The 1961 Eruption of Kilauea Volcano Hawaii

GEOLOGICAL SURVEY PROFESSIONAL PAPER 474-D

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By D. H. RICHTER, W. U. AULT, J. P. EATON, *and* J. G. MOORE

SHORTER CONTRIBUTIONS TO GENERAL GEOLOGY

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A detailed account of the three summit eruptions and one flank eruption that occurred during 1961 and the accompanying tumescence, seismic activity, and active faulting

UNITED STATES GOVERNMENT PRINTING OFFICE, WASHINGTON : 1964

UNITED STATES DEPARTMENT OF THE INTERIOR

STEWART L. UDALL, *Secretary*

GEOLOGICAL SURVEY

William T. Pecora, *Director*

FIRST PRINTING 1964
SECOND PRINTING 1966

For sale by the Superintendent of Documents, U.S. Government Printing Office
Washington, D.C. 20402 - Price 35 cents (paper cover)

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By D. H. Richter, W. U. Ault, J. P. Eaton, and J. G. Moore

ABSTRACT

The 1961 eruption of Kilauea Volcano, through the period February 24 to September 25, 1961, consisted of three summit eruptive phases followed by a flank eruptive phase. Tumescence of the Kilauea summit area, which began in the summer of 1960, continued virtually unchanged throughout and after the three periods of summit eruption. Rapid detumescence accompanied the flank eruption. Seismic activity during tumescence was moderate and persistent, but it gave no particular forewarning of imminent eruption. However, a swarm of relatively large earthquakes and strong harmonic tremor preceded the flank eruptive phase by about 16 hours.

The three summit eruptive phases were confined to Halemaumau, the deep crater within Kilauea caldera. During the first summit phase, which lasted only 8 hours, on February 24, a small collapse pit on the floor of Halemaumau was filled with 320,000 cubic yards of lava. Within a few hours after fountaining ceased, most of the new lava had drained back through the eruptive vents. During the second summit phase, which lasted from March 3 to 25, the same collapse pit was refilled. The third and most voluminous of the summit phases began on July 10 when lava fountains burst from the crater floor along a zone more than 1,500 feet long. The eruption continued until July 17, forming a new lake of lava 210 feet deep and 17.3 million cubic yards in volume. Backflow after fountaining resulted in a loss of approximately 1.3 million cubic yards. The 1961 eruptive cycle ended with a flank eruption along a 14-mile segment of Kilauea's east rift zone from September 22 to 25. Thirteen small, discontinuous lava flows, whose total volume was about 1.9 million cubic yards, were produced; and a large number of new cracks emitted volcanic fume and steam. Drainback of large volumes of lava into cracks apparently occurred at all the outbreaks, and no large flows were formed.

The total volume of new lava added to the surface by all the 1961 eruptive phases is approximately 18.2 million cubic yards. Measured rates of extrusion ranged from 660 cubic yards per hour during the second summit phase to 114,000 cubic yards per hour during the third summit phase.

Temperatures of the erupting lava ranged from 1,085° to 1,127° C in the three summit eruptive phases.

The lavas range from tholeiite basalt in the summit and upper rift zone areas to tholeiite olivine basalt lower on the rift zone. Variation diagrams based on eight new chemical analyses indicate that the composition of the 1961 lavas was affected by three types of differentiation: (1) removal of magnesian olivine, (2) removal of augite and minor plagioclase, and (3) addition of magnesian olivine. The first type affected the composition of both the summit and flank lavas; the second type produced the characteristic differences between the summit and flank lavas; and the third type was responsible for the range in composition of the flank lavas.

Extensive faulting and cracking along the east rift zone preceded, accompanied, and followed the flank eruptive phase. New faults having as much as 20 feet of vertical displacement were formed, and many old faults were reactivated. The 1961 flank activity occurred along the north side of the rift zone, which is noticeably bipartite; the north side is characterized by graben-horst topography and the south side, by cinder cones.

INTRODUCTION

In February 1961, only 1 year after its spectacular 1959–60 eruption, Kilauea Volcano resumed activity with a brief eruption at its summit. This eruption began a 7-month period of sporadic activity consisting of four distinct eruptive phases which are collectively referred to as the 1961 eruption of Kilauea. This terminology, which was adopted for the sake of convenience, is not without a geologic basis. All the individual eruptive phases of 1961 resulted from a single filling of Kilauea's magma reservoir and conformed to the previously described sequence of tumsecence, summit eruption, flank eruption, and detumescence (Richter and Eaton, 1960).

Kilauea Volcano, on the island of Hawaii (fig. 1), is the southeasternmost, and probably the youngest, of the basaltic volcanoes that form the mid-Pacific Hawaiian Archipelago. Although Kilauea is only 4,090 feet above sea level at its summit and is dwarfed by its lofty 13,700-foot neighbors Mauna Loa and Mauna Kea, it rises some 20,000 feet above the ocean floor and constitutes a volcanic pile of tremendous bulk. Historic eruptive activity of Kilauea has been confined to the summit caldera and to the two rift zones that extend down the flanks of the volcano from the summit to far below sea level. The relatively flat-floored summit caldera is indented by the deep crater Halemaumau (fig. 2), the usual site of summit eruptive activity.

During the past decade (1952–62) Kilauea Volcano has shown a marked increase in the frequency of eruption. In June 1952 an 18-year period of quiescence was terminated by a 4½-month-long summit eruption in Halemaumau (Macdonald, 1955). A brief summit eruption in May 1954 (Macdonald and Eaton, 1957), followed by a flank eruption which lasted from February to May 1955 on the east rift zone (Macdonald and Eaton, 1955), was the first of three successive eruptive periods in which a very close relation between summit and flank activity was observed. The second of these summit-flank eruptions began with the spectacular summit activity in Kilauea Iki crater in November and December 1959 and ended with the flank activity at Kapoho along the east rift zone in January and February 1960 (Richter and Eaton, 1960). The

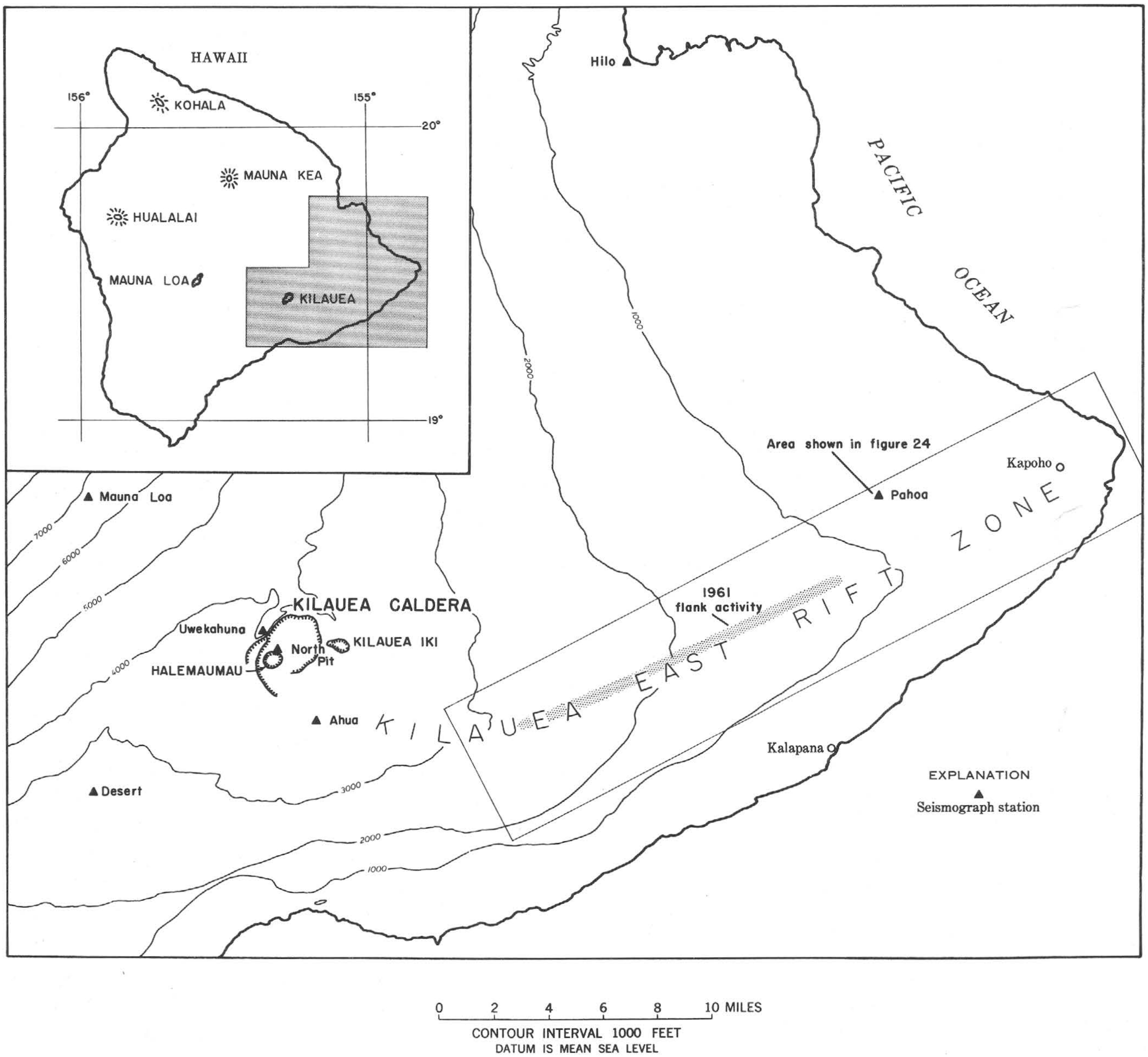

FIGURE 1.—Index map of eastern Hawaii showing the summit region and east rift of Kilauea Volcano and the location of U.S. Geological Survey seismograph stations. Halemaumau is shown on large-scale maps in figures 2, 10, 14, 16, and 18. Outlined area of Kilauea east rift zone is shown in figure 24.

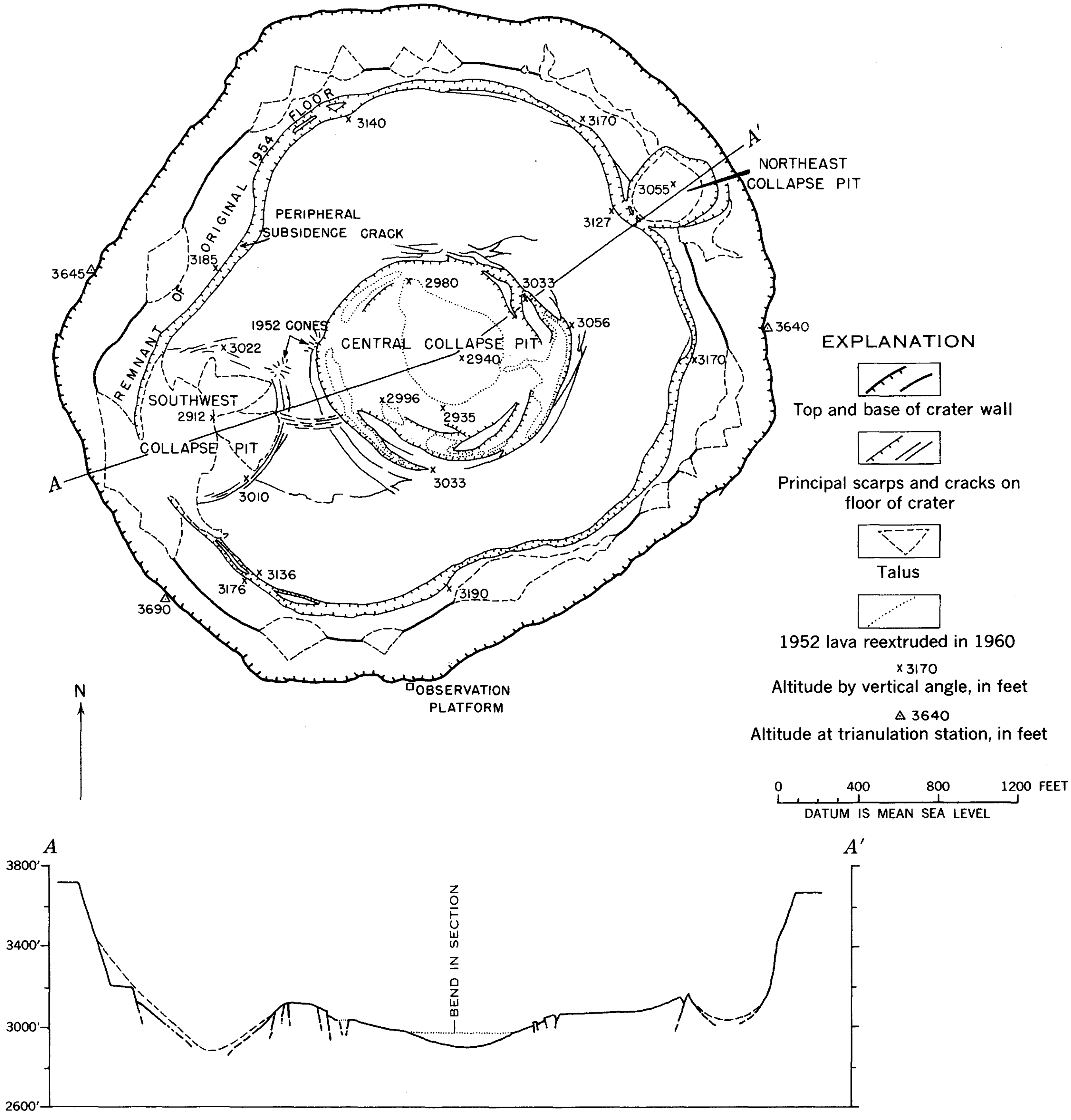

Figure 2.—Map and section of Halemaumau crater, in the floor of Kilauea caldera, before the 1961 summit eruptions. All collapse features in the bottom of Halemaumau occurred during the summit subsidence of February–March 1960. (See fig. 20 for section *A–A'*.)

culmination of the 1959–60 eruption was the dramatic subsidence of the Kileauea summit area and the 350-foot collapse of the bottom of Halemaumau. The 1961 eruption followed the same pattern but had three separate summit phases and one very brief flank phase.

Although the period 1952–62 appears to be one of relatively strong eruptive activity for Kilauea, the average annual rate of lava extrusion is only slightly greater than for all the historic period (1823–1962). Between 1952 and 1962 approximately 42 million cubic yards of lava per year were added to the surface of the volcano, and according to the data of Stearns and Macdonald (1946), the rate during the last 139 years has been 33 million cubic yards per year. Of significance, however, is the increased flank activity and concomitant increase in volume of lava extruded from the rift zones of Kilauea in the last 10 years. During this period the annual rate of extrusion from the rift zones has been 28 million cubic yards per year, whereas over the longer period the rate has been less than 5 million cubic yards per year.

This paper summarizes the observations and data collected by members of the U.S. Geological Survey's Hawaiian Volcano Observatory during the 1961 eruption. We sincerely thank all our observatory coworkers for their contributions and excellent support. The help of Hawaii Volcanoes National Park personnel and the support of the Hawaii Air National Guard in air reconnaissance are gratefully acknowledged.

PRE-ERUPTION TUMESCENCE AND SEISMIC ACTIVITY

In July 1960, only 4 months after the great summit detumescence of Kilauea that accompanied and followed the 1960 flank eruption, water-tube tiltmeters (Eaton, 1959) revealed a resumption of outward tilting along the northwest rim of the caldera. The renewed tumescence, when first detected by the east-west component of the permanent short-base tiltmeter at Uwekahuna on the rim of the caldera, was extremely slight and gradual (fig. 3). During September the north-south component of the instrument at Uwekahuna also began to indicate tumescence. Remeasurement at the network of long-base tiltmeter stations on the volcano in mid-November clearly showed that the entire summit region of Kilauea was swelling rapidly as magma accumulated in the relatively shallow reservoir a few kilometers beneath the caldera.

Tumescence accelerated markedly on October 22 and continued at an extremely rapid rate until November 5,

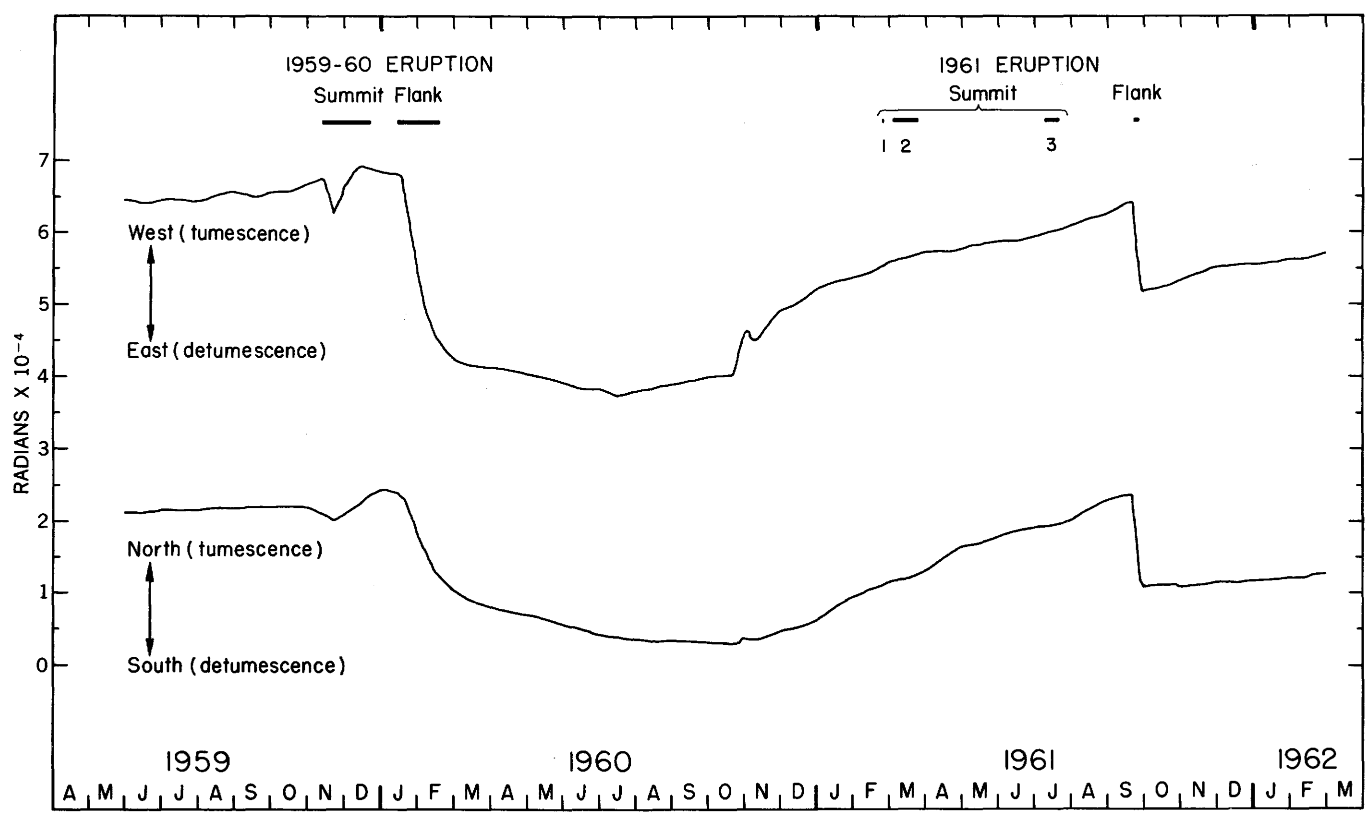

FIGURE 3.—Ground tilting of the Kilauea summit area as indicated by daily readings of the short base water-level tiltmeter at Uwekahuna (fig. 1) from late 1959 to early 1962. Periods of eruption (actual extrusion of liquid lava) are shown at top.

when a sudden reversal of tilt was detected by the short-base tiltmeters. By November 11, however, tumescence had resumed, and it remained at a relatively high and fairly uniform rate until the flank eruption in September 1961. The relation between ground tilting and change in volume of the Kilauea summit established during the 1960 subsidence indicated that the observed rate of tumescense between November 1960 and September 1961 could have been maintained by the addition of approximately 10^7 cubic yards of magma per month to the shallow reservoir within the volcano.

Seismic activity during the period of tumescence was, in general, moderate, and there was no indication of a gradual buildup prior to the summit eruption as there was prior to the 1959 outbreak in Kilauea Iki (fig. 1) (Richter and Eaton, 1960). Beneath the summit of Kilauea, swarms of deep (55–60 kilometers) and intermediate (10–15 kilometers) earthquakes occurred principally during the early stages of tumescence. Throughout the period of tumescence, many shallow (<5 kilometers) earthquakes and occasional earthquakes from a depth of about 30 kilometers originated beneath the summit. The possibility that the early seismic activity was actually tracing the progress of the magma as it rose from its source in the mantle through the conduits leading into the volcano is intriguing but highly conjectural. The local seismic activity, on the other hand, did correlate very closely with the rate of tumescence and probably was the result of structural readjustment in the relatively thin carapace of brittle rocks overlying the inflating reservoir.

In October 1960 two swarms of deep earthquakes, originating in the mantle 55–60 kilometers beneath Kilauea Volcano, were recorded on the seismograph net around the summit area (fig. 1). The first of these lasted from October 4 through 7 and consisted of more than 4,000 earthquakes and accompanying harmonic tremor; the second swarm had a like number of disturbances; it began gradually on about October 8, built up to a maximum of 900 earthquakes daily on October 18 and 19, and ceased abruptly on October 20. In late October, seismic activity appeared to shift to a much shallower zone in the mantle beneath the volcano; occasional earthquakes began to emanate from a depth of 30 kilometers. Coincident with the beginning of the 30-kilometer deep activity, swarms of earthquakes and harmonic tremor also began to emanate from a depth of 10–15 kilometers beneath the summit end of the southwest rift. This intermediate-depth activity was short lived, and by October 28 it had virtually stopped. The deeper earthquakes at 30 kilometers, however, continued intermittently throughout the entire period of summit tumescence.

Shallow earthquakes in the caldera area averaged 30 per day through September and the first half of October 1960. During the period of accelerated tumescence in late October and early November, the number of local quakes increased dramatically, reaching a maximum of more than 500 earthquakes per day on October 31. The largest of these had a magnitude of 3.2; it occurred at $21^h 32^m$ on October 27 and was centered along the outermost peripheral fault bounding the north rim of the caldera. Although no evidence of vertical displacement was observed along the scarp, ground movement accompanying the quake damaged water tanks and caused extensive cracking of pavement in the Kilauea Military Camp area on the caldera's north rim.

After the rapid tumescence in early November, the frequency of local earthquakes decreased; they averaged about 100 per day from that time until the first summit eruption on February 24, 1961. Occasionally, the frequency of local earthquakes increased to nearly 300 per day during this period, but there was no seismic forewarning of imminent eruption. Most of the local earthquakes were detected only by the short-period vertical seismometer at the North Pit station (fig. 1) on the caldera floor, although some of the larger disturbances were recorded at all stations in the Kilauea seismic net, and a few were felt by residents of the Kilauea summit area.

DESCRIPTION OF THE ERUPTION

FIRST SUMMIT PHASE

At about 04^h00^m on February 24, 1961, the seismographs in Kilauea summit area (fig. 1) began to record a minor swarm of small, shallow earthquakes and weak harmonic tremor that originated at shallow depths near Halemaumau. The earthquake swarm lasted only 15 minutes; the weak tremor, however, persisted. At about 07^h07^m the harmonic tremor increased abruptly in intensity, heralding the beginning of eruption.

A thin, inconspicuous column of bluish volcanic fume rising from Halemaumau crater was seen from the east rim of Kilauea caldera at 07^h20^m, but it was not until 07^h50^m that observers first reached the crater rim. The eruptive activity was confined within the small, northeast collapse pit, 400 feet in diameter, on the floor of Halemaumau (fig. 4), where a lava fountain was spurting to heights of 50–100 feet in the southwest side of the pit (loc. B, fig. 4), and a series of smaller fountains played from a line of vents along the extreme east side of the pit (loc. A). By 08^h10^m the southernmost of the fountains at A was spurting to a height of 100 feet and two new vents at C and D were also erupting.

The nearly flat talus-covered floor of the 140-foot-deep pit was rapidly covered by new lava, and by 08^h35^m the lava had risen to the level of the vent at locality B. Waves generated in the turbulent area at the base of the fountain swept across the pond, and a distinct but rather weak current moved in the opposite direction from the vents at localities A and C toward locality B. Although the level of the pond continued to rise, it was evident that lava was draining away through the drowned vent at locality B.

At 09^h02^m the pond reached the level of the vent at locality D, and by 09^h24^m fountains at both localities B and D were reduced to violent surges that occasionally blasted lava to heights of about 50 feet. The most consistent fountaining was at locality C, where a single narrow jet shot to heights of 100 feet. A squat, massive fountain at A played from the southernmost vent, while from the smaller vents along the short rift extending northward from locality A several lava rivulets cascaded down the short slope into the pond. Hot turbulent air currents above the fountains carried light frothy pumice and Pele's hair higher than the rim of Halemaumau, 500 feet above the vents. Most of this pyroclastic material was carried over Halemaumau by the northeast tradewinds, but minor amounts fell on the crater rim above the collapse pit. The composition of this material is given in column 1, table 4.

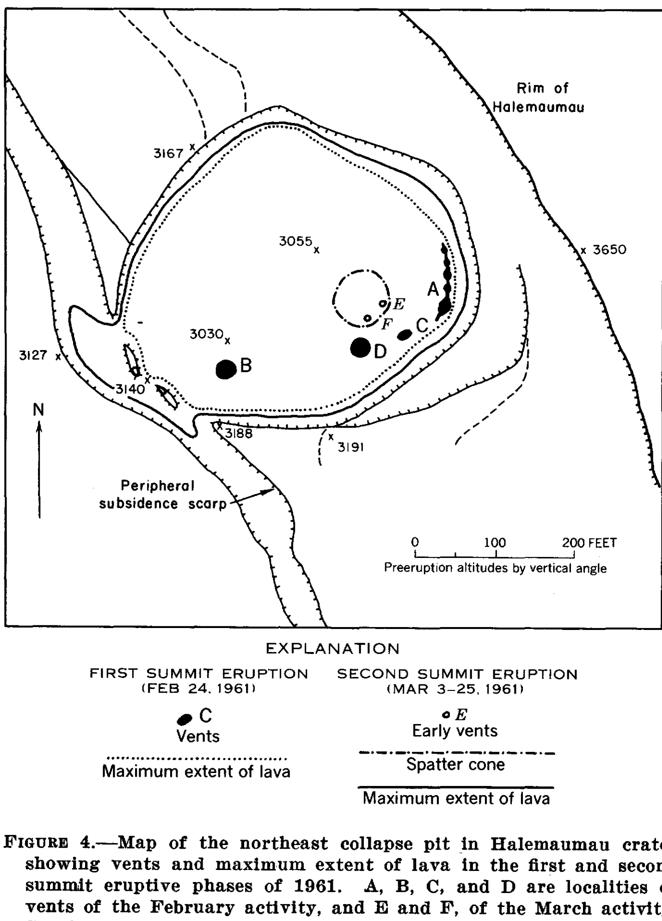

FIGURE 4.—Map of the northeast collapse pit in Halemaumau crater showing vents and maximum extent of lava in the first and second summit eruptive phases of 1961. A, B, C, and D are localities of vents of the February activity, and E and F, of the March activity. See figure 2 for setting in Halemaumau.

All the vents were covered by the rapidly rising lava by 10^h15^m, when the pond reached its maximum depth of about 110 feet. Lava draining into the vents at localities B and D frequently reduced the surging fountains to a rolling boil, and at 10^h33^m the pond began to pour back into the vent at B at an accelerated rate. Within a few minutes the crusted pond surface was lowered about 5 feet, leaving a glistening black ring to mark the high stand of the lava. Occasionally, activity revived at B, sending great surges of lava across the pond and impeding the backflow; but by 11^h23^m the vent was virtually dead. The level surface of the pond had subsided more than 10 feet and was continuing to drop rapidly (fig. 5). Large rafts of blackened crust continually moved across the pond toward the vent, where they plunged into the agitated orange-yellow fluid and disappeared.

The fountaining at localities A, C, and D continued unchanged through this early period of strong backflow; at 13^h30^m the pond surface was about 50 feet below its high stand, and the vents at localities A and C were again exposed. By 14^h30^m, however, shortly after the vent at locality D reappeared above pond level, activity at the fountains began to wane. Fountaining ceased in the vents at locality A by 14^h50^m, and at locality C by 14^h55^m. The remaining fountain at D continued to emit spatter sporadically until 15^h08^m, when it too died, marking the end of the very brief first phase of the summit eruption.

Lava drainage down the vent at locality B and heavy fuming from the other inactive vents continued through the rest of the day and into the evening. After dark, the collapse pit resembled a small steel factory: a thin bright-red incandescent ribbon of lava flowed slowly toward locality B; a pale yellowish-blue flame issued from the vent at C; and the orifice of the vents at locality A glowed brightly. At 21^h00^m 30-foot-high flames were also issuing from five vents at locality A; by 23^h50^m, however, flaming was no longer visible, and the intensity of the glowing in all the vents had greatly diminished.

By the next morning (February 25), evidence of the eruptive activity of the preceding day had virtually disappeared. Approximately 10 feet of broken lava crust remained in the bottom of the collapse pit, and a thin black coat of new lava lined its walls; the pit, however, was virtually the same size as before the eruption. Of the 320,000 cubic yards of lava which filled the pit during the height of activity, probably less than 30,000 cubic yards remained. Moreover, the vents at localities

B, C, and D were not distinguishable on the rubble-covered floor, and only a minor amount of fume emission marked the line of vents at locality A, higher up on the wall of the pit.

Harmonic tremor, which had remained at a relatively high level throughout the 8-hour eruption, abruptly decreased to about one-tenth of its eruption level when fountaining ceased. During the next 2 days the tremor continued to decrease, and by February 28 it had disappeared altogether. The eruption did not appear to affect the overall tilt pattern (fig. 3). Short-base tiltmeters around the caldera continued to show a steady inflation of the summit area during and after the eruption; remeasurement of the long-base tiltmeter stations indicated that the pattern and rate of tilting for the 3-month interval ending with the eruption had not changed significantly from that of the previous 2-month period.

SECOND SUMMIT PHASE

At about 22^h00^m, on March 3, 1961, mild eruptive activity resumed in the northeast collapse pit in the floor of Halemaumau. Inclement weather, however, hampered visibility in the crater, and only occasionally could a reflected pink glow be seen on the clouds drifting over the pit.

By the next morning (March 4, 1961) the weather had cleared, and a fume cloud rising from the pit was

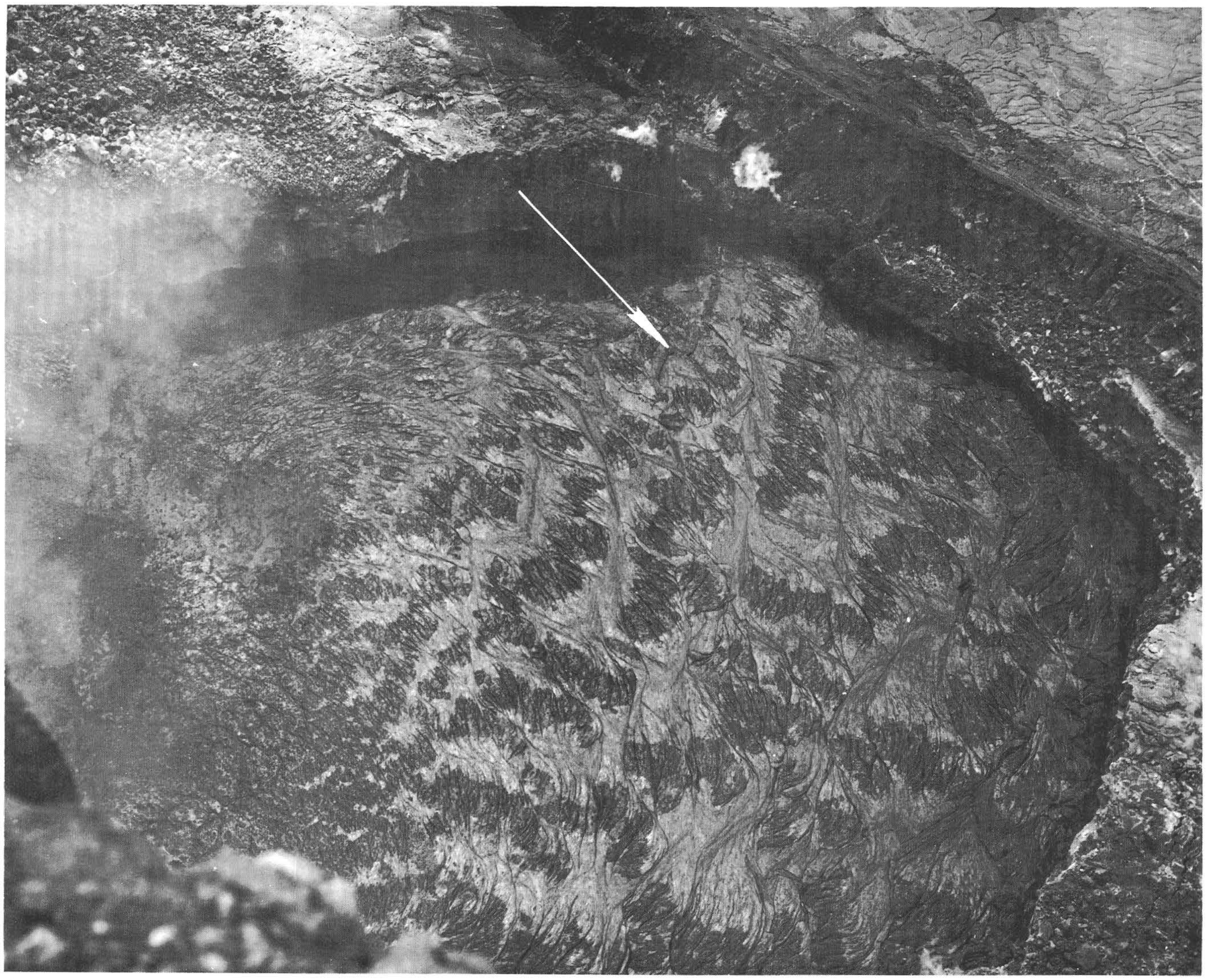

FIGURE 5.—Northeast collapse pit in Halemaumau crater at 11^h15^m on February 24, 1961, about 1 hour after lava pond reached its maximum depth. Backflow down vent at locality B (arrow) has lowered pond surface about 10 feet, while vents along side of pit (left) continue to fountain. On level pond surface black patches of crust (dark gray) are surrounded and rafted toward vent at locality B by fluid incandescent lava (light gray). View is toward south from northeast rim of Halemaumau; distance across pit is about 400 feet.

clearly visible. Viscous lava tossed from two small vents (locs. E and F, fig. 4), slightly north of the February 24 vents at localities C and D, had already built up a small spatter cone on the floor of the pit, and a number of short flows were oozing from the periphery of a new flow that covered about half of the old floor. Viewed from the rim of Halemaumau directly above the east end of the pit, liquid lava could be observed rising and falling rhythmically every few seconds within two small caldrons that had developed over the vents. The rhythmic oscillation of the lava level was apparently controlled by intermittent release of gas. Large expanding bubbles of gas lifted the lava surface as they rose through the liquid contents of the caldrons. When they burst at the surface, spatter was thrown from the vent, and the liquid inside the vent dropped to its former level.

As the harmonic tremor gradually increased, the eruptive activity also increased. By nightfall, bursts of spatter sprayed from the vents at intervals of about 1 second, and the surface of the new lava contained a myriad of incandescent cracks. From these cracks and from the base of the two spatter cones, short viscous flows were continually reforming the surface of the slowly filling pond.

By $16^{h}00^{m}$ on March 5 only the easternmost spatter vent (loc. E) remained active; the vent at locality F was covered by fresh spatter but was apparently the source of a loud hissing roar that emanated from the area. New lava nearly covered the bottom of the pit; but, unlike the pond of February 24, a distinct slope could now be observed between the high area around the base of the spatter cone and the far edges of the new pond. The pond apparently was not only being filled by the meager spatter tossed from the vent but also by a number of shallow tubes leading out from the base of the caldron over the vent.

Conditions of the eruption were little changed by the morning of March 6. The pond had risen slightly during the night, and new flows now covered the entire floor of the pit. Spatter, in bursts 30–40 feet high, blasted from the vent at locality E approximately once per second. The spattering was accompanied by loud, dull reports that might be compared to the noise emitted from a huge pot of boiling oatmeal.

On March 7 the pond was about 20 feet deep, and the beginning of crustal foundering indicated that it had a fluid core covered by a relatively thin crust (fig. 6). At $11^{h}45^{m}$ the caldron in the now large spatter cone was partly bridged by a thin cap of congealed spatter, from which hung long incandescent stalactites of pasty lava. Through the day more and more spatter froze on the cap, and by evening only three small apertures exposed the liquid beneath.

During the night the cap collapsed, and by $10^{h}00^{m}$ on March 8 the 20-foot-wide caldron of sloshing lava was once more fully exposed. At the north base of the spatter cone, a small window in the crust exposed a stream of lava surging in phase with the rise and fall of lava in the caldron. At $21^{h}30^{m}$ the window in the tube was closed, and only the boiling caldron and a number of short flows oozing from cracks on the surface of the pond were still active.

On March 9 the pond was about 60 feet deep. The orifice at the top of the 30-foot-high spatter cone had again been reduced in size by the accumulation of spatter, but the caldron beneath appeared to be larger. At $14^{h}30^{m}$ a 100-foot-square section of the crust in the southwestern part of the pond was rapidly engulfed by upwelling, roaring liquid lava. Other smaller areas of the crust of the pond also foundered as the liquid lava in the pond broke through the sloping restraining crust and spread outward to establish a new, more nearly level surface. The most intense foundering occurred in the most steeply sloping part of the pond surrounding the base of the cone.

The activity in the pit was somewhat reduced on March 10. Only a small, narrow opening remained in the top of the cone, and spatter emission was very sporadic. For the next 2 days this low level of activity changed little. The opening above the caldron remained small, and during the morning of March 12 it was completely closed by a thick cap of spatter (fig. 7). Even then, however, fume escaping from the porous top of the cone, together with a sloshing sound emanating from the cone, indicated that the caldron was still liquid filled.

At $22^{h}00^{m}$ on March 13 the harmonic tremor doubled in intensity and the rate of spatter emission increased. Spatter shot to heights of 100 feet from an enlarged orifice over the caldron, and by $23^{h}00^{m}$ the entire east end of the pond around the spatter cone was aglow with many small flows. Through the next day (March 14) the activity remained at this high level. Several small lava flows issued from a breach in the east side of the spatter cone; on the south side of the cone, lava was extruded intermittently from a small vent which had a fascinating trapdoorlike lid. When lava rose in the caldron, the hinged "trapdoor" opened and a small amount of lava gushed out; as the lava receded in the caldron the "door" closed, shutting off the flow.

At $13^{h}00^{m}$ on March 14, the pond was approximately 90 feet deep, rising 30 feet during the preceding 5 days. However, because many surface features on the crust

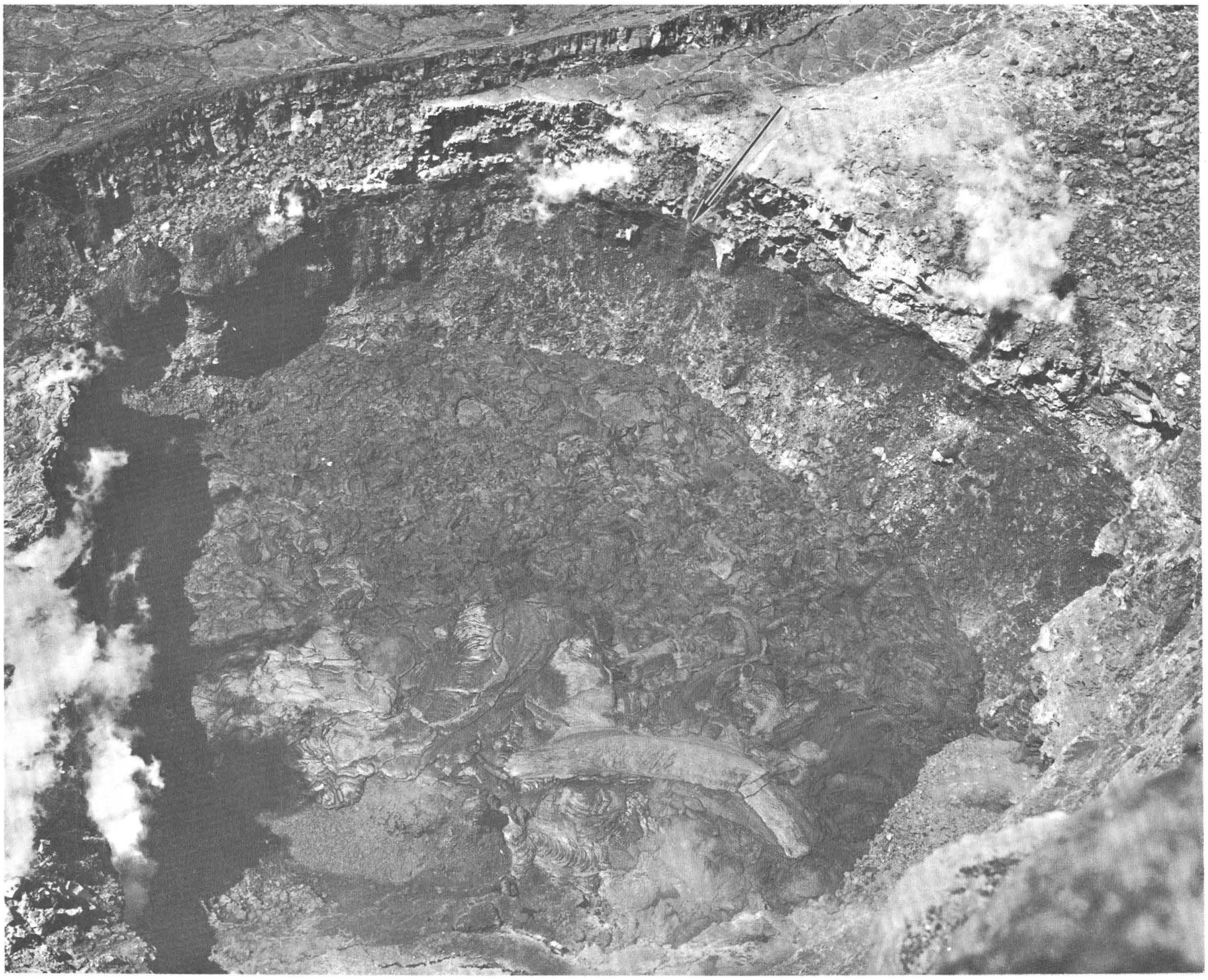

FIGURE 6.—Northeast collapse pit in Halemaumau crater at 11^h45^m on March 7, 1961. Lava pond is about 20 feet deep, and opening at top of new cone (compare with fig. 8) is partially bridged over. Note the high lava mark of February 24 pond on wall of pit (arrow), which is about 60 feet above level of pond in this photograph. View is toward west from northeast rim of Halemaumau.

that covered the pond were more than 3 days old, it was evident that much of the pond was filled by subsurface injection of new lava. Moreover, the crust was practically level everywhere except immediately around the cone, and crustal foundering had become negligible.

By March 15 spatter activity had decreased again, and only occasionally could lava be seen splashing in the caldron over the vent. On March 16 collapse of the spatter-encrusted top of the cone enlarged the caldron orifice to approximately 25 feet in diameter, and, although spatter emission remained minor, liquid lava was generally visible in the caldron until March 24.

The lava pond was filled to a depth of approximately 100 feet by March 17. Along the entire north and east sides of the pit, lava stood at the maximum level reached by the pond of February 24; only at the extreme west end of the pit was the pond some 5 feet below the level of February 24. Within 2 days the last trace of the February lava was covered and early in the morning on March 19 the pond level reached the height of the lowest part of the narrow ridge that separated the northeast collapse pit from the larger peripheral subsidence crack on the main floor of Halemaumau. At 11^h30^m a small stream of lava began to pour over the 20- to 30-foot-high scarp and into the deep crack at its base. The rate of flow of the pond lava into this crack increased rapidly during the next few hours, and by the afternoon of March 20 at least three vigorous streams were observed flowing from the pond.

Between March 20 and 23, frequent collapse of the unstable upper part of the cone occasionally allowed lava to drain from the caldron and form small flows that spread over the east end of the pond (fig. 8). On March 21 the largest of these caldron-fed flows sent a narrow tongue of lava to within a few feet of the breach in the west wall of the pit.

On March 24 only a small glowing hole could be seen in the top of the spatter cone. There was no indication of lava flowing over the subsidence scarp, and only a few small lava oozes were active on the pond's surface. An occasional whooshing noise, accompanied by increased exhalation of fume from the vent indicated that liquid lava was still in the conduit. At $20^{h}00^{m}$ on March 25 the amplitude of the harmonic tremor decreased to a very low level, and the eruption was virtually over. Throughout the next few days an occasional burst of harmonic tremor was recorded, but at no time was there any evidence of renewed surface activity.

The lava pond in the small northeast collapse pit was approximately 105 feet deep (5 feet above the pond of February 24) at the cessation of activity. No measurable drainage of lava occurred either during or after the eruption; apparently the thick flanks of the spatter cone prevented backflow into the open vent.

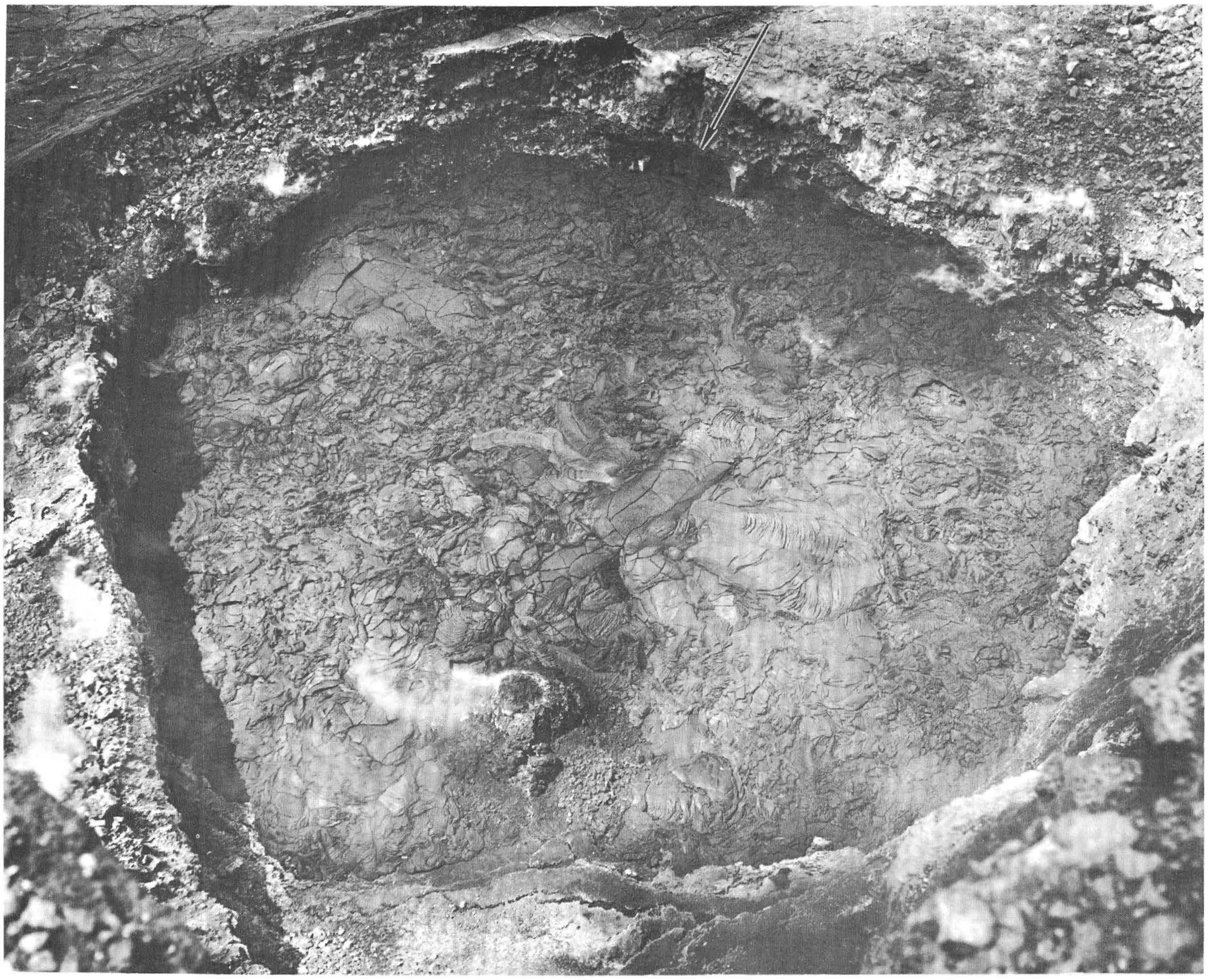

FIGURE 7.—Northeast collapse pit in Halemaumau crater at $11^{h}45^{m}$ on March 12, 1961. Lava pond is about 75 feet deep and about 15 feet below the high lava mark of the February 24 pond (arrow). Fume escapes from the top of the cone, which is completely covered with a lid of congealed spatter. Viewpoint is the same as in figures 6 and 8.

THIRD SUMMIT PHASE

Evidence from the short-base tiltmeter at Uwekahuna indicated that the general tumescence of Kilauea's summit continued practically without interruption during and after the second summit eruption phase in March (fig. 3). Releveling of the long-base tiltmeter stations in February, May, and June, however, indicated that the rate of tilting during the period from May to June was about one-half the rate during the period from February to March. But even this reduced rate was large when compared to the tilting prior to the 1959 eruption of Kilauea Iki.

During the last 2 weeks in June, a strong swarm of earthquakes originating in the upper end of the southwest rift zone of Kilauea was recorded on the Desert seismograph. The number of these earthquakes averaged more than 175 per day between June 17 and June 21; the number declined to about 100 per day during the last week in June, and to about 60 per day during the first week of July. Local shallow earthquakes in the caldera region, as recorded on the North Pit seismograph, increased from about 70 per day during June to about 120 per day in the 2-week period preceding the eruption in July. Only a few of these were felt.

FIGURE 8.—Northeast collapse pit in Halemaumau crater at 15^h00^m on March 20, 1961. Lava pond has reached its maximum depth of about 105 feet, completely covering the February 24 lava, and is spilling into peripheral subsidence crack (upper left) near outer edge of main crater floor. Caldron of fluid lava is visible in spatter cone. Viewpoint is the same as in figures 6 and 8.

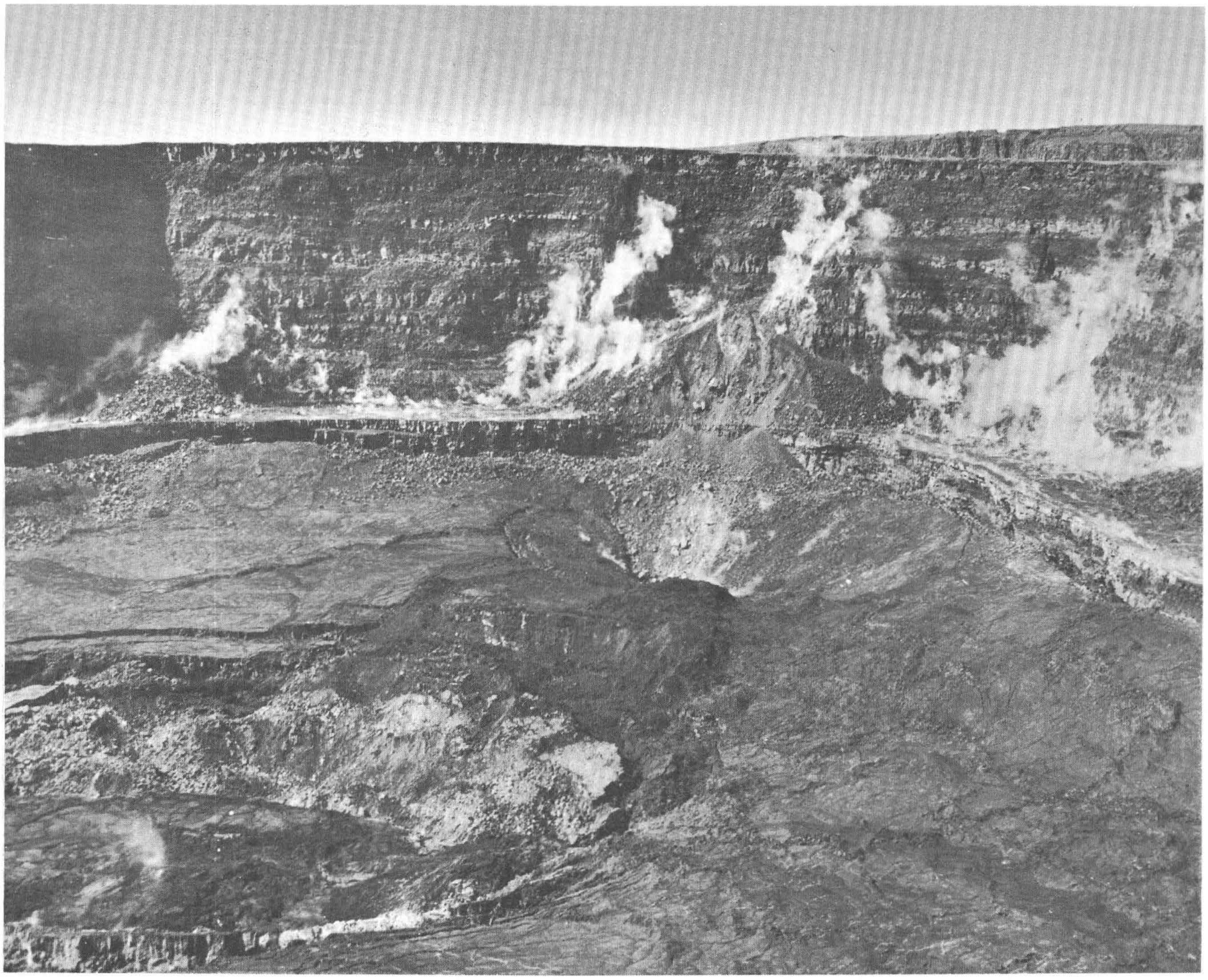

FIGURE 9.—Halemaumau crater before the third summit eruptive phase showing the collapse features formed during the summit subsidence in February 1960. Over central collapse pit (bottom left) and southwest collapse pit (center right) the crater is approximately 750 feet deep. View is toward the southwest from the northeast rim of Halemaumau. The northeast collapse pit (site of the February and March 1961 eruptive phases) is out of view to bottom left.

At about 19^h00^m on July 10 weak harmonic tremor, accompanied by a series of small to moderate shallow earthquakes, began to record on the seismographs around the summit of Kilauea. For about 1 hour, tremor and earthquakes gradually increased in magnitude, and one quake at 19^h50^m was felt on the north rim of the caldera. At the onset of tremor and earthquakes, the traces on the long-period horizontal-component Press-Ewing seismograms at Uwekahuna began an hour-long excursion owing to rapid northwestward tilting away from Halemaumau (tumescence). The maximum rate of tilting occurred at 19^h35^m, and by 20^h05^m tilting had ceased.

A brightly illuminated fume cloud lit the sky above Halemaumau at 20^h15^m on July 10, and at 20^h30^m the top of a tall lava fountain could be seen spurting above the west wall of the crater from the U.S. Geological Survey Volcano Observatory at Uwekahuna. At

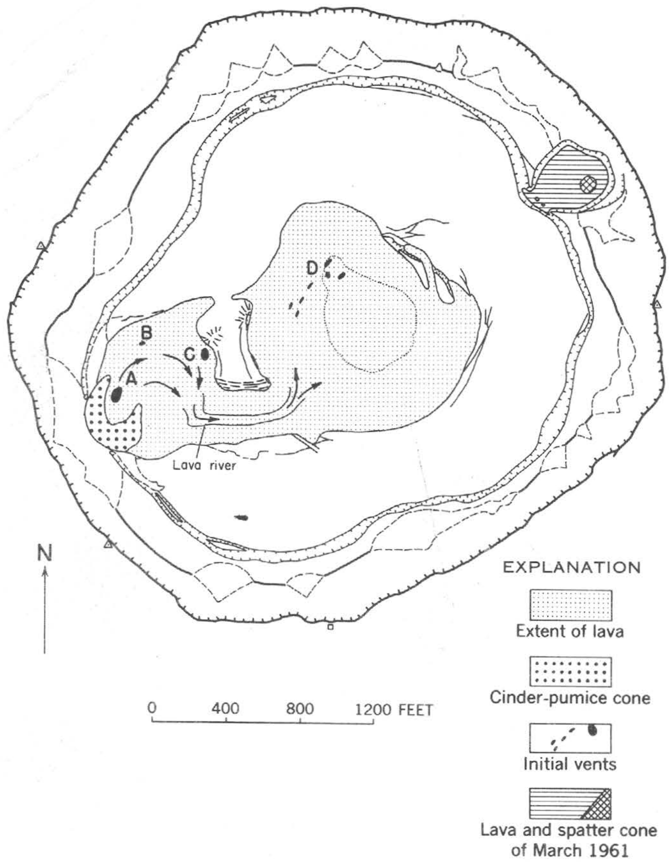

FIGURE 10.—Halemaumau crater at 06h00m, July 11, 1961. Dotted line under the new lava outlines bottom of the central collapse pit.

20h32m observers reached the south rim of Halemaumau, after driving through falling pumice along the crater-rim road half a mile southwest of the crater, and found lava fountains erupting from the central and southwest 1960 collapse pits on the crater floor (figs. 2, 9).

In the southwest collapse pit, fountains at localities A and B (fig. 10) were reaching heights of 50 and 100 feet, respectively; at locality D, in the central collapse pit, a number of lower fountains were playing along a short arcuate rift halfway up the northwest wall of the pit (fig. 10). By 20h35m the vent at B was inactive, but a new vent at C on the east side of the southwest collapse pit had opened, and a fountain was playing to heights of 100–200 feet. All the vents, including those of the February–March eruptions, lay approximately along a line trending about N. 65° E. across the floor of Halemaumau, which was virtually coincident with the alinement of the 1952 and 1954 eruptive fissures in Halemaumau (Macdonald and Eaton, 1957).

Lava from the vents at localities A and C rapidly filled the 120-foot-deep southwest collapse pit, and by 22h30m lava began to overflow onto the main floor of Halemaumau. In the larger central collapse pit lava had reached the base of the fountains, forming a pond which was 40–50 feet deep. Small spatter ramparts around the vents at D, which had built up to the level of the main floor around the pit, were also inundated rapidly by the rising lava, and by 22h50m lava was overflowing into the large peripheral cracks around the central pit. At 22h57m lava flows from the southwest pit reached the central pond, and by 23h30m a well-defined lava river had formed between the two ponds (fig. 11). The velocity of slabs of darkened crust that were rafted from the outlet of the southwest pond to the central pond was approximately 3 miles per hour. The vents in the central pit had been completely submerged by the rising lava, and by 01h30m on July 11 the activity was reduced to a small number of low, surging boils. In the southwest pit, the vent at locality C was also covered by the rising liquid lava, but the fountain continued to blast through the pond to heights of 50–100 feet. Composition of the pumice ejected at 02h00m is given in column 2, table 4.

Soon thereafter the fountains surging through the pond above the vents in the central pit began to pulsate and for more than 1 hour created a remarkable wave pattern across the pond. By 03h20m, however, activity from the vents beneath the central pond was reduced to a feeble bubbling, and a crust formed over most of its surface. As the crust thickened and became more rigid, agitation of the liquid in the pond induced by an occasional surge from the vents locally forced lava out over the surface and formed a new crust.

At daybreak the lava was still largely confined to the separate ponds in the two collapse pits, and there were minor overflows onto the main floor north of the central pit (fig. 10). The large arcuate cracks immediately peripheral to the central pit were almost completely covered. The lava river pouring out of the southwest pit flowed between natural levees which it had built up on the broad area of new lava between the two ponds, and another smaller stream was beginning to encircle the 1952 cones on their north side.

The height of the main fountain at locality A decreased from 300–600 feet in the morning to about 200–300 feet throughout the rest of the day. Pumice and spatter thrown out by the fountain built up spatter ramparts around the vent, and thus the orifice was continually being raised above the level of the pond.

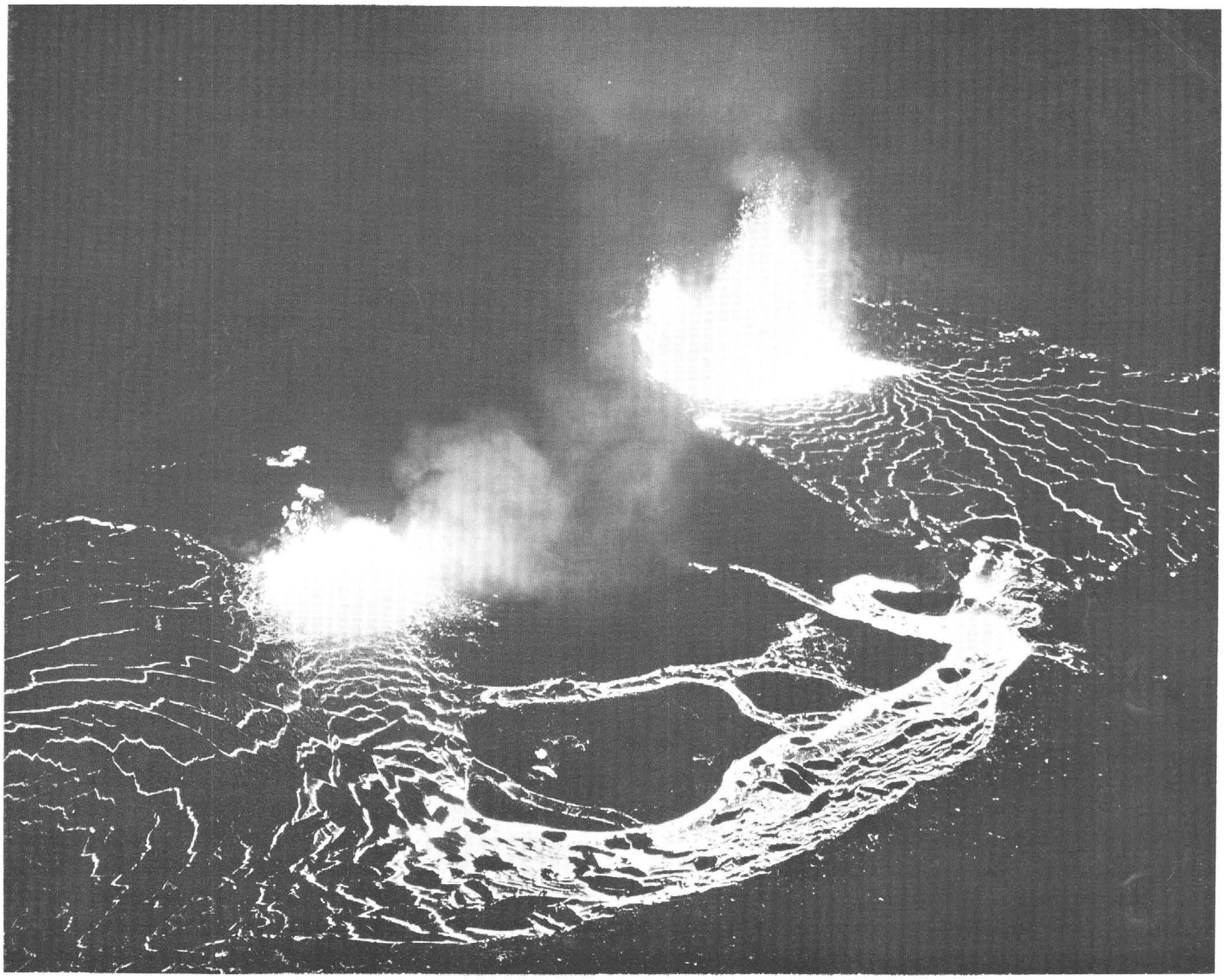

FIGURE 11.—Eruptive activity in Halemaumau crater at approximately 23^h30^m, July 10, 1961. Lava erupted from the vents at locality A (out of picture to the left) and locality C (left) has filled the southwest collapse pit, and a lava river carries the overflow to the central collapse pit. (See fig. 10 for localities). Lava fountains at the vents at locality D (right) in the wall of the central collapse pit are shooting to heights of 150 feet. View is toward the north from the southwest rim of Halemaumau.

Abundant pumice was also falling on the rim of Halemaumau above the fountain and on the caldera floor toward the southwest. The surging fountain at locality C continued unchanged, whereas at locality D, in the central pond, activity increased slightly during the morning, and occassional blasts of spatter reached heights as great as 50 feet.

During the morning, the two ponds coalesced, leaving the 1952 cones and the cracked pressure ridge connecting the two collapse pits as an island in the rising lava lake. At noon on July 11 a large part of the lake over

FIGURE 12.—Eruptive activity in Halemaumau crater at approximately 13^h30^m, July 11, 1961. Lava pond over the central collapse pit is confined by a natural rubble levee 10–15 feet high. In left background the lava river pours from base of main fountain (loc. A, fig. 10), and in the central pond a small burst of spatter shoots above the vents at locality D (right). View is toward the west from the east rim of Halemaumau.

the central pit was impounded by a natural rubble levee which maintained the lake surface more than 10 feet above the surrounding terrain (fig. 12). This transient feature was formed by lava spreading outward from the agitated boiling area at locality D to the margin of the lake, where it plunged downward behind the levee and deposited its load of frozen crustal fragments. Small secondary fountains that were produced where the lava plunged downward behind the levee added minor amounts of reinforcing spatter to the barrier. Through the early afternoon, lava flows discharged from the mouth of the river advanced rapidly eastward

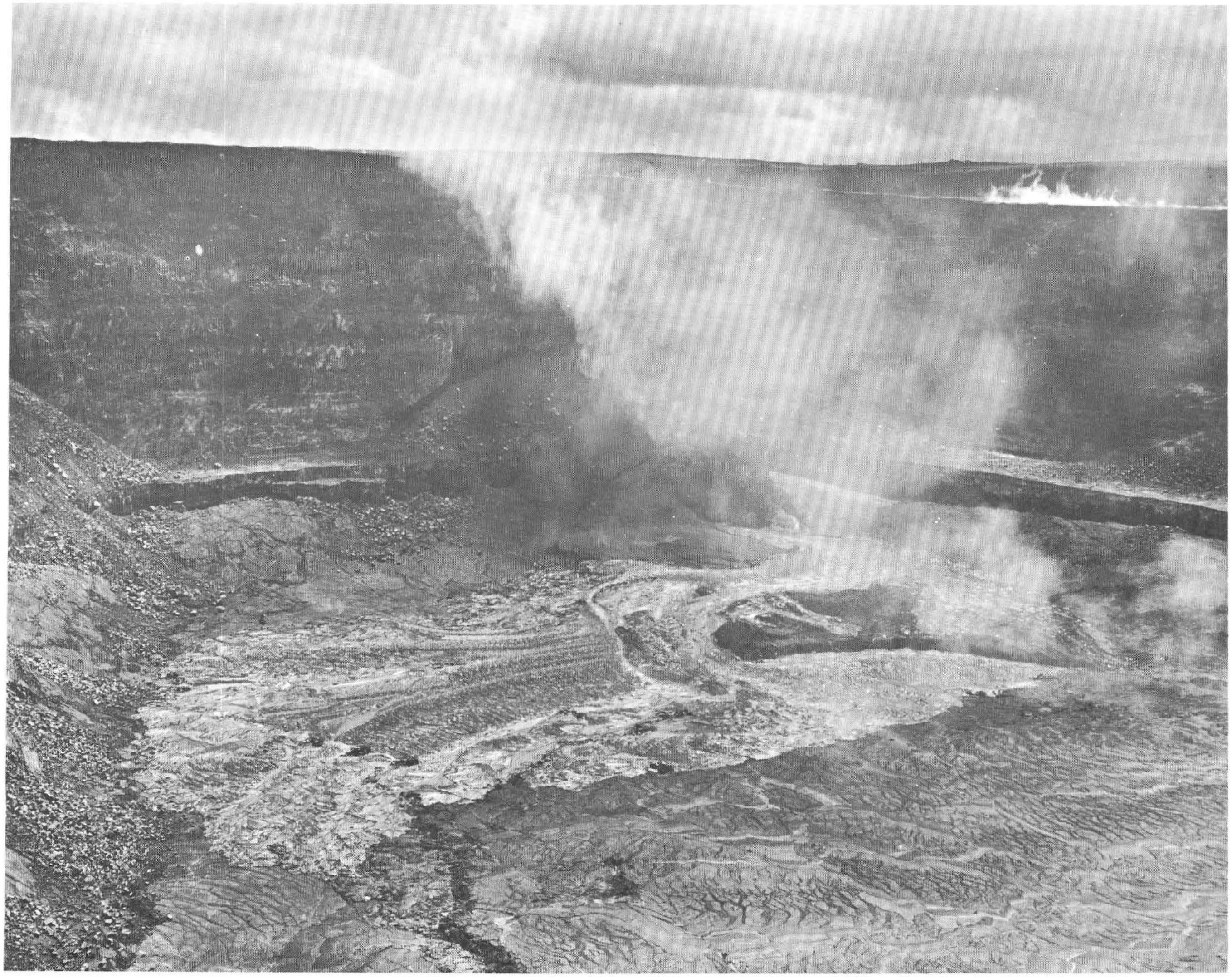

FIGURE 13.—Same view as in figure 12, one-half later, showing the raised lava pond over the central collapse pit being covered by flows discharging from the lava river.

across the lake, and within a few hours all vestiges of the raised pond had been covered by new flows (fig. 13). This confinement of a lava lake by a levee of its own making has been observed many times in Halemaumau and is evidently a common phenomenon of lava-lake activity (Macdonald, 1955).

The conditions in Halemaumau at 18^h00^m are shown in figure 14. By this time the lake had expanded laterally over a large part of the crater floor, leaving the pressure ridge and the 1952 cones as three isolated islands. Activity in the vent at locality D had decreased again by 17^h00^m, and at 21^h35^m activity at the vents at localities C and D had ceased. By 23^h00^m the one remaining fountain, at locality A, was averaging only 100 feet in height, and even it, occasionally, subsided to a massive center of boiling lava.

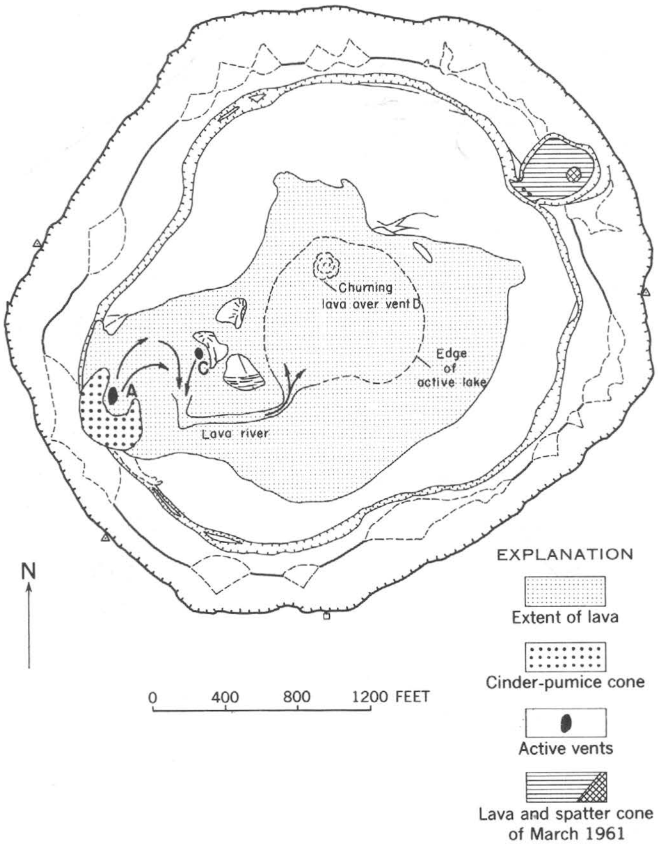

FIGURE 14.—Halemaumau crater at $18^{h}00^{m}$, July 11, 1961.

During the night the lava-river changed course, and by morning on July 12 it was flowing in a broad stream almost due east between the 1952 cones and the pressure ridge, of which only the very tops still remained above the level of the lake (fig. 15). Pieces of darkened crust were rafted along this stream at about 6 miles per hour. Throughout the day the surface of the lava lake rose steadily, and at $10^{h}00^{m}$ it covered an area of about 70 acres to a depth of 140 feet above the central collapse pit. By $11^{h}00^{m}$ the fountain had built up a large cinder-pumice cone on the talus behind the vent, and slumping from the cone into the vent occasionally deflected the spray of the fountain to the east. The accumulation of spatter around the base of the fountain continued to maintain the level of the vent above the level of the lava lake. At night the lake surface was aglow from the myriad of incandescent cracks that criss-crossed its surface. Lava oozed from these surface cracks and from around the periphery of the lake, and crustal foundering was continually exposing large patches of incandescent, fluid lava.

On July 13 at $00^{h}30^{m}$ the fountain at locality A rose to heights of 800 feet and vigorously threw out large chunks of pumice as much as 1 foot across. Within a few minutes, however, the fountain subsided to heights of 100–500 feet and continued at these heights for the rest of the night. By $11^{h}00^{m}$ the three islands were completely covered, and the broad lava river flowed directly over them (fig. 16). The lake surface, which covered most of the central nearly flat part of the main saucer-shaped collapse pit in Halemaumau, had increased to about 90 acres. An exceedingly active and probably higher area, which was marked by numerous lava oozes and local patches of crustal foundering, extended from the central deeper part of the lake northward to the margin of the lake. Spatter falling on the south rampart of the enlarged cinder cone throughout the day fed a number of viscous rootless flows that moved sluggishly down the outer slope of the cone and out over the lake (composition of pumice given in column 3, table 4).

On July 14 the height of the fountain generally fluctuated between 100 and 300 feet, but at times the fountain diminished to a huge boiling mass. About $23^{h}00^{m}$ a new vent was first noticed at the base of the spatter rampart just north of the main fountain. This vent discharged a small steady stream of lava that poured directly into the main river.

Fountain heights continued to decrease on July 15, but the rate of lava extrusion remained about the same. By noon the lava lake was more than halfway up the steep part of the large saucer-shaped collapse pit of 1960, and its surface, which now covered 101 acres, exhibited an intricate pattern formed by hundreds of small pahoehoe flow units (fig. 17).

In the afternoon it was evident that the rising lake was slowly encroaching upon the vent area, and by nightfall the lava river was running wide and slowly. In the disturbed area where the river sluggishly emptied into the central part of the lake, many "lightning-shaped" cracks radiated out over the entire lake surface. Around the margin of the lake several large flows were active, and at about $20^{h}00^{m}$ the first lava from the

FIGURE 15.—Eruptive activity in Halemaumau crater at approximately 15h00m, July 12, 1961. The main lava fountain, at base of new cinder-pumice cone, is about 200 feet high. The lava river pouring from base of fountain has changed course (see figs. 12 and 13) and is running between the remnant 1952 cones (black arrows) and the 1960 pressure ridge (white arrow). View is toward the northwest from the south rim of Halemaumau.

lake began to pour into the outermost large peripheral subsidence crack of 1960 along the south side of the crater.

A low massive fountain continued unabated throughout July 16, and an occasional deluge of spatter from the fountain fell on the cone around the vent. (Composition of pumice is given in column 4, table 4.) The small gushing vent had ceased erupting during the night and was no longer visible. By late afternoon lava was rapidly filling the peripheral subsidence crack along the south side of the crater and was beginning to flow into this crack on the north side. At 21h30m the lake reached the level of the vent and forced the fountain to jet through an ever-increasing cover of liquid lava. This agitation at the vent occasionally sent out waves across the lake surface, adding more cracks to the maze of incandescent cracks already lacing the surface.

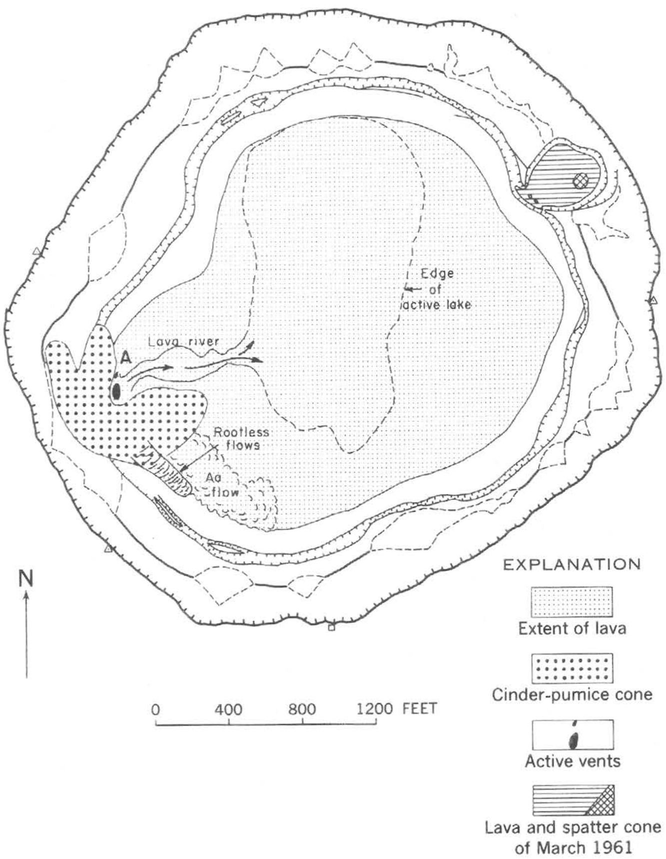

FIGURE 16.—Halemaumau crater at 11^h00^m, July 13, 1961.

At 03^h50^m on July 17 the fountain was covered by the rising lake and died. For several hours a small secondary fountain played over the vent area as a small stream of lava poured back into the vent from the lake. Even after a stable crust formed over the vent, lava continued to drain from the lake. As the lake surface lowered, the crust continually foundered and reformed; often when large sheets of lava swept rapidly over the surface, small secondary fountains, produced by release of air trapped in the old crust, played briefly from the fluid. By early afternoon, when all backflow appeared to have ceased, the central part of the lake and the area near the vent were distinctly lower than the rest of the lake. Around most of this area a scarp as much as 15 feet high was visible, and scattered over the subsided floor were many small islands, perhaps remnants of former pressure ridges and other solidified masses that had formed during the late stages of lake filling but which were not disturbed by crustal foundering (figs. 18 and 19). Once formed, many of these solidified masses continued to grow and served as degassing chimneys.

The eruption lasted 16½ hours less than 1 week. During this period the total volume of lava extruded was approximately 17.3 million cubic yards, which formed a new lava lake in Halemaumau 210 feet deep with a total surface area of about 112 acres. The progress of crater filling is shown graphically in the cross-section on figure 20.

Pumice produced from the main lava fountain was carried as far as 2 miles southwest of Halemaumau by the northeast trade winds. It fell as a thin blanket ranging in thickness from a fraction of an inch downwind from the crater to more than 2 feet near the crater. On the caldera floor directly above the fountain area, strong, turbulent updrafts swept up out of the crater and continually reworked the light pumice. In places along the rim of the crater where downsweeping eddy currents were strongest, drifts of pumice more than 4 feet deep were formed (fig. 21).

FLANK PHASE

The 17 million cubic yards of lava erupted into Halemaumau in July did not reduce the pressure within the volcanic reservoir, and by September 1961 the volcano appeared to be capable of imminent eruption. The degree of tumescence of the summit of Kilauea was approaching that which prevailed before the flank eruption of early 1960, and the rate of tumescence was considerably greater than at that time (fig. 3).

At 12^h36^m on September 21 a swarm of large, shallow earthquakes accompanied by strong harmonic tremor began to emanate from the vicinity of Napau Crater on the east rift zone of Kilauea Volcano 7 miles from the summit. The earthquakes and tremor continued through the afternoon; about 30 quakes were reported felt by residents of the National Park and of the small community of Volcano, 2 miles east of the park.

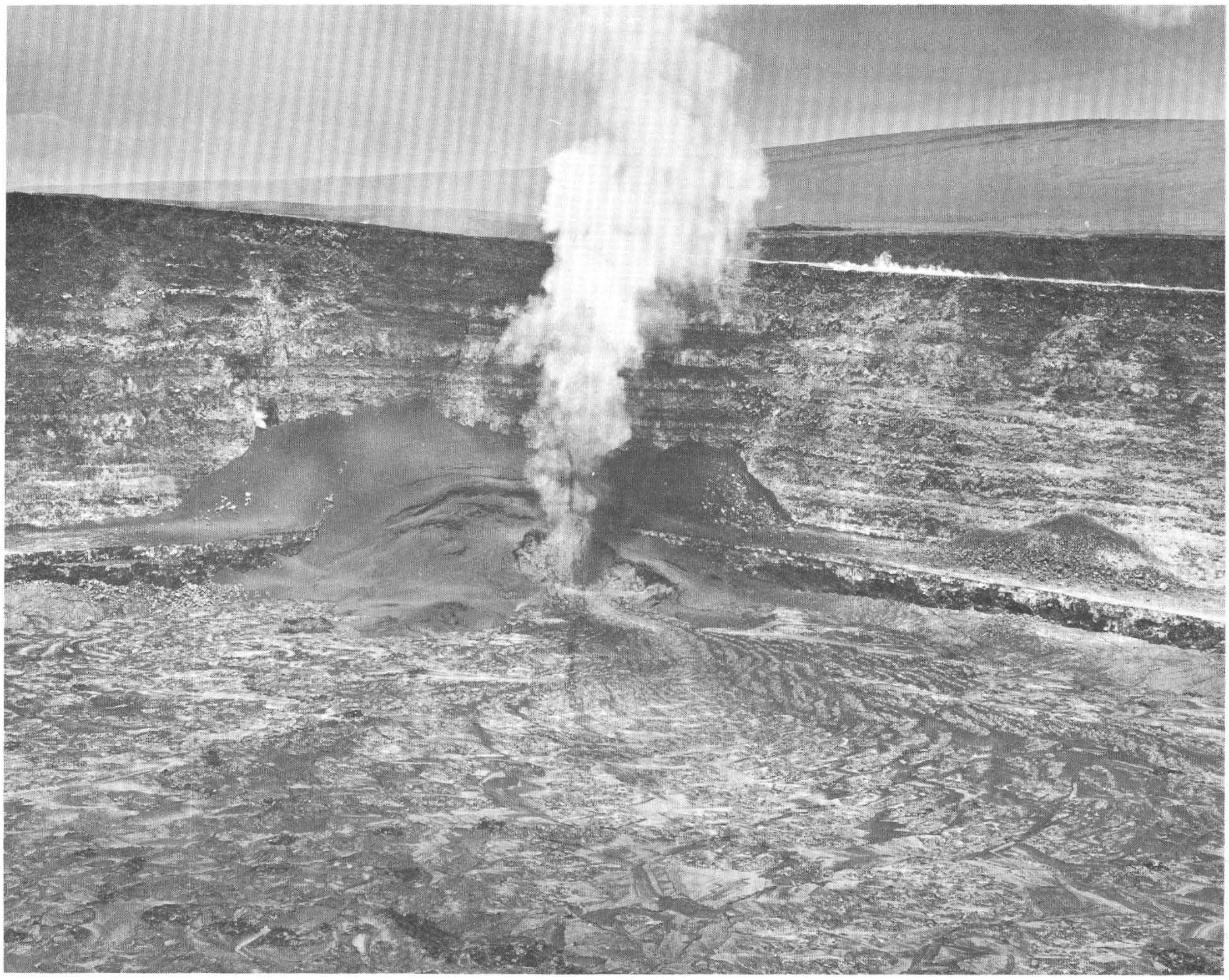

FIGURE 17.—Eruptive activity in Halemaumau crater at approximately 12^h00^m, July 17, 1961. Relatively level lava lake covers 101 acres, and the lava river pouring from base of fountain flows down only a slight gradient. Mauna Loa Volcano is visible on the western horizon. Viewpoint is the same as in figure 12.

By late afternoon the number and intensity of the earthquakes decreased, and the harmonic tremor subsided. A rapid detumescence of the summit of Kilauea appears to have accompanied the earthquakes and tremor. The permanent short-base tiltmeter at Uwekahuna indicated that in the 24 hours from 09^h00^m on September 21 to 09^h00^m on September 22 the summit lost more than one-half the inflation it had undergone during the previous 14 months. Moreover, deflections of the traces of the horizontal-component Press-Ewing seismographs at Uwekahuna indicate that much of this subsidence occurred in 1 hour (fig. 22). These instruments showed marked deflection beginning at 13^h30^m, becoming very rapid at 13^h55^m, and tapering off by 14^h34^m. It was evident that magma was moving rapidly from its reservoir beneath the summit of Kilauea, but the time or location of a possible outbreak could not be determined.

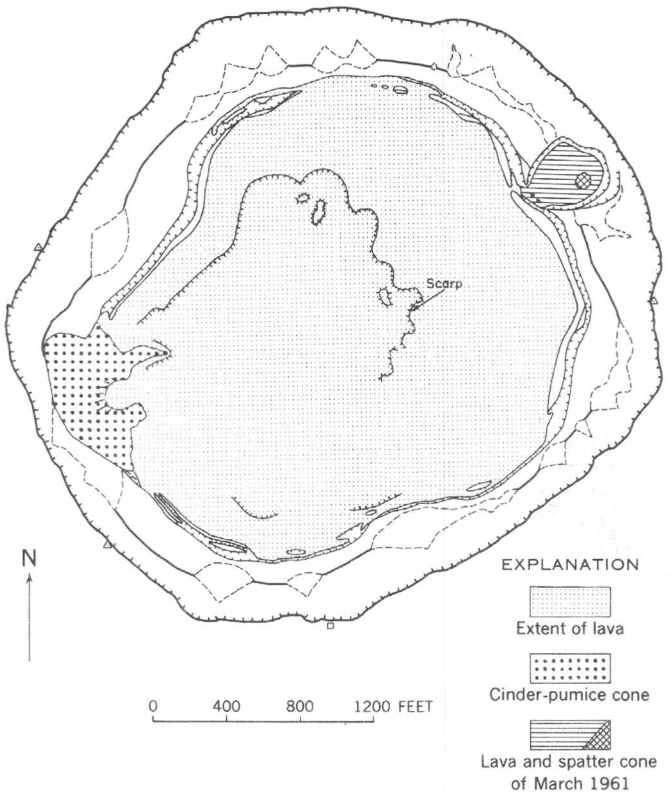

FIGURE 18.—Halemaumau crater on July 18, 1961, at the end of the third summit phase of the 1961 eruption.

Next morning (September 23) before sunrise, a glow in the east was seen by tourists at the Volcano House Hotel and a strong smell of wood smoke, at times mixed with a slight odor of sulfur dioxide pervaded the summit area. Unfortunately, however, most of the summit region and the east rift zone was covered by a low heavy cloud bank. By 06^h45^m the clouds over the area south of the summit had dissipated, and a hazy band of brownish-gray volcanic fume extending southwestward for almost 15 miles was revealed.

The first attempts to locate the apparent outbreak were not successful. Puu Huluhulu, a cinder cone on the upper east rift zone, was climbed at 08^h00^m, and although visibility from its top was less than one-quarter mile owing to heavy overcast, wood smoke and volcanic gases were strong enough to cause eye irritation. Further reports of glow over the east rift zone, the earliest of which was observed at 04^h30^m, soon began to be received at the observatory; and at about 08^h00^m a pilot on a regular tourist flight saw lava fountains, through a break in the clouds, near Kalalua Crater, 12 miles east of the summit. The fountains were feeding a small lava flow moving northward.

Through the cooperation of the Hawaii National Guard, our first flight over the east rift zone, at 12^h00^m, revealed a number of discontinuous fissures, some as long as 1,000 feet, extending from west of Napau Crater to east of Kalalua Crater, a distance of approximately 9 miles (fig. 23; see also fig. 24). There was no lava fountaining, but all fissures were emitting copious steam and blue-tinted volcanic fume, and around three of the fissures small pads of new lava were visible.

At 14^h00^m a ground party reached the westernmost of the steaming fissures between Napau and Makaopuhi Craters. This fissure, a few feet wide and about 700 feet long, was emitting steam and minor volcanic fume. The heat, as well as sulfur deposited by the fume, had killed the vegetation within a few feet of the crack.

As most of the active part of the rift was in nearly impenetrable rain forest, only the westernmost flow of September 22 was examined. However, aerial reconnaissance and photography during the eruption was adequate to map the flows and estimate their volume. Lava had been extruded from six of the newly formed fissures (fig. 24), but the resultant flows were all small; they covered a total of only 16 acres and comprised about 0.15 million cubic yards of new lava. As most of these flows swept through the jungle, the trees were burned off at their bases and the unburned upper parts fell on top of the flow. The result is a thin, shelly pahoehoe flow covered by entangled fallen trees.

On September 22 tremor recorded at the summit abated somewhat, but tremor recorded at Pahoa, near the east rift zone 24 miles from the summit, intensified (fig. 22). At 17^h02^m a large shallow earthquake in the vicinity of Kalapana, 6 miles southeast of Kalalua Crater, rocked the entire island. These events suggested that the next outbreak would be farther down the rift, east of the earlier surface activity.

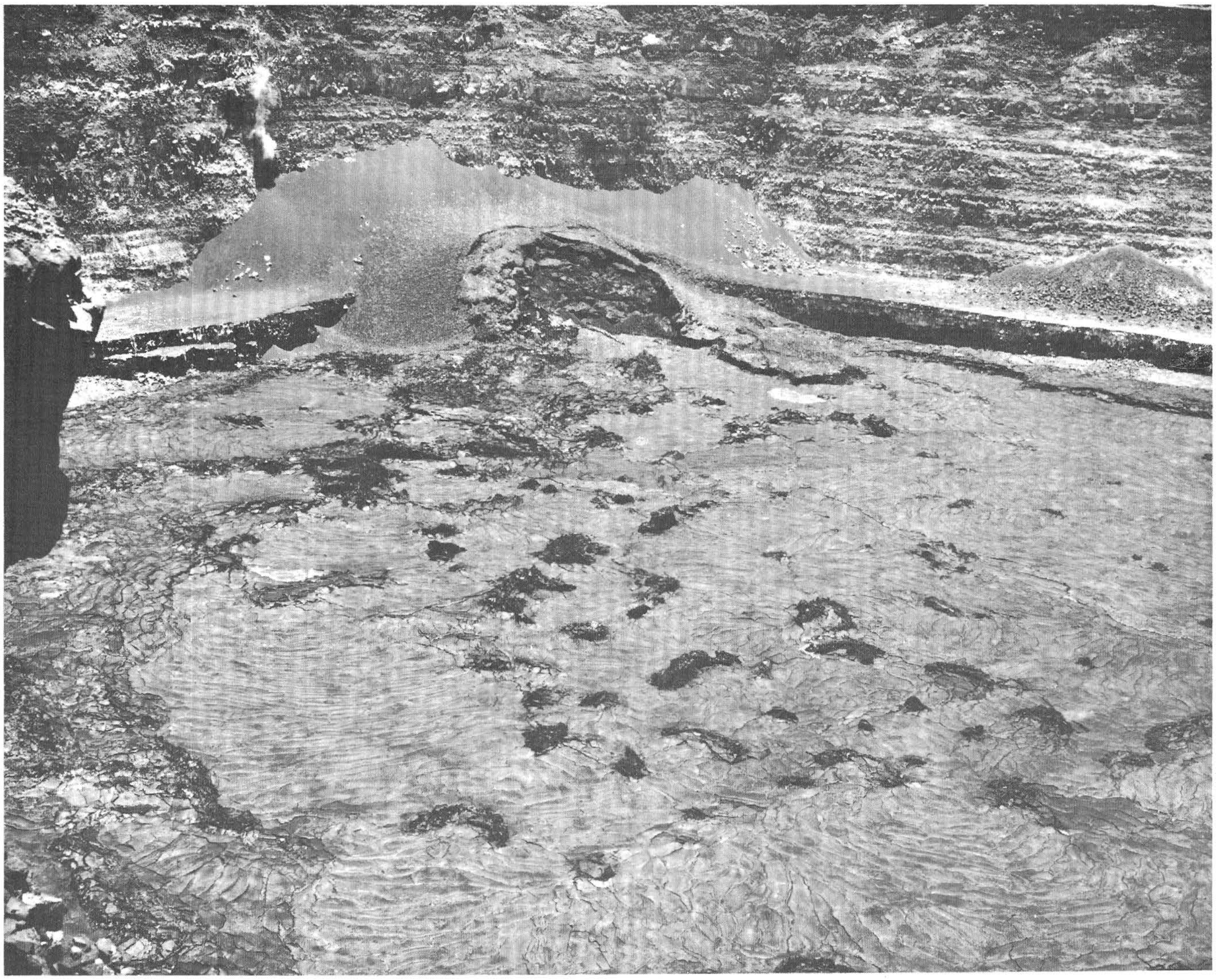

FIGURE 19.—Halemaumau crater at approximately 12^h30^m July 17, 1961, less than 9 hours after the cessation of fountaining. Backflow has lowered the central part of the lake about 15 feet, leaving a number of islands protruding above the surface. Two light-gray areas (near vent and at left center) are fluid lava welling up over the surface. Viewpoint is the same as in figures 12 and 17.

At about 10^h00^m on September 23 a series of audible explosions heralded the resumption of eruptive activity along a discontinuous series of rifts 2½ miles long, centered about 5 miles east of the activity of the preceding day. Most of this activity was very shortlived, as at 10^h20^m the only fountains observed from the air were along a single eruptive fissure, more than 700 feet long, northwest of Heiheiahulu Crater (fig. 24). When first seen, these fountains were small, but by 10^h30^m they were shooting to heights of 300 to 400 feet (fig. 25). From the fountains, thin but voluminous lava flows began to spread rapidly through the dense forest and down both the north and south flanks of a slight ridge which marks the east rift zone in this area. At 12^h30^m the Civil Defense Agency ordered evacuation of towns along the seacoast south of Pahoa. Most of the lava poured back into a large sumplike crack several hundred feet southeast of the eruptive rift, however, and no extensive flow resulted.

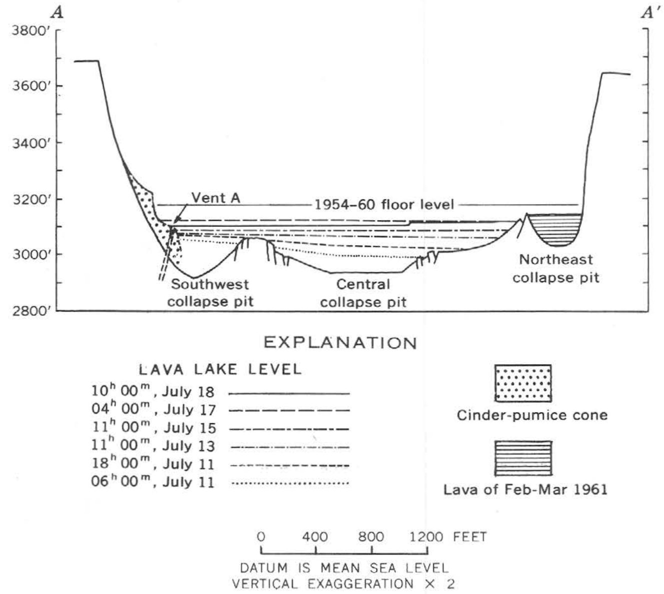

Figure 20.—Cross section of Halemaumau along *A–A′* of figure 2 showing formation of the lava lake during the third summit eruptive phase.

The strong fountaining near Heiheiahulu Crater ceased about 01^h00^m on the morning of September 24. At this time harmonic tremor subsided at all the seismograph stations on Kilauea, and the rift zone was relatively quiet. Reconnaissance from a helicopter later in the morning revealed no activity along any of the erupting rifts of the preceding day, except the emission of volcanic fume. In the large fountain area (fig. 25) the vent fissure was brightly incandescent for a distance of about 600 feet, but elsewhere the vents were dark.

Six new lava flows, covering a total of approximately 175 acres, were produced during the September 23 activity. For convenience in description, the three largest are called, from west to east: Heiheiahulu flow (148 acres, Kaumuki flow (16 acres), and Jonika flow (9 acres). (See fig. 24.) Associated with the flows throughout this part of the rift zone are a large number of new cracks and faults, many of which discharged only volcanic fume. The largest of these faults can be detected on aerial photographs of the region taken shortly after the eruption, and, where they produced displacements large enough to be seen clearly, they outline a series of grabens parallel to the rift zone.

Lava tree molds, some standing 14 feet high, are abundant on the flows of September 23. They were produced where fluid lava flowing through the forest became chilled around the larger trees. After most of the lava drained away and the lava surface was lowered, the vertical molds around the trees, most of which had burned away, remained standing. The tree molds are especially well preserved on the Jonika flow and have been described in another paper (Moore and Richter, 1962).

Activity resumed again at about 14^h15^m on September 24, when a number of small lava fountains began to play from a 500-foot-long fissure 1 mile northeast of Kalalua Crater and southwest of the activity of the previous day (fig. 24). The fountains were generally less than 50 feet high, and most of the lava fell back into the vent or onto the flanks of the two small elongated cones which were built up. Later in the evening a short-lived series of large shallow earthquakes originating in the Kalapana area (fig. 1) shook the island. Three of these quakes were felt over the entire island, and the largest, at about 19^h30^m, had a magnitude of 5.5.

By early next morning (September 25) the eruption was over. Minor displacement on the faults at the east end of the eruptive area continued at a decreasing rate for a few days, and great amounts of steam and fume boiled from the vents for at least 2 weeks. The rapid and dramatic subsidence of the summit, which resulted from the withdrawal of about 70 million cubic yards of magma, halted very abruptly on September 25 more or less contemporaneously with the cessation of fountaining (fig. 22).

VOLUME AND RATE OF EXTRUSION OF LAVA

The total volume of lava extruded during all four phases of the 1961 eruption was approximately 21.2 million cubic yards (table 1). However, both during and immediately after most of the eruptive phases, part of the lava, totaling about 2.9 million cubic yards, was withdrawn, leaving a net accumulation of approximately 18.3 million cubic yards of new lava on the surface. The greatest accumulation occurred during the week-long third summit phase, when 17.3 million cubic

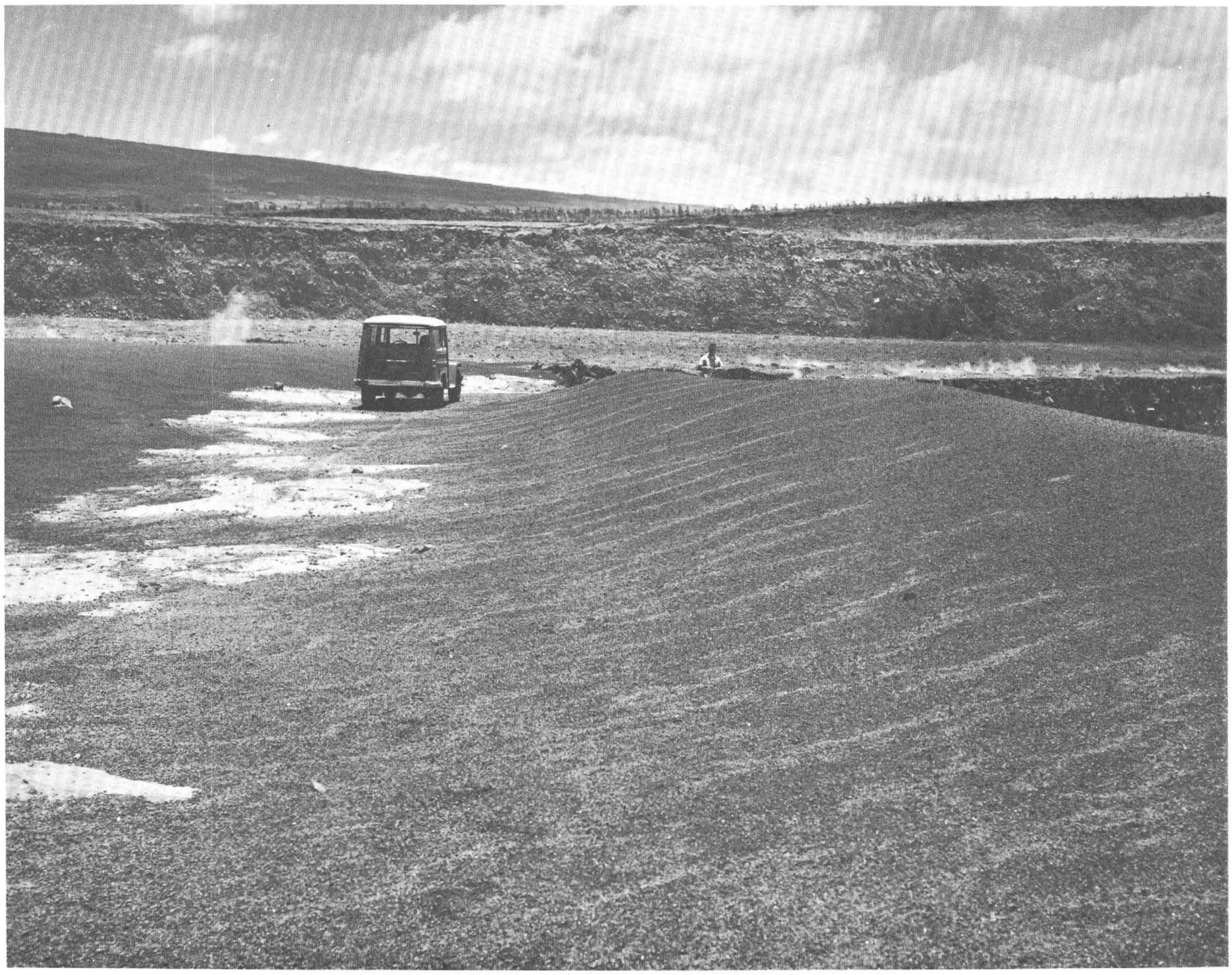

FIGURE 21.—Drifts of pumice along the southwest rim of Halemaumau (right) on the floor of Kilauea caldera. Kilauea caldera wall is visible in the background.

yards, or about 82 percent of the total volume extruded during the entire eruption, filled the bottom of Halemaumau. The 1.9 million cubic yards of lava remaining on the surface after the 3-day flank phase is distributed among 13 small flows scattered along a 12-mile segment of the east rift zone. Of this amount, more than 90 percent (1.7 million cubic yards) is in the six flows extruded on September 23, the second day of flank eruptive activity. The Heiheiahulu flow of September 23, largest of the flank flows, contains about 1.5 million cubic yards, more than three times the volume of lava in the other 12 flows.

The rate of lava extrusion varied considerably between different eruptive phases, but, with the exception of the flank eruption with its many outbreaks, it was fairly constant during a given phase. Table 2 shows

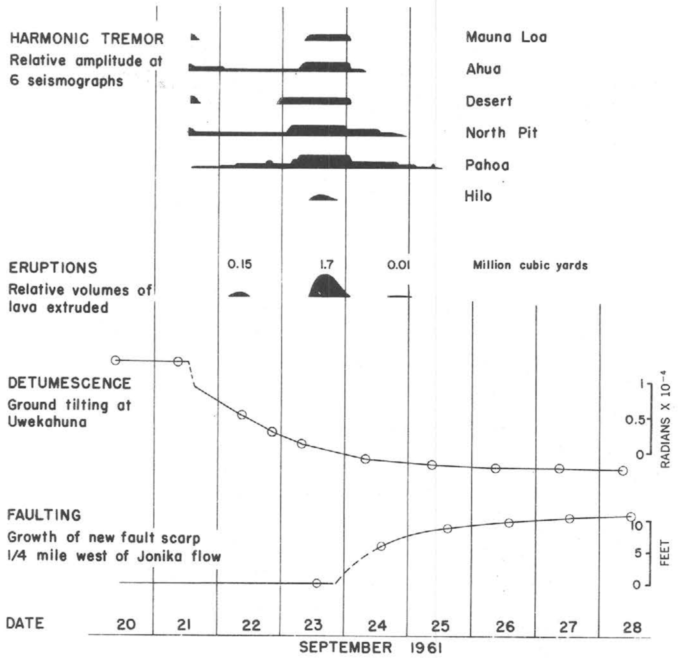

Figure 22.—Chronology of events during the September 1961 flank eruption.

the volume and rate of lava extrusion and withdrawal as measured daily by vertical angles from the rim of Halemaumau for the third summit phase. Rates of extrusion based on these daily measurements ranged from 74,000 to 149,000 cubic yards per hour; the average rate over the entire week was 114,000 cubic yards per hour. This rate, which was the highest measured for

Table 1.—*Volume and rate of lava extrusion during the 1961 eruption of Kilauea*

	Volume of lava extruded (cubic yards)	Average rate of extrusion (cubic yards per hour)	Volume of lava withdrawn (cubic yards)	Volume of lava remaining on surface (cubic yards)
First summit phase (07h07m–15h08m, Feb. 24, 1961)	320,000	40,000	290,000	30,000
Second summit phase, (22h00m, Mar. 3–20h00m, Mar. 25, 1961)	350,000	660	0	350,000
Third summit phase (20h15m, July 10–03h50m, July 17, 1961)	17,300,000	114,000	1,300,000	16,000,000
Flank phase (04h30m, Sept. 22–Sept. 25, 1961)	[1] 3,200,000	------------	[1] 1,340,000	1,860,000
Total	21,170,000	------------	2,930,000	18,240,000

[1] Based on visual estimates only.

any comparable length of time during the eruption, is similar to extrusion rates observed in past Halemaumau eruptions. The lowest average extrusion rate, on the other hand, was 660 cubic yards per hour during the relatively feeble 3-week-long second summit phase. Except for the periods of lava lake activity in Halemaumau prior to 1924, this extremely low rate is probably unique for a complete eruptive phase in the recorded history of Kilauea.

Table 2.—*Volume and rate of lava extrusion and withdrawal during the third summit eruptive phase*

[Eruption began at 20h15m on July 10]

Date	Time	Duration since last measurement (hours)	Volume (cumulative) of new lava	Volume (cumulative) of lava withdrawn	Average rate (cubic yards per hour)
			Cubic yards		
July 11	10h00m	13¾	2,000,000	0	145,000
12	10h00m	24	5,400,000	0	142,000
13	11h00m	25	7,800,000	0	96,000
14	12h00m	25	10,100,000	0	92,000
15	11h00m	23	11,800,000	0	74,000
16	11h00m	24	14,800,000	0	125,000
17	03h50m	16¾	17,300,000	0	149,000
17	10h00m	6¼	16,500,000	800,000	128,000
18	10h00m	24	16,000,000	1,300,000	21,000
For period of extrusion only	------------	151½	17,300,000	------------	114,000

During the flank phase, visual estimates of the rate of extrusion range from a few thousand to 200,000 cubic yards per hour for the different eruptive rifts. The most voluminous outpouring of lava, 200,000 cubic yards per hour at the Heiheiahulu vents, which continued for about 15 hours, is similar to rates measured during the 1960 and 1955 flank eruptions of Kilauea.

Backflow of lava into source vents and other fissures was common during all but the second summit phase. In the first summit phase about 90 percent of the extruded lava poured back into the eruptive vents within a few hours after the cessation of activity. During the flank phase lava disappeared below the surface apparently at all the major outbreaks. Most of the backflow occurred along cracks and fissures that paralleled the structural grain of the rift zone but which were generally unrelated to the immediate source vents. Some of these cracks and fissures marked fault scarps adjacent to the eruptive rift, but many were long open tension cracks that showed no evidence

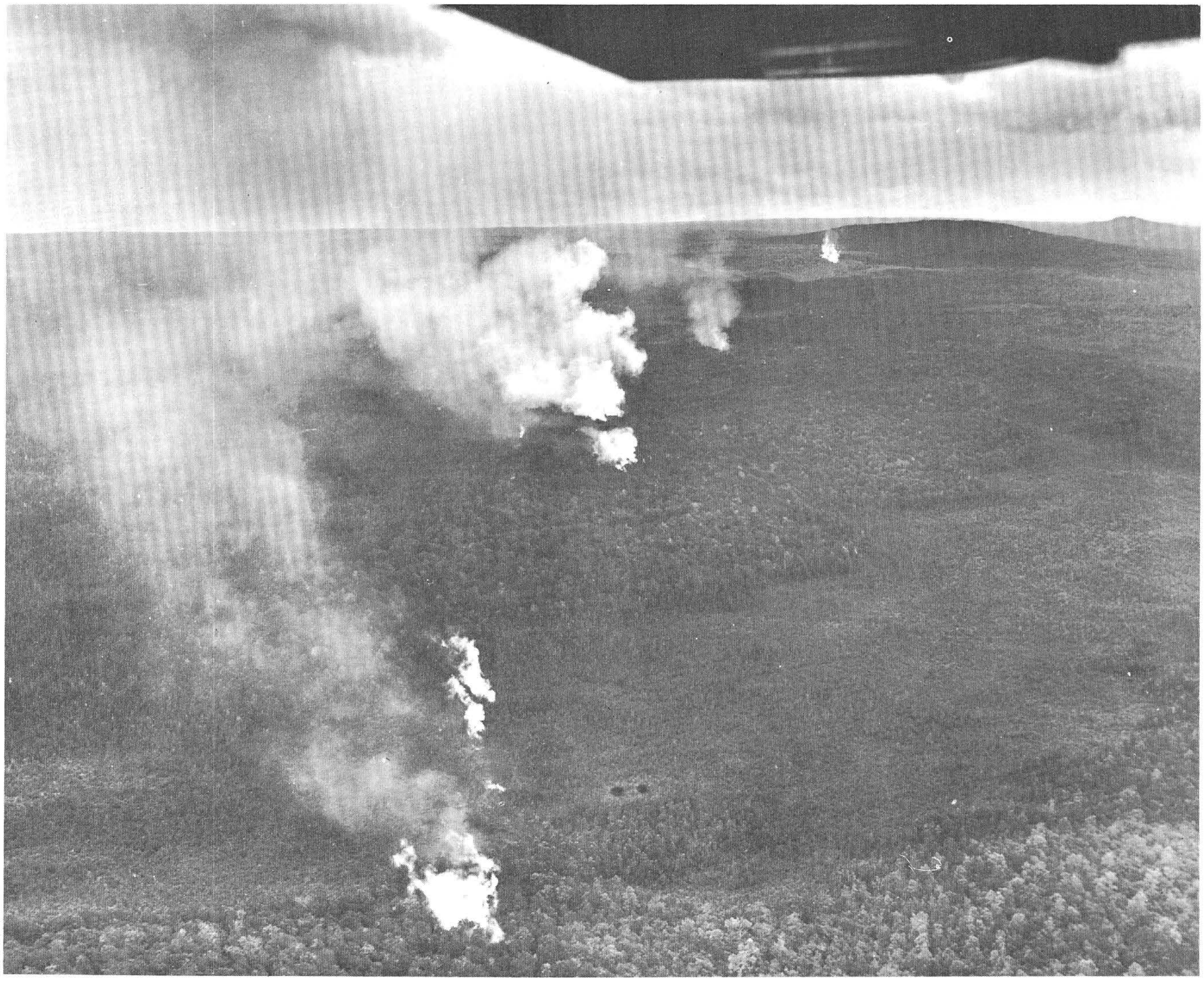

FIGURE 23.—Aerial view toward the southwest, photographed directly above Kalalua crater, showing the upper part of the active zone along Kilauea's east rift zone at 12^h00^m on September 22. The low secondary lava cone, Kane Nui o Hamo, is visible just below the skyline on right, and Napau Crater is between the two farthest vents. Note the en echelon arrangement of the vents.

of vertical or lateral movement. Maximum backflow occurred at the Heiheiahulu outbreak, where the rate of withdrawal appeared to equal the rate of extrusion during the greater part of the eruption.

TEMPERATURE OF THE LAVA

Temperatures of the erupting lava were measured throughout the three summit eruptive phases by two incandescent filament-type optical pyrometers. No measurements were made during the flank phase owing to the inaccessibility of the eruptive vents. All observations of the summit eruptions, with the exception of those of the first phase, were made at night from the rim of Halemaumau, at a distance of 600–800 feet from the vents. The observed temperatures are listed in table 3. No corrections have been made for adsorption between fountain and pyrometer or for emissivity

TABLE 3.—*Lava temperatures during 1961 eruption of Kilauea*

Eruptive period	*Temperature (°C)*
First summit phase	1,095–1,125
Second summit phase	1,096–1,114
Third summit phase	1,085–1,127

of the lava, and abnormally low readings resulting from visible fume or mist between the pyrometer and the vent have been omitted.

Lava temperatures in the short first summit phase were necessarily measured during daylight hours. Although care was exercised to read temperatures only when the lava fountains were in the shade, the temperatures listed may be slightly high because of reflected sunlight. During the second summit phase, conditions were excellent for optical pyrometer measurements. The boiling caldron of lava over the vent, with a relatively small orifice opening to the surface, formed a nearly perfect cavity-type black body. Temperatures of lava in the third summit phase were measured in the core of the lava fountain where heat loss by radiation was held at a minimum (Ault and others, 1961).

As discussed in the following section on petrography, the temperature range of 1,085°–1,127° C for the summit lavas seems to correlate closely with their chemistry and mineralogy. Throughout the brief first phase and the much longer second summit phase there was no observed variation in temperature with time. However, the possibility of consistently high measurements during the first phase and the lack of measurements, owing to poor visibility, through the early part of the second phase may have precluded the detection of any systematic temperature change. In the more voluminous third phase, the range of temperatures increased from 1,085°–1,087° C during the first 4 hours of eruption to 1,106°–1,127° C during the rest of the eruption. This change apparently resulted from the withdrawal of heat from the early lava as it rose to the surface through the relatively cool rocks in the higher part of the volcanic edifice.

PETROCHEMISTRY

The lavas of the 1961 eruption are tholeiite basalts and tholeiite olivine basalts. The distinction between the two types is based chiefly on the amount of modal olivine present as phenocrysts; those lavas containing less than 5 percent olivine are called basalts, whereas those containing more than 5 percent olivine are called olivine basalts (Macdonald, 1949). Although none of the 1961 lavas examined were completely devoid of olivine phenocrysts, the olivine content in the lavas erupted at the summit is less than one-half of 1 percent by volume. The groundmass of the lavas erupted during the flank activity and the related pyroclastic ejecta

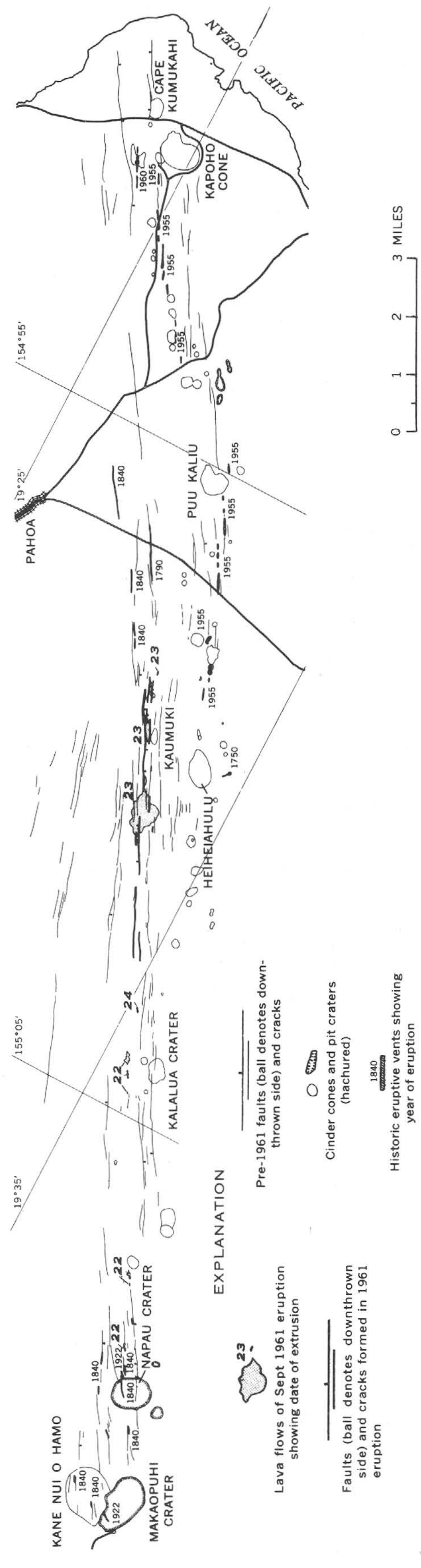

FIGURE 24.—Map of part of the east rift zone of Kilauea showing the historic eruptive vents as well as the 1961 vents and faults. Map was compiled from aerial photographs.

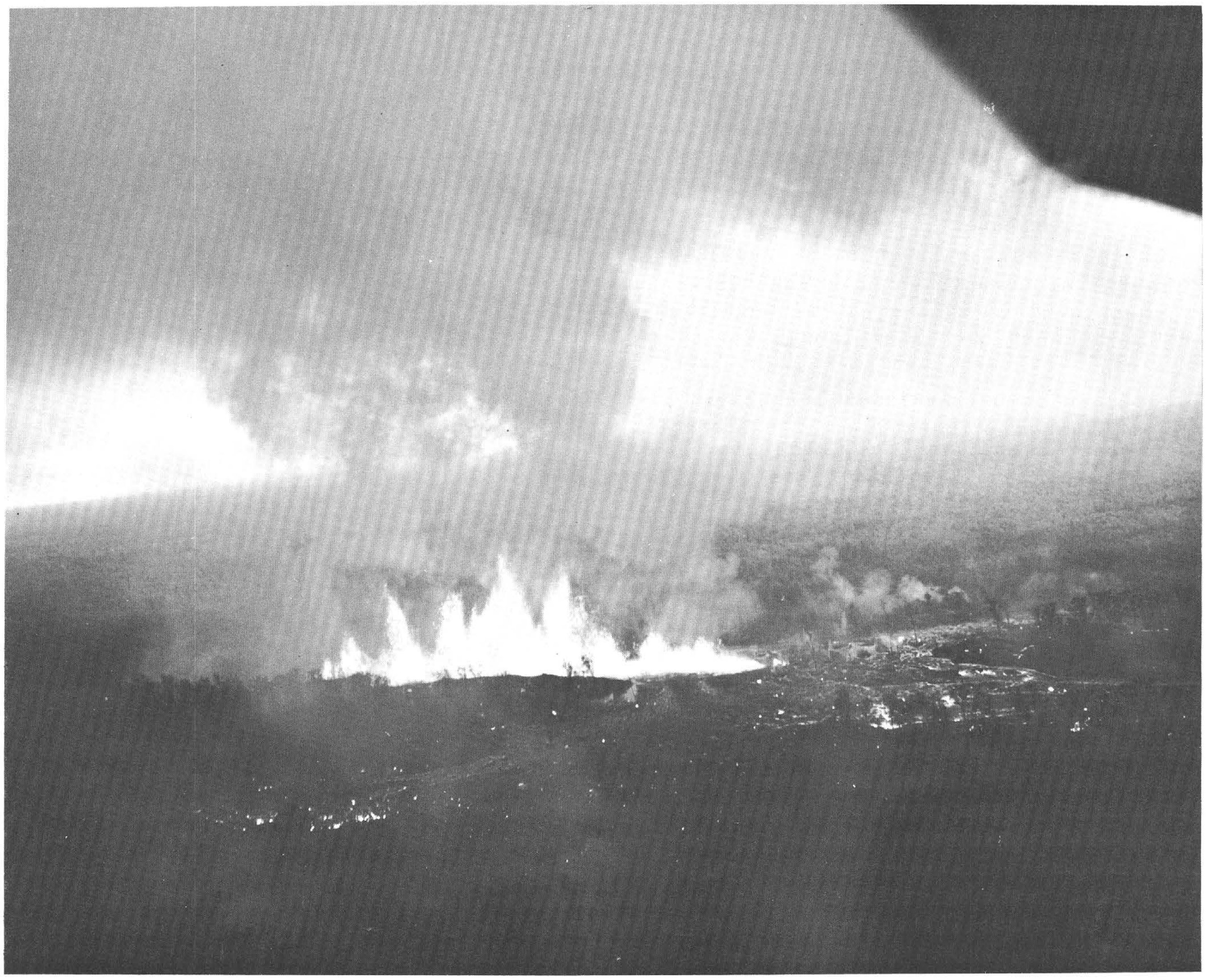

FIGURE 25.—Lava fountains 300 feet high at the Heiheiahulu flow, 17^h00^m on September 23. Note trees burning around the active margin of the flow.

from both the summit and flank activity range from completely glassy in the pumice and in rapidly cooled tops of flows to intersertal in more slowly cooled interiors of flows. Very small laths of plagioclase and small poorly formed stubby prisms of clinopyroxene constitute the groundmass minerals. No hypersthene was observed in any of the sections studied.

Eight new chemical analyses—four from the first and third summit eruptive phases and four from the flank eruptive phase—are presented in table 4, together with the calculated norms for all the analyzed samples and the modal olivine content for the flank lavas.

The summit lavas, as indicated by the chemical analyses of pumice thrown up on the rim of Halemaumau by the lava fountains, are all very similar in composition. A subtle difference in content of SiO_2, Al_2O_3, and MgO between the lavas of the first and third summit phases may reflect changes caused by the removal of minor olivine or the assimilation of feldspar and glass, or a combination of both. Within the week-long third summit phase, however, there was virtually no change in the composition of the 17.3 million cubic yards of lava erupted. Samples collected a few hours after the beginning of eruption (analysis 2, table 4), during the middle of the eruption (analysis 3, table 4), and within a few hours of the cessation of activity (analysis 4, table 4), do not vary in silica composition by more than 0.03 of 1 percent and for all intents and purposes are identical in this respect. Thin sections of the pumices of the third summit phase reveal a few small (as much as 1 mm in diam.) phenocrysts and microphenocrysts of sharply euhedral olivine (Fa_{14}); heavy-mineral concentrates from crushed bulk samples of the pumice contain a few small crystals of clinopyroxene as well as olivine. Smaller bulk samples of pumice from the first summit phase also contained olivine phenocrysts of approximately the same composition as those in pumice of the third phase, but they apparently were lacking in clinopyroxene.

TABLE 4.—*Chemical analyses, norms and modal olivine of lavas from the 1961 eruption of Kilauea*

[Analysts: E. L. Munson (samples 1–4) and C. L. Parker (samples 5–8)]

	1	2	3	4	5	6	7	8
Chemical analyses								
SiO_2	50.22	50.36	50.39	50.39	50.26	50.38	49.96	50.22
Al_2O_3	13.64	13.70	13.69	13.69	13.87	13.68	13.30	13.28
Fe_2O_3	1.29	1.44	1.41	1.28	2.94	3.36	2.75	1.69
FeO	9.63	9.54	9.59	9.68	8.62	8.06	8.73	9.70
MgO	7.74	7.54	7.49	7.53	6.75	7.30	8.56	8.44
CaO	11.34	11.31	11.36	11.36	10.88	10.57	10.34	10.28
Na_2O	2.32	2.36	2.33	2.31	2.45	2.45	2.34	2.39
K_2O	.55	.54	.53	.54	.59	.59	.57	.59
H_2O+	.04	.00	.02	.04	.02	.01	.04	.06
H_2O-	.04	.01	.01	.00	.02	.03	.02	.01
TiO_2	2.76	2.77	2.76	2.78	3.04	3.02	2.91	2.92
P_2O_5	.27	.27	.27	.27	.30	.30	.25	.26
MnO	.17	.17	.17	.17	.18	.17	.18	.18
CO_2	.01	.01	.00	.01	.05	.01	.01	.02
Cl	.02	.02	.02	.02	.02	.02	.02	.01
F	.04	.04	.04	.03	.04	.04	.04	.04
	100.08	100.08	100.08	100.10	100.03	99.99	100.02	100.09
Less O	.03	.03	.03	.02	.02	.02	.02	.02
Total	100.05	100.05	100.05	100.08	100.01	99.97	100.00	100.07
Norms								
Q	0.00	0.96	0.96	1.02	2.88	3.36	1.32	0.18
Or	3.34	2.78	2.78	2.78	3.34	3.34	3.34	3.34
Ab	19.91	19.91	19.91	19.39	20.96	20.96	19.91	20.44
An	24.74	25.30	25.30	25.58	25.02	24.46	23.91	23.63
Di	24.23	23.31	23.80	23.58	21.89	20.80	20.36	20.73
Hy	19.99	19.56	19.22	19.82	14.99	15.43	20.84	23.05
Ol	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
Mt	1.86	2.09	2.09	1.86	4.18	4.87	4.18	2.55
Il	5.32	5.32	5.32	5.32	5.78	5.78	5.47	5.47
Ap	0.67	0.67	0.67	0.67	0.67	0.67	0.67	0.67
	100.06	99.90	100.05	100.02	99.95	99.90	100.00	100.06
Modal olivine								
Ol	(1)	(1)	(1)	(1)	0.3	0.4	5.1	7.3

1. Tholeiitic basaltic pumice erupted Feb. 24, 1961, from Halemaumau.
2. Tholeiitic basaltic pumice erupted 02^h00^m, July 11, 1961, from Halemaumau.
3. Tholeiitic basaltic pumice erupted 12^h00^m, July 13, 1961, from Halemaumau.
4. Tholeiitic basaltic pumice erupted 13^h00^m, July 16, 1961, from Halemaumau.
5. Tholeiitic basalt erupted Sept. 22, 1961, Kilauea east rift zone, 9 miles from summit (lava flow one half mile northeast of Napau Crater).
6. Tholeiitic basalt erupted Sept. 23, 1961, Kilauea east rift zone, 17 miles from summit (Heiheiahulu lava flow).
7. Tholeiitic olivine basalt erupted Sept. 23, 1961, Kilauea east rift zone, 18 miles from summit (Kaumuki lava flow).
8. Tholeiitic olivine basalt erupted Sept. 23, 1961, Kilauea east rift zone, 19 miles from summit (Jonika lava flow).

[1] Not determined.

Lavas from the flank eruptive phase, on the other hand, are markedly different from those extruded during the summit phases and, as a group, show an indistinct but apparently systematic change along the rift zone. The flank lavas are higher in total iron, titania, and soda and are lower in lime than the summit lavas of similar silica content. This difference is also reflected in the norms of the two groups, as magnetite, ilmenite, and albite are richer and diopside is poorer in the flank lavas. The systematic change in composition of the flank lavas along the rift zone is best shown by the progressive increase in normative hypersthene and modal olivine away from the summit. At the westernmost flow (analysis 5, table 4), just east of Napau Crater (fig. 24), the lavas are macromineralogically similar to those erupted at the summit but contain only 15 percent normative hypersthene. Nine miles farther down the rift, at the Heiheiahulu flow (analysis 6, table 4), both modal olivine and normative hypersthene are slightly more abundant; some of the olivine phenocrysts are as much as 4 mm in diameter. At the Kaumuki (analysis 7, table 4) and Jonika (analysis 8, table 4) flows along the extreme east end of the 1961 outbreak zone, the increase in olivine content and normative hypersthene is even greater. In the Jonika flow, where conspicuous phenocrysts of olivine as large as 5 mm in diameter constitute more than 7 percent by volume of the lava, normative hypersthene reaches a maximum of 23 percent. Some of the larger olivine phenocrysts in the Jonika and Kaumuki flows appear to have undergone incipient resorption around their margins but most are euhedral and a few of the smaller phenocrysts are skeletal. The fayalite content of the olivine decreases from Fa_{18} at the westernmost flow to Fa_{12} in the larger phenocrysts at the Jonika flow. As in the westernmost flow, however, the smaller skeletal olivine phenocrysts in the Jonika and Kaumuki flows may represent a more fayalitic olivine phase. Microphenocrysts of clinopyroxene (approx, $Wo_{40}En_{50}Fs_{10}$) and plagioclase feldspar (An_{60-64}) are present in all the flank lavas in amounts ranging from a few tenths of 1 percent to 3 percent by volume.

The difference in composition between the flank and summit lavas and the change in composition of the flank lava with respect to distance from the summit is well shown on the CaO variation diagram on figure 26. CaO was chosen as a reference base (abscissa) in the variation diagram because of its relatively wide range in the 1961 lavas (10.28–11.36 percent) and its sensitivity to slight changes in olivine content. Superposed on the diagram are the control lines[1] for olivine (Fa_{15}), augite ($Wo_{40}En_{49}Fs_{11}$), and plagioclase (An_{63}); the augite-plagioclase control "field" is stippled. Assuming that the lava erupted during the third and final summit phase represents the "parental" magma of the flank lavas, one may conclude from the variation diagram that the compositional shift between the last summit lavas (large open circle) and first flank lava (No. 5) could not have been brought about by either the

[1] Compositions of the control minerals are from the following sources: Olivine, Murata and Richter (1961, table 1, analysis 10); augite, Muir and Tilley (1957, table 4, analysis 4a); plagioclase, Hess (1960, table 10, analysis EB–41).

addition or loss of olivine. The shift does, however, appear to be controlled by the removal of augite and minor plagioclase. On figure 26 the field between the augite and plagioclase control lines indicates the effect which removal, or addition, of a mixture of these two constituents will have on a liquid similar in composition to the lavas of the third summit phase. Upon removal of a mixture of augite and plagioclase, the composition of the resultant liquid will shift away from the augite and plagioclase compositions (to the left) along a line which, if extended back (to the right), lies in the control field. Regardless of the width of the control field, the shift due to augite-plagioclase removal is remarkably consistent and indicates that the proportion (roughly 5 to 1, augite to plagioclase) of these two minerals removed from the system was constant. Furthermore, the diagram also shows the nature and plausible mineralogic control of the chemical changes within the flank lavas. Invariably, the plots showing oxide in relation to CaO form a straight line parallel to the olivine control line. Clearly, these data, together with the norms and olivine modes of the flank lavas, show that the magma feeding the flank eruptions became progressively enriched in olivine at lower elevations away from the summit.

In spite of the extremely limited range in silica content (49.96–50.39 percent) in the 1961 lavas, a similar chemical-mineralogical relation between the summit and flank lavas is evident on the normal SiO_2 variation diagram shown on figure 27. Again, as with the CaO variation diagram, the compositional shift between the late summit lavas and first flank lavas cannot be attributed to olivine control but rather to the removal of augite and minor plagioclase. As would be expected with such slight variations in silica content, the changes in composition within the flank lavas are not too clearly defined or orderly. Trend lines for CaO, $FeO+Fe_2O_3$, Na_2O and TiO_2 do, however, parallel their respective olivine control lines, but for Al_2O_3 and MgO the scatter is too great to reliably determine any trend.

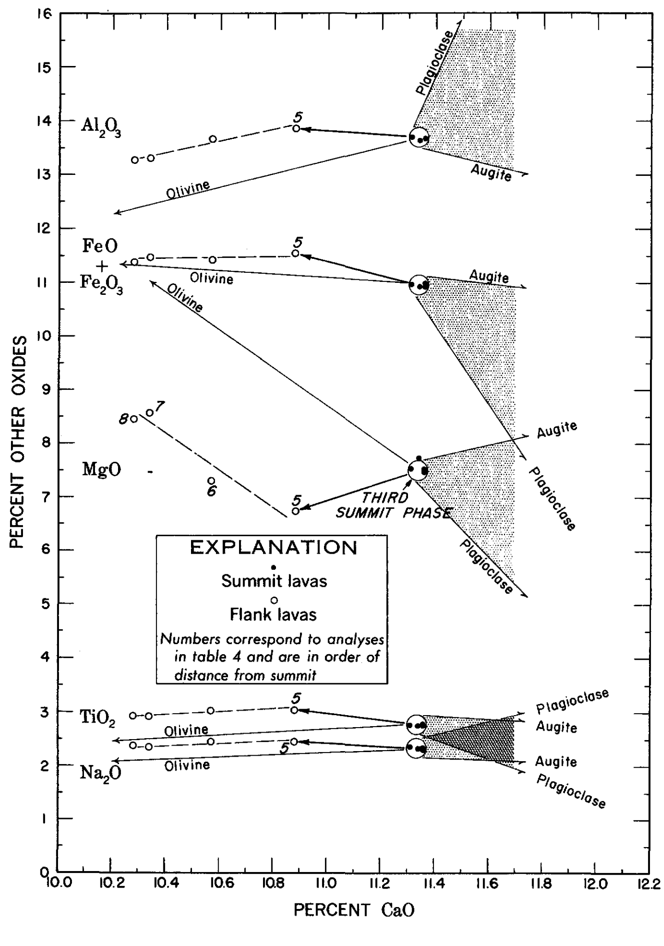

FIGURE 26.—CaO variation diagram of 1961 lavas showing the olivine, augite, and plagioclase control lines. Stippled area denotes control "field" of mixtures of augite and plagioclase. Heavy arrow shows shift in composition from last summit lavas to first flank lavas, and dashed line denotes trend of flank lavas.

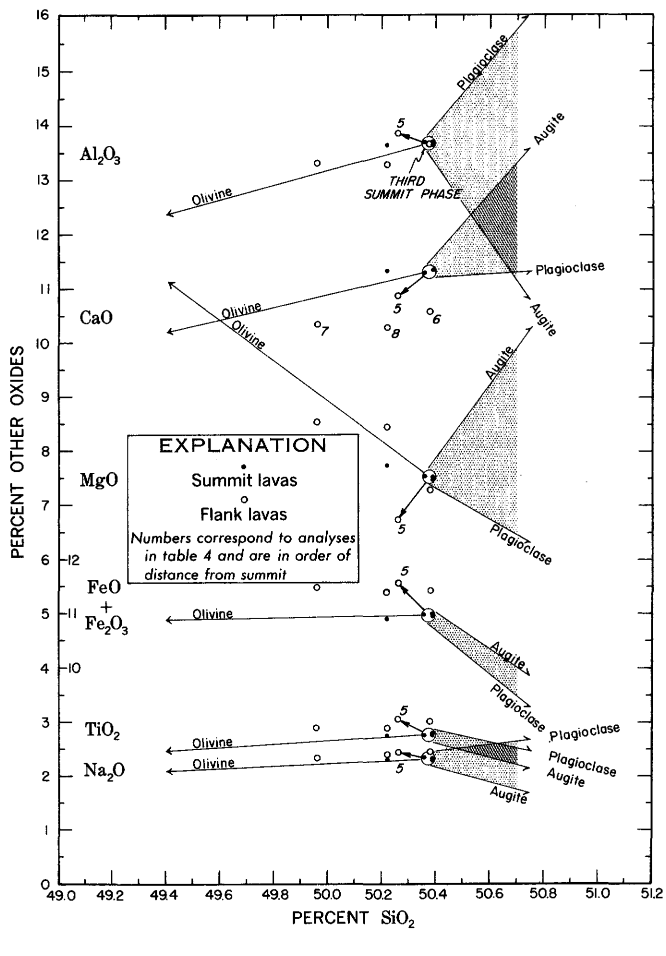

FIGURE 27.—SiO_2 variation diagram of 1961 lavas showing the olivine, augite, and plagioclase control lines. Stippled area denotes control "field" of mixtures of augite and plagioclase. Heavy arrow shows shift in composition from last summit lavas to first flank lavas.

From the evidence shown on the variation diagrams, the following three steps are postulated to have taken place in the differentiation of the 1961 lavas.

1. Removal of early-formed magnesian olivine from magma in upper part of magma reservoir.
2. Removal of augite and minor plagioclase from olivine-poor magma produced in step 1.
3. Addition of magnesian olivine-rich magma to magma produced in step 2.

The first step in the differentiation scheme affected the composition of both the summit and flank lavas; the second step accounts for the characteristic compositional difference between the summit and flank lavas; and the third step is responsible for the range in composition of the flank lavas.

It is not unreasonable, in view of the many analyses now available of Kilauean lavas, to assume that the primary magma within the shallow reservoir beneath the summit of Kilauea which fed the 1961 eruptive vents was of the appropriate composition (49–50 percent SiO_2, 8–10 percent MgO) to induce crystallization of relatively large amounts of magnesian olivine. Between September 1960 and the flank eruption in September 1961, during which time the shallow magma reservoir was rapidly filling, olivine evidently began to crystallize and sink, and so the upper part of the reservoir was depleted of olivine (step 1). This upper part was then tapped by the summit eruptions in February, March, and July 1961, without undergoing any further marked differentiation.

The differentiation which brought about the change in composition of the flank lavas very likely occurred during the early period of magma transit through the relatively cool rocks of the upper part of the rift zone. During passage along the 10- to 20-mile-long course, the magnesian olivine-free magma continued to crystallize in a normal manner. As temperatures decreased, first augite and then plagioclase, both accompanied by minor amounts of increasingly fayalitic olivine, began to appear as crystalline phases in the magma. Most of the augite and some of the plagioclase were apparently removed somewhere in transit; therefore, the flank lavas are relatively poor in lime and rich in iron and titania, as compared with the summit lavas (step 2). This same type of differentiation has been invoked by Tilley and Scoon (1961) to explain the evolution of flank lavas of the 1955 Kilauea eruption. The nature of the mechanism which isolated these phases from the system, however, remains obscure. The removal of augite and minor plagioclase might have been caused by gravity settling, or by the formation of a rind—on the cold walls of the conduit—enriched in the higher melting phases, particularly in augite, calcic plagioclase, and minor olivine.

The last changes in the composition of the flank lavas are due principally to olivine control (step 3). Evidently as the flank eruption continued, and more and more magma moved down the east rift zone toward the vents, the deeper olivine-rich parts of the magma reservoir beneath the summit were tapped. Mixing of this olivine-rich magma with the early flank magma affected most of the lava extruded along the flank, the lava becoming progressively more mafic away from the summit while still reflecting the change caused by the removal of augite and plagioclase.

Although the changes in composition due to olivine control (step 3) during the 1961 eruption are subtle, they are apparently somewhat analogous to the changes that occurred in the 1840 eruption of Kilauea, in which the lavas erupted near the summit were generally olivine poor and those erupted at lower elevations along the east rift zone were olivine rich. Macdonald (1944) has proposed that the upper 1840 vents tapped higher parts of the magma chamber from which olivine had been lost by gravity settling, whereas the lower 1840 vents were fed by magma enriched in olivine from the lower part of the chamber. In part, this same phenomenon was observed during the summit phase (Kilauea Iki) of the 1959–60 eruption, in which the lavas changed from olivine poor to olivine rich in the first 3 days of eruption (Murata and Richter, 1962). During this early 3-day period the lavas were very similar in temperature (1,075°–1,130° C) and in composition (49.6–50.1 percent SiO_2) to the 1961 summit lavas. After the first 3 days of the 1959 eruption, the temperature increased rapidly, the SiO_2 content decreased, and phenocrystic olivine became very abundant. Thus it appears that the upper part of the Kilauea magma reservoir, which erupts first, has been depleted of MgO and enriched in SiO_2 by the early crystallization and settling of olivine. In the 1961 eruption, olivine-rich lavas were not erupted at the summit because the eruption ceased before the deeper magmas were tapped. However, olivine-rich material was eventually tapped and erupted during the flank phase, but only after other compositional changes, brought about by the removal of augite and plagioclase, had occurred during the passage of magma through the relatively cool rift conduits leading from the summit reservoir to the site of the flank outbreak.

GROUND MOVEMENTS DURING FLANK PHASE

During the period of tremor which preceded the actual eruptive outbreak, the entire summit region of Kilauea subsided, presumably because the magma stored in the reservoir beneath the caldera moved eastward within the rift zone. The fact that much of this subsidence occurred within 1 hour indicates that draining of the reservoir was extraordinarily rapid. The magnitude of subsidence at the summit of the volcano is equal to a decrease of volume of about 70 million cubic yards; presumably this decrease in volume was due to the withdrawal of that much magma from below the summit region into the rift zone. Only about 3.2 million cubic yards of lava were extruded, however, and the history of the rest is perplexing. It is very possible that the unaccounted magma is still in chambers within the rift zone or that it has been injected into deep fissures to form dikes along the rift zone. A 3-foot-wide fissure that is 14 miles long, or almost the total length of the zone affected by the September eruption, and that extends to a depth of 2 miles could receive more than 70 million cubic yards of magma. Although seismic evidence argues strongly to the contrary, it is conceivable that the magma continued to drain eastward through the rift zone, feeding a submarine eruption somewhere along the 45-mile extension of the rift zone.

Cracking and faulting along the rift began early in the eruption and continued for several days after extrusion of lava had ceased. Complete observation of this cracking and faulting unfortunately was not possible, and the precise time relations between cracking and faulting, seismic activity, and eruption are not fully known. However, it is known that some cracking occurred very early to produce the en echelon arrangement of fissures, which on the morning of September 23 were observed from the air to be emitting steam and volcanic fume, and that some faulting continued for more than 3 days after all eruptive activity had ceased.

The actual observed vertical displacement on a south-facing fault scarp which offsets a jeep trail between the Jonika and Kaumuki flows is plotted on figure 22. A farmer of that area walked this trail at $13^{h}30^{m}$ on September 23 and saw no offset. At the time of his visit all the lava had been extruded at the Jonika flow but the fountains were still playing a few hundred yards toward the southwest at the Kaumuki outbreak. At $14^{h}00^{m}$ on September 24 the fault scarp was 7 feet high (fig. 28); the fault scarp continued to grow until September 28, when it reached a height of 10.8 feet (fig. 30). Hence, this faulting occurred during and after the last part of the eruption.

One of the highest new scarps is between the Kaumuki and the Heiheiahulu flows. This south-facing fault scarp is 20–25 feet high in some places and is commonly bordered on the downthrown side by a crack more than 25 feet deep below the surface of the downthrown block (fig. 29) Much of this fault has formed

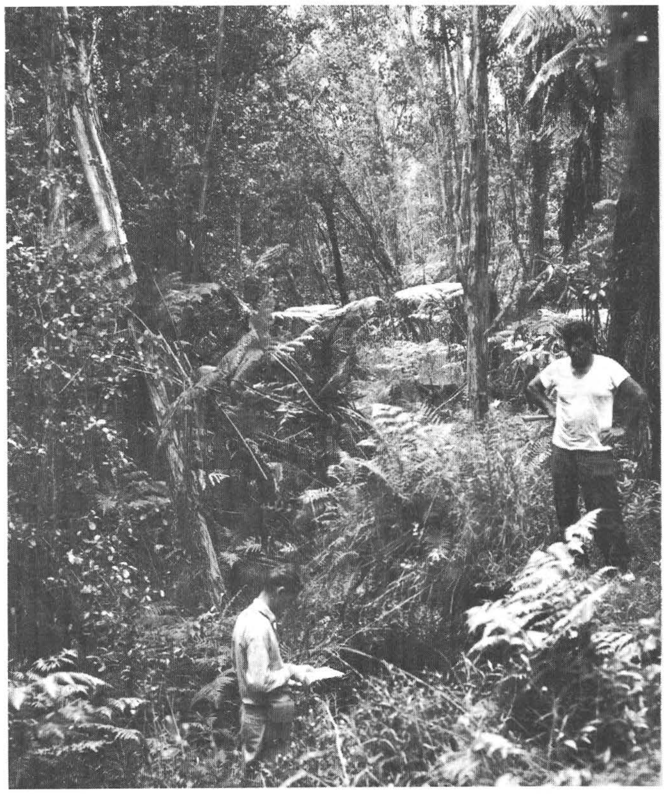

FIGURE 28.—Southeast-facing fault scarp midway between the Jonika and Kaumuki flows at $12^{h}00^{m}$ on September 24. Vertical displacement is 7 feet, with the southeast (left) side down.

along the site of a preexisting scarp, and the latest movement has added from a few feet to more than 20 feet to the height of the scarp. Because fresh lava which ponded in the newly formed depression at the base of the scarp has been offset to some extent by movement along the fault, it is apparent that faulting occurred both before and after the formation of the flow.

The en echelon arrangement of the September eruptive rifts and steaming fissures is such that each successive break to the west is offset to the north. The same pattern was noted by Macdonald (1959, p. 57) in the southwestern vents area of the 1955 flank eruption, but he noted that the pattern is reversed in the northeastern vent area.

All the vents, faults, and fissures visible on aerial photographs along the major part of Kilauea's east rift zone are shown on figure 24. The map also delineates all known historic eruptive vents. In the inaccessible and uninhabited region along the rift zone between Kaumuki and Napau Crater, the map is no doubt incomplete, and very possibly several recent-looking vents and lava flows in this region were produced during the 1840 eruption.

The en echelon arrangement of features along the rift is shown not only by the 1961 and 1955 fissures, but

FIGURE 29.—New south-facing fault scarp about 20 feet high between the Heiheiahulu and Kaumuki flows. Dangling roots and the vines stretched between the upthrown and downthrown blocks indicate the recent movement. Man in center of the photograph indicates scale.

also by the overall pattern of all the elements of the rift. Moreover, the reversal in the direction of the en echelon elements is a major feature of the structure of the rift. This reversal occurs roughly near Puu Kaliu about 3 miles southeast of Pahoa (fig. 24); both to the west and to the east, the vents of the 1955 eruption are successively offset to the north. Hence, the vents west of Puu Kaliu are offset to the right and east of Puu Kaliu, to the left. However, the 1840 vents south of Pahoa are offset to the left and perhaps represent a shift of the region of reversal. The reasons for the en echelon arrangement and for the reversal of direction are not known. Perhaps the pattern of vents in future flank eruptions will shed more light on this problem.

The map of the east rift zone (fig. 24) also shows the bipartite division of the rift into two overlapping belts. The northern belt, which contains the September 1961 eruptive vents, is composed of subparallel fissures and faults which produce a graben and horst topography. The southern belt is marked by cinder cones and some pit craters. A preliminary study of the southwestern rift zone of Kilauea shows a similar dual structure. The fissure-fault belt is on the northwest and the cinder cone-pit crater belt is on the southeast. Exactly the same pattern is repeated on a much smaller scale in the 1961 eruptive area. The vents of the Heiheiahulu, Kaumuki, and Jonika flows from which the small lava flows originated generally are on the south side of the zone of faulting.

FIGURE 30.—Same fault scarp shown in figure 28, 2 days later (12^h00^m, September 26), with the men standing at approximately the same positions. Vertical displacement has increased to 10.8 feet.

The significance of this dual structure, both on a large and small scale, is not clearly understood, and a fuller interpretation must await critical study of seismic data recorded during the eruption. One possibility is that the rift zone, which represents a major tensional feature, is not vertical, but rather dips to the south. The northern belt of faults and fissures represents its actual intersection with the surface, whereas the southern belt of cinder cone is produced by volcanic conduits piercing vertically through the hanging wall of the structure.

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U.S. GOVERNMENT PRINTING OFFICE: 1966 O—207-460