads do not extend east of Makaopuhi Crater, trails are widely separated, and the region is overgrown by a tropical forest that thrives on an annual rainfall of 100–200 inches. Fortunately a series of photographs were taken in 1954, and additional photographic coverage of varying quality was made after each successive flank eruption.

The older lava flows of the rift zone have been divided into three map units which are based on the character of the covering vegetation. The oldest unit, early prehistoric basalt, includes flows whose forest cover is the most mature. Ohia trees average about 30 feet in height, and beneath the trees a canopy of tree ferns from 10 to 15 feet high obscure the ground from the air. There is little surficial material except for ash and spatter near vents, and the lava surface is generally fresh although locally it is covered with a few inches of dead vegetation and a tangle of fallen trees. The early

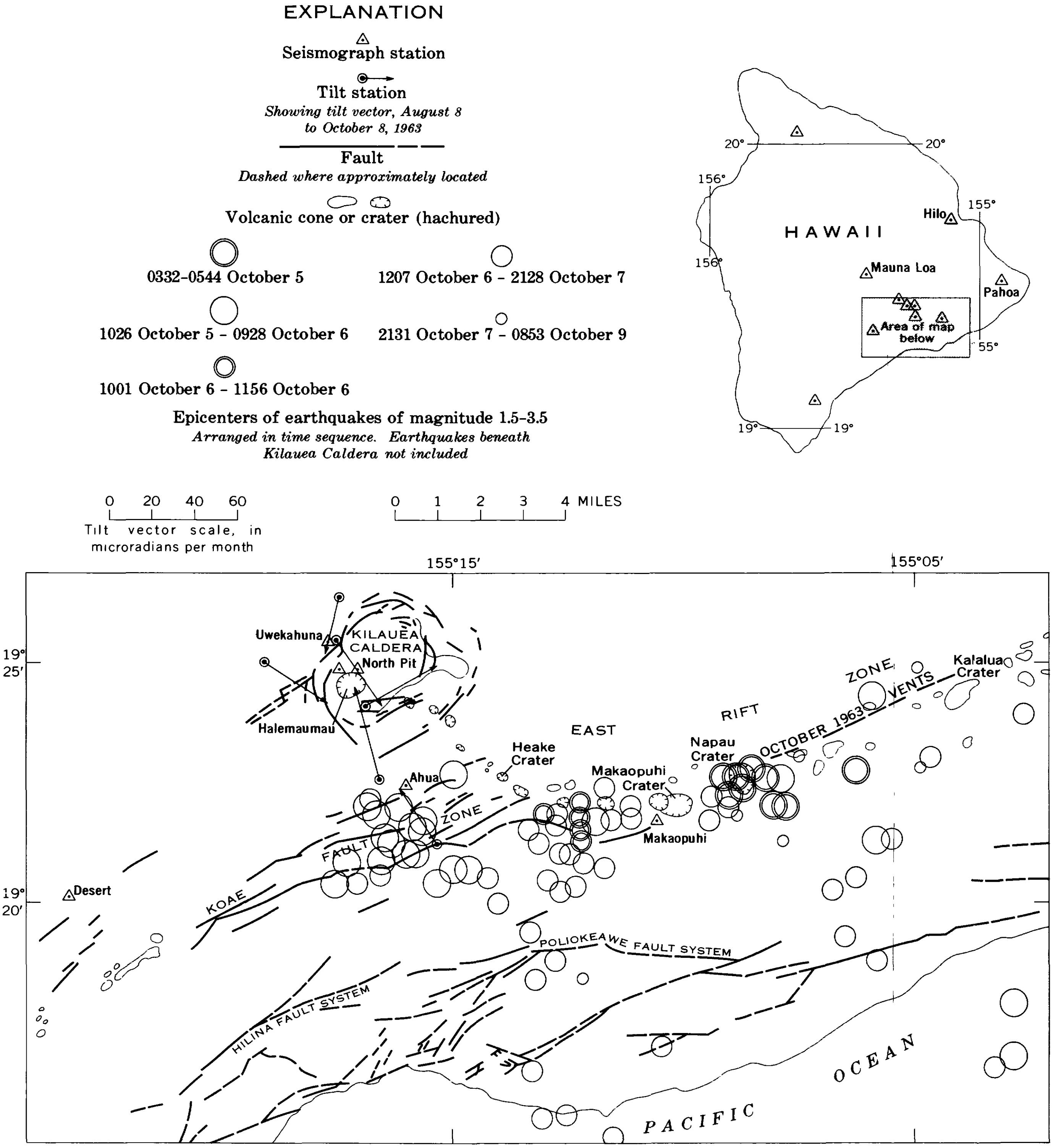

FIGURE 1.—Summit region of Kilauea Volcano. Geology modified from Stearns and Macdonald (1946).

prehistoric basalt is considered to be younger than approximately 10,000 years because in no place is it covered by the Pahala Ash, a widespread ash unit which has a radiocarbon date of 10,000–17,000 years old (Rubin and Berthold, 1961). Moreover, the Pahala Ash has not been identified in any of the pit craters and so is presumed to underlie the several hundred feet of lava flows exposed in the pit crater walls.

The next younger unit, late prehistoric basalt, is in most places densely covered by small to medium ohia trees 10–20 feet high. Judging from this vegetation, the late prehistoric basalt is assumed to be older than about 300 years and younger than a few thousand years. The pit craters within the mapped area probably formed during this period because several of them (Napau Crater, the small crater southeast of Napau Crater, and Makaopuhi Crater) cut this unit, and lava of this unit fills the older east pit of Makaopuhi Crater.

The next younger unit, very late prehistoric and early historic basalt, is overgrown by small trees that are up to 10 feet high and by low staghorn ferns a few feet high. This unit includes lava flows known to have been erupted in 1840 and others that have similar vegetative cover.

Throughout historic time, the east rift zone has been the more active of Kilauea Volcano's two rift zones. Fifteen eruptions have been reported on the east rift zone between about 1750 and 1965, and only three on the southwest rift zone (Stearns and Macdonald, 1946). Information on early eruptions is scanty, but probably more unreported eruptions broke out along the east rift than along the southwest rift because it is more inaccessible, covered with heavier vegetation, and more likely to have a heavy cloud cover.

For convenience, the location of the historic eruptive vents is projected onto a straight line 32 miles long drawn from the center of the principal vent of Kilauea Caldera (Halemaumau) to the east cape of the island (fig. 2). Distances are measured along this line from Halemaumau. The October 1963 eruptive fissures are on the 8- to 14-mile segment of this line. The geologic map (pl. 1) includes the 6- to 19-mile segment of the rift zone.

The earliest historic activity along the east rift zone, the eruptions of 1750(?) and 1790(?), is recorded mainly in Hawaiian folklore, and details of these eruptions are only assumed. The 1750(?) lava was erupted from a vent at the 19-mile point of the rift zone just beyond the east end of plate 1. The 1790(?) vents were located along the 21- to 23-mile segment.

Records of the next recorded eruption, in 1840, are incomplete. Lava was erupted along the 5- to 9-mile segment; eruptive vents occurred within Alae Crater, north and east of Makaopuhi Crater, and in and north of Napau Crater. The greatest volume of lava, however, was extruded from vents farther east along the 20- to 24-mile segment; much of this lava poured into the sea. According to old records (Dana, 1849, p. 189) natives reported additional activity in the interior between the 5- to 9-mile and 20- to 24-mile active segments of the rift zone. Aerial photographs of the region show several lava flows of similar age (based on vegetation) in the intermediate zone, and these flows have been tentatively

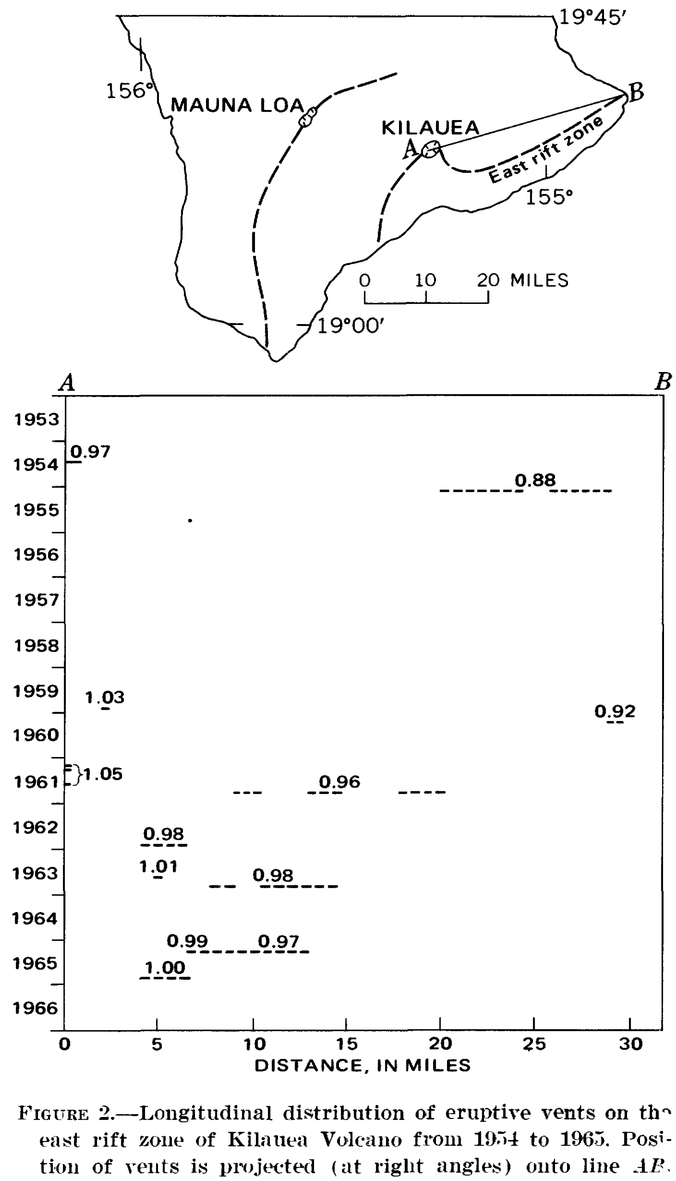

FIGURE 2.—Longitudinal distribution of eruptive vents on the east rift zone of Kilauea Volcano from 1954 to 1965. Position of vents is projected (at right angles) onto line *AB*, which connects a point in the center of Halemaumau in Kilauea Caldera with a point on the east cape of the island. Distance is measured from the center of Halemaumau. Numbers are the $CaO/(FeO+0.9Fe_2O_3)$ ratio at 50.4 percent SiO_2 of rift zone and summit lavas as shown in table 3. Index map shows southern half of island of Hawaii.

assigned to the 1840 eruption on the geologic map. They occur in the 9- to 12-mile segment of the rift zone.

In 1884 an apparent submarine eruption occurred just east of the east cape of the island in shallow water (Stearns and Macdonald, 1946, p. 111); a column of water, steam, and smoke shot several hundred feet in the air.

Small eruptions occurred on the upper part of the rift zone in May 1922 and August 1923 (pl. 1). The 1922 eruption (Stearns and Macdonald, 1946, p. 115) produced a small pond of lava in the west crater of Makaopuhi (6½ miles on the rift zone); the pond was fed from a fissure which was later active in the March 1965 eruption. A second 1922 vent, at the 9-mile position, built a small spatter cone on the east rim of Napau Crater; this cone is still visible even though lavas of the October 1963 and March 1965 eruptions have swept around its base. A small eruption in 1923 (Stearns and Macdonald, 1946, p. 116; Finch, 1923; Stearns and Clark, 1930, pl. 1) poured out a small amount of lava on the west side of Makaopuhi Crater at the 6-mile position of the rift zone. The cited references do not agree on the exact position of the lava that erupted in 1923. The two flows shown on plate 1 as belonging to the 1923 eruption appear on aerial photographs as young flows overgrown with the same amount of vegetation. The northeasterly flow corresponds to the mapping of Stearns and Clark (1930) and the description of Finch (1923); the southwesterly flow corresponds to the mapping of Stearns and Macdonald (1946, pl. 1).

These small flank eruptions were followed in 1924 by violent phreatic explosions in Halemaumau and by cracking, faulting, and formation of a graben on the east cape of the island along the 30- to 32-mile segment of the rift zone. This sequence of events indicates a rapid draining of the summit reservoir of the volcano and is possibly related to migration of magma out along the east rift zone where lava may have emerged farther east as an unobserved submarine eruption.

A new pattern of increased frequency of east rift zone eruptions began in 1955. From 1955 through 1965, eight rift eruptions occurred, whereas from 1750 to 1955 only five east rift eruptions (and two questionable submarine eruptions) were reported. Part of this difference is no doubt due to incomplete records of early activity, but it is unlikely that any but the smallest eruptions were unreported since 1840. The inhabitants of the volcano region, both native and immigrant, have always had a keen awareness of volcanic activity.

The position of east rift eruptive vents of the last decade is summarized in figure 2. Almost every part of the 32-mile-long rift zone has been active, though since 1961 activity has been restricted to the 4- to 20-mile segment. Eruptive activity seems to be generally moving up the rift zone despite several notable exceptions. Clearly, predictions of the site of the next eruption are little better than guesses.

Prior to the 1961 eruption, every flank eruption of Kilauea Volcano (and Mauna Loa Volcano as well) was followed by at least one summit eruption. During much of the historic period up to 1924, continuous lava-lake activity occurred in and near Halemaumau. Since 1961, however, the increased east rift zone activity has been accompanied by total absence of any summit activity.[1]

The individual eruptive vents on the east rift zone (pl. 1) are the upper ends of magma-filled fissures or feeder dikes that extend from the summit reservoir beneath Kilauea Caldera. Most of the vents are discontinuous on the surface, rarely exceeding half a mile in length, though at some shallow depth they must be continuous. Within the mapped area, most of the dikes of the last decade occur in a narrow zone less than a quarter of a mile wide except near the west margin of the map where the right-offset en echelon arrangement of the vents produces the north curve of the rift zone (Moore and Krivoy, 1964, p. 2042). The activity of the last decade has occurred about midway across the 2-mile width of the rift zone.

The individual vents of each eruption, as well as the rift zone as a whole, show a characteristic en echelon arrangement. In the map area most of the 1840, 1922, 1961, 1962, October 1963, and March 1965 eruptive fissures are slightly offset to the right. This effect is visible on a finer scale when an eruption is viewed from the air, for each mapped fissure is actually made of shorter elements, each slightly offset to the right. On a larger scale, the entire rift zone where it curves northward toward Kilauea Caldera (on the west end of pl. 1) shows a profound right offset en echelon pattern. The 1962 vents, for example, are offset nearly half a mile near Alae Crater west of Makaopuhi Crater (Moore and Krivoy, 1964).

Generally wherever the offset of eruptive fissures is greatest (from 0.1 to 0.5 mile), pit craters occur between the offset segments. This relation holds on the upper east rift zone and also on the extreme lower east rift zone where the zone curves slightly north and is offset to the left at the group of pit craters 6 miles southwest of the east cape of the island (see Macdonald and Eaton, 1964, pl. 1).

[1] Activity within Halemaumau resumed in November 1967 and was still continuing in June 1968.

EVENTS OF 1963 PRECEDING THE ERUPTION

Following the December 1962 eruption, Kilauea Volcano was especially active. Three periods of collapse and associated ground cracking and one small eruption preceded the eruption in October (fig. 3). Each of these four events was preceded by an uplift of the caldera region, presumably caused by magma from depth entering and inflating the reservoir beneath the summit. This uplift is indicated by northwest ground tilting at Uwekahuna, located on the northwest side of the region of uplift. Each of the collapses and eruptions was accompanied by a dramatic subsidence of the summit caused by underground movement of magma from the reservoir eastward into the rift zone. No lava reached the surface during any of the three collapses (May 9, July 1, and August 3, 1963), but extensive ground cracking of the Koae fault zone south of the Caldera occurred during the first two (Koyanagi and others, 1964).

The daily number of shallow earthquakes originating beneath Kilauea Caldera that are recorded on the North Pit seismometer is tabulated as a general index of local seismicity (fig. 3). The pattern of these earthquakes during 1963 bears a crude relation to the amount of magma in the summit reservoir as recorded by daily ground tilting at Uwekahuna. Generally when the summit reservoir is most empty, as after an eruption, the daily count of earthquakes is less than about 40 per day. As the reservoir fills and apparently stresses its roof, walls, and floor, the count of earthquakes increases to more than 100 per day. This relation, however, is complicated by swarms of earthquakes which seem to be related to the rate of filling rather than to the amount of filling. Such a swarm occurred in late December 1962 and early January 1963. Another factor not represented in figure 3 is the movement of the center of inflation, which will affect the north-south and east-west components of tilt at any one station differently. Any localized uplift directly south of the Uwekahuna station, for example, may produce earthquakes, but the uplift will not be recorded by the east-west component of ground tilt at that station.

DESCRIPTION OF THE ERUPTION

The eruption was immediately preceded by a marked subsidence of the summit of Kilauea which began at 0306 October 5 (fig. 4). This subsidence and the resultant tilting of the ground was indicated by deflection of the long-period seismographs at Uwekahuna. At 0316, seismographs at the summit (North Pit) and upper east rift zone (Makaopuhi) began recording strong harmonic tremor and local shallow earthquakes. The subsidence and the harmonic tremor presumably resulted from magma moving from the summit reservoir

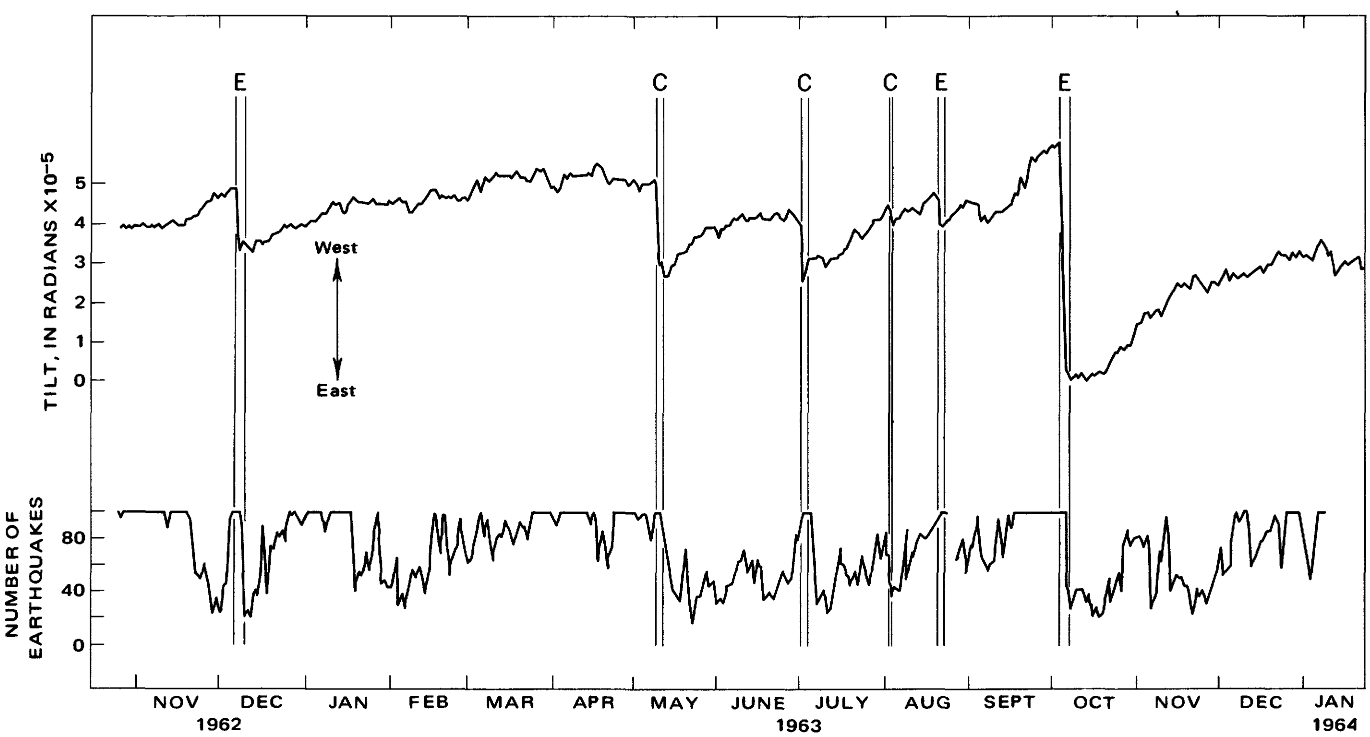

FIGURE 3.—Relations of Kilauean eruptions (E) and collapses (C), ground tilting at Uwekahuna, and daily number of shallow caldera earthquakes recorded at the North Pit seismometer during the period November 1962 to January 1964.

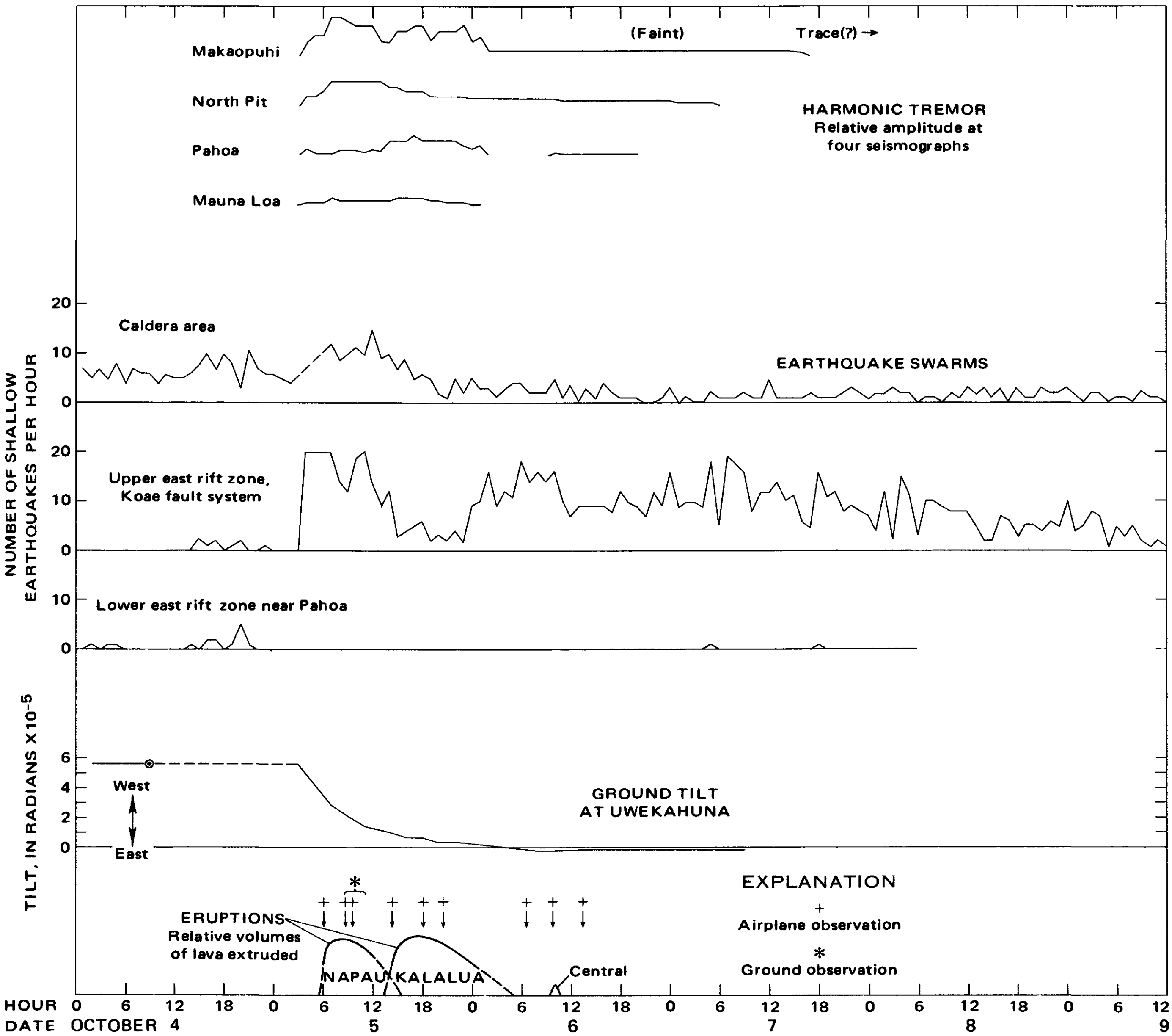

FIGURE 4.—Chronology of events during the October 1963 Kilauea east rift eruption.

of the volcano into the east rift zone dike system. At 0525 an apparent air shock awakened most residents of the summit area, and following it the harmonic tremor increased markedly. The eruption in Napau Crater probably began at this time.

At 0608 Observatory staff members arrived at Makaopuhi Crater and observed a billowing fume cloud and heard a faint roaring noise to the northeast, although vision was impaired by heavy low clouds and light rain. At 0605 a pilot in a cropduster aircraft flew over Napau Crater and, despite low overcast, observed lava fountaining from a fissure extending across the floor of the crater. The fountain was still active on his return flight at 0845. At 0735 the roaring noise at Makaopuhi had diminished to faint booming sounds, and the fume cloud was not visible because of heavy rain clouds.

At approximately 0730 a party of pig hunters on the Kalapana trail about 2 miles south of Napau Crater began to smell strong sulfur fumes and heard a roaring noise to the north. Shortly afterward, scorched leaves and wood ash, carried by the wind from the north began falling near them. They abandoned the hunt and headed up the trail, arriving at Makaopuhi at 0840.

At 0850 an Observatory party arrived at the southwest rim of Napau Crater and observed a line of lava fountains across the floor of the pit crater that were erupting up to 50 feet high; the fountains were about in the same position as the 1840 vents. About 70 percent of the crater floor was covered by new lava which appeared to be at least 20 feet thick. The trail to the lava trees on the northwest side of Napau Crater was cut by an eruptive fissure 650 feet north of the junction with the Napau Crater overlook trail. When this fissure was first seen at 0905, it had already erupted spatter and a small pad of lava and was emitting copious amounts of choking sulfurous gas.

At 0930 the eruptive area was again seen from the air. In addition to the vents in and near Napau Crater, a line of vents 3–4 miles east-northeast of Napau Crater was fountaining lava 50 feet high.

The vents in Napau Crater were partly roofed over with congealed spatter at 1055, but violent agitation of liquid lava could be seen beneath the spatter from the northwest rim of the pit crater. On the far side of the crater (northeast), new sheets of fluid lava could be seen spreading over the lake surface, but their source could not be determined because of very heavy fume.

Beginning slightly before 1400, new outbreaks occurred 3–6 miles east of Napau Crater. The exact pattern of eruptive activity in this area is incompletely known because of the inaccessibility of the region, the cloudy weather, and the featureless aspect of the landscape when viewed from the air. At 1400, abundant brown fume was visible from Glenwood on the Hilo road in the vicinity of Kalalua Crater; lighter colored fume billowed from two other vent areas up the rift, both were probably within 3 miles of Kalalua Crater.

At 1410, a flight over the vents just northwest of Kalalua Crater revealed lava fountains one-fourth mile long and 150 feet high. When the same fountains were observed again at 1800, they still occasionally attained heights of 150 feet but diminished intermittently to heights of 50–75 feet. Two lava flows fed by the fountains had begun to move side by side down the rift zone in an east-northeast direction. Much of the lava in the northern stream flowed north into a large crack. The complete absence of this crack in photographs taken in October 1961 suggests that it was formed during the early phases of this eruption.

By 2030 October 5, the two flows, dominantly of pahoehoe type, were about 1¼ mile east-northeast of the source vents and were moving at less than a quarter of a mile per hour. The advancing flow fronts and transverse cracks perpendicular to the length of the flow were brightly incandescent in the darkness. Hundreds of twinkling flares, dotting much of the surface of the flows, were caused by trees bursting into flame when surrounded by the thin lava flows.

During most of the night a bright red glow was visible from Pahoa, Kalapana, and Hilo despite intermittent rain and cloudy weather. By 0320 October 6 the intensity of the glow had decreased, and the glow was last reported at 0400. A flight over the eruption area at 0630 revealed that all of the eruptive vents were quiet. Some of the fissures were glowing red and shooting red-orange flames 10–15 feet into the air, but eruption of lava had ceased. However, cessation of lava extrusion had apparently occurred only shortly before 0630 because the fronts of the two lava flows were still moving slowly through the forest about 1½ miles from their source. All of the vents from Kalalua to Napau Crater were vigorously steaming and degassing, and the vapors were being carried southwest by the prevailing trade winds (fig. 5). The eruptive vents, which were clearly delineated by escaping gases, are offset in a right-hand en echelon fashion.

A flight over the eruptive area revealed a final short-lived outbreak which occurred about 0940 October 6. When observed at 0950 the new lava fountain, which had previously been spouting up to 25 feet high, was only spattering feebly, and it presumably stopped soon after. This fissure was about 3 miles east-northeast of Napau Crater, midway along the line of eruptive vents (fig. 4).

LAVA FLOWS

During the eruption about 15 new lava flows and areas of spatter were formed; about 9 million cubic yards of new lava covered about 3.9 million square yards (1.3 square miles) of tropical forest on the east rift zone (table 1). Many of the areas of new lava are very small and represent material erupted by short-lived fountains which broke through cracks in the rift zone and erupted spatter, probably for only a few minutes. The three largest flows are in Napau Crater, 2 miles west of Kalalua Crater, and north of Kalalua Crater.

TABLE 1.—*Area and volume of lava erupted in October 1963*

No.	Lava flow	Area (sq yd × 10^3)	Thickness (yd)	Volume (cu yd × 10^3)
1	Flows and spatter west of Napau Crater	9	1	9
2	Napau Crater fill	553	5	2,765
3	Flows and spatter between Napau Crater and No. 4	44	1	44
4	Flow 1 mile east of Napau Crater	177	1	177
5	Flow 2 miles east of Napau Crater	57	1	57
6	Flow 2½ miles west of Kalalua Crater	570	2	1,140
7	Flows and spatter between Nos. 6 and 8	76	1	76
8	Large flow north of Kalalua Crater	2,402	2	4,804
	Total	3,888		9,072

The flow in Napau Crater covers about 75 percent of the wooded floor of the pit crater (fig. 6). This flow was fed by a line of vents trending N. 60° E. across the northern part of the crater. The vents are offset in a right-hand en echelon pattern and lie about 100 feet north of a similar line of vents formed in the 1840 eruption. The crater fill was also partly fed by vents extending northeast from the northeast rim of the crater. These vents, 200–300 feet south of the 1922 vents, supplied lava that poured down 30–40 feet over the crater rim in three cascades, joining the new lava ponding on the crater floor.

New lava tree molds are abundant on the edge and are scattered on the floor of Napau Crater. They were formed when fluid lava flowed through the forest and became chilled against the larger trees, after which the lava surface was lowered as the lava flowed away or contracted (Moore and Richter, 1962). The highest tree molds, as well as the high-level lava crust on the edge of the ponded lava, record the highest level that the pond attained during the eruption. This level is as much as 9 feet above the surface of the ponded lava; the lowering of the pond surface is the result of shrinkage caused by cooling and loss of gas as well as lateral flow of lava away from the vents. The remaining lava fill in Napau Crater is estimated to average about 15 feet thick and to total about 2,765,000 cubic yards in volume.

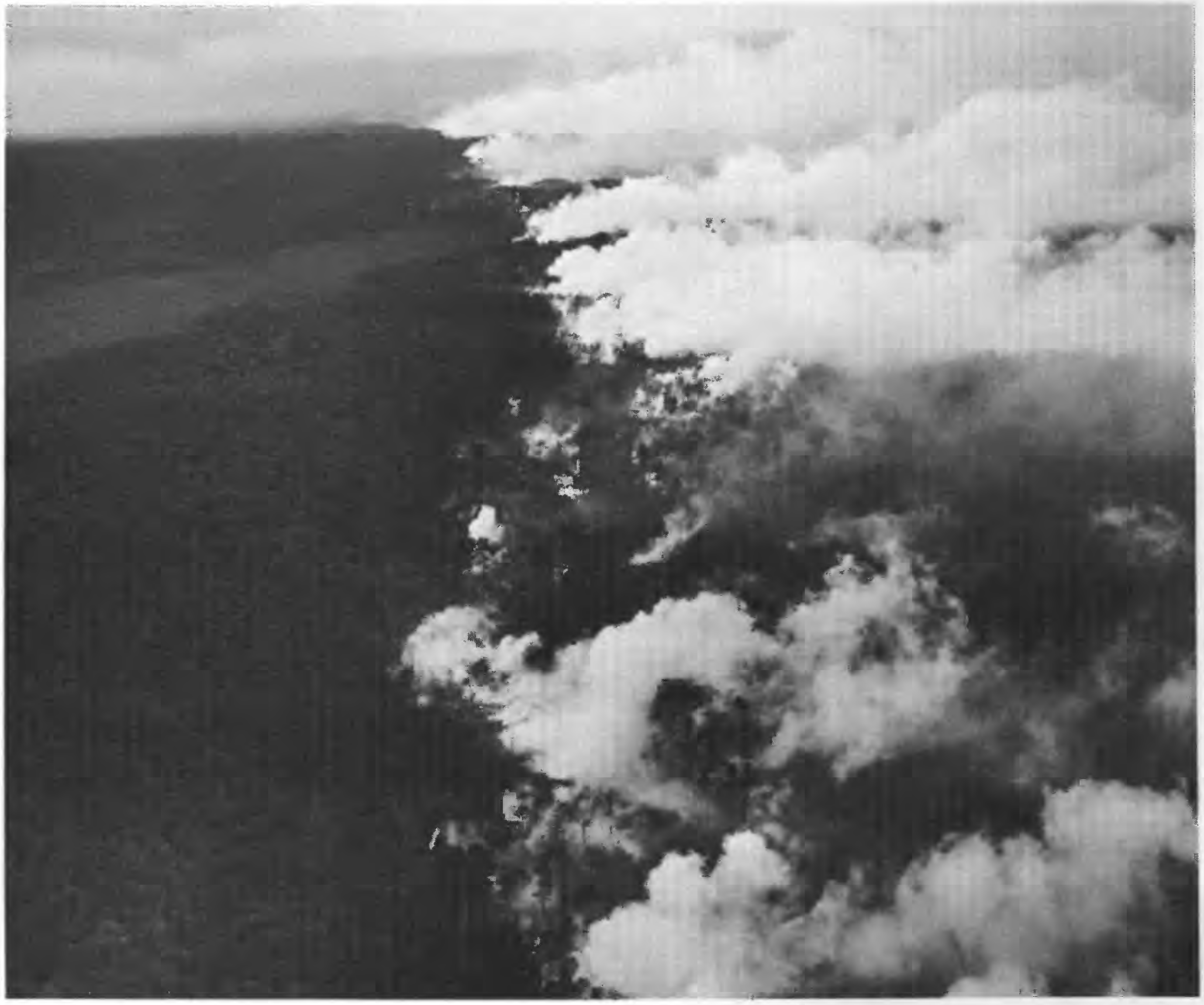

FIGURE 5.—Vigorous degassing of eruptive fissures extending 4 miles east of Napau Crater. Photograph taken 0930, October 6, 1963. View northeast.

FIGURE 6.—View eastward across the floor of Napau Crater showing lava of October 5, 1963, and degassing vent on far side. This lava, which is marred by abundant tree molds, was later completely covered by lava of the March 1965 eruption. Photograph taken October 9, 1963.

A flow nearly a mile long, which is notable because of the large number of tree molds which cover its surface, occurs midway on the part of the rift zone active in October 1963. Apparently this lava was extremely fluid and swept through the forest in a thin sheet (about 6 ft thick) that quickly chilled around the trees and did not remain hot long enough to destroy the tree molds. This flow has been subsequently covered by March 1965 lava (pl. 1).

The largest flow is 2½ miles long and more than one-half mile wide and originated from vents north and northwest of Kalalua Crater. It averages about 6 feet thick and has a volume of nearly 5 million cubic yards. The feeding fountains, active during the night of October 5, built small spatter ramparts beside the vents up to 8 feet high.

EARTHQUAKES, TREMOR, AND TILTING

Beginning shortly after 0300 on October 5, magma began moving underground from the summit reservoir beneath Kilauea Caldera eastward on the rift zone to the eruptive vents near Napau Crater. This movement is demonstrated by (1) rapid tilting and subsidence of the summit beginning at 0306, as recorded by deflection of the Press-Ewing seismographs at Uwekahuna, (2) beginning of continuous harmonic tremor, as recorded at all the summit seismograph stations and at Pahoa at 0316, and (3) beginning of a period of many shallow earthquakes at 0322 originating from the summit and the upper east rift zone (fig. 4).

The short-base tiltmeter at Uwekahuna indicated that half of the subsidence was complete at 0800, just 2 hours after the eruption began and 5 hours after the tremor began. The subsidence continued at a reduced rate throughout the eruption and appeared to terminate and maintain a new low stable level by about 0800 October 6.

The harmonic tremor began rather abruptly at all the summit stations and at Pahoa and continued for many hours after the eruption was over. The relative amplitude of tremor (fig. 4) at the different stations reflects the underground passage of magma from the summit reservoir progressively eastward to the eruptive vents. The tremor ampliture was greatest at North Pit from 0700 to 1300 October, at Makaopuhi from 0700 to 2300 October 5, and at Pahoa from 1400 October 5 to 0100 October 6.

However, the similarity of the pattern of the beginning of tremor at both North Pit and Makaopuhi suggests that the magma did not move with a distinct front from the summit reservoir (near North Pit) along along the rift zone past Makaopuhi. More likely, the rift zone was still charged with magma remaining from the Aloi eruption (December 1962), the noneruptive collapses of May, July, and August 1963, and the eruption of August 1963. Hence, shortly after 0300 October 5, magma in a large part of the rift zone between Makaopuhi and the summit probably began moving en masse down the rift zone.

A detailed study of the harmonic tremor during October 5 was made by means of a dense array of seismometers in the summit region of Kilauea Volcano (Shimozuru and others, 1966). This work shows that early in the eruption, tremor was most intense near Uwekahuna and Halemaumau. Later, in the evening of October 5, the region of greatest intensity of tremor became elongated and formed a rather straight zone extending from the northeast side of Halemaumau to the upper east rift zone near Heake Crater (fig. 1). The data suggest that magma transmission from the summit reservoir to the east rift zone follows this zone of intense tremor. The change in position of the region of greatest tremor intensity would reflect fluctuations in volume or velocity of magma passing a given part of the rift zone.

Earthquake activity was at a high level before and during the eruption, and shallow earthquakes occurred over an extensive part of the upper east rift zone and summit of Kilauea Volcano (fig. 1). Prior to the eruption, an abnormally high number of shallow earthquakes was recorded beneath Kilauea Volcano. By September 16, 1963, these earthquakes reached a frequency of more than 100 per day, and they exceeded that level up to the time of the eruption (fig. 3). During the first part of the eruption the shallow caldera earthquakes increased to a somewhat higher level, and during the first 10 hours approximately 125 earthquakes of about magnitude ½ to 1½ occurred in the caldera area (fig. 4). After 2000 October 5, these earthquakes dropped off and remained at an abnormally low level for several weeks.

A few hours before the eruption, a small flurry of earthquakes occurred on the lower east rift zone near the Pahoa seismograph.

The continuous slow movement of magma from depth into the summit reservoir apparently deformed the roof and wallrocks, and thereby caused the increase of small earthquakes before the eruption. As pressure and stresses increased, magma in the east rift zone that remained from the December 1962 and August 1963 eruptions broke through an obstruction near Napau Crater, began flowing east through the rift zone, and was erupted in the zone of fissures extending 4 miles east of Napau Crater. This initial breakthrough near Napau Crater generated the early swarm of earthquakes in that region (fig. 1).

Subsequent subsurface flow of magma from the summit reservoir caused the roof rocks to subside to such an extent that some of the subsidence was accommodated by movement in the Koae fault zone. This movement caused the swarm of earthquakes both in the central part of the Koae fault zone and, a few hours later, near the intersection of the fault zone and the east rift zone (fig. 1). Subsequent earthquakes migrated east and south on the rift zone as new stresses were applied by the shift of magma through subsurface conduits from the summit to the flank of the volcano.

During the period October 4–14, the short-base tiltmeter at Uwekahuna recorded an inward tilt of 84 microradians, which represents the approximate withdrawal (and consequent subsidence) of 33 million cubic yards of magma from the summit reservoir. This withdrawal compares with a withdrawal of approximately 3 million cubic yards during the August 1963 eruption and of 36 million cubic yards during the March 1965 eruption.

Hence this eruption, like many past eruptions such as that of September 1961 (Richter and others, 1964, p. D32) and December 1962 (Moore and Krivoy, 1964, p. 2039), produced a much larger collapse of the summit than can be accounted for by the volume of erupted lavas. The remaining 24 million cubic yards (33 million cubic yards of collapse minus 9 million cubic yards of extruded lava) must now be stored in the rift zone undergoing cooling and differentiation.

Unfortunately, the long-base tiltmeters which surround the summit region (fig. 1) were read on August 8 and October 8 and not shortly after the small flank eruption of August 21–23 (Peck and others, 1964). Hence the tilt vectors plotted in figure 1 record the cumulative ground tilt during the August 21–23 eruption and accompanying collapse, the resumption of uplift, and the October 5–6 eruption and collapse. The second collapse, however, was by far the most important event, and the tilt vectors on the map portray chiefly this collapse.

PETROLOGY OF THE LAVAS

The lavas of the October 1963 eruption are tholeiitic basalt and tholeiitic olivine basalt that are similar to lava in the last previous eruption of August 1963 and to lava of the following eruption of March 1965 (table 2). All of the lavas contain some olivine; the average modal olivine content in 11 samples (table 3) is 5.6 percent. The percent olivine is highly variable, even within a single hand specimen, but the lavas that erupted farther east on the rift zone have a tendency for being richer in olivine than the lavas that erupted farther west. The western four samples collected within the upper 2.4 miles of the rift active in October 1963 average 0.9 percent olivine. The eastern four samples from the lower 1.7 miles of the active rift average 5.8 percent olivine. One sample in the intermediate section, however, contains 29.5 percent olivine; this percentage must represent a concentration of olivine crystals on a hand-specimen scale because the chemical analysis of another sample of the rock does not reflect such a high olivine content (table 2).

Olivine occurs as phenocrysts several millimeters in size and as small crystals ranging up to 0.05 millimeter in size. The small olivine crystals are generally skeletal in outline, and many contain glass-filled cavities.

TABLE 2.—*Lime and iron content of recent lavas erupted on the summit and east rift zone of Kilauea*

Eruption	Average at 50.4 percent SiO_2		$\frac{CaO}{FeO+0.9Fe_2O_3}$	Reference
	$FeO+0.9Fe_2O_3$	CaO		
1954	11.6	11.2	[1] 0.97	Macdonald and Eaton (1964).
1955	11.8	10.4	.88	Do.
1959	11.25	11.55	[1] 1.03	Murata and Richter (1966).
1960	11.6	10.7	.92	Do.
1961 summit	10.85	11.35	1.05	Richter, Ault, Eaton, and Moore (1964).
1961 flank	11.2	10.8	.96	Do.
1962	11.05	10.86	[1] .98	Moore and Krivoy (1964).
1963, August:				
Lava	10.94	11.11	1.01	Peck, Wright, and Moore (1966).
Ooze	13.7	9.5	.69	Do.
1963, October	11.07	10.87	.98	This paper.
1965, March:				
Makaopuhi Crater	11.12	11.0	.99	Wright, Kinoshita, and and Peck (1968).
East on rift	11.22	10.85	.97	Do.
1965, December	11.08	11.06	1.00	Fiske and Koyanagi (1968).

[1] Based on only one analysis.

The groundmass of the lavas ranges from transparent brown glass in the drastically chilled pumice and flow surfaces, through opaque black glass in the chilled lava, to an intersertal mesh of clinopyroxene and plagioclase in the more slowly cooled interior of lava flows.

Chemically all of the lavas are tholeiitic basalts with normative quartz (table 2). The seven analyses are remarkedly uniform; they average 50.51 percent SiO_2 and do not deviate by more than 0.27 percent from this value.

It has been shown previously (Richter and others, 1964, p. D29–D31) that lavas erupted from the east rift zone of Kilauea Volcano show a systematic chemical change compared with those from the summit of the volcano. The change is most notable in the decrease in CaO and increase in total iron in flank lavas as compared with summit lavas of the same general SiO_2 content. This change in composition can be best explained by the removal of plagioclase and pyroxene during cooling of the summit magma while it moved along the rift zone from the summit reservoir, and while it was tem-

TABLE 3.—*Chemical analyses, norms, and modal analyses of basalts from October 1963, eruption of Kilauea Volcano and adjacent areas*

[Analyst: G. O. Riddel]

	1	2	3	4	5	6	7	8	9	10	11	12	13
Chemical analyses													
SiO_2	50.63	50.56	50.52		50.24	50.49			50.43			50.73	48.05
Al_2O_3	13.78	13.64	13.74		13.78	14.20			13.63			13.72	10.33
Fe_2O_3	1.06	1.73	1.31		1.27	1.53			1.19			1.25	1.34
FeO	9.97	9.52	9.90		9.89	9.31			10.01			10.49	10.19
MgO	7.42	7.64	7.41		7.25	7.39			7.68			6.43	17.39
CaO	10.97	10.99	10.95		10.84	10.91			10.82			10.18	8.14
Na_2O	2.40	2.32	2.40		2.45	2.47			2.48			2.60	1.66
K_2O	.57	.56	.56		.57	.58			.58			.69	.36
H_2O+	.04	.05	.05		.32	.09			.08			.12	.17
H_2O-	.02	.01	.02		.02	.02			.02			.01	.02
TiO_2	2.70	2.65	2.71		2.72	2.76			2.80			3.30	2.04
P_2O_5	.28	.25	.29		.26	.29			.28			.35	.19
MnO	.17	.17	.17		.17	.17			.17			.17	.17
CO_2	.03	.03	.02		.04	.03			.00			.00	.01
Cl	.02	.02	.02		.02	.02			.02			.02	.01
F	.05	.04	.05		.04	.04			.04			.05	.04
Subtotal	100.11	100.18	100.12		99.88	100.30			100.23			100.11	100.11
Less O	.02	.02	.02		.02	.02			.02			.02	.02
Total	100.09	100.16	100.10		99.86	100.28			100.21			100.09	100.09
Norms													
Q	0.80	1.41	0.94		0.69	0.92			0.07			2.04	0.00
or	3.37	3.31	3.31		3.37	3.43			3.43			4.08	2.13
ab	20.15	19.47	20.15		20.57	20.74			20.83			21.84	13.97
an	25.23	25.23	25.15		25.00	26.03			24.43			23.81	19.71
di	22.01	22.21	21.98		21.77	21.03			22.24			19.84	15.33
hy	20.98	20.18	20.63		20.32	19.73			21.33			19.34	21.70
ol	.00	.00	.00		.00	.00			.00			.00	20.70
mt	1.54	2.51	1.90		1.84	2.22			1.73			1.81	1.94
il	5.13	5.03	5.15		5.17	5.24			5.32			6.27	3.87
ap	.66	.59	.69		.62	.69			.66			.83	.45
hl	.03	.03	.03		.03	.03			.03			.03	.02
fr	.08	.06	.08		.06	.06			.06			.07	.07
cc	.07	.07	.05		.09	.07			.00			.00	.02
Total	100.05	100.10	100.06		99.53	100.19			100.13			99.96	99.91
Modal analyses													
Olivine	0.4	1.5	0.4	1.4	29.5	4.7	0.5	5.0	5.0	9.1	4.2		19.0
Pyroxene	.4						.3				.3		
Plagioclase	.7												
Glass (includes fine-grained groundmass)	98.6	98.5	99.6	98.7	70.5	95.3	99.2	95.0	95.0	90.9	95.5		81.0
Total	100.1	100.0	100.0	100.1	100.0	100.0	100.0	100.0	100.0	100.0	100.0		100.0

1. Tholeiitic basalt erupted Oct. 5, 1963, from vent west of Napau Crater. 1.1 mile from northeast rim Makaopuhi Crater.
2. Tholeiitic basalt erupted Oct. 5, 1963, from fissures within Napau Crater. 100 yards from northwest edge of crater fill and 1.2 mile from northeast rim Makaopuhi Crater.
3. Tholeiitic basalt erupted Oct. 5, 1963, from vent east of Napau Crater. 2.6 miles from northeast rim Makaopuhi Crater.
4. Tholeiitic basalt erupted Oct. 5–6, 1963, from vent on north side prehistoric spatter cone. 3.5 miles from northeast rim Makaopuhi Crater.
5. Tholeiitic olivine basalt erupted Oct. 5–6, 1963, from larger flow 2 miles east of Napau Crater. 3.8 miles from northeast rim Makaopuhi Crater.
6. Tholeiitic basalt erupted Oct. 5–6, 1963, ⅓ mile above upper end largest 1963 lava flow. 5.5 miles from northeast rim Makaopuhi Crater.
7. Tholeiitic basalt erupted Oct. 5–6, 1963, near upper end largest 1963 lava flow. 5.8 miles from northeast rim Makaopuhi Crater.
8. Tholeiitic olivine basalt erupted Oct. 5–6, 1963, at upper end largest 1963 lava flow. 5.9 miles from northeast rim Makaopuhi Crater.
9. Tholeiitic olivine basalt erupted Oct. 5–6, 1963, at vent 300 yards downrift from upper end largest 1963 lava flow. 6.0 miles from northeast rim Makaopuhi Crater.
10. Tholeiitic olivine basalt erupted Oct. 5–6, 1963, near lower end of largest 1963 lava flow. 6.9 miles from northeast rim Makaopuhi Crater.
11. Tholeiitic basalt erupted Oct. 5–6, 1963, near lower end of largest 1963 lava flow. 7.2 miles form northeast rim Makaopuhi Crater.
12. Tholeiitic basalt erupted Oct. 5–6, 1963, near lower vent of largest 1963 lava flow. 7.7 miles from northeast rim Makaopuhi Crater.
13. Tholeiitic olivine basalt erupted 1840?, near north margin of largest 1963 lava flow. 6.0 miles from northeast rim Makaopuhi Crater.

porarily stored in the rift zone before erupting on the flank.

One measure of this chemical change is the $CaO/(FeO+0.9Fe_2O_3)$ ratio of the lavas at a fixed SiO_2 content. This ratio has been determined for 50.4 percent SiO_2 and entered in table 3 and figure 2. The ratio is generally greater than 1 for summit lavas and less than 1 for flank lavas. A measure of the extreme to which this differentiation can proceed is indicated by a value of 0.69 for ooze filter pressed into a drill hole in the August 1963 Alae lava lake.

The most highly differentiated lavas are produced by those factors which allow the most complete cooling and separation of the early crystallizing plagioclase and pyroxene phases in the rift zone. Presumably such cooling is not possible in the summit lavas because of the large volume of the reservoir underlying the caldera and the constant supply of fresh magma from depth. The greatest cooling could occur in the rift zone if (1) travel distance is great, (2) wallrocks are cold, (3) conduits are thin (large surface area), and (4) magma is temporarily stored for long periods of time. The distance from the summit to the erupting vents, as shown in figure 2, is a measure of factor 1; the length of time since the last previous eruption will affect factors 2 and 4. Generally rift zone lavas are most differentiated (lower $CaO/(FeO+0.9Fe_2O_3)$ ratio) if they have moved a long distance down the rift zone or if it has been a long time since the last previous flank eruption (fig. 2).

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