THE 1959-60 ERUPTION OF KILAUEA VOLCANO HAWAII

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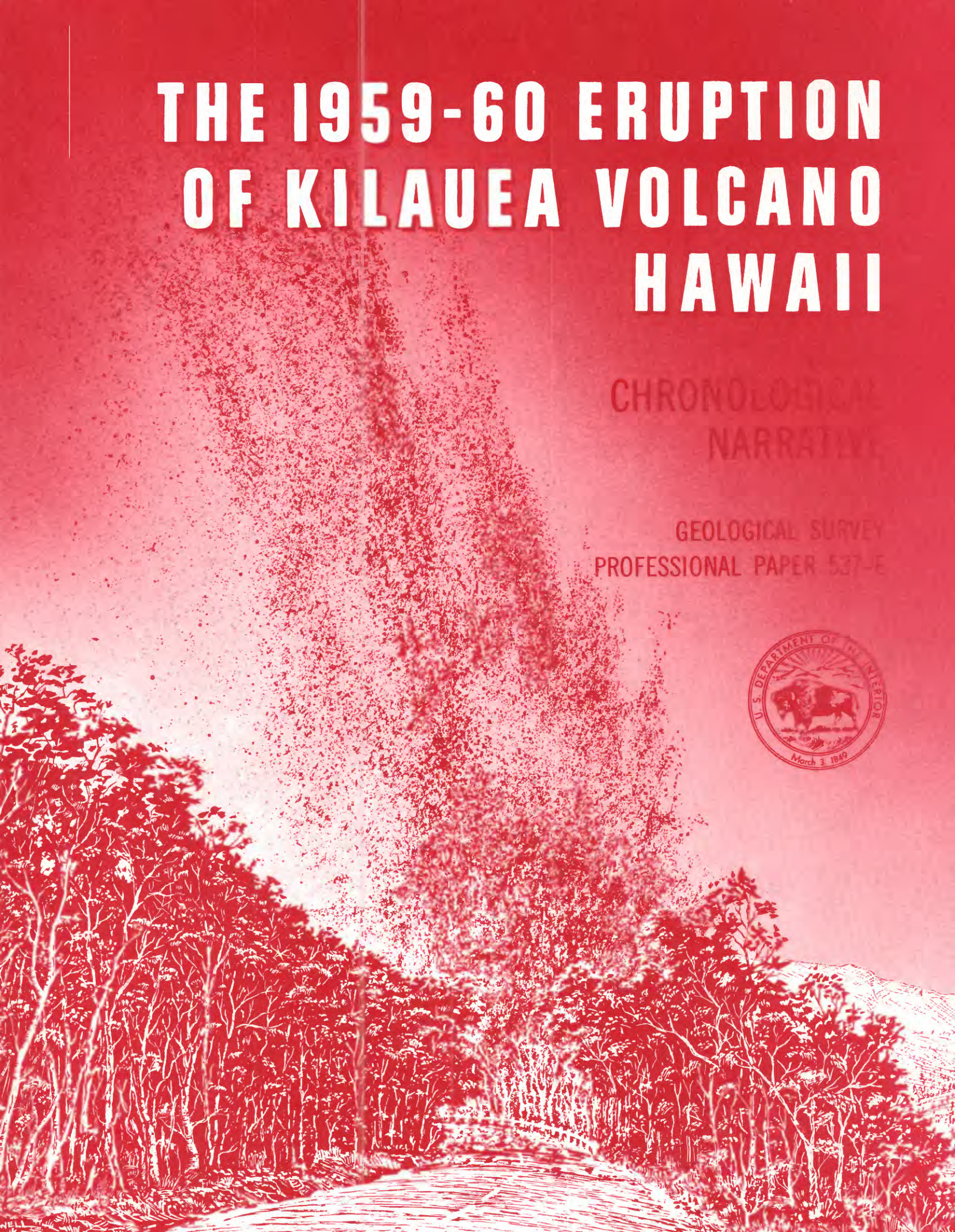

CHRONOLOGICAL NARRATIVE

The 1959–60 Eruption of Kilauea Volcano Hawaii

Lava fountain, 900 feet high, and full lava lake during the eighth phase of the summit eruption in Kilauea Iki Crater. The tops of rising lava jets appear as bright-orange patches through a shroud of cooler, darker falling clots of pumice, and a brown cloud of still cooler pumice fragments and dust drifts downwind left of the fountain. Sulfurous bluish fume rises from a floating island of cinder and pumice detached from the cone during the third phase. View west from Byron Ledge overlook. The slope of Mauna Loa rises gradually to the right in the background.

Chronological Narrative of the 1959-60 Eruption of Kilauea Volcano, Hawaii

By D. H. RICHTER, J. P. EATON, K. J. MURATA, W. U. AULT, *and* H. L. KRIVOY

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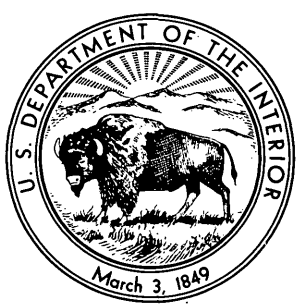
GEOLOGICAL SURVEY PROFESSIONAL PAPER 537-E

A detailed and pictorial account of an eruptive sequence consisting of a summit eruption, a flank eruption, and a summit collapse



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CHRONOLOGICAL NARRATIVE OF THE 1959–60 ERUPTION OF KILAUEA VOLCANO, HAWAII

By D. H. RICHTER, J. P. EATON, K. J. MURATA, W. U. AULT, and H. L. KRIVOY

ABSTRACT

In the evening of November 14, 1959, Kilauea Volcano on the Island of Hawaii renewed activity with an eruption at its summit. This chapter is a detailed pictorial chronological narrative of that summit eruption and the interrelated flank eruption and summit collapse that followed.

The 1959 summit eruption occurred in Kilauea Iki, a collapse crater adjacent to the main summit caldera of Kilauea. The eruption consisted of 17 separate eruptive phases, which ranged in duration from 1 week to 1¾ hours. At the cessation of activity on December 20, 1959, Kilauea Iki Crater held 50 million cubic yards of lava in a lake 335 feet deep.

After the summit eruption shallow earthquakes migrated out Kilauea's east rift zone, and on January 14, 1960, a flank eruption began near the town of Kapoho. During the next 37 days of virtually uninterrupted activity, 160 million cubic yards of lava, covering about 2,500 acres, was erupted. The small villages of Kapoho and and Koae, a United States Coast Guard station, and a number of residences along the coast were destroyed.

Almost concurrent with the beginning of the flank eruption, the summit area of Kilauea rapidly deflated as magma moved from beneath the summit out the rift zone to the flank eruption area. Culmination of the summit subsidence occurred on February 7, 1960, when the floor of Halemaumau—a deep crater in Kilauea caldera—collapsed because of the withdrawal of the still fluid core of the 1952 lava lake. Two smaller collapses on March 9 and March 11 in Halemaumau marked the end of the 1959–60 eruption of Kilauea.

INTRODUCTION

At 8:08 p.m. on November 14, 1959, Kilauea, Hawaii's youngest volcano, renewed activity with an eruption at its summit. Thus began the spectacular surface display of the most complete sequence of eruptive activity ever observed at Kilauea—a sequence which has been recorded in far greater detail than for any previous major eruption in Hawaii.

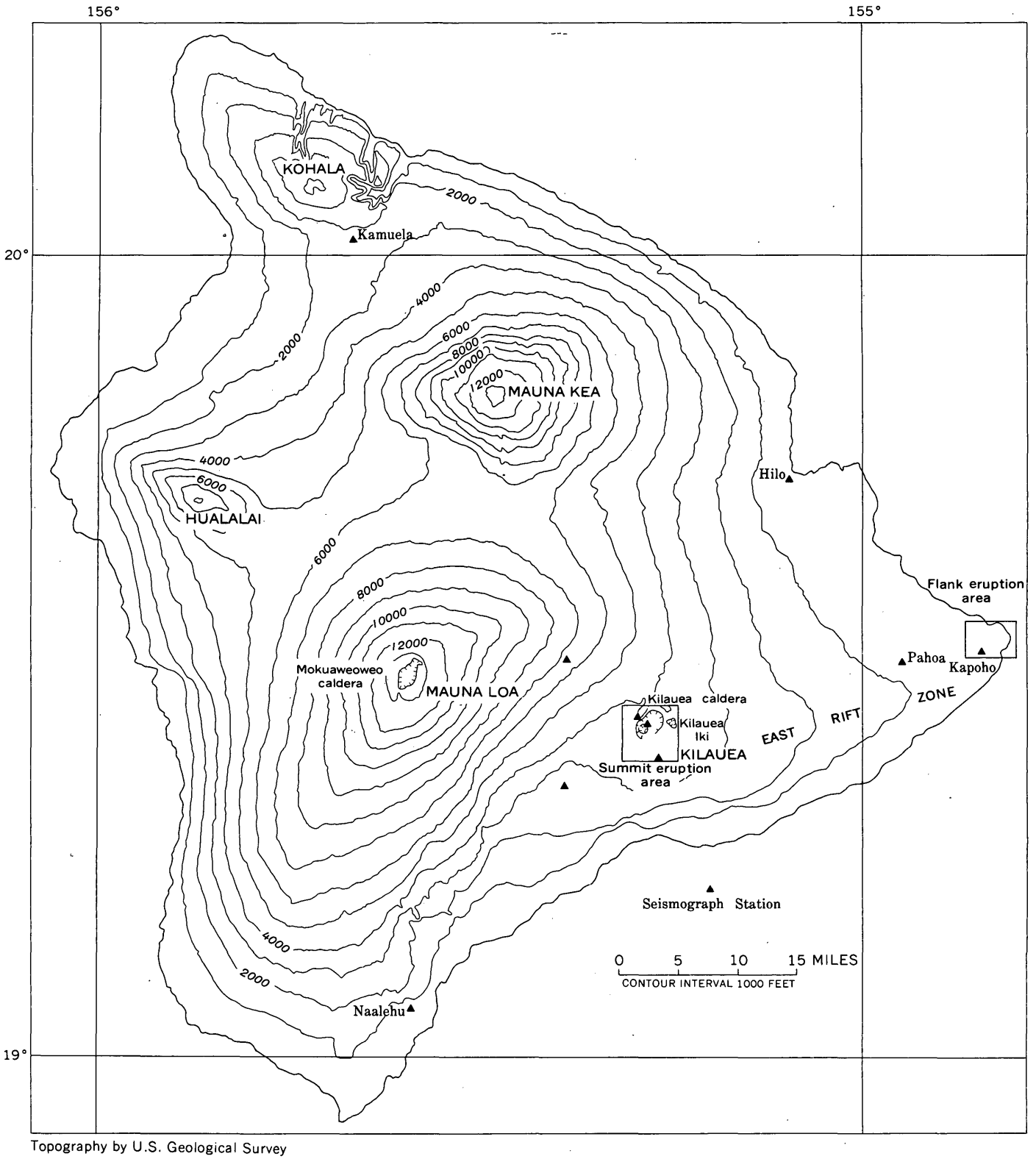
Expansion of the staff and facilities of the U.S. Geological Survey's Hawaiian Volcano Observatory shortly before the eruption provided for on-the-spot petrological and geochemical studies and, in keeping with experience gained during the last eruption in 1955, a modified and substantially expanded geophysical program. Fortunately, both the summit and flank eruption areas were easily accessible, so that problems of observation, measurement, and collection were reduced almost to those of a laboratory experiment, and the work was freed from many of the trials and tribulations that hamper the studies of a scientific expedition.

Either through automatic recording or through observation, measurement, and collection at frequent intervals, virtually continuous records were kept of the primary parameters of the eruption; namely, earthquakes, volcanic tremor, tilting of the ground, rate of lava extrusion, lava fountain height, and the temperature, chemistry, and petrography of the lava. Study of the variation and interplay of these parameters has yielded a far more detailed picture of the internal structure and eruptive mechanism of Kilauea than is available for any other volcano.

This chapter is devoted to a detailed illustrated chronological account of field observations of the eruption. Other chapters of this professional paper treat particular facets of the eruption in greater detail.

GEOGRAPHIC SETTING

Kilauea, on the Island of Hawaii, is the southeasternmost volcano along the 1,500-mile-long mid-Pacific Hawaiian Archipelago. The volcano rises to an altitude of slightly more than 4,000 feet on the southeast flank of Mauna Loa, its massive and lofty neighbor volcano (fig. 1). The broad summit of Kilauea is indented by a relatively flat floored caldera, 2½ miles long and 2 miles wide, with walls as much as 400 feet high. In the southwest part of the caldera the deep nearly circular collapse pit of



Topography by U.S. Geological Survey

FIGURE 1.—Map of the Island of Hawaii showing summit and flank eruption areas on Kilauea and location of U.S. Geological Survey seismograph stations.

Halemaumau, or the "fire-pit" as it is commonly referred to, marks the site of most summit activity in historic time. Prior to the summit collapse in 1960, Halemaumau was approximately 3,500 feet in diameter and 500 feet deep. Two rift zones, an east and a southwest, radiate from the summit area and extend down the slopes of Kilauea to far below sea level. All flank eruptions originate along these rift zones; the east rift zone, as shown by its strong topographic expression, dominates activity.

Kilauea Iki, site of the 1959 summit eruption, is a collapse or pit crater approximately 1 mile long and half a mile wide. Before the eruption, this crater was as much as 700 feet deep. Although separated from Kilauea caldera by a low flat ridge, Kilauea Iki is within the peripheral fracture fault system that circumscribes the summit area of Kilauea. The last eruptive activity involving Kilauea Iki was in 1868 when a small lake of lava 37 acres in extent filled the bottom of the crater.

The 1960 flank eruption area was on the east rift zone of Kilauea near the small village of Kapoho 29 miles from the summit (fig. 1). At the time of outbreak the eruptive vents were between 2 and 3 miles from the ocean and between 90 and 150 feet above sea level.

ACKNOWLEDGMENTS

The authors are indebted to the technical staff of the Hawaiian Volcano Observatory through whose excellent support and efforts this chapter has been made possible. Special thanks are also due the superintendent and his staff of Hawaii Volcanoes National Park for their interest in, and active support of, our studies and for the observational and photographic data they themselves contributed to the record.

Other governmental agencies who, through various means of support, facilitated our investigations and who deserve recognition and thanks are the Hawaii Air National Guard, Hawaii Police Department, Hawaii Civil Defense Agency, and the United States Coast Guard.

Also we would like to thank the many persons throughout the island who have contributed observational data. Although it is impossible to acknowledge all these contributors individually, our appreciation is no less sincere.

BRIEF HISTORY OF KILAUEA VOLCANO

Little is known of the eruptive activity of Kilauea before the beginning of the 19th century when the first missionaries from North America and Europe reached the Hawaiian Islands. Hawaiian stories and legends go back many centuries before this, but Kilauea was the home of gods, and the Hawaiian history of the volcano is a mixture of fact and folklore. Between 1823, when William Ellis, a British missionary, first viewed the caldera, and about 1880, visits to the summit were brief and sporadic, and accordingly many details of eruptive activity were never observed or recorded. In 1880 a hotel was built overlooking the caldera and visits were more frequent and observations more detailed. Realizing the need for a permanent observational facility to study the volcano, the publicly supported Hawaiian Volcano Research Association built and staffed the Hawaiian Volcano Observatory in 1912. Since that date a continual record of Kilauea activity has been kept and the observatory has undertaken many diverse investigations of volcanic processes.[1] In 1919, the observatory came under the sponsorship of the U.S. Government.

The known summit eruptions, flank eruptions, and summit collapses of Kilauea Volcano since 1790 are listed in chronologic order in table 1. Not included are the long periods of lava-lake activity in the caldera or in Halemaumau; summit eruptions that are listed are those in which measurable amounts of lava have been added to either the caldera or Halemaumau. The data are arranged in an attempt to show the interdependence between the summit and rift zones, as was so clearly illustrated in the summit eruption, flank eruption, and summit collapse sequence of the 1959–60 eruption. However, the three events which appear to constitute a sequence or cycle of activity do not necessarily manifest themselves by recognizable physical activity at the surface; hence, one or more events of a postulated sequence may be missing from the record. Moreover, the record has suffered from lack of observational data, especially prior to 1912, and some of the early indicated sequences of activity may have little basis in fact.

In 1823, and for almost the next 50 years, activity at the summit of Kilauea involved almost the entire caldera, and from the scattered reports of infrequent observers it appears that eruptive activity was virtually continuous. Evidently just prior to a visit by Missionary Ellis, a collapse involving most of the

[1] The Hawaiian Volcano Observatory, staffed and operated since 1947 by the U.S. Geological Survey, occupies two buildings perched on the northwest rim of Kilauea caldera. Three short-period vertical seismograph stations in the region of the Kilauea summit and southwest rift zone and one on the slopes of Mauna Loa (fig. 1) telemeter signals to the observatory where they are visibly recorded. A fifth seismograph station at the observatory, referred to as Uwekahuna, houses a three-component long-period seismograph and a two-component short-period seismograph, both of which record optically. Elsewhere around the island, the observatory maintains seismograph stations at Pahoa, Hilo, Kamuela, and Naalehu (fig. 1). A permanent short-base liquid tiltmeter is maintained in the Uwekahuna seismograph vault, and stable piers for long-base portable tiltmeters are established at seven locations in the summit area.

TABLE 1.—*Summit and flank eruptions and summit collapses of Kilauea Volcano since 1790*

[Sources of information: Brigham (1909), Finch (1940), Jaggar (1938), Macdonald (1955), Macdonald and Eaton (1964), and Stearns and Macdonald (1946)]

Beginning date	Summit eruption		Flank eruption		Summit collapse	
	Locality	Volume (cu yd)	Locality	Volume (cu yd)	Locality	Volume (cu yd)
1790 Nov. (?)			East rift	3.8×10^7		
1790?					Caldera	[1] Large
1815(?)	Caldera	(?)				
1823 Feb.–July			Southwest rift	1.5×10^7		
pre-Aug.					Caldera	64×10^7
1832 Jan. 14	Caldera	(?)				
July					Caldera	69×10^7
1840 May 30			East rift	28.1×10^7		
June (?)					Caldera	28.7×10^7
1868 April 2	Kilauea Iki	(?)				
April 2 (?)			Southwest rift	0.03×10^7		
April					Caldera	24.7×10^7
1877 May 4	Caldera	(?)				
May 21(?)	Keanakakoi	(?)				
1885 March	Caldera	(?)				
1886 March 17					Halemaumau	5.2×10^7
1891 March 7					---do---	4.5×10^7
1894 March 21	Caldera	(?)				
July 7	---do---	(?)				
July 11–12					Halemaumau	1.1×10^7
1916 (?)					---do---	0.9×10^7
1918 Feb. 23	Caldera	0.03×10^7				
1919 Feb. 7	---do---	3.5×10^7?				
Nov.					Halemaumau	1.3×10^7
Dec. 21			Southwest rift	6.2×10^7		
1921 March 18	Caldera	0.9×10^7				
1922 May 28			Upper east rift	(?)		
May (?)					Halemaumau	2.8×10^7
1923 Aug.			East rift	0.01×10^7		
1924 April			---do---	([2])		
May 10					Halemaumau	[1] 26.4×10
July 19	Halemaumau	0.03×10^7				
1927 July 7	---do---	0.3×10^7				
1929 Feb. 20	---do---	0.2×10^7				
July 25	---do---	0.4×10^7				
1930 Nov. 19	---do---	0.8×10^7				
1931 Dec. 23	---do---	1.0×10^7				
1934 Sept. 6	---do---	0.9×10^7				
1938 May 28			Upper east rift	([2])		
1952 June 27	Halemaumau	6.4×10^7				
1954 May 31	Halemaumau-caldera	0.9×10^7				
1955 Feb. 28			East rift	12.0×10^7		
1959 Nov. 14	Kilauea Iki	5.0×10^7				
1960 Jan. 13			East rift	16.0×10^7		
Feb. 7					Halemaumau	2.9×10^7

[1] Violent phreatic explosions.

[2] Many earthquakes, accompanied by faulting, along the east rift zone suggested that lava intruded the rift zone, but none was erupted onto the surface.

caldera floor had occurred; this left a vast depression about 800 feet deep containing a very active lava lake and a number of lava fountains. By 1832 this large depression in the caldera had filled with new lava and in July of that year there occurred another collapse of the same magnitude as that in 1823. During the next 36 years, two more periods of slow caldera infilling were followed by rapid collapse of most of the caldera floor. The last of the great caldera collapses, in April 1868, apparently brought about a marked change in the volcanic vent system beneath the caldera. Since that time no collapse has involved a major part of the floor and the caldera has slowly filled to form the relatively flat plain seen today.

Although eruptive activity during the first 30 years of observation took place over most of Kilauea's floor, the southwest part of the caldera was generally the site of the largest and most active lava lake or strongest lava fountaining. In the caldera collapse of 1868, a new crater, about 200 feet deep, formed in the collapsed caldera floor, and this new crater, Halemaumau, emerged as a dominant physical feature. By 1886 Halemaumau and the caldera floor had filled again, and in the collapse of that year a triangular pit formed at the site of Halemaumau.

During the next 8 years (1886–94) Halemaumau was almost continually active. In 1894, following a collapse in Halemaumau, activity abated, and between 1895–1907 Kilauea was active less than 60 percent of the time. In 1907 summit activity increased, and with the exception of two 1-month periods in 1913 and 1922 an active lava lake filled Halemaumau for the next 17 years (1907–24). In 1918, 1919, and 1921, Halemaumau filled and flows were released across the caldera floor, and in 1916, 1919, and 1922 Halemaumau suffered moderate collapses. In May 1924, after the lava lake suddenly withdrew, allowing groundwater to penetrate the volcanic conduit system, a paroxysmal phreatic explosion enlarged Halemaumau to nearly 3,500 feet in diameter and 1,300 feet in depth.

In the following 11 years seven small eruptions of short duration began the process of refilling the enlarged crater. The last of these, in 1934, marked the beginning of a 17-year-long quiescent period, the longest period of inactivity in Kilauea's observational history. Activity at Kilauea summit resumed in 1952 with an eruption in Halemaumau. The 1952 eruption was followed by another one in Halemaumau and on the caldera floor in 1954 and by the eruption in Kilauea Iki in 1959.

Nine separate flank eruptions, six along the east rift zone and three along the southwest rift zone, have been recorded at Kilauea between 1790 and 1960. Six of these flank eruptions, in 1790, 1823, 1840, 1868, 1922, and 1960, immediately preceded collapses at the summit of the volcano. In addition at least two rift-zone seismic crises have occurred (in 1924 and 1938) that involved faulting and that evidently indicated that magma was moving into the rift zone.

SUMMARY OF ERUPTION

The 1959 summit eruption of Kilauea Volcano began at 8:08 p.m. on November 14, 1959, in Kilauea Iki Crater after a 3-month period of rapid tumescence and increased seismicity. The eruption started from a single fissure halfway up the 600- to 650-foot south wall of the crater and rapidly extended in both directions to form a discontinuous curtain of fire half a mile long. Activity gradually ceased in the outermost vents and by the afternoon of November 15 only one vent, in the west end of the crater, remained active. As the eruption continued, both the rate of lava extruded from this single vent and the size of the lava fountain increased. On November 21, after the level of the lava in the crater reached the level of the vent, the eruption ceased, leaving a lake 335 feet deep containing 40 million cubic yards of lava.

In the next 4 weeks, 16 additional eruptive phases ranging in duration from 32½ hours (fourth phase) to 1¾ hours (14th phase) occurred in Kilauea Iki. The last phase stopped during the morning of December 20, 1959, and marked the end of the summit eruption. All these later and shorter phases of the eruption appear to have been fed by the same vent-conduit system that fed the week-long first phase and all ceased to erupt soon after lava reached the level of the vent. Backflow of lake lava down the vent, both during and following an eruptive phase, was exceptionally well recorded throughout the eruption.

The volume of lava erupted into Kilauea Iki during the 17 eruptive phases and the volume withdrawn by backflow is shown graphically in figure 2. A quantitative measure of the rate of extrusion and withdrawal is expressed by the slope of the lines in the graph. The lava lake attained its greatest depth (414 feet) and volume (58 million cubic yards) at the end of the eighth phase on December 11, 1959. At the end of the summit eruption, after the last recorded backflow on December 23, 1959, the lava lake contained slightly less than 50 million cubic yards and had a maximum depth of about 365 feet. Rates of lava extrusion were generally much higher during the shorter and later eruptive phases than

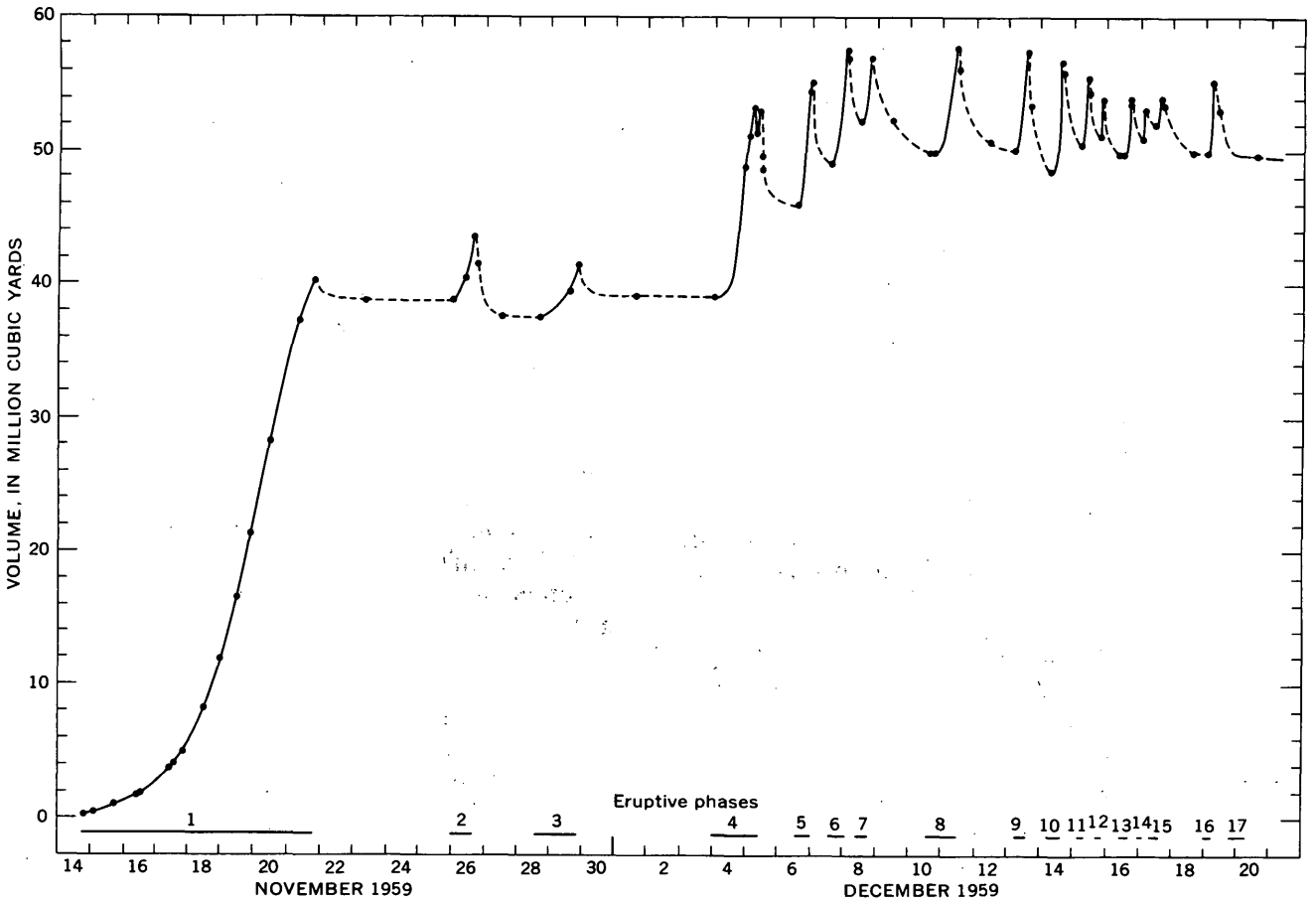


FIGURE 2.—Volume of lava erupted into Kilauea Iki during the 1959 summit eruption. Dashed line after the end of an eruptive phase represents backflow of lava down the vent. Each dot is a volume measurement.

in the first phase. Maximum rate of extrusion during the first phase was 500,000 cubic yards per hour; during the 16th phase the extrusion rate was a phenomenal 1,600,000 cubic yards per hour. Similarly, backflow rates were higher following the shorter eruptive phases. Moreover, in all eruptive phases after the fourth there was little or no net volume gain in the lake. The increased tempo of activity during the shorter eruptive phases also was reflected in the height of the lava fountain. During the first phase a maximum height of 1,200 feet was measured; in the 15th phase the lava fountain roared to an unprecedented height of 1,900 feet.

After the cessation of eruptive activity in Kilauea Iki on December 20, 1959, tilt measurements continued to show swelling of the summit area; this swelling strongly suggested that magma was still moving into the volcano and that the eruption was not over. Late in December, earthquakes along Kilauea's east rift zone, 25 miles from Kilauea Iki gave the first indication of magma moving out of the summit area. By mid-January the earthquake activity had migrated downrift to the vicinity of the village of Kapoho, and on January 13, 1960, faults bounding an old graben, which contained part of the village, were reactivated and the graben began to subside.

At 7:30 that evening the flank eruption began along a line of en echelon fissures that extended through the middle of the graben a few hundred yards north of the village. The main fountain area, 2 miles from the sea coast, soon produced a steady stream of lava that slowly flowed down through the graben and reached the sea on the night of January 15. By the end of the first week of eruption the low graben was virtually filled. Besides continuing to push slowly into the sea, flows began to spread laterally out of the graben. These flows gradually destroyed most of the village of Kapoho, the smaller community of Koae, the United States Coast Guard station at Cape Kumakahi, and a number of beach residences along the coast. Although the extrusion of lava had virtually ceased by February 6, 1960, the main vent continued to emit gas, pumice, cinders,

and minor spatter until February 20 when the eruption ended. The flank activity produced approximately 160 million cubic yards of lava and covered about 2,500 acres, including about 500 acres of new land beyond the former coastline.

On January 17, 1960, 4 days after the beginning of the flank eruption, tilt measurements revealed that the summit was rapidly deflating, evidently because of a massive withdrawal of magma from the summit area. By the end of January, a swarm of strong shallow earthquakes was occurring under the caldera area, and new cracks and steaming areas had begun to develop on the floor of Halemaumau. Then, on February 7, a fissure apparently extended up into the still liquid core of the 1952 lava lake in Halemaumau, thus allowed lava to drain away and resulted in a rapid collapse of Halemaumau's floor. On February 9 and March 11 two smaller collapses occurred in the bottom of Halemaumau; the latter ended the summit collapse of the 1959–60 eruption sequence. Total volume of the three collapses in Halemaumau was approximately 29 million cubic yards.

CHRONOLOGICAL NARRATIVE

The 1959–60 eruptive episode of Kilauea Volcano had its real beginning months before the first surface outbreak and miles beneath the Kilauea summit. Between November 1957 and February 1959 measurements from newly installed sensitive tiltmeter bases around the summit indicated that the whole caldera region was tilting outward, apparently because magma was welling up from the mantle and accumulating in the reservoir several miles beneath the caldera. After several moderate earthquakes just southeast of the caldera on February 19, 1959, swelling stopped, and from May until August the volcano slowly deflated. Then between August 14 and 19, 1959, a great swarm of earthquakes, accompanied by periods of spasmodic tremor from a source about 35 miles deep just beyond the northeast corner of the caldera, was recorded by the seismograph net on Hawaii. Evidently this activity again allowed magma to move into the conduits beneath the volcano, because shortly afterward rapid swelling of Kilauea resumed and continued up to the time of eruption.

Little or no seismic activity accompanied the early swelling of the volcano. At most, occasional weak harmonic tremor, originating perhaps 3 to 10 miles below the surface and lasting as much as half an hour, marked the upward migration of magma. Then in mid-September a sensitive seismograph at the northeast edge of Halemaumau began to record a series of very shallow tiny earthquakes. Although these quakes were small and barely recordable on seismographs only 1 mile away, their number was impressive, and by the first of November more than 1,000 per day were being recorded. Remeasurement of the tilt bases at this time also revealed a dramatic acceleration in the rate of swelling; it was at least 3 times faster than the rate of swelling measured during the previous months.

SUMMIT ERUPTION

FIRST PHASE

NOVEMBER 14, 1959

In midafternoon on November 14, earthquakes originating from below the caldera suddenly increased about tenfold in number and intensity. Throughout the late afternoon and early evening the entire summit region shook as earthquakes marked the opening of the eruptive fissure toward the surface. Then at about 20^h08^m a bright-orange fume cloud suddenly lit the night sky over Kilauea Iki Crater. The vigil of the "volcano watchers" outside the windows of the Volcano Observatory was over—the eruption had begun.

At 20^h30^m, when observers first reached Byron Ledge overlook (fig. 3 and fig. 4), lava fountains up to 50 feet high were spurting from a line of discontinuous fissures (A, B, C, D, E, and west end of F, fig. 5) halfway up the 600- to 650-foot south wall of the crater. From the easternmost fissures (B, C, D, E, and F), lava cascaded down the steep forested slopes in braided "fire falls" to the bottom of the crater 300 feet below. Lava from rift A ponded in the higher western bay of the crater and thence flowed eastward through the narrow trough toward the main crater floor. Lava from rift E had reached the base of the crater wall and was feeding a small incandescent lava pad that was spreading over the 36-acre floor of the main crater. Within a few minutes the lava stream flowing down from the west bay, fed principally by fissure A with minor contributions from B, C, and D, also reached the main floor and began to spread out in a second pad of lava. The two lava pads soon coalesced into a single flow unit that advanced slowly eastward across the crater floor.

During the first hour and a half, the line of fountains extended rapidly in both directions along the crater wall. By 21^h00^m all the fissures of F and G and the west end of the fissures at H were fountaining vigorously. Soon thereafter another fountain began at I, relatively high on the crater wall above the lower part of the active fissure at A. By 21^h30^m,

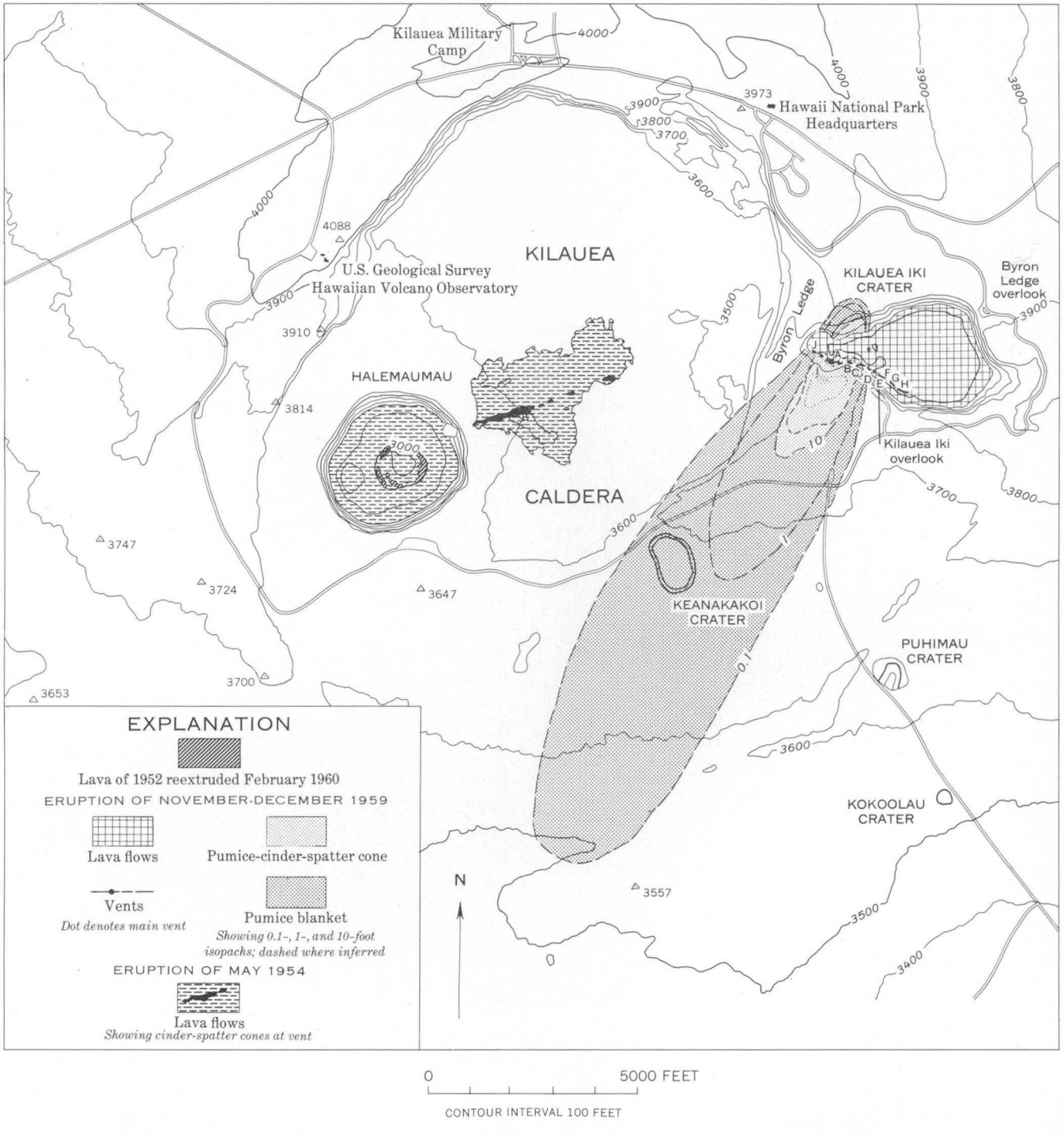


FIGURE 3.—Map of the Kilauea summit area showing principal 1959 eruptive features in and around Kilauea Iki and the 1960 collapse in Halemaumau. Location of outline and vents of the 1954 flow on the caldera floor is from Macdonald and Eaton (1957).

fountaining had spread to the easternmost fissure at H and was commencing at J, a very small fissure at the southwest end of the crater. These last outbreaks marked the maximum lateral development of the erupting rift; lava fountains, which were now playing along every fissure, formed a discontinuous curtain of fire 2,500 feet long (fig. 5, middle photograph) and up to 100 feet high.

For the next half hour the entire rift remained active, and a swelling throng of spectators at Byron Ledge overlook kept a hushed watch over this awesome manifestation of Earth's beauty and might. Glow from the fountains, the "fire falls", the lava river, and the lava lake bathed the entire crater in a soft orange-red light. Small forest fires flared up sporadically on the crater walls, and burning trees—their bright yellow flames flashing like giant sparklers—were carried swiftly down the "fire falls" and lava river onto the lava lake where they floated slowly across the darkening surface until they burned out.

During this period of maximum fountaining, we attempted twice to look into the crater from the Kilauea Iki overlook, leeward and directly above the fountains at G and H, but strong sulfur dioxide fumes borne out of the crater by warm turbulent updrafts drove us back after a few seconds.

The curtain of fire was short lived. By 22^h00^m fountaining had visibly abated at the vents along H, and at 22^h15^m it had ceased there entirely. In rapid succession, fountaining ceased at G (22^h40^m) and at J (23^h15^m). The fountains along I decreased to sporadic bursts of spatter by 23^h00^m and continued in this manner until the early morning of the next day. As the fountains died in the outermost fissures, activity increased noticeably in the vents at A, B, C, and possibly D.

NOVEMBER 15, 1959

The curtain of fire continued to shrink through the night and the early morning hours of November 15. The easternmost vents along E were dead by 00^h40^m; the vent at F ceased fountaining at 01^h00^m (fig. 5, bottom photograph), and by 03^h00^m activity had abated at the remaining vents along E and at those along C and D. The fountain at A was confined by this time to one vent, approximately in the center of the fissure, and was consistently spurting to a height of 150 feet. The volume of lava issuing from this vent increased slowly as other fountains disappeared. At 03^h10^m all the vents along E were dead. The vents along C ceased fountaining at 04^h10^m; by 04^h20^m, I, the intermittently spattering vent, was also quiet. At about 04^h30^m the vents along D stopped erupting; only the vents at A and B were active.

Shortly after midnight very fluid lava had covered the entire floor of the main crater. A few tens of feet from the base of the lava rapids, now the only source feeding the lake, a dark crust formed rapidly on the glowing lava, and incandescence was restricted to the everchanging pattern of cracks that crisscrossed the surface. At 03^h00^m the first party (National Park Service) that went into the crater on the east side estimated that the lava lake was about 5 feet deep.

Pale-blue flames, at times tinged with yellow, flickered above the vents along H, G, F, and E after fountaining ceased. These flames persisted for nearly 2 hours as they gradually decreased in intensity. Fume, smoke, and oncoming daylight probably account for the fact that such flames were not observed along the western vents.

Early in the morning the first U.S. Geological Survey party managed to get as far as the vents at I, where fountain noises were recorded on tape. At daybreak we made our second trip into the west end of the crater (fig. 6) in an attempt to collect gas and lava samples from the base of the main fountain at A. We were able to cross the vents along the west end of A and to approach within a few hundred feet of the fountain. The main flow of lava was directed away from us by a small spatter rampart, but occasionally a flow breached this wall and poured westward toward where we were working. Besides the disconcerting flows, which set vegetation afire as they advanced slowly toward us, we were continually broiled by radiant heat from the fountain and flows and were bathed in strong, at times choking, sulfur dioxide fumes from the dead vents upon which we were working. Moreover, incandescent blobs of gas-inflated spatter thrown 100 to 150 feet high above our heads by the fountain posed a real danger. After remaining in the area for about half an hour to test various schemes for sampling the fluid lava, we climbed back up the crater wall.

During the day, fountaining at A increased slowly (fig. 7). The other remaining fountain, in the B vent area, was very sporadic. During the morning it appeared to be dead, but early in the afternoon (14^h25^m) it was reactivated, apparently at the time of an unusually large, but brief, surge of lava from the main vent. At 16^h30^m it was still emitting occasional bits of spatter and sending out a sluggish flow. By nightfall it was completely inactive; only the vent at A continued fountaining throughout the eruption.

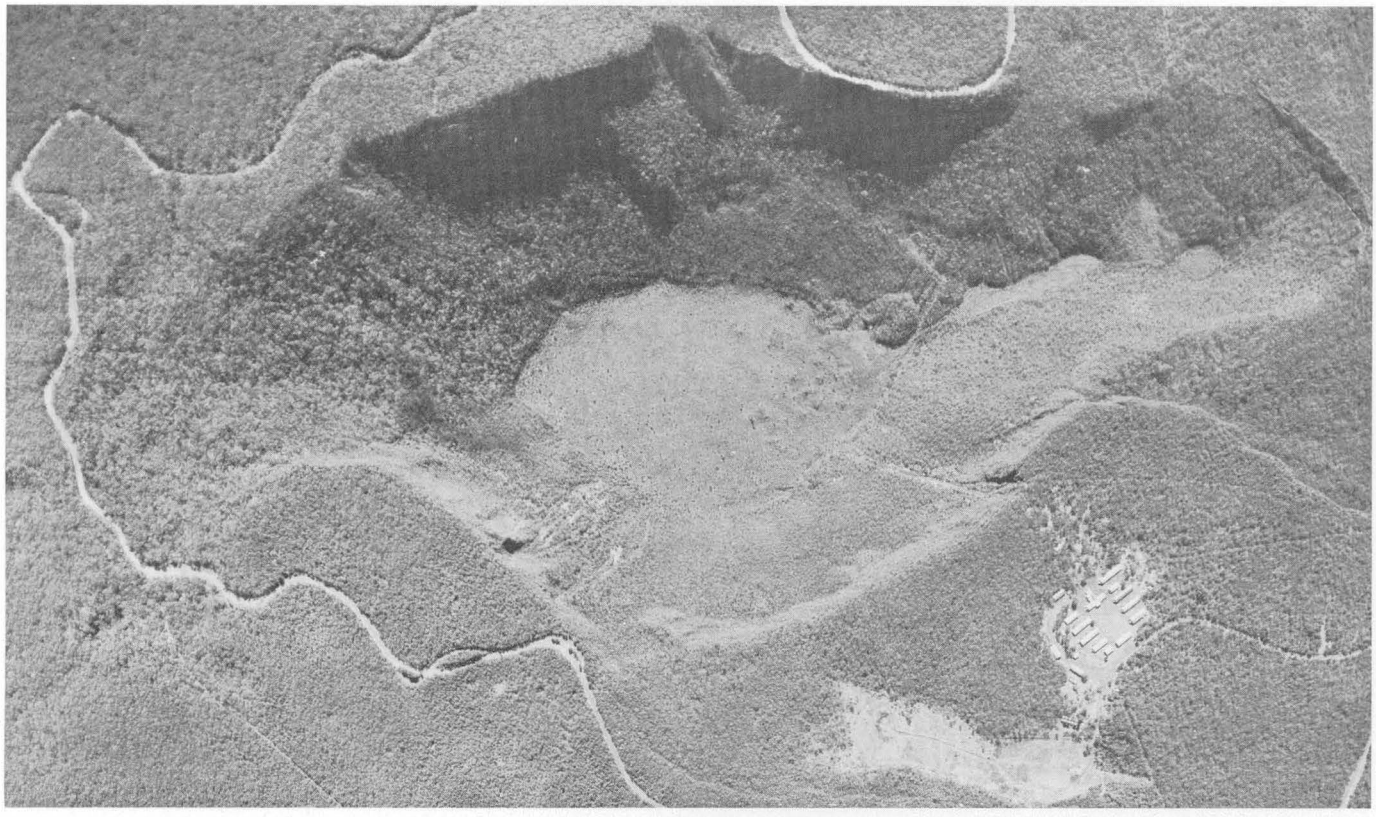
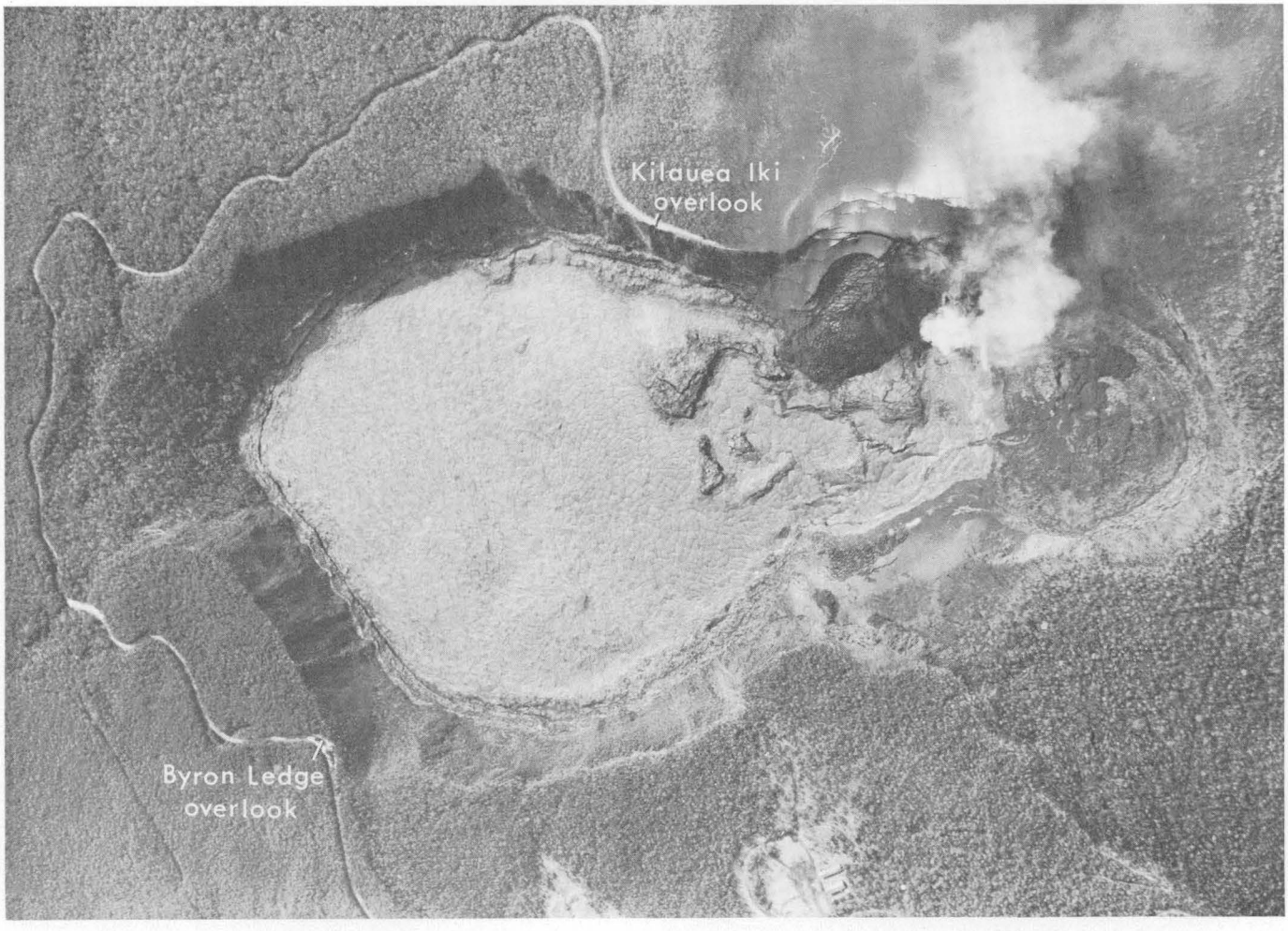


FIGURE 4 (above and right).—Aerial views of Kilauea Iki Crater before and after the 1959 summit eruption. The two principal overlooks into the crater, from which many of the pictures reproduced in this paper were taken, are labeled. Both photographs are approximately the same scale, but the one on the right shows considerable distortion. *Above:* U.S. Navy aerial photograph taken in 1948. The flat, elliptical floor of the main crater covers about 36 acres, and the very small, circular west bay floor, about 1 acre. *Right:* National Park Service photograph taken December 24, 1959, after cessation of activity. Fume rises from the main vent area. The surface of the new 370-foot-deep lava lake has an area of about 140 acres.

With all but one of the original vents dead, the pattern of the lava river in its course from the vent at A to the large deep eastern section of the crater was well established. The vent at A, at an altitude of about 3,460 feet, was on the steep south wall of the crater 60 feet above and slightly east of the small west pond (alt 3,400 ft) and 90 feet above the relatively narrow trough that connected the west pond with the floor of the main crater (alt 3,130 ft). Extremely fluid lava emerging from the vent poured through a breach in the small spatter rampart at the base of the fountain and cascaded down (northward) to the channelway leading to the east pond (fig. 8, top photograph). Although the flow down the crater wall was deeply incised in the fountain rampart, occasional surges of lava, or blockages in the cascade channel, forced lava over the sides of the rampart. This formed a temporary braided pattern on the crater wall and sent some lava northwestward into the west pond. When the lava reached the bottom of the crater wall, it was confined in the narrow trough leading eastward from the elevated west pond to the main crater floor. Here it flowed in a sluggish stream averaging 50 feet in width, for about 900 feet as it descended another 90 feet (5° to 10° grade) before spilling over the crest at the top of the lava rapids and falls leading down to the main lake (fig. 8, bottom photograph). As the lava flowed along the river its surface cooled to a thin dark crust which was continually stretched, cracked, and torn apart by the motion of the stream. At the top of the rapids the crust was further disrupted, much like ice breaking up above a waterfall; then it was rafted down the rapids by the leaping incandescent lava. Passing over the steep rapids, which were on a slope of about 30°, the lava descended another 150 feet to the bottom of the crater. During the first night when the rapids were at their highest, pieces of crust were carried down the 290-foot length of the rapids



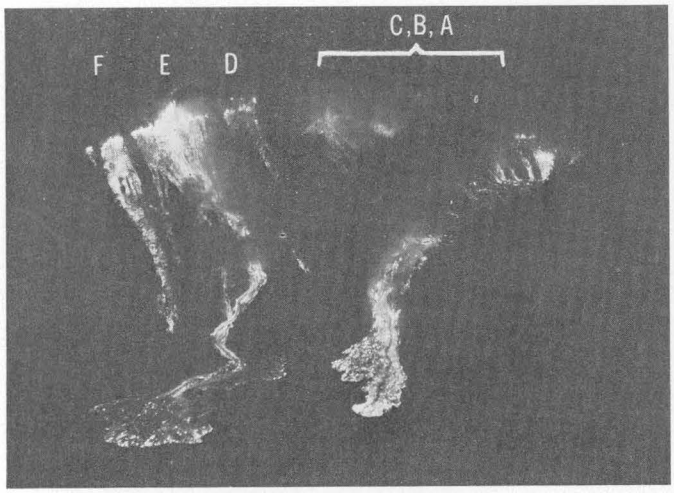
in about 10 seconds at an average speed of about 20 miles per hour.

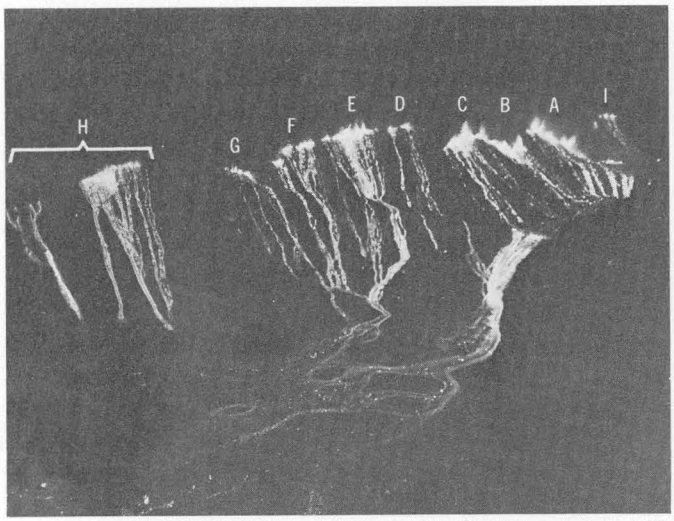
Late in the afternoon two of us descended into the east end of the crater to sample the gases from the dead vents at H and to establish markers on the crater wall to measure the rise of the pond. The 37-acre floor of the crater was covered to a depth of about 15 feet with lava that already had a relatively cool but very rough surface. The smooth pahoehoe surface on the first flows that covered the floor had been broken and thrown into a jumble of crags by the push of later lava as it poured into the lake and spread fanwise at the foot of the lava rapids. Most of the lava now entering the crater, however, was flowing under the crust and beginning to form the molten lake that remained for a decade under the crust in Kilauea Iki. As the crust floating on the molten lake slowly rose and pulled away from the sloping crater walls, innumerable small pahoehoe flows oozed up from below to fill the gap between crust and crater wall around the entire periphery of the lake.

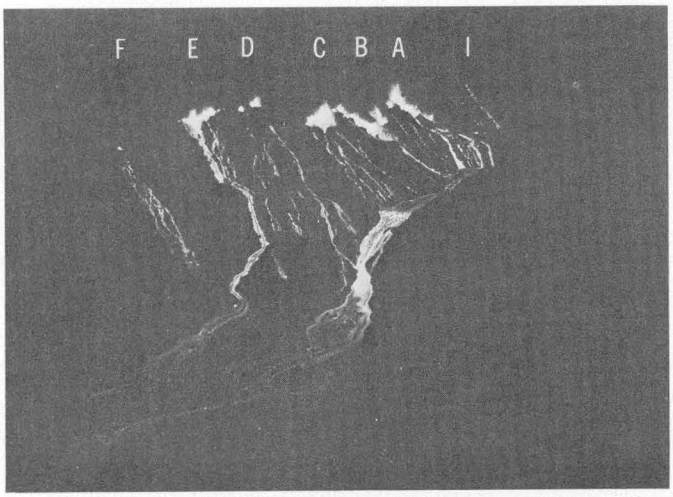
NOVEMBER 16, 1959

There was little change in activity through the night and morning hours of November 16; the fountain consistently played to heights of 150 to 200 feet with a possible increase in the rate of lava extrusion, and the surface of the lake remained a craggy mass of broken slabs.

At noon another party descended into the east end of the crater and walked across the frozen crust of the new lake to the foot of the lava rapids—a distance of about 1,000 feet. The lake by this time was 25 feet deep—10 feet had been added in the last 20 hours—but the rough crust was cool enough so that we could venture out upon it. At the lava rapids we could approach the turbulent naked stream no closer than 50 feet because of the intense heat it radiated. As it poured down the steep slope the lava was confined to a channel averaging about 15 feet in width; in one place it raced through a narrow tube of its own making which occasionally was overrun when a heavy surge came down the channel. The fall was a bright orange, incandescent, twisting







ribbon that made a slurred gurgling sound as it glided past us. Along the narrow part of the channel, partly congealed lava stalactites, attached to the overhanging channel walls and hanging down to the level of the flowing stream, flapped back and forth as waves of lava struck them. At the bottom of the cascade a stationary wave of lava, similar in appearance to a standing water wave in rapids, crested 2 or 3 feet above the level of the stream just before it widened into a sluggish river and disappeared beneath the frozen crust of the lake. We remained by the rapids photographing the turbulent stream until increased fountaining at its source sent a veritable flood of lava over the crest above us; and, as automobile-sized blocks of semi-solid incandescent lava began tumbling down the overflowing channel, we beat a hasty retreat across the swelling lake.

This more copious outpouring from the fountain continued through the afternoon, and by 20^h00^m a thin surface flow covered the western third of the lake. At 21^h00^m the lava stream was again pouring beneath the lake crust and the surface flow had almost ceased.

NOVEMBER 17, 1959

Through the night activity gradually increased, and by early morning of November 17 the fountain was playing to heights of 200 to 250 feet. Cinder and spatter as well as pumice were now falling and accumulating rapidly on the rim of the crater leeward of the vent, where a new cinder cone was beginning to grow. Lava from the base of the fountain was largely directed northwestward into the shallow west end of the crater, whence it cascaded down over a broad slope into the lava river (fig. 9).

At 10^h45^m the lava lake was an estimated 55 feet

FIGURE 5 (left).—Start of the 1959 summit eruption in Kilauea Iki showing the wax and wane of the curtain of fire as seen from Byron Ledge overlook. *Top:* November 14, 1959, 20^h35^m, approximately half an hour after beginning of activity. Active fountain areas from right to left are A, B, C, D, E, and F. Fountains along A, B, and C are partially hidden by fume. Lava streams from E and from A, B, and C have reached the floor of the main crater. *Middle:* November 14, 1959, 21^h30^m. Maximum development of the eruptive rift and curtain of fire. Only area J, at the extreme right, is not shown. Small bright specks on flows are burning trees. *Bottom:* November 15, 1959, 01^h15^m. Vigorous fountaining is restricted to vents along A, B, C, D, and E, and intermittent spatter activity continues at I (extreme right). The orifice of one vent along F (extreme left) still glows, but fountaining has ceased. Volume of lava pouring down main cascade has increased. Photograph by National Park Service.

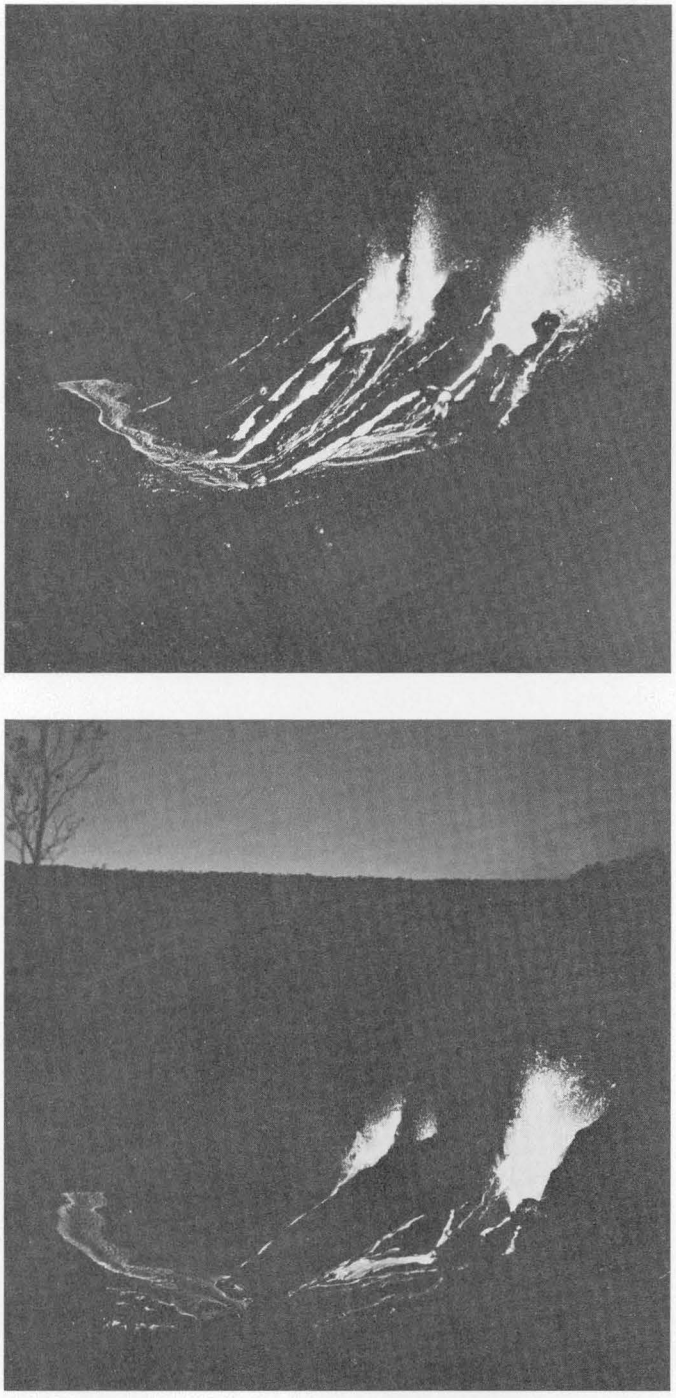


FIGURE 6.—Two views of the fountains at A, B, and C looking eastward from Byron Ledge. *Top:* November 15, 1959, 04^h00^m. Activity at A (right) is now restricted to one fountain, whereas two fountains continue to play from B. Slight activity at C can be seen just above the left fountain at vent B. Main lava river is flowing eastward through the trough from the higher west end of the crater into the lava lake, which is not visible in picture. *Bottom:* November 15, 1959, 06^h00^m. Fountaining at C has ceased and has visibly abated at B. Horizon is east wall of Kilauea Iki Crater approximately 1 mile away.

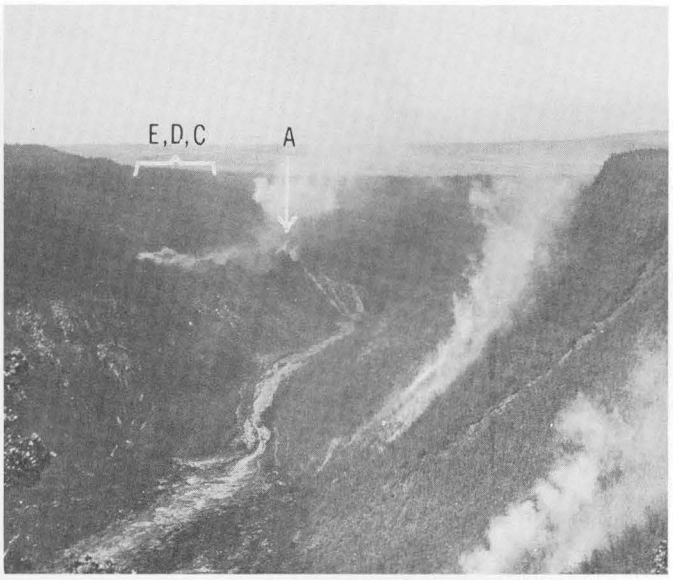


FIGURE 7.—November 15, 1959. View from Byron Ledge overlook showing the fountain at A, braided lava cascades down the crater wall to the lava river, the main cascade, and the lava lake. Fume rises from the activity at A and from the dead vents at C, D, and E. On the north wall of the crater a number of forest fires sweep up the slope. Photograph by National Park Service.

deep—30 feet deeper than at noon the day before. Except for a small central area with remnants of the old rough blocky crust, its surface was now covered by smooth pahoehoe, which came partly from flows which had spread eastward over the lake from the base of the cascade and partly from fresh lake lava brought to the surface by widespread disruption and foundering of the crust. By late afternoon the last vestige of the old rough surface had disappeared, and the pond was exceptionally smooth and level over its entire extent. Around the margin of the lava lake and as much as 50 feet from shore, torchlike jets of yellow flame marked the position of trees and ferns engulfed by the rising lava. Superheated gases from the rapid destructive distillation of this organic matter tore through the liquid surface with an explosive report, burned furiously for a few seconds, and then disappeared suddenly when lava shut off the temporary degassing conduits.

The fountain continued to grow in size throughout the day and was reaching heights of 350 feet by late afternoon (18^h00^m); at 21^h00^m occasional bursts over 600 feet high were measured (fig. 10A, top left photograph). The rate of lava outpouring also continued to increase. The narrow lava cascade characteristic of the three preceding days rapidly evolved into a broad turbulent fall that again discharged

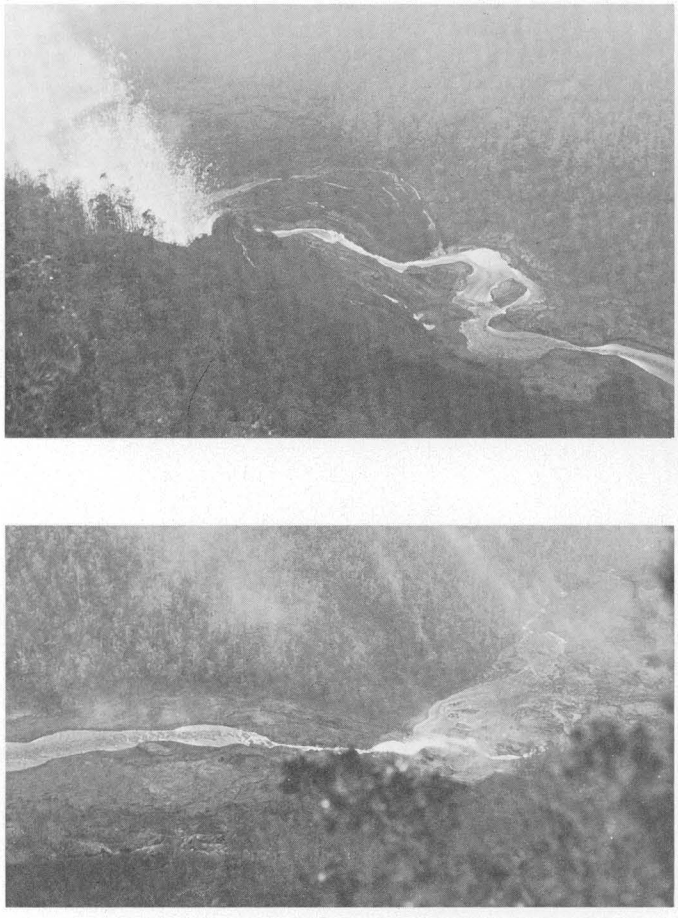


FIGURE 8.—Views from the west end of Kilauea Iki overlook showing the main fountain, lava river, cascades, and lava lake. *Top:* November 16, 1959, 15^h00^m. The main fountain, about 150 feet high, feeds the incised lava cascade that pours down the steep slope to the river. Note extreme turbulence at base of cascade. *Bottom:* November 16, 1959, 15^h00^m. East end of the lava river and the rapids and falls along the main cascade feeding the lava lake.

its load beneath the crust of the deepening lake. At night the everchanging pattern of incandescent fractures attested to the thinness of the lake's crust as the surface rose like that of water in a filling reservoir.

With the increase in fountain height, pumice was wafted high into the air by the hot turbulently rising fume cloud, and cinder and spatter accumulated rapidly on the cone. Eight hundred feet southwest of the fountain, trees stripped of foliage and bathed in fountain light stood like glowing skeletons as incandescent pumice rained down upon them, and 3,500 feet southwest of the fountain, pumice was beginning to form a thin blanket on the Crater Rim road. Large arcuate segments of the steep cone, perched precariously on the crater rim above the

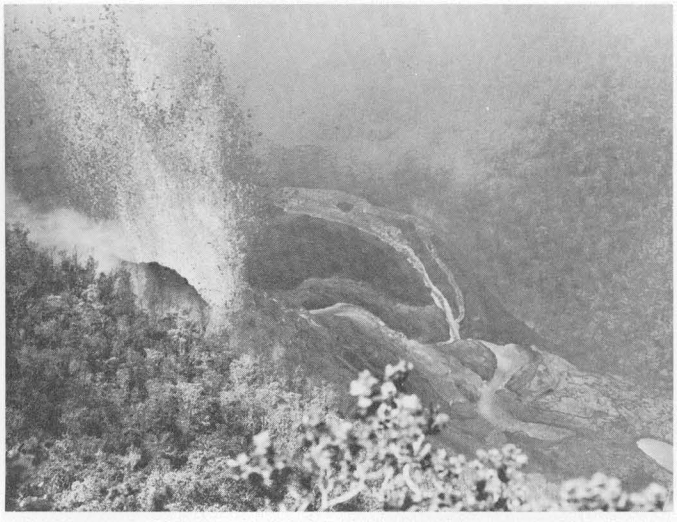


FIGURE 9.—November 17, 1959, 13^h00^m. Same view as figure 8 (top photograph), showing increased fountaining and a higher river bed raised by numerous overflows along its banks. Note lava river disappearing in the crusted-over channel and reappearing farther downstream as an incandescent sheet.

fountain, occasionally broke loose and slid and tumbled down into the vent.

NOVEMBER 18, 1959

During the night and early morning of November 18 conditions remained virtually unchanged. The fountain continued shooting to heights of 600 feet and light pumice continued to shower the area leeward of the fountain; by 08^h00^m, 1 to 1½ inches of pumice had fallen on the Crater Rim road.

Activity once more gradually increased during the morning, and by 13^h50^m the fountain was reaching heights of 750 to 800 feet. At 12^h00^m the lava lake was 112 feet deep and was rising at the impressive rate of nearly 3 feet per hour.

Emission of hot gases, accompanied by subsurface detonations in the crater wall above the lava lake, was first noted during the midday trip into the east end of the crater to measure the lake depth. The gases, which contained abundant water vapor and probably methane and had a strong organic odor, were escaping from joints and fractures in the old rocks as much as 50 feet above the lake surface. Many of the emission areas were hot enough to char the surrounding vegetation, but no flames were visible. Most of the explosions occurred a few feet below the surface and were accompanied by a dull muffled report; some were close enough to the surface, however, to blast out small explosion craters. The gases were evidently derived from the destructive distillation of humic material and vegetation

and from the vaporization of vadose water in the crater wall as it was covered by the rapidly rising lava. Explosions probably resulted from the ignition of mixtures of this gas and air, which accumulated in the permeable crater wall near the edge of the rising lake.

Through the afternoon the fountain continued to grow in size, and at 19^{h}00^m it reached a height of 1,050 feet. The lava river was a 300-foot-wide band of uncrusted incandescent fluid pouring into the lake; there was only a slight break at the top of the rapidly vanishing cascade (fig. 10, middle and bottom left photographs). At 23^{h}15^m the depth of the lake reached 150 feet, an increase of 38 feet in 11 hours.

During a nighttime trip into the crater to measure the height of the lake, pale blue wispy flames were seen flickering over many of the steaming areas along the crater wall. The flames were very feeble and intermittent; even the slight disturbance of the air in the vicinity of a vent caused by a person walking past it commonly induced the flame to flash on or off.

NOVEMBER 19, 1959

At 00^{h}25^m, November 19, the lake reached the top of the main cascade; its thin crust, still laced with a network of incandescent cracks and festooned with arcuate glowing overflows, was continually foundering and reforming.

Through the early morning the fountain remained virtually unchanged. It consistently reached heights of about 1,000 feet and occasional bursts reached 1,150 feet. The output of lava and pumice was enormous and still appeared to be increasing. Slides from the inner face of the cone, or possibly some other constriction in the orifice of the vent, occasionally reduced the fountain height and at the some time deflected a part of the fountain northward across the lava river to form spectacular V-shaped jets (fig. 10, top right photograph).

Pumice from the fountain continued to fall like black rain on the cone and the area far to the leeward. As the liquid lava burst from the vent and rose in a throbbing stream into the sky, larger clots of material continued to enlarge and fragment as the gases dissolved in them boiled off far above the vent. The top of the cone had reached an altitude of about 3,830 feet above sea level, about 160 feet above the ledge (alt 3,670 ft) on which it was building and 370 feet above the vent.

At 11^{h}50^m the lake had attained a depth of 190 feet and, in spite of its increasing area, was filling at a rate in excess of 3 feet per hour. With the main cascade buried, the impetus to flow under the crust and only slightly disturb the surface was removed. Where the broad river joined the lake, it now spread out across the width of the lake driving the rough blocky crust before it. In response to this general thrust from the west on the crust, arcuate pressure ridges 5 to 10 feet high began to form around the eastern margin of the lake.

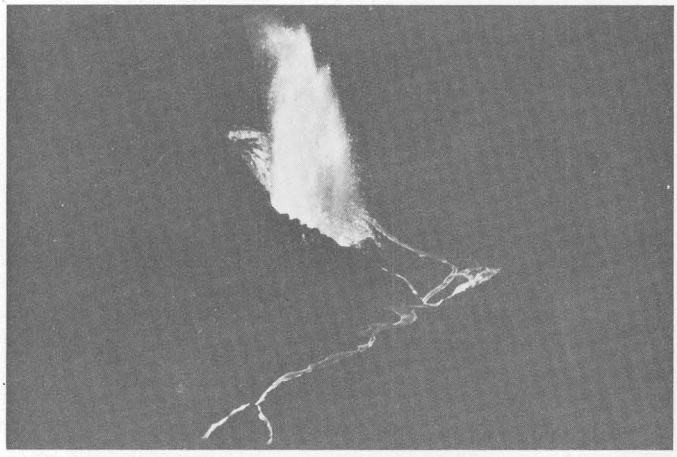
Under the continued rain of pumice and cinder, the cone was growing rapidly, but it was also becoming very unstable. The top of the cone, as it was viewed from the Kilauea Iki overlook early in the afternoon, was about 100 feet above the level of the road. The vent side was nearly a vertical wall with a slight overhang at the top. By late afternoon, however, the entire top of the structure had collapsed, so that the apex of the cone was no longer visible above the level of the road.

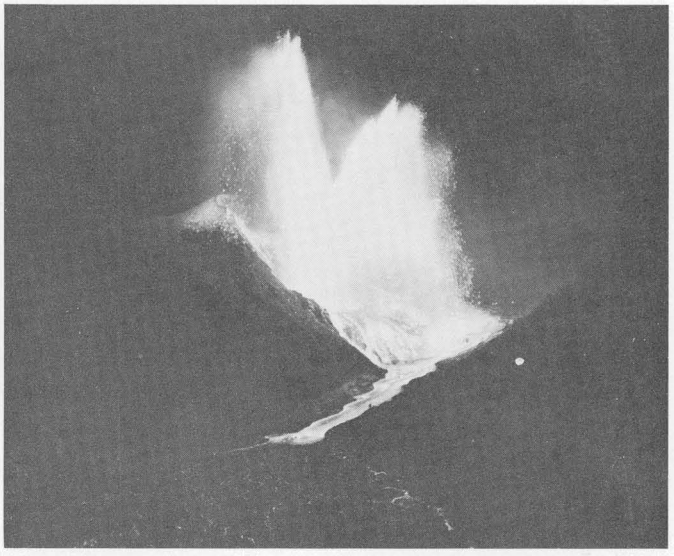
During the afternoon, the now rampant fountain for the first time threw heavy spatter onto the north crater wall, approximately 900 feet from the vent. The impact of this material on the thoroughly desiccated remains of plants and soil so long exposed to the intense radiant heat of the fountain generated an ominous boiling dark-brown cloud of dust that rose to join the swirling fume column ascending above the vent.

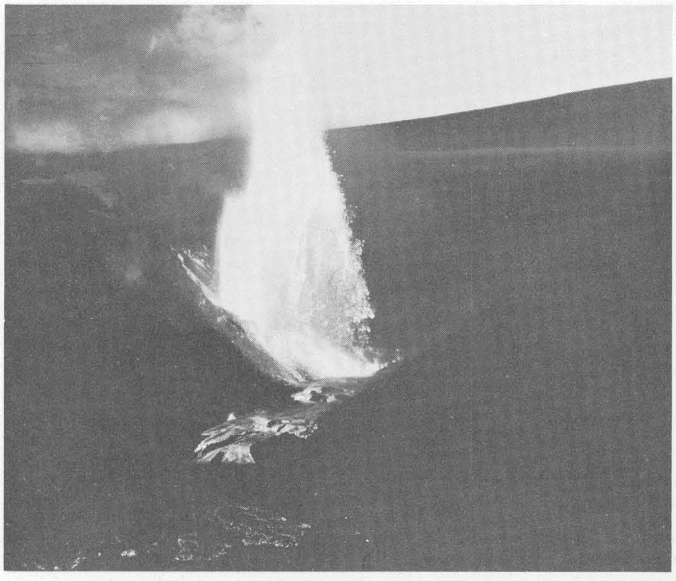
At 21^{h}15^m the lava lake was 225 feet deep and was rising at a rate of 4 feet per hour. As we observed the lake surface from the crater rim, it appeared that more and more lava was flowing across the top of the lake, and the breakout of small flows in front of the larger advancing fronts suggested considerable gradients (locally, at least) from west to east across the lake. The short river pouring out of the vent area at this time was more than 500 feet wide and only a few lava islands impeded its flow into the lake (fig. 11).

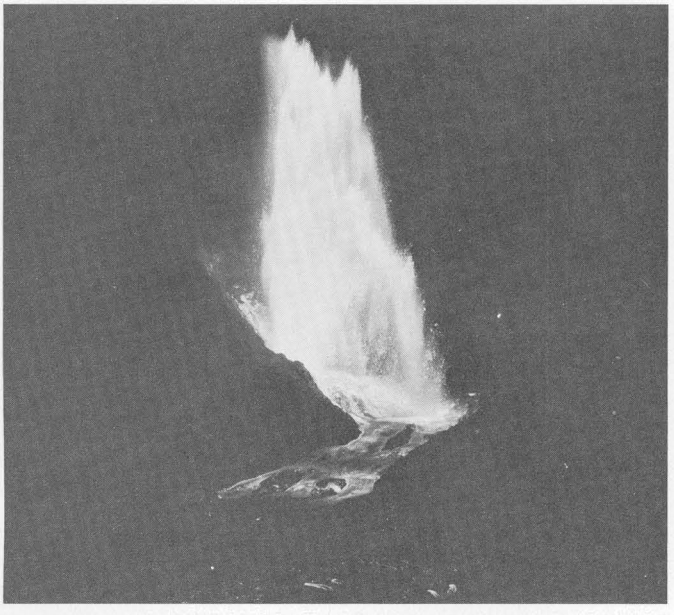
NOVEMBER 20, 1959

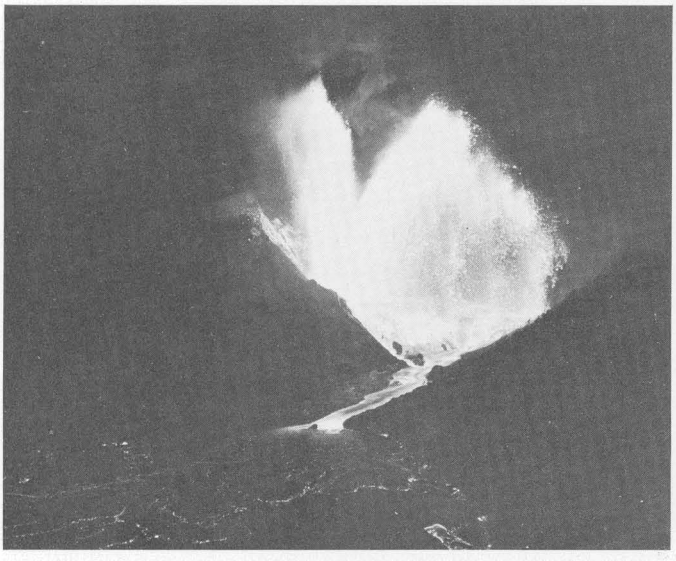
Fountaining and rate of lava output remained virtually unchanged throughout November 20. The cone continued to slump and widen its base (fig. 12), but its height increased very slowly. Much of the ejecta, now being hurled to the higher parts of the cone, consisted of very fluid spatter that accumulated in thin rootless flows and oozed downhill after landing. Because of slight variations in wind direction or a change in the inclination of a fountain jet, many of these very fluid masses were hurled beyond the area already covered by earlier ejecta, where they fell as cow-dung bombs, often setting the forest afire. Leeward of the cone, cooler pumice continued

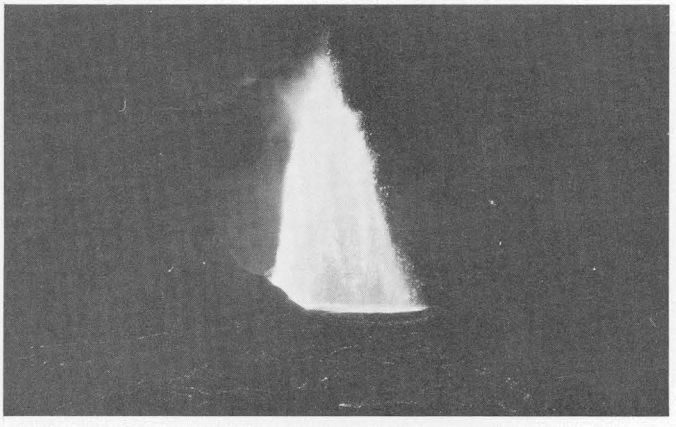












to fall in great quantities; at noon the maximum thickness on the Crater Rim road was 8 inches.

At 12^{h}07^m the lake was 270 feet deep, and the crests of some of the pressure ridges at the east end of the lake were 10 to 15 feet higher and still appeared to be pushing slowly upward.

By early evening the lake's surface had reached the vent, and it extended as a single flat sheet over the entire crater. The fountain was still playing to heights of 800 to 1,000 feet, and occasionally hot gas, without liquid lava, burst out with almost explosive violence between the cone and fountain.

NOVEMBER 21, 1959

An indication of a leveling off, or a possible decrease in activity, was first noted when the depth of the lake was measured at 09^{h}30^m, November 21. The lake was 320 feet deep, and the rate of filling during the last 20 hours had decreased to 2½ feet per hour. By this time, also, the exceptionally level surface of the lake (fig. 13, bottom photograph) had risen above the level of the vent, and the fountain was blasting through several feet of very fluid lake lava before jetting skyward. This agitation in the lake at the base of the fountain generated large waves—much like a localized disturbance in a body of water—which traveled the short distance across the pond to the opposite shore where they broke like waves on a beach. (See fig. 30.) Spatter falling from heights as great as 800 feet also agitated the fluid lava lake around the fountain (fig. 13, top photograph). (Also see fig. 30.) Immediately after the impact of a mass of spatter, a narrow spout of lava leaped far above the surface and then fell back into the lake. Some of these impact rebounds rose at least 30 feet, and at times hundreds danced at once over the surface of the lake.

Through the day the fountain continued to jet over the lake, and it appeared that the vent was being slowly built up by the accumulation of cinder and spatter along the ramparts that extended into the lake at a rate faster than the rise of the en-

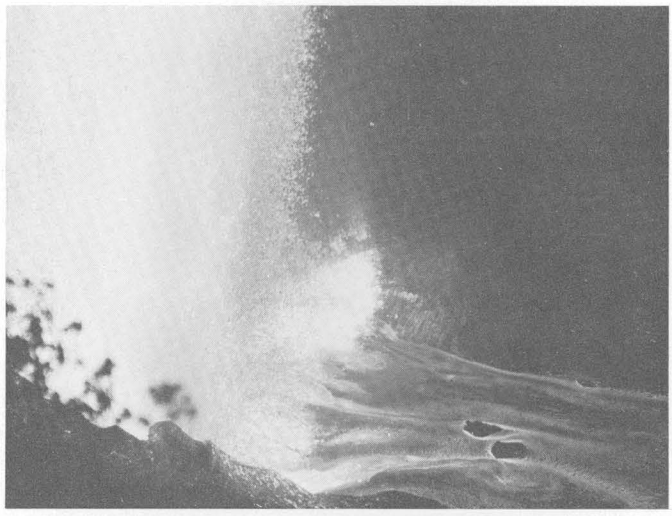


FIGURE 11.—November 18, 1959, 22^{h}00^m. Base of lava fountain and broad lava river viewed from west end of Kilauea Iki overlook. Note the incandescent spatter of fountain discharge on the wall of the crater opposite the fountain.

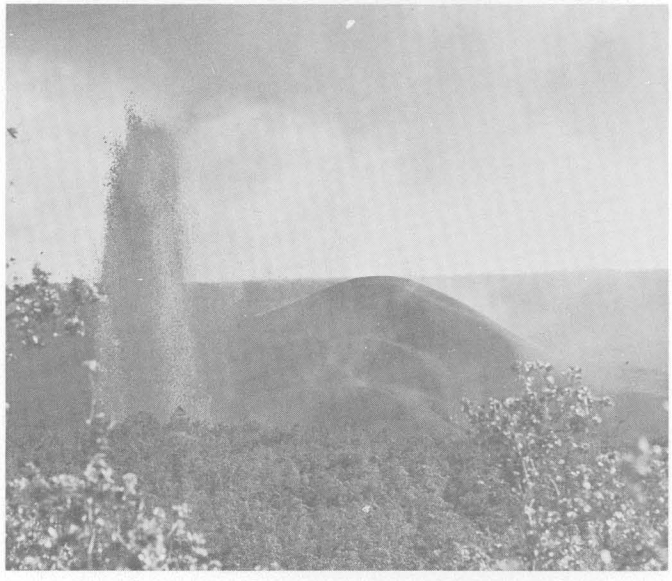
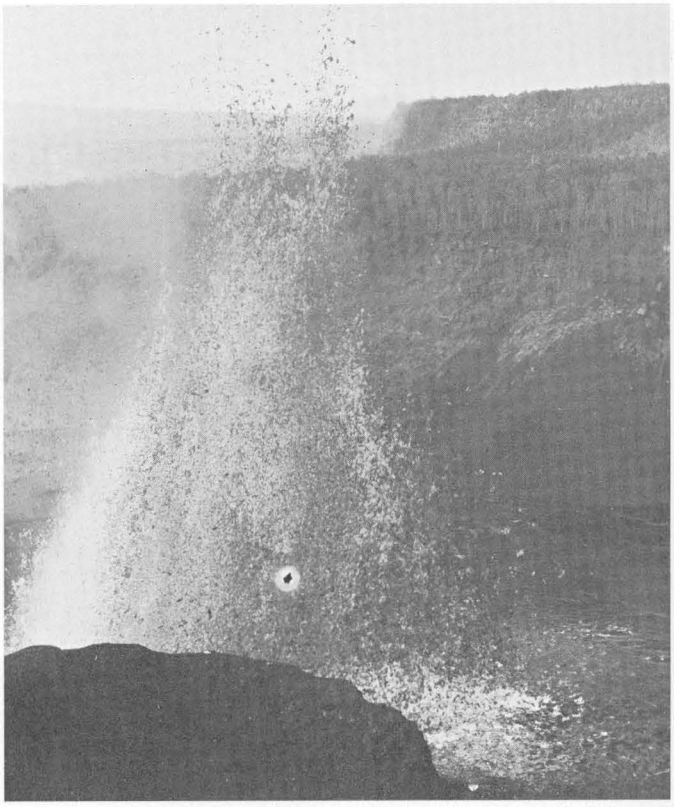


FIGURE 12.—November 20, 1959, early afternoon. Fountain and cone from the north end of Byron Ledge, showing prominent slump features along inner face of cone.

FIGURE 10 (left).—Development of lava fountain and rise of lava lake during the first phase of activity. Photographs are from Byron Ledge overlook. *Top left:* November 17, 1959, 20^{h}30^m. 400-foot fountain with relatively small lava output. Lava lake is approximately 75 feet deep. Note nearly horizontal pumice plume wafting off top of fountain. Photograph by National Park Service. *Middle left:* November 18, 1959, 17^{h}30^m. 850-foot vertical fountain with greatly increased lava output. Lava lake is approximately 130 feet deep. *Bottom left:* November 18, 1959, 22^{h}00^m. V-shaped fountain with vertical jet about 650 feet high. Growing cone at left of fountain has just been deluged with a shower of incandescent spatter. Lava lake, approximately 150 feet deep, has almost reached top of main cascade. *Top right:* November 19, 1959, 05^{h}00^m. 800-foot, V-shaped fountain. Slightly larger cone is being bombarded by spatter. Lava lake, 170 feet deep, is beginning to cover lava river. *Middle right:* November 19, 1959, 20^{h}30^m. 1,000-foot massive fountain and broad lava river. Lake is approximately 220 feet deep. *Bottom right:* November 21, 1959, 06^{h}00^m. Lava lake, approximately 315 feet deep, has reached vent, and ejecta from the 750-foot fountain are falling directly on lake surface.



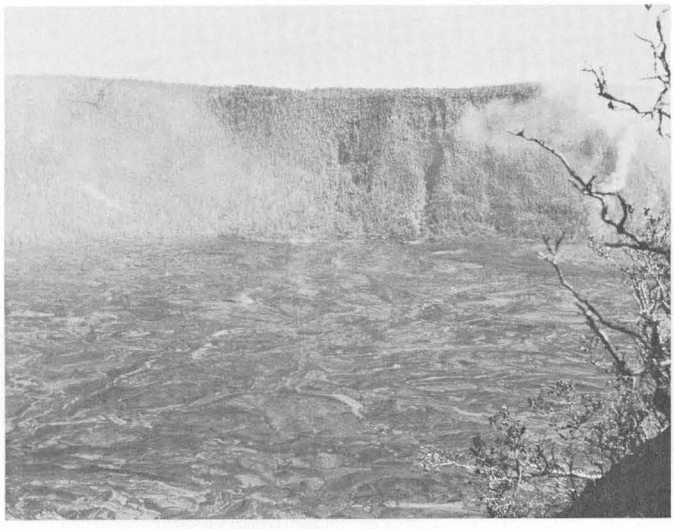


FIGURE 13.—Fountain and lake during the last day of the first phase, viewed from Kilauea Iki overlook. *Top:* November 21, 1959, 12^h30^m. Relatively small fountain with ejecta falling directly upon the lake surface. *Bottom:* November 21, 1959, 13^h00^m. Exceptionally level surface of the 330-foot-deep lava lake. Lighter areas and bands are fluid lava oozing and squeezing up around foundering plates of the crust on the continually reworked surface.

FIGURE 14.—November 21, 1959, 18^h00^m. Northward-jetting fountain is blasting through the lake lava and debris is falling on the lake surface. View is from Byron Ledge.

croaching lava (fig. 14). However, at 19^h25^m, enough lake lava apparently found its way into the upper parts of the conduit to cap the vent effectively, and within 40 seconds the fountain decreased from a spurting giant 700 feet high to a few gas bubbles rising from the lava over the vent area.

Such was the unexpected end of the first phase of the summit eruption. It lasted half an hour less than one week and filled Kilauea Iki Crater to a depth of 335 feet with approximately 40 million cubic yards of lava.

NOVEMBER 22, 1959

The first light of morning on November 22 revealed a yellowish-white cap on the strongly degassing cone. Later in the day, during a gas-sampling trip to the top of the new cone, we were subjected to very strong choking sulfur dioxide gas and found it necessary to breathe through dampened rags for brief forays into the gas-charged atmosphere or to use gas masks for a longer stay. The color on the cone was due to the alteration of pumice to a

hygroscopic yellow material and to sublimates of white sulfates and yellow sulfur forming on the pumice.

After fountaining ceased, pahoehoe flows oozing up through fractures in the crust and pouring up over the edges of foundering crustal plates continued to rework the surface of the lake (fig. 13, bottom photograph). At 15h00m, observers on the north crater rim opposite the vent first noticed liquid lava moving toward the vent area. After dark this phenomenon was clearly discernible, and at 22h00m a 15-foot-wide stream of lava moving at a speed of about 5 feet per second was observed flowing into the grotto at the orifice of the vent. The lake of lava was clearly draining into the source fissure.

NOVEMBER 23, 1959

In the morning of November 23 we climbed down into the crater to examine the vent. Except for a few small pinnacles, which acted as local degassing chimneys, and the elongate pressure ridge at its east end, the lake was virtually level. But it was about 7 feet below the maximum height attained by the lava at the cessation of fountaining on the night of November 21. A few small pahoehoe tongues were still flowing across the lake surface, but at the vent the lava was completely crusted over, and only a slight incandescence was visible in the deeper cracks.

NOVEMBER 24, 1959

Except for the cessation of local pahoehoe flows on the lake surface, conditions on November 24 remained virtually unchanged from the previous day.

NOVEMBER 25, 1959

No change.

SECOND PHASE

NOVEMBER 26, 1959

At 00h30m, November 26, the second phase of activity was heralded by boiling lava and mild spattering in the throat of the vent. By 01h00m the sky over the crater area was brilliantly illuminated, and 15 minutes later, when we reached Byron Ledge overlook, the fountain was 50 feet high and had produced a thick circular flow which had reached the north side of the crater opposite the fountain. In the cone west of and slightly above the main vent, a small vent was spurting small jets of lava in sympathy with the pulsations in the main vent.

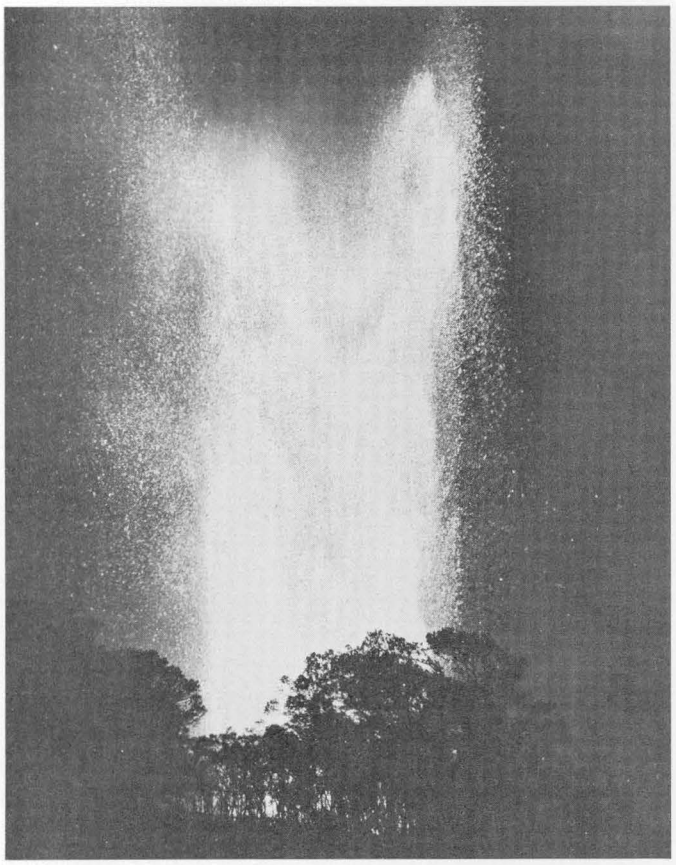
The fountain remained small and rarely exceeded 100 feet in height during the next 2 hours. The lava it was erupting was relatively viscous; possibly it was degassed lava that had drained back after the first phase. By 03h15m the lava had increased in fluidity and the height of the fountain had increased; between 03h15m and 11h00m the fountain averaged 200 to 300 feet in height, and occasional bursts reached 400 feet.

On a sampling trip into the west bay at 05h30m, it was found that the flows entering this part of the crater were being extruded from at least seven openings in the old lake crust and were not direct surface flows from the vent. The subcrustal tubes feeding these erupting cracks apparently extended back 200 to 300 feet to a source under the relatively high and very fluid lava pad around the vent.

Through the rest of the morning and early afternoon, the fountain continued to grow in size, reaching a maximum height of 1,000 feet at 15h30m. The rate of lava extrusion also increased during the day, but the amount of pumice added to the cone was relatively small. By noon, when the surface flows reached the east end of the lake, the fountain rose as a sporadic V-shaped fan, throwing floods of liquid lava onto the ramparts of the cone, whence it cascaded in bright incandescent sheets down to the lake.

At 16h35m the fountain, which had been spurting to heights of 800 feet, died almost instantaneously. Backflow into a small bubbling pond over the vent began almost immediately. At 16h40m the pond drained away and exposed a veritable river of lava pouring underground. After a minute or two the rapid inflow deluged the chasm with lava, causing a surge that rose to splash over the 50-foot-high spatter rampart. The lake then closed in above the vent, and at 17h00m it appeared from the crater rim that the backflow had stopped; but later evidence showed that the lake must have continued to drain through channels under the thin crust. On a trip into the east end of the crater at 19h40m, it was found that the level of the lake was approximately 10 feet below the high lava mark and was still subsiding slowly. A forest of "lava trees," exposed by the withdrawal of the lava, stood at the edge of the lake; many were still emitting flames as the last remnants of organic matter within them burned away.

The second phase of activity flooded the old lake surface with an additional 23 feet of lava, raising it 16 feet above the highest level of the first phase. The total depth of the lake when the fountain died was 351 feet.



NOVEMBER 27, 1959

In the morning of November 27 it was evident that a tremendous withdrawal of lava from the lake had occurred during the night. The resulting collapse dropped the lake's thinly crusted surface 35 to 45 feet in the west bay and 25 to 30 feet in the main body of the crater, leaving a black ledge 25 to 75 feet wide completely encircling the crater.

During the day the only indication of recent activity was the emanation of blue sulfurous gas fumes from the vent. At night, however, these fumes were illuminated by sluggish streams and oozes of lava still flowing from beneath the crust and into the open vent.

NOVEMBER 28, 1959

The vent continued to emit copious fume throughout November 28. Fume was also rising from a number of jagged, broken pinnacles protruding from the relatively flat surface of the collapsed part of the lake. Many of these fuming areas appeared to be remnants of the degassing chimneys observed after the first phase of activity, which were subsequently covered by the flood of second-phase lavas and were again exposed by the withdrawal (drainback) second-phase lava.

THIRD PHASE

NOVEMBER 28, 1959—CONTINUED

The third phase of eruptive activity began at about 16^h30^m on November 28, when blobs of spatter were again observed shooting above the rampart around the vent. Within an hour a 300-foot fountain was surging in the vent; by 18^h15^m a broad fountain was raging to heights as great as 650 feet and was pitching washtub-size masses of spatter onto the Crater Rim road southeast of the vent. The fountain continued to grow rapidly in height and reached 1,200 feet by 21^h00^m (fig. 15).

Only minor lava flows that were restricted to the area at the base of the fountain were observed during the night (fig. 16). The fountain, however, poured tremendous quantities of pumice and heavier spatter onto the crater rim in the lee of the fountain. Most of this pyroclastic debris was falling east of the summit of the old cone, and at about 22^h00^m a new cone began to develop rapidly on the east shoulder of the old one. The Crater Rim road, which

FIGURE 15 (left).—High third-phase fountain from Kilauea Iki overlook. *Top:* November 28, 1959, 22^h00^m. Twin vertical jets shoot to heights of 1,200 feet. *Bottom:* November 29, 1959, 09^h00^m. Inclined jets shoot to 1,400 feet and pumice is being wafted even higher. Blobs of spatter litter road near the guardrail.

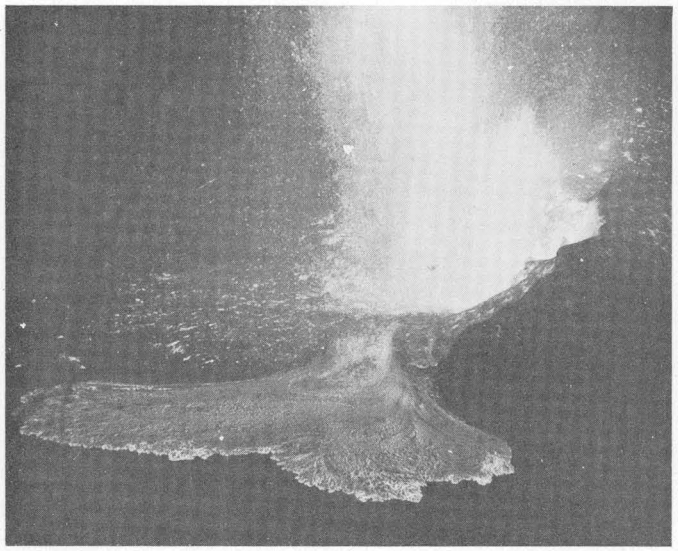


FIGURE 16.—November 28, 1959, 21^{h}00^m. View from Byron Ledge showing small incandescent tongues of very fluid lava flowing into the west bay of the crater from the base of the fountain.

had skirted the south and east sides of the cone and heavy fallout area, was soon covered by 20 feet of pumice and was impassable.

The tremendous impact of the heavier pieces of cinder and spatter that plummeted down from the top of the fountain was clearly demonstrated during the night, when chunks up to 2 feet in diameter rained down upon the road and shattered the 4- by 6-inch wooden guardrail (fig. 15, bottom photograph). Other pieces smashing onto the road punched shallow saucerlike depressions in the asphalt surface. One large spatter blob that fell on Byron Ledge, north of the fountain, measured about $1\times2\times4$ feet. Its fluidity was indicated by the detailed cast of a delicate tree-fern branch imbedded on its underside. On impact, the blob plowed out a crater several inches deep, and rolled back the sod of the forest floor around its periphery.

NOVEMBER 29, 1959

Through the night and early morning of November 29 the fountain continued jetting to great heights, generally as a single narrow plume. At 01^{h}50^m the fountain reached 1,350 feet, and a few incandescent projectiles attained heights of 1,500 feet before arcing downward. During this stage, incandescent pumice was wafted as high as 1,800 feet in the hot turbulent draft above the jet, and cooler lighter pieces were carried much higher. The constantly changing patterns in the surging pumice plume that resulted from variations in wind direction and intensity were fascinating to watch. Often, glowing clouds of pumice swirled directly over our heads, only to be carried far beyond us into the forest before falling. Between 02^{h}00^m and midmorning the fountain consistently played to a height of 1,400 feet (fig. 15, bottom photograph) and by 09^{h}00^m, 70 to 80 feet of pumice covered the road, an increase of more than 50 feet in 11 hours.

Although no appreciable flow of lava into the lake had yet been observed during the third phase, it was evident at daybreak that the lake was filling slowly, apparently by subcrustal ingress of lava from the vicinity of the vent. By midafternoon the old second-phase crust on the east end of the lake had been raised about 10 feet above its former level and lava was beginning to squeeze up around the entire margin of the floating crust. Moreover, unlike the previous phases when lava flooded over the surface and maintained a more or less liquid level, the lake surface now sloped gently upward toward the vent.

Occasionally, during the day, large parts of the cone collapsed into the vent and reduced the fountain to heights as low as 200 feet and deflected the reduced jets of lava toward the north (fig. 17). Otherwise, the lava fountain sprayed majestically into the sky. At 12^{h}38^m bursts reached 1,500 feet, although much pumice was carried up to 2,200 feet; at 12^{h}53^m a burst of 1,700 feet was recorded, and until 16^{h}00^m, the fountain consistently spurted to 1,400 feet.

At 16^{h}24^m the fountain decreased rapidly in height,

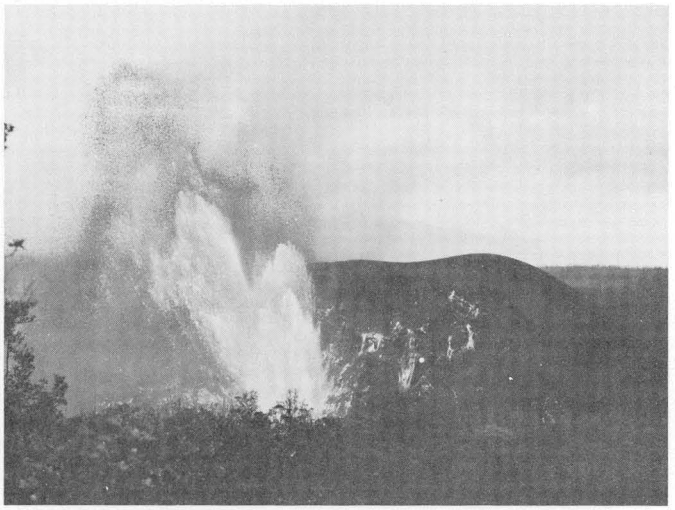


FIGURE 17.—November 29, 1959, 08^{h}00^m. View from trail leading down to Byron Ledge showing the reduced fountain deflected northward by a collapse of the inner part of the cone. Note the new cone developing on the left shoulder of the old main cone (immediately to the right of the fountain).

almost ceasing entirely, and great surges of lava in the vent accompanied by loud thumping noises sent waves of fluid lava over the lake. These were the first surface flows of appreciable volume since the third phase began. Slowly the fountain reestablished itself, only to founder again when a large part of the cone slid down into the vent. Once more the fountain regained its height; but at 16^h37^m it foundered again, sending out additional surges of lava across the pond. Early in the evening it became apparent that a large part of the east side of the cone, which had slumped onto the lake the night before, was being rafted slowly eastward by the strong flows pouring from the base of the fountain. By 20^h00^m this island had floated 800 feet from the cone and a distinct series of concentric pressure ridges were forming around its "bow".

The fountain never fully recovered after the foundering during the afternoon. After 17^h00^m it averaged about 600 feet in height and produced only a minor amount of pumice, although large quantities of lava continued to burst from the vent. Evidently, degassed heavy lake lava was finding its way into the conduit and impeding the flow of new material.

The end of the fountaining came suddenly at 21^h47^m, and once more backflow began immediately. The third phase of activity added 20 feet of lava to the lake, but this was 10 feet short of the high lava mark of the second phase.

Backflow into the gaping vent increased in rate until 22^h20^m, when the seemingly bottomless conduit filled. Lava still continued to drain into the vent, however, but at a much reduced rate and without the turbulence that accompanied the plunging lava fall into the open conduit.

After the cessation of fountaining, large parts of the steep unstable inner face of the cone began tumbling into the lake, and the cone's glowing interior was exposed. Most of the avalanche debris, including sections of the cone as much as 50 feet in diameter fell toward the vent; the part that did not plummet directly into the vent was immediately engulfed by the backflowing lava.

NOVEMBER 30, 1959

The backflow had practically ceased by the morning of November 30, and the resulting collapse of the lake surface was relatively minor, averaging about 12 feet over the entire central area. Moreover, there was no crustal foundering like that following the first two phases, primarily because the second-phase crust was not completely destroyed during the third phase.

Despite its relatively short duration, the third phase produced far more spatter and pumice than any other phase of the entire summit eruption. Crater Rim road was blanketed by more than 10 feet of pyroclastic debris for a distance of over 2,000 feet, and the section nearest the vent was actually covered by the east shoulder of the new east cone (fig. 18). In the Summer Camp area, a campground 3,000 feet from the vent, 30 inches of pumice was added to a 10-inch pumice accumulation laid down by the first and second phases (fig. 19); pumice fragments were carried 10 miles southwest of the fountain by prevailing winds.

Early in the evening a large section of the cone slid down onto the lake, and the exposed interior of the cone remained incandescent for about 3 minutes.

DECEMBER 1, 1959

Slides continued raveling off the face of the cone on December 1, and deep arcuate cracks parallel to the crater rim—the surface expression of larger slip blocks—were beginning to develop along the crest of the two coalesced cones.

DECEMBER 2, 1959

No change.

DECEMBER 3, 1959

On December 3 a trip to the vent area on the lake disclosed no evidence of fluid lava movement. A large pile of cone debris with a steep blocky front inched forward from the west spatter rampart,

FIGURE 18.—November 30, 1959. Third-phase pumice blanket, southwest of cone, on buried Crater Rim road (cleared area between denuded ohia trees). Main cone, in center of picture, is about 2,000 feet away; small east cone is behind trees on the right.

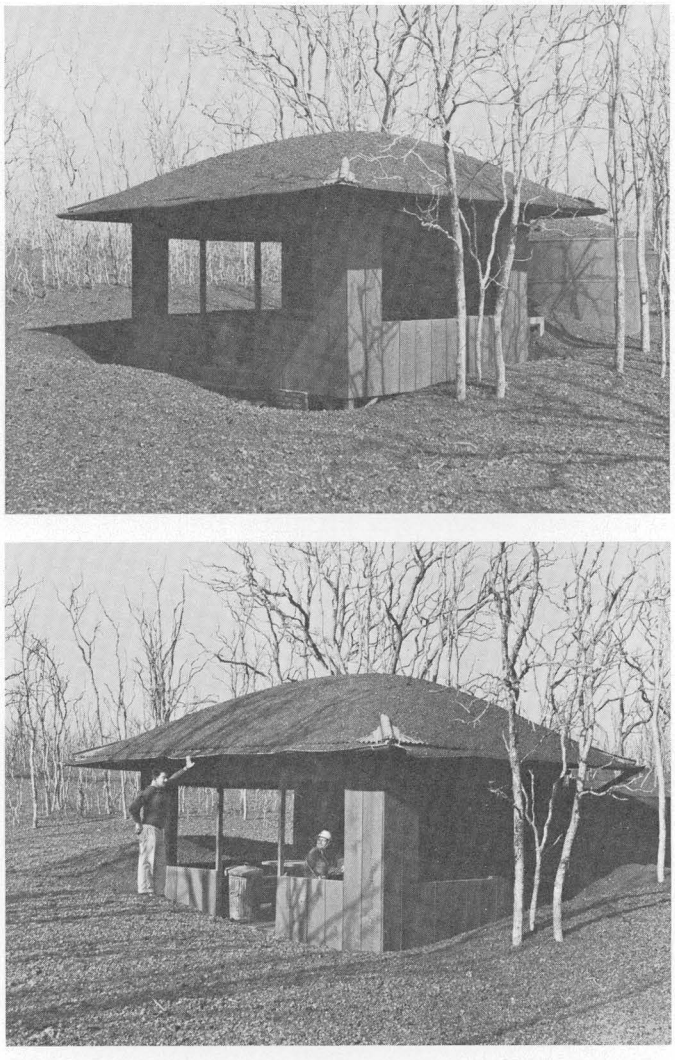


FIGURE 19.—Pumice blanket in the Summer Camp area 3,000 feet southwest of vent. *Top:* November 30, 1959. Small shelter after third phase of activity; 40 inches of pumice covers ground. *Bottom:* December 15, 1959. Same view after the 11th phase of activity; total pumice depth is about 55 inches.

and a constant trickle of rocks rained down the inner face of the cone. The small west bay of the pond had a very uneven surface, and a high central area about 15 feet below the high lava mark was surrounded by a 100-foot-wide moat 15 to 20 feet deep.

FOURTH PHASE

DECEMBER 4, 1959

At about 01^h00^m, December 4, slight spattering was once more visible in the vent, and by 01^h45^m a small fume cloud, illuminated a pale red by the churning lava, was emanating from the orifice. Thus began the fourth phase of activity, the longest and largest of the eruptive periods except for the first phase. It was characterized by an unusually quiet outpouring of very hot lava and only moderate fountaining.

Between 02^h00^m and 09^h00^m we watched the renewed activity from the north rim of the crater directly opposite the vent. As the scene was illuminated more clearly by light from spatter and churning lava, it became evident that the seat of activity was on the steep face of the cone about 40 feet above the lake. Two separate openings about 15 to 20 feet in diameter were clearly visible in the vent area—one was emitting gas and minor spatter accompanied by loud booming noises, and the other, 25 to 30 feet to the west, was extruding a steady stream of lava that cascaded down the steep front of the cone and produced a small flow on the crust of the lake. By 05^h00^m a spatter and lava rampart had been built up around the vent area, forming a large caldronlike bowl containing lava in a continual state of agitation (fig. 20, top photograph). Small streams of lava poured through a number of breaches in the rampart and occasionally a heavy surge deluged the entire rim—all of this was added to the small flow advancing across the lake. For 2 hours the activity remained unchanged; the small pond in the caldron continued to boil, and spatter blown out of the easternmost opening shot up to heights of 100 feet. At 07^h41^m a small fountain suddenly appeared through the new flow at the base of the caldron rampart, and 10 minutes later another began a few tens of feet to the east. These two fountains played to heights of 50 feet for about an hour, when their activity gradually decreased, and by 09^h00^m they had disappeared completely.

At 09^h45^m we entered the west bay of the crater to sample the flows spreading out from the vent (fig. 20). During our stay on the lake the rate of lava output increased noticeably, and shortly after we climbed out of the crater (11^h20^m) the entire rampart, which formed the north lip of the caldron, was aflood with lava. During the next few minutes, as fountaining continued to increase, the rampart disappeared; It is very likely that the rampart was broken down and was carried away by the deluge of lava now pouring out of one large vent.

Throughout the afternoon, the fountain gushed like a giant artesian spring. Occasionally it spurted to heights of 200 to 250 feet, and tremendous quantities of lava were expelled onto the lake surface. New flows completely covered the old lake crust by 18^h30^m, and at 23^h25^m the lake surface stood 24

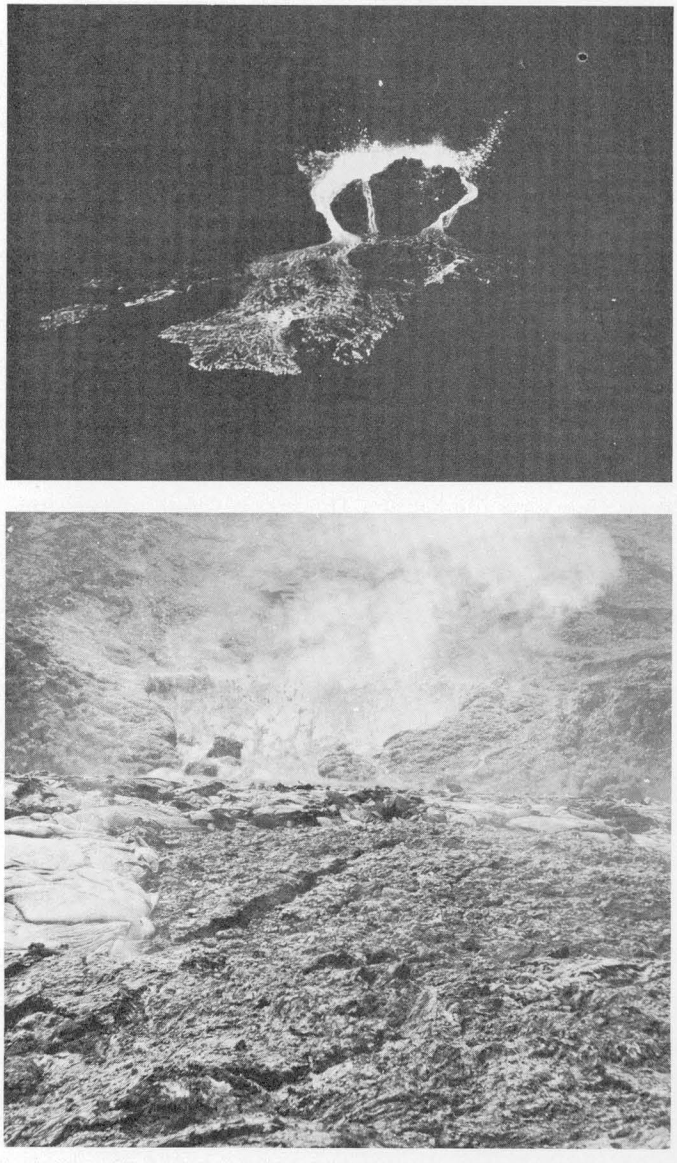


FIGURE 20.—Views of fourth-phase fountain and lava flows. *Top:* December 4, 1959, 06^{h}00^m. Small fourth-phase fountains feed early flows on the lake surface 40 feet below the vent. View from crater rim opposite vent. *Bottom:* December 4, 1959, 12^{h}00^m. Small spatter fountain plays in caldron over vent. Lava pours over breach in caldron and spreads across cooled third-phase lava in foreground.

feet above the high lava mark left by the second phase of activity.

DECEMBER 5, 1959

A marked increase in fountain height, accompanied by minor pumice production, was noted during the early morning hours of December 5. By 02^{h}00^m the fountain was consistently reaching a height of 300 feet and occasional bursts of spatter reached 500 feet. At 03^{h}00^m the vent was still rolling out great quantities of lava. The entire lake appeared to be awash, and wholesale foundering of the crust cut the surface of the lake into a myriad of dark patches bordered by ever-changing ribbons of incandescent orange to deep-red lava. Temperatures as high as 1192°C—this was the hottest lava observed during the entire eruption—were measured in the fluid core of the fountain at this time.

At 04^{h}45^m the fountain began to falter beneath the rising lake. At times the lake was thrown up in violent boiling surges over the vent, and at times the fountain burst through the confining tide and jetted hundreds of feet into the air (fig. 21). This surging continued for about 2 hours, until 06^{h}45^m, when the entire lake surface began to lower and a strong current flowing in the direction of the still-active vent became evident along the south side of the lake. By 07^{h}00^m the level of the lake had dropped about 10 feet and the backflow toward the base of the fountain appeared to be even stronger. In the next few minutes a small lake-within-a-lake, marked by a strong counter-clockwise circulation of lava, formed over the apparent backflow opening near the base of the fountain. Meanwhile, the fountain had regained its strength and continued to shoot to heights of 300 to 500 feet. At 07^{h}30^m backflow was still evident but the lake level no longer appeared to be dropping. The backflow gradually ceased, and by 08^{h}30^m the level of the lake had risen to within a few feet of the level attained by the lava 2 hours earlier.

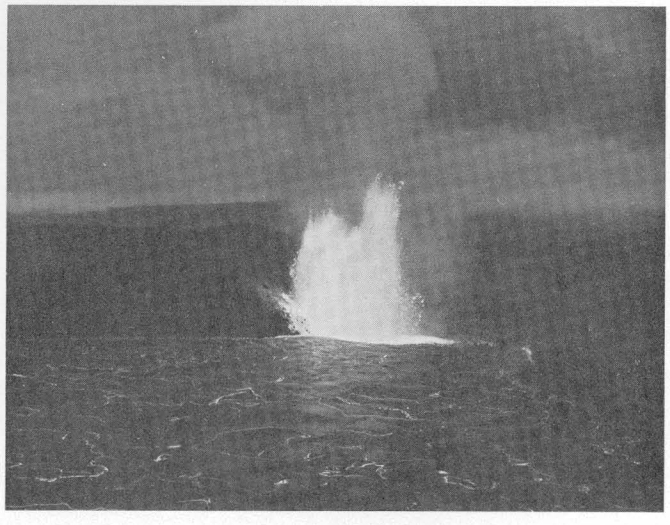


FIGURE 21.—December 5, 1959, 06^{h}30^m. High, exceptionally level lava lake and relatively small fountain of the fourth phase just prior to the period of backflow concurrent with fountaining, as viewed from Byron Ledge overlook. Crust of lake is continually foundering and reforming.

The lava in the pond was unusually fluid. Waves generated at the base of the fountain rose in 5-foot-high breakers as they washed onto the shore opposite the vent; the surface of the lake near the vent rolled and pitched like the ocean driven before a storm.

Again at 09^{h}00^m the fountain began to falter beneath the rising lake. Seven times after 09^{h}20^m the fountain was reduced to bubbling at the vent and appeared to be dead, only to reappear with a mighty burst. Finally, at 09^{h}27^m, when the level of the lake reached the high 06^{h}45^m lava mark, the fountain faltered for the last time, and a dead calm settled over the vent.

The fourth phase of activity lasted 32½ hours and filled the lake to a depth of 395 feet; this was 44 feet above the previous maximum that was attained during the second phase.

Unlike the close of the last two phases, perceptible backflow did not begin as soon as the fountain died. Instead, the lake remained calm and level, and only the incandescence in a few cracks revealed the fluid interior. By 09^{h}45^m, however, the backflow had begun in earnest; from the east foot of the cone on the south rim of the crater a constant clatter and rumble was audible as the thickening crust was crumpled and dragged toward the vent by the retreating lava. Later in the morning it was evident from the crater rim opposite the vent that the turbulent draining had ceased and the backflow stream was pouring into a small pond that filled the vent (fig. 22). In the east end of the crater, at 12^{h}10^m, the lake surface had subsided about 20 feet and was still dropping rapidly. The large part of the cone that had floated out into the pond during the third phase, and which had been entirely covered by the fourth phase lavas, was again protruding from the lake. Lava trees had also formed along the east shore of the lake, but they were too fragile to stand more than a few minutes and they collapsed with the rapid retreat of the lava.

Backflow at a much diminished rate continued throughout the day. At 16^{h}00^m, from a vantage point opposite the vent, two streams, one from the large east lake and a smaller one from the west pond, were seen to be pouring over the lip of the vent. By 20^{h}20^m the smaller stream from the west had ceased and the stream from the east was relatively small.

DECEMBER 6, 1959

Backflow was still evident in the morning of December 6, and at 11^{h}00^m a small sluggish stream continued to flow toward the vent. Subsidence of the lake, measured in the east end of the crater at 15^{h}45^m, was 33 feet.

FIGURE 22.—December 5, 1959, late morning. A steady stream of lake lava flows westward into the small circular pond over the vent. Lake level is approximately 15 feet below the high mark of a few hours earlier. View from north end of Byron Ledge. Photograph by National Park Service.

FIFTH PHASE

DECEMBER 6, 1959—CONTINUED

The fifth phase of activity began at 14^{h}48^m, December 6, when strong blue fume followed by minor bubbling was observed in the vent area. The fountain rapidly increased in strength; at 14^{h}58^m spatter was being tossed 50 feet high, 30 minutes later the fountain was cresting at 300 feet, and at 15^{h}54^m it had reached 1,000 feet. Later in the afternoon, pieces of cone slumped into the vent and diverted the fountain northeastward across the lake, and, at times, extremely large arcing jets struck the north wall of the crater.

Tremendous quantities of lava also poured out from the base of the fountain and formed a single flowfront that moved eastward across the old fourth-phase lake and covered its entire surface by about 17^{h}20^m. Between 21^{h}10^m and 22^{h}30^m a number of small secondary fountains up to 20 feet in height sprang up through the new flow at scattered points on the lake. These fountains probably were caused by the release of volatiles that had been trapped by the flow during its rapid engulfment of the old crust. At 22^{h}00^m freshly-set fires around the entire

margin of the lake indicated that the lava had risen above the old level and was setting fire to the trees. On a trip into the crater at 23^{h}00^m, we found that the lake had risen 38 feet during the preceding 8 hours, an average rate of almost 4.8 feet per hour.

DECEMBER 7, 1959

The high fountaining continued until 00^{h}23^m, December 7, when it stopped very abruptly; this marked the end of the fifth phase. Although no active backflow was visible, it was obvious by 00^{h}50^m that lava was draining away, as the whole lake surface had sagged and was pulling away from the edge.

Continued draining through the night again completely changed the lake by morning. The black ledge, now 50 to 100 feet wide, formed a glistening shelf around the entire crater, and the exceptionally level surface of the lake was almost 30 feet below it. At 08^{h}50^m two streams of lava, one from the main east lake and one from the smaller west pond, were still flowing toward the vent, and the crust over the main lake was locally foundering and reforming.

SIXTH PHASE

DECEMBER 7, 1959—CONTINUED

This respite was short lived, however, and at 15^{h}30^m, December 7, spatter that was again being tossed up in the vent heralded the start of the sixth phase. The spattering soon evolved into a low fountain, and at 16^{h}15^m it grew into a rolling boil of lava with occasional bursts shooting to 100 feet. By 17^{h}15^m the fountain was a broad fan-shaped liquid curtain pulsating between 50 and 350 feet high and pouring out a great flood of lava. Later in the evening, occasional bursts from the fountain flung viscous blobs as high as 750 feet, but in general the activity was comparable to that of the fourth phase—gas-drive and pumice production was minor but lava output was voluminous.

From Byron Ledge the liquid core of the fountain appeared almost yelow-white as it spewed up out of the orifice (fig. 23). By 23^{h}30^m the inner face of the cone was constantly aglow from a persistent deluge of spatter, and numerous rootless pahoehoe flows, fed only by the accumulation of this falling liquid, cascaded down the flanks of this cone.

DECEMBER 8, 1959

By about 01^{h}00^m, December 8, lava had filled the lake to the previous high level reached by the fifth phase. At 02^{h}30^m we were at the edge of the lake in the east end of Kilauea Iki watching the rise of lava, when the fountain began to pulsate irregularly,

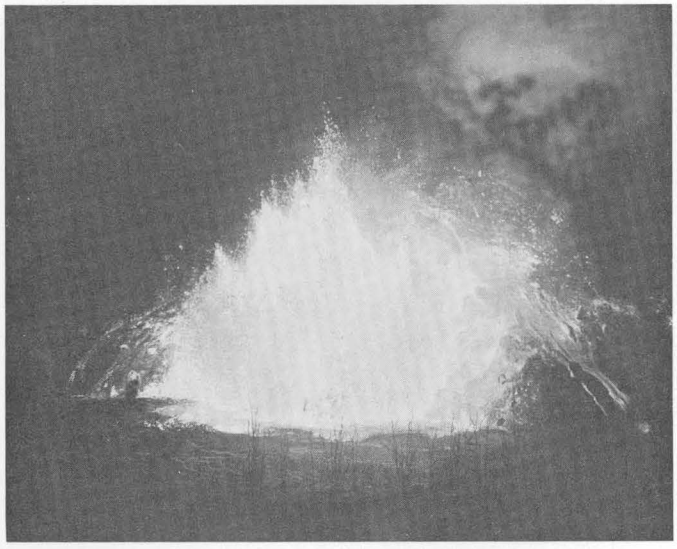


FIGURE 23.—December 7, 1959, 23^{h}30^m. Low, broad fountain of the sixth phase and spatter-fed flows cascading down the flanks of the cone. Note the waves forming on the lake at the base of the fountain. View from north end of Byron Ledge. (See fig. 22 for contrast.)

and abruptly at 02^{h}45^m it died. Within a few minutes the level of the lake began to lower rapidly and to withdraw from the crater wall, leaving a lava coating on the trees and old lake surface. By 03^{h}00^m the lake level had dropped about 2 feet, indicating a rate of withdrawal of 2 million cubic yards per hour.

The sixth-phase lava reached a level 10 feet higher than that of the fifth phase, and the depth of the lake was increased to 413 feet at the cessation of fountaining.

At daybreak conditions on the lake were very similar to those on the previous morning, after the fifth phase. The great withdrawal of lava had lowered the lake surface about 25 feet. One stream was still visible pouring into the vent and copious fume was issuing from it. In the small west pond subsidence was not nearly so pronounced, as large volumes of solid cone debris, aa flows, and viscous pahoehoe had aided in filling this end of the crater during the last 5 days.

SEVENTH PHASE

DECEMBER 8, 1959—CONTINUED

The seventh phase started about 13^{h}00^m, December 8, with splashing and bubbling in the vent area. However, unlike the previous eruptive phases, which either developed rapidly into a large fountain or boiled out great quantities of lava, the activity continued at a low level for almost 4 hours. During

most of this time a narrow stream of lava continued to drain from the lake and to flow beneath the small pool of new lava over the vent area.

Suddenly at 16^h53^m the fountain roared to 850 feet. Five minutes later it was playing to 1,150 feet, and then gradually within the next hour it attained a maximum height of 1,400 feet. Coincident with the increase in fountaining, large quantities of lava began to pour from the vent, and within 2 hours the old lake surface was completely covered. The high fountain was also producing large amounts of spatter, cinder, pumice, and cored bombs (fig. 24), most of which were falling in the saddle between the main cone and the smaller east cone and were noticeably changing the overall profile of the cone mass.

At 20^h12^m, the fountain stopped abruptly, and backflow into the vent began immediately (fig. 25). At first the orifice remained open as it swallowed the returning lava; but later (21^h50^m) a counterclockwise whirlpool formed over the vent, much like the vortex above the outlet in a draining tub of water.

DECEMBER 9, 1959

The seventh phase failed to reach the high lava level of the sixth phase by a few feet, and by morning on December 9 the lake had subsided as far as it had after the sixth phase. Subsidence continued through the day as shown by the increasing prominence of several islands protruding through the surface of the lake. Otherwise, the lake remained exceptionally level while its crust continually foundered and reformed (fig. 26).

FIGURE 24.—Three-foot, spatter-encrusted, cored lava bomb photographed where it fell on the east side of the cone during the seventh phase of activity. Photograph by R. T. Haugen, National Park Service.

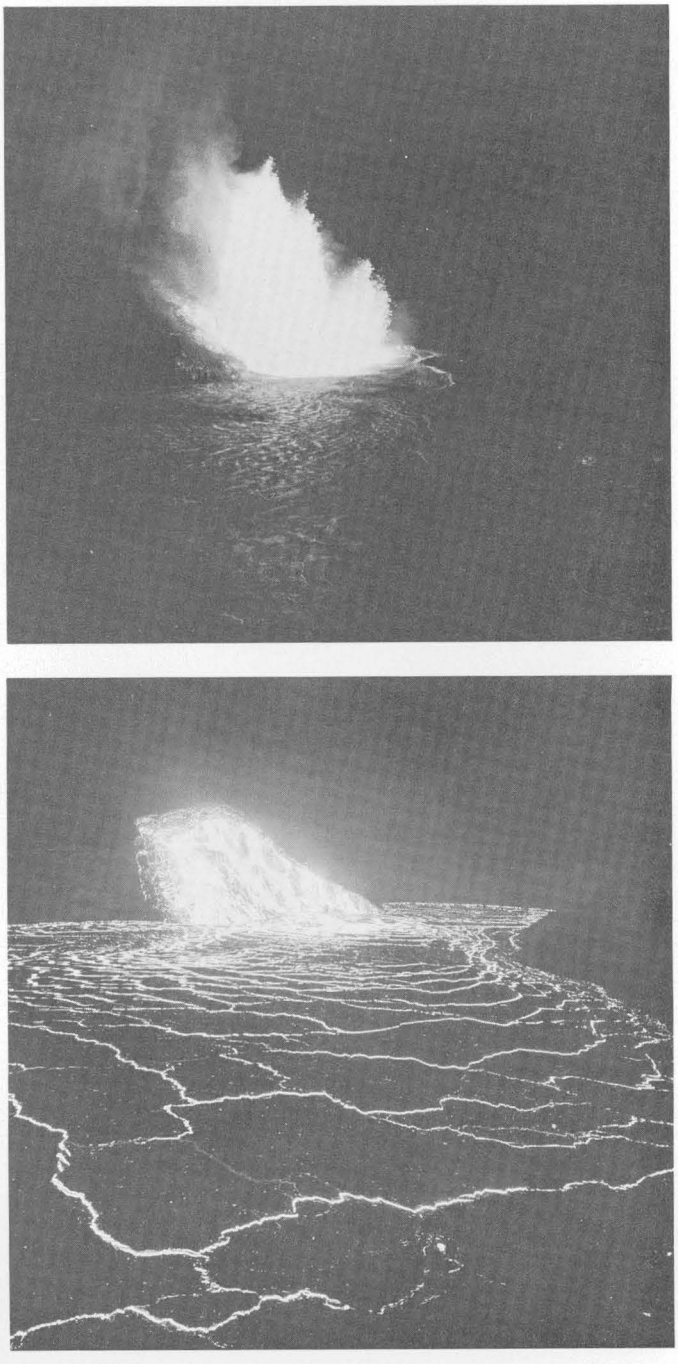


FIGURE 25.—End of the seventh phase of activity as seen from Byron Ledge overlook. *Top:* December 8, 1959. Fountain and lake a few minutes before activity stopped. Photograph by National Park Service. *Bottom:* December 8, 1959, about 20^h12^m. Same view a few seconds after fountaining stopped. The cone is still aglow from incandescent spatter, and the lake crust is already fractured and moving as lava pours back down the vent. Photograph by National Park Service.

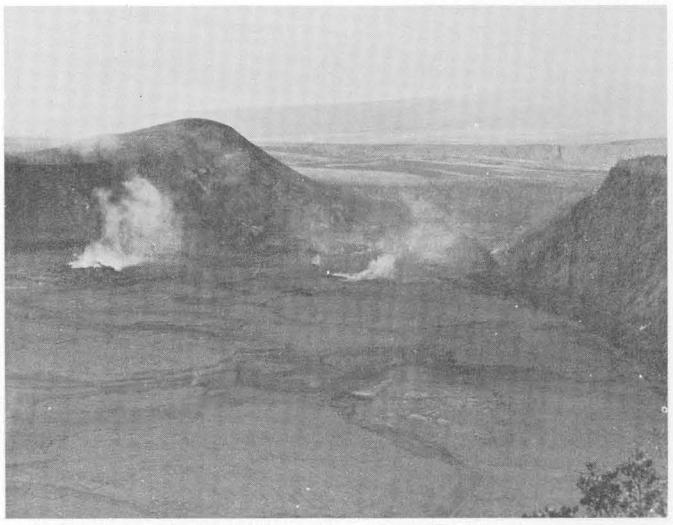


FIGURE 26.—December 9, 1959, morning. Lava lake after maximum subsidence following the seventh phase. Black ledge is visible along base of crater wall at the right. The large degassing prominence at the left is the cone island which formed during the third phase and reappeared after every later subsidence of the lake. Two smaller islands in center of picture are also degassing. The extremely level surface of the lake is maintained by continued foundering and reforming of the crust.

EIGHTH PHASE

DECEMBER 10, 1959

The vent and lake remained quiet until about 15^{h}15^m, December 10, when spatter was again observed being tossed out of the vent. Intermittent spattering continued for almost 11 hours before a fountain developed; this prelude was very similar to the shorter, 4-hour-long prelude to the seventh phase.

During the latter half of this period of spattering, a small pond of incandescent lava, measuring about 100 by 150 feet, slowly formed in the vent area. By 21^{h}00^m a congealed ring of lava around the margin of this small pond had raised the lava level about 30 feet above the main lake floor. Shortly thereafter, however, the ring was breached, and a small tongue of pahoehoe spread slowly across the lake toward the northeast.

DECEMBER 11, 1959

Activity in the form of 30- to 50-foot-high intermittent bursts of spatter continued virtually unchanged until about 02^{h}00^m, December 11, when huge bubbles of lava 20 to 30 feet in diameter began to burst from the vent. Slowly the bubbling evolved into a pulsing fountain that would shoot up to 200 feet or so for a few seconds and then die down to practically nothing; then it would rise to several hundred feet for a few more seconds and then die again. After 40 minutes of this sporadic behavior the "die outs" ceased and the fountain jetted to heights of 700 to 1,000 feet.

At 03^{h}30^m the fountain suddenly inclined from near vertical to about 45° and heavy masses of spatter as much as 3 feet in diameter were hurled almost 1,000 feet northeastward across the lake onto the main crater wall opposite the fountain. This bombardment continued for about 20 minutes before the fountain reestablished its vertical attitude. Spatter covered an area of about 1 acre along the crater rim to a maximum depth of 3 feet and completely denuded the lush forest growth (fig. 27). This was the only occasion during the entire eruption that fluid ejecta landed in this area, and it was indeed fortunate that no spectators were present on this ofttimes-crowded vantage point.

During the rest of the early morning the fountain played to heights of 600 to 1,000 feet while the lake filled rapidly with lava (fig. 28). At 08^{h}14^m the fountain began to surge between heights of 200 and 700 feet and finally decreased to a few bubbles at 10^{h}48^m. Although the eighth phase was virtually ended, and backflow had commenced at a moderate rate, fresh lava appeared to continue rising from the vent, forming a thin pad of lighter material that floated above the streams of heavier lava draining from the lake. Within the next 25 minutes, however, as the backflow rate increased, the pad shrank and finally disappeared. At 11^{h}25^m the vent was visible for a few minutes, but by 11^{h}40^m the draining lava had filled it to the surface and a clockwise whirlpool developed over the orifice.

Maximum development of the lava lake for the entire eruption was attained during the eighth phase of activity, when the lake reached a depth of 414 feet and the area of the surface was 153 acres. In the nine subsequent eruptive phases the lava never again reached this level (fig. 29).

The lake continued to drain throughout the day and evening. Crustal foundering and reforming of the lake surface was especially well marked during this period and appeared to be a direct consequence of the attempt of the fluid lake lava to reach a common liquid level in the concave bowl formed by the continual subsidence of the lake. In the evening this phenomenon was even more dramatic as crack after crack in the crust opened and allowed brightly incandescent lake lava to well up and overrun a small area of the surface before solidifying. In this manner an entirely new surface crust was formed on the lake every few hours. Crustal foun-

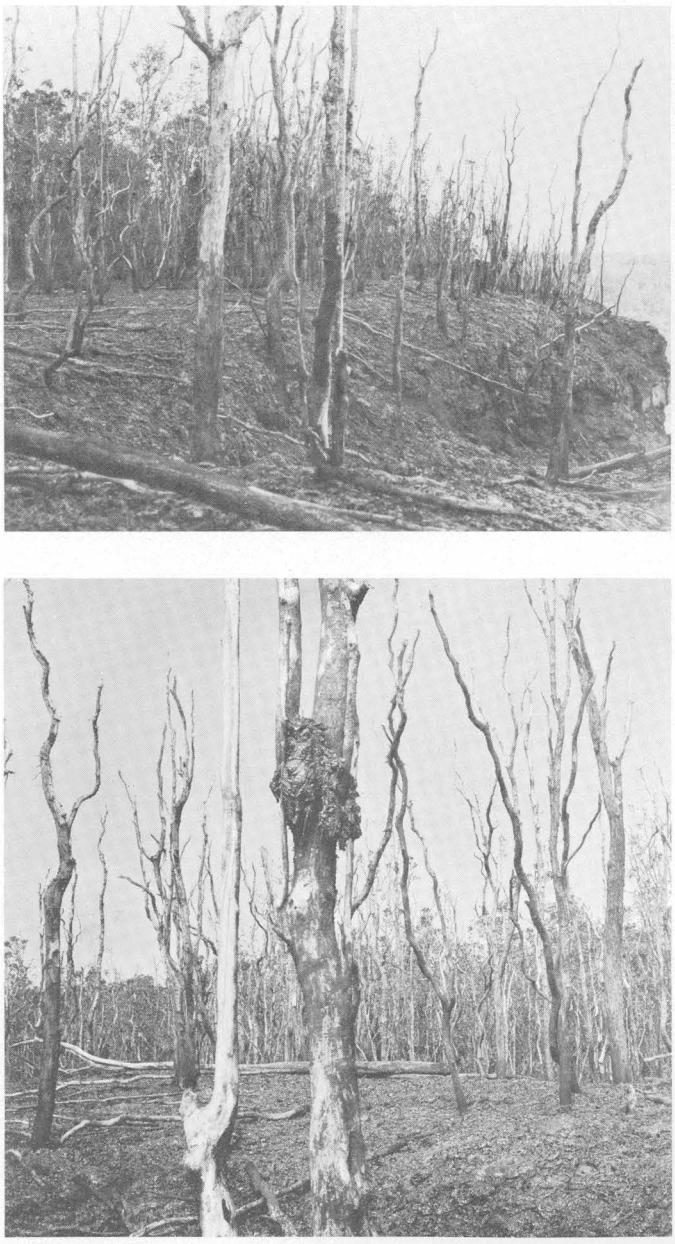


FIGURE 27.—Two views of area on the crater rim opposite vent deluged by spatter during the eighth phase of activity. *Top:* December 11, 1959. Denuded and burned ohia trees on the rim of main crater wall almost 1,000 feet from vent. *Bottom:* December 11, 1959. Same area showing spatter draped in burned ohia trees. Photograph by National Park Service.

dering also took place to a lesser extent during periods of lakefilling. However, in this case, the lake surface was slightly convex and foundering occurred principally around the edge of the lake where lava flowed out in an attempt to maintain a liquid level.

During the rising period of the sixth phase, the process of crustal foundering was closely observed in the east end of the crater. The process was cyclic and began with molten lava lapping over the leading edge of the crust. Within seconds, or at most a minute, a major crack would form several feet back in the crust parallel to the edge, and a number of minor cracks would form perpendicular to the edge. Then lava would rapidly well up in the major crack simultaneously separating the small part of crust from the rest and tilting the detached block so that it slipped forward, or was dragged under, into the molten lava. The upwelling lava also lapped over the new leading edge of the old crust setting the stage for another cycle.

DECEMBER 12, 1959

By the morning of December 12, total subsidence of the lake was approximately 30 feet, and a few areas were still undergoing crustal foundering. The vent was once more open and was emitting a small amount of bluish fume, but no backflow was evident.

NINTH PHASE

DECEMBER 13, 1959

The ninth phase began at 05^h08^m, December 13, with feeble spattering in the vent, followed within a few minutes by a sluggish lava flow. Slowly the activity increased to a rolling boil of lava by 06^h25^m and then to a pulsating fountain oscillating between 100 and 700 feet in height by 07^h00^m. The fountain vacillated in this manner for about 2½ hours before steady activity was maintained in the vent. Lava extrusion during this period was extremely strong, however, and by 08^h15^m the entire surface of the lake was covered by new lava.

Steady fountaining lasted for only a few hours. At 12^h34^m the fountain began to surge between heights of 200 and 600 feet, and within a few seconds, at 13^h40^m, it died completely. Backflow was not apparent for more than 20 minutes, but slowly the crust began to break and flow toward the vent. At 14^h35^m a pad of lighter fluid material similar to that observed at the close of the eighth phase was evident over the vent, and the draining lake lavas flowed beneath it at a rapidly increasing rate. The pad soon disappeared, and by 16^h00^m a vigorous stream was pouring back over the lip of the open vent.

TENTH PHASE

DECEMBER 14, 1959

Draining of the lake continued through the night. At 07^h45^m, December 14, however, lava began to rise in the vent, and occasional bursts of spatter

were thrown up onto the ramparts of the cone. In a slow beginning, similar to those of the seventh and eighth phases, this very intermittent activity persisted until 10^h40^m, when large volumes of lava began rolling out of the vent. Suddenly at 11^h00^m the fountain roared to life, increasing to a height of 1,100 feet in less than 8 minutes and showering the cone and nearby lake area with tremendous quantities of pumice and spatter.

The lake level rose rapidly as lava was added to it, both by flows across its surface and by subcrustal injection, and by 15^h00^m lake lava was again interfering with the fountain (fig. 30). During the next half hour the fountain surged between 0 and 600 feet and ceased finally altogether at 15^h36^m. Drainage was apparent within minutes after the fountain stopped, but no surface movement of the lake lava was visible. By 18^h45^m conditions had changed drastically; the lake surface had dropped about 10 feet, and a large stream was pouring from beneath the crust down a 75-foot-long channel that led into the vent.

The crust of the lake remained virtually unbroken after the 10th phase activity, and minor crustal foundering was restricted to the area near the vent. Subcrustal draining continued through the night, and by midnight the surface of the lake had a definite concave appearance.

ELEVENTH PHASE

DECEMBER 15, 1959

After only a few hours, the relative quiet following the 10th phase was shattered by the beginning of the 11th phase. The 11th phase started like previous phases with gentle spattering in the vent at 06^h11^m, December 15, but unlike the others it developed into a roaring 1,000-foot fountain within a few minutes. The rate of lava extrusion was also high, and by 07^h30^m new flows had resurfaced the entire lake. The high fountaining (500 to 900 feet) and voluminous lava extrusion continued until the end of the phase, which came abruptly at 10^h25^m.

The lake started to drain as soon as the fountain stopped (fig. 31). At 11^h15^m the lake level was down about 5 feet and an enormous flow was pouring back down the open vent.

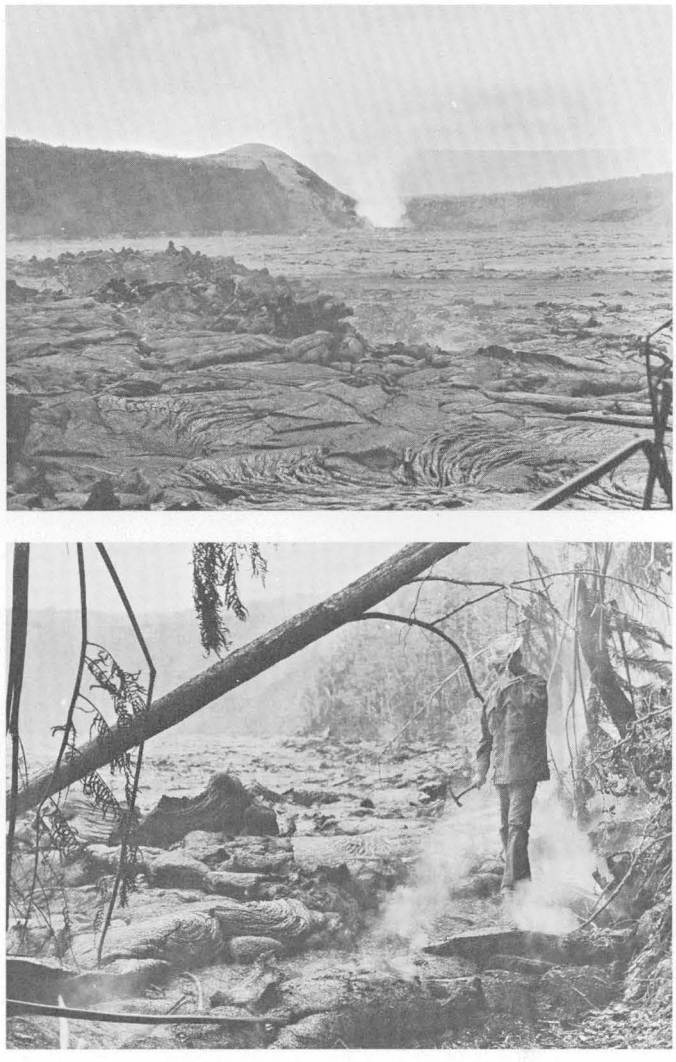


FIGURE 29.—Lava lake after the eighth phase of activity. *Top:* December 11, 1959, afternoon. Looking westward across lava lake toward cone and fuming vent. Fluid part of lake in the background is down about 20 feet below the black ledge (foreground) and is still subsiding. *Bottom:* December 11, 1959, afternoon. Detail of structure on the lava lake at east end of crater. Small pahoehoe flows and bulbous oozes of the eighth phase lavas (left) overtop the sixth phase lavas on which man is standing.

With every filling and subsequent draining of the lava lake the black ledge had become more prominent. Over most of its length it now averaged 100 feet in width, and in many places its precipitous

FIGURE 28.—December 11, 1959, 10^h30^m. Closeup of fountain top and view of lava lake at its highest level a few minutes before the end of the eighth phase. At this distance the nature of the fountaining lava is clearly visible. Large incandescent clots of gas-inflated lava glow bright orange as they spurt skyward in the core of the fountain; then they darken rapidly through tones of red to steely gray as they plummet back to earth. The high crater rim on the extreme right, above the forest seared brown by radiant heat from the fountain and by burning undergrowth, was drenched in glowing spatter during the night when an avalanche of cone debris deflected the jetting fountain across the lake. Mauna Kea, an extinct volcano 32 miles away, shows pale blue on the horizon. View north from Kilauea Iki overlook.

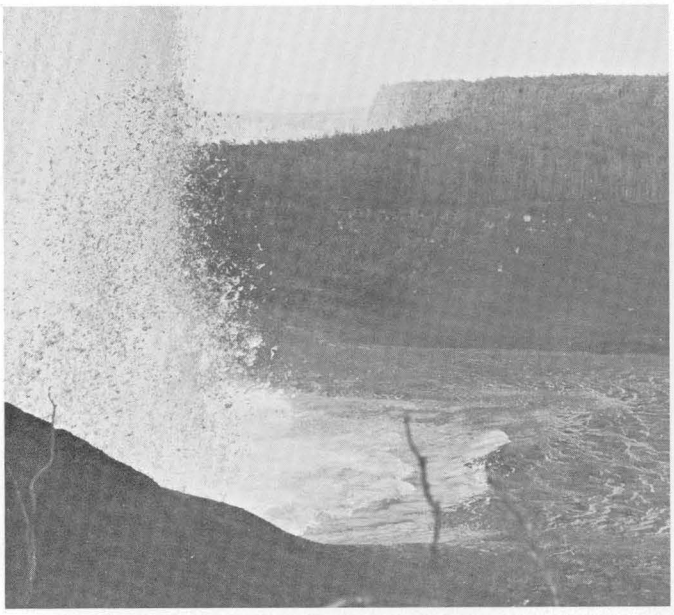


FIGURE 30.—December 14, 1959, 15^h00^m. Fountain and lake from west end of Kilauea Iki overlook showing development of lava waves at base of fountain in high lava lake.

scarp prevented access to the lake. In the small west bay of the crater, which received little lake lava after the 10th phase, but which was continually being filled by aa flows and slides from the cone, the black ledge was much less prominent.

TWELFTH PHASE

DECEMBER 15, 1959—CONTINUED

The eruptive phases were becoming much shorter and more frequent. At 19^h30^m, December 15, the 12th phase began, and within 30 minutes after the first splashing in the vent, the fountain was jetting to heights of 1,000 feet. Again, there was heavy pumice production and a strong outpouring of lava. By 20^h30^m the entire lake surface was covered to a depth of more than 5 feet, and the lava in the crater was rising faster than 1 foot every 10 minutes. This accumulation indicated the phenomenal extrusion rate of 1,900,000 cubic yards per hour. Then, exactly 2 hours after the 12th phase started, the fountain ceased.

At 22^h00^m, the wide river of backflowing lava, as observed from the cone almost directly above the vent, produced a loud roar as it poured into the open fume-emitting orifice (fig. 32). When the vent filled at 22^h35^m the noise and fuming also stopped, and a slow clockwise whirlpool swirled in a caldron 100 feet wide by 200 feet long. The rapid backflow during this period affected the entire lake surface; long arcuate tension cracks crossed the lake

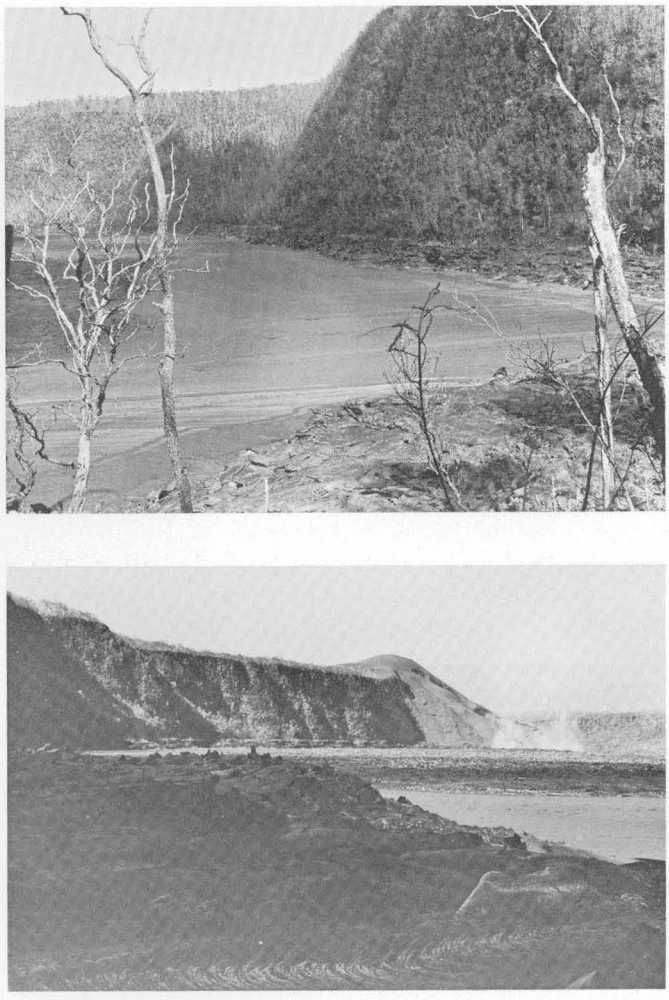


FIGURE 31.—Subsidence of lake shortly after the end of the eleventh phase of activity. *Top:* December 15, 1959, 11^h15^m. View from trail at east end of lake 45 minutes after the end of fountaining. The lake level has subsided about 5 feet. The rough lake crust, swept toward the vent by the backflowing lava, has left a swath of flat drag-marked incandescent lava between the crust and the black ledge. Height of black ledge above lake is approximately 20 feet. *Bottom:* December 15, 1959, 11^h20^m. View of lake from black ledge showing cone, fuming vent, and the band of new surface between the rough crust and black ledge.

floor normal to the direction of flow, and shear fractures, parallel the direction of flow, formed along both edges of the lake.

DECEMBER 16, 1959

In the morning of December 16 the level lake surface, which still was undergoing considerable crustal foundering, was about 20 feet below its high stand at the end of the 12th phase. Around a part of the lake a moat 5 to 7 feet wide and 10 to 15 feet deep and incandescent at the bottom separated the lake from the black ledge.

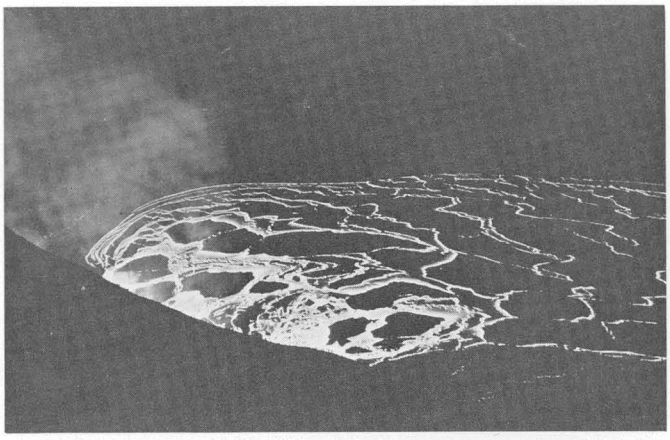


FIGURE 32.—December 15, 1959, 22^h00^m. A wide stream of lava pours back into the vent half an hour after the end of 12th phase. Huge rafts of solid lake crust, continually breaking as the backflow stream converges near the vent, are mixed and swallowed with the returning lava. View from top of cone almost directly above vent.

THIRTEENTH PHASE

DECEMBER 16, 1959—CONTINUED

The 13th phase started about 13^h35^m, December 16, and, like the two previous phases, increased from a few bursts of spatter to a roaring fountain within a few minutes. The fountain then leveled off at a height of 600 to 900 feet. Lava extrusion was apparently not as copious as during the 12th phase, and it was not until 15^h10^m that the new flows reached the east end of the lake. At 16^h35^m the fountain began to surge, dying out almost altogether and then rising as high as 800 feet. By 17^h19^m it appeared that a great inrush of lake lava was choking the fountain, and after a few unsuccessful attempts to blast through this "cold" lava, the fountain died.

Rapid backflow began immediately after the cessation of fountaining. At 17^h39^m the entire vent area seemed to collapse, and lava poured into the opening from all sides. Thirty minutes later this voluminous backflow was reduced to a relatively narrow stream.

About 21^h00^m there was a hard downpour of rain in the crater area and the sky began to glow brightly. The crust of the lava lake was undergoing wholesale foundering, and secondary fountains up to several feet high developed over much of its surface. This unusual activity lasted for only a few minutes, and the reformed surface again cooled to a darkened crust within 20 minutes.

FOURTEENTH PHASE

DECEMBER 17, 1959

At approximately 02^h15^m, December 17, after a brief 9-hour interlude, the 14th and shortest phase of the eruption began. It lasted for only 1¾ hours, during which time a very erratic, surging fountain played to heights of 200 to 700 feet above the vent. Only a little pumice was produced, but toward the end of the phase copious outpouring of lava swept across the lake surface (fig. 33). When the fountain ceased at 04^h02^m strong backflow began immediately.

FIFTEENTH PHASE

DECEMBER 17, 1959—CONTINUED

Seven hours later, at 11^h10^m, spatter was once more observed in the vent, and for almost 2 hours a small fountain bubbled to heights between 25 and 50 feet. During this time a small stream of lava drained from the lake into the same conduit from which the fountain issued.

At 13^h53^m, December 17, lava suddenly began to surge from the vent, and 12 minutes later this culminated in an awesome and terrifying 1,900-foot-high fountain (figs. 34 and 35). The large amount of pyroclastic material produced by this huge fountain deluged the area around the vent and cone (fig. 36) and generated a dark turbulent dust cloud that clothed the ominous spectacle in the crater in swirling darkness. The fountain remained high for only a few minutes; by 14^h10^m it had decreased to heights

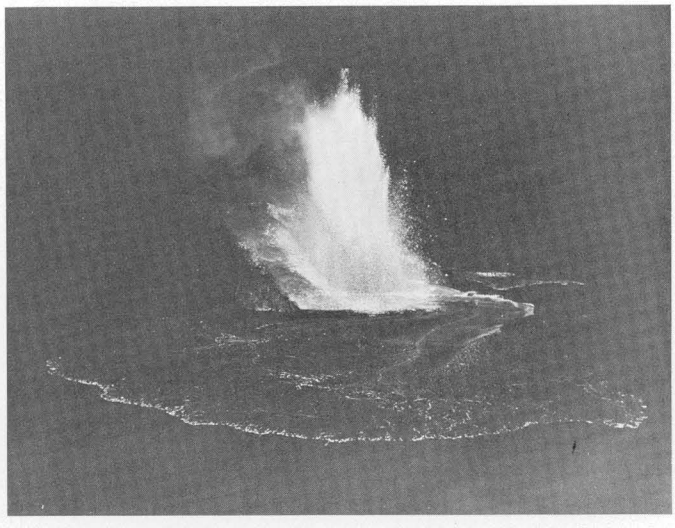
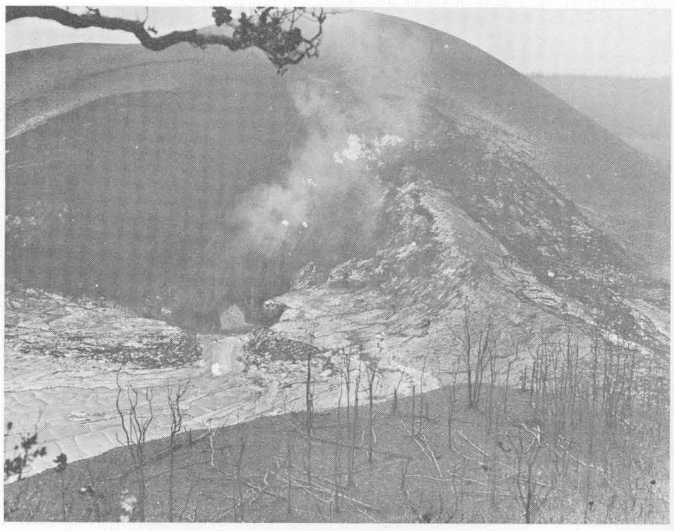


FIGURE 33.—December 17, 1959, 03^h45^m. Fountain of the 14th phase, from from Byron Ledge overlook, 17 minutes before activity ceased. The copious outpouring from the vent sweeps across the lake surface as one flow unit.



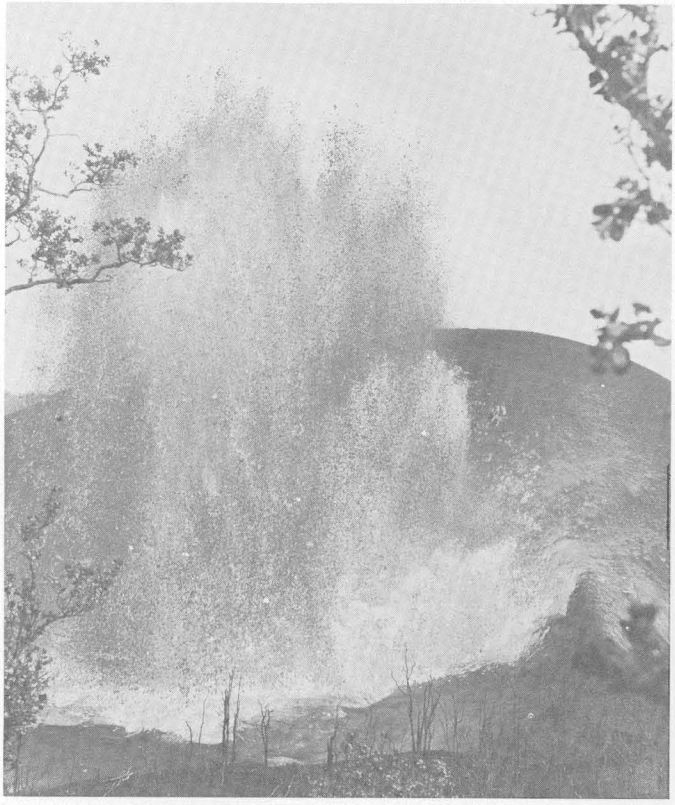


FIGURE 34.—Development of 1,900-foot-high fountain during the 15th phase of activity as seen from the crater rim opposite the vent. *Top:* December 17, 1959, 13^h45^m. Small lava boil in vent during early stage of the 15th phase. Stream of lake lava continues to flow back toward the vent. *Bottom:* December 17, 1959, about 10 minutes later. Fountain roars out of vent and is splashing entire vent area with liquid spatter.

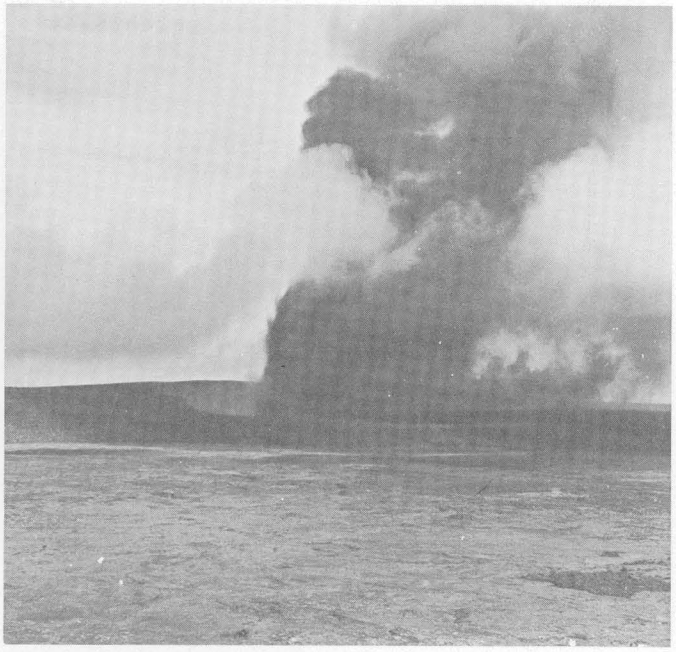


FIGURE 35.—December 17, 1959, 14^h05^m. The 1,900-foot-high fountain as seen from the U.S. Geological Survey's Hawaiian Volcano Observatory. Top of fountain is inside the pushed-up cloud bank, and tremendous quantities of pumice rain out of the dark cloud on the right of the fountain.

FIGURE 36.—December 17, 1959, afternoon. Cone and end of road west of Kilauea Iki overlook as seen immediately after the 1,900-foot-high fountain of the 15th phase. Note the large masses of spatter lying on road.

ranging between 500 and 700 feet. At 14^{h}41^m the fountain, still pouring large quantities of lava into the lake, began to surge, and at 15^{h}32^m it stopped.

For about 1 minute before the fountain died, lake lava drained back toward the vent. When the fountain did stop, the orifice was open and the stream of returning lava poured over the lip. By 19^{h}00^m only a small stream was still flowing into the vent.

Throughout the afternoon and into early evening, avalanches were continually spalling off the inner face of the cone. Much of this debris, including some very large sections of the cone, slid directly into the vent and were immediately engulfed by the draining lava.

DECEMBER 18, 1959

Lava continued to drain from the lake throughout December 18. In the morning, reports of "splashing" in the vent from observers at Byron Ledge overlook were possibly due to occasional turbulence in the upper levels of the conduit. At 17^{h}30^m a backflow stream still persisted, and fume emanating from the vent was illuminated by the churning lava.

SIXTEENTH PHASE

DECEMBER 19, 1959

At approximately 02^{h}40^m, December 19, after more than a day's repose, the 16th phase began. For 20 minutes the activity was restricted to a small boiling fountain. Then during the next 25 minutes the fountain built up to a height of 1,500 feet. Great quantities of very fluid lava pouring from the base of the fountain flowed rapidly over the lake, and by 04^{h}05^m, only an hour after appreciable lava extrusion began, a new flow had covered its entire surface. After cresting at 1,500 feet for a few minutes the fountain subsided and played to heights of 400 to 800 feet until the cessation of activity at 06^{h}16^m.

Backflow started immediately. At 07^{h}10^m a 200-foot-wide river was pouring into the open vent carrying great blocks of darkened crust that were torn apart as they approached and plunged into the open vent (fig. 37). The backflow was accompanied by considerable noise and moderate fuming. During the morning many active fronts of crustal foundering swept from west to east across the lake. The rapid engulfment of large segments of the crust generally resulted in a line of small secondary fountains as the entrapped gases were released at the surface. In the afternoon and evening, the lake crust continued to reform, but generally in smaller more localized areas and at a much slower rate than earlier in the day.

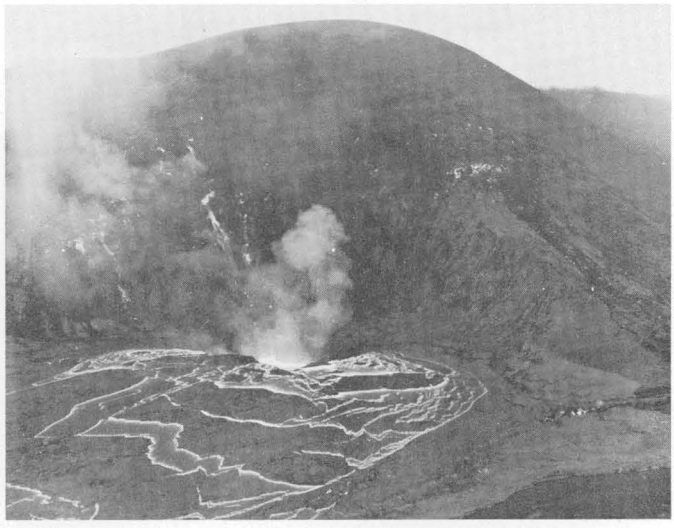


FIGURE 37.—December 19, 1959, 07^{h}15^m. Backflow after the 16th phase of activity, as seen from the crater rim opposite the vent. A 200-foot-wide river pours back into vent, carrying large sections of dark lake crust. Note that sections of crust, pulled apart by differential movement of the liquid beneath them, continue to float. Inner walls of cone glow where slides have bared the incandescent interior.

SEVENTEENTH PHASE

DECEMBER 19, 1959—CONTINUED

The 17th and final phase of the summit activity probably began about 20^{h}45^m, December 19, when spatter was once again observed in the vent. During this phase, which continued intermittently over a period of 11¼ hours, no large fountain developed, nor was there any significant lava extrusion. Spatter was thrown as high as 100 feet a few times, and toward the end of the phase a small tongue of lava flowed out from the vent and covered about an acre of the old lake surface.

Most of the minor fountaining and other activity observed during this unique 17th phase was probably related to the concurrent drainage of the lava lake. As there was very little evidence indicating an addition of fresh lava from below during this period, most of the spatter and flow material probably represented reworked lake lava.

DECEMBER 20, 1959

By 08^{h}00^m, December 20, no further sign of liquid lava, either on the lake or in the vent, was visible—all activity had ceased (fig. 38). Fume continued to emanate from the vent for several days, and slides and rockfalls down the face of the cone were numerous.

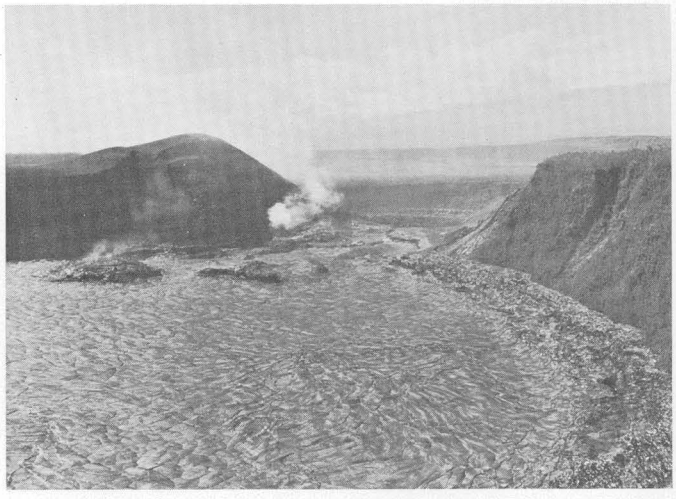
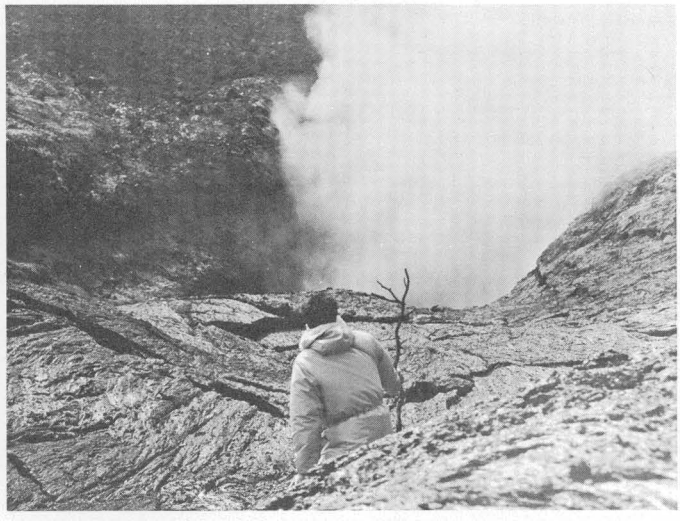


FIGURE 38.—December 20, 1959. View from Byron Ledge overlook after all activity ceased. The black ledge, 50 to 200 feet wide and approximately 50 feet high, surrounds the entire lake. Vent and largest island continue to emit fume. Compare with figure 7 taken on second day of eruption. Photograph by R. T. Haugen, National Park Service.



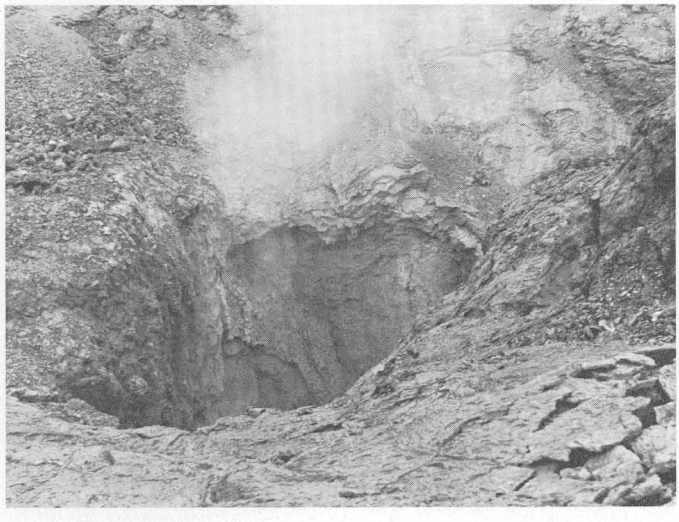


FIGURE 39.—Closeup views of vent. *Top:* December 22, 1959. Strong emanation of fume from vent, 2 days after cessation of activity. Lava flows in front of observer are from the 17th phase. *Bottom:* December 24, 1959. Slightly closer view showing only minor fume emission from the vent. Dense lava coating the wall of vent has already begun to spall off. Vent is 100 feet across greatest dimension.

POST-ERUPTION SUPPLEMENT

On December 22, 1959, a group of Geological Survey and National Park Service personnel went into the crater to examine the vent (fig. 39). At that time the vent was still emitting large quantities of choking sulfurous fumes, but it was possible, by breathing through a wet cloth, to approach the north lip and peer into the conduit. The upper diameter of the vent was approximately 100 by 50 feet, and at the lower limit of view about 75 feet down—but not the bottom—it narrowed to about 50 by 40 feet. Some of the rocks at this lower level were still slightly incandescent, but no liquid material was visible; nor did rocks thrown into the vent appear to hit anything but solid material on the bottom. The estimated depth of the vent, as calculated from the time required for a rock to fall to the bottom, was 200 feet.

Two days later, on December 24, 1959, we visited the vent area again. Fume emission was considerably reduced, and some of the spatter lining of the conduit had spalled off; but, otherwise, conditions were virtually unchanged (fig. 39, bottom photograph).

FLANK ERUPTION

While each of the later phases of the eruption at Kilauea Iki poured its lava into the lake and then swallowed most of it up again, the summit of the volcano continued to swell rapidly. When surface activity ceased on December 21, far more lava was stored in the shallow reservoir beneath the caldera than when the eruption began. Weak harmonic tremor that continued to agitate the North Pit seismograph in Kilauea caldera indicated that lava was still moving beneath the bulging summit and warned that the eruption might revive with little notice.

During the last week in December a swarm of small earthquakes began to record on the seismograph at Pahoa (fig. 1). By means of a sensitive portable seismograph the source of these earthquakes was soon traced to the east rift zone of

Kilauea southeast of Pahoa near the site of the outbreak of the 1955 eruption. Prospects for an early eruption in that area diminished during the first week in January as the swarm declined.

At the beginning of the second week in January the source of the swarm moved down the rift zone toward the sea, and the size and frequency of earthquakes increased. The number of earthquakes recorded on the sensitive vertical-component seismograph at Pahoa rose steadily from less than 100 on January 8 to more than 1,000 on January 12.

During the afternoon of January 12 the portable seismograph was again used to pinpoint the source of the swarm. At several places along the rift zone just north of Kapoho, a farming community of 290 inhabitants 7 miles east of Pahoa and 29 miles from the summit of Kilauea, the seismograph was in almost constant motion as half a dozen earthquakes were recorded per minute. Foci of some of the quakes were less than 2 km (kilometers) from the seismograph and probably almost directly beneath it. At about 17^h00^m, inquiry at Kapoho revealed that none of these tiny earthquakes had been felt, although they originated at shallow depths nearly beneath the village. By 20^h00^m it appeared that the swarm had abated somewhat.

JANUARY 13, 1960

At about 05^h45^m, January 13, earthquakes from the vicinity of Kapoho increased markedly in size and frequency, and the zone from which they originated moved upward to a very shallow depth. Half an hour later, Mrs. Kongo Kimura, wife of the U.S. Geological Survey seismograph operator in Pahoa, reported by telephone that many earthquakes were being felt in and near Kapoho.

When we reached Kapoho[2] at 08^h10^m cracks trending N. 60° E. had already opened across the Pahoa-Kapoho road on the west edge of town. The cracks extended eastward through the village along the Kapoho fault scarp, which bounded the south edge of a small prehistoric graben in the rift zone just north of Kapoho. In 1924 this fault had been reactivated, with a maximum displacement of 12 feet, when the graben subsided during the great swarm of earthquakes that shook the region prior to the steam blast eruptions in Halemaumau. Although it was supposed that the large volume of lava withdrawn from the caldera region at that time was injected into the rift zone near Kapoho or discharged through it to pour out in an unseen submarine eruption beyond Cape Kumukahi, no lava reached the surface. Again in 1955, minor displacements occurred along the fault, at the west end of Kapoho, just before the opening of the easternmost vents of the 1955 eruption on the outskirts of town.

On the portable seismograph, set up beside the widening cracks near the west end of town, the level of seismic disturbance was about 10 times higher than on the previous day. Frequent large earthquakes kept the ground beneath our feet in almost constant motion. Low-pitched booming sounds accompanying the largest quakes heightened the apprehension of the quiet group of disbelieving onlookers who watched their village being gradually torn asunder. Minute by minute old cracks lengthened and widened and new ones appeared, although no immediate physical change accompanied even the largest earthquakes.

A zone of virtually continuous cracking could be traced from the cracked road on the west end of town for about 1,500 feet northeastward along the Kapoho fault. From that point to the Koae-Pohoiki road, heavy brush and broken terrain prevented easy access to the fault. Where the Koae-Pohoiki road crossed the ancient scarp, it was striped with new ½- to 1-inch-wide cracks striking about N. 65° E. and arranged in a crude en echelon pattern in a zone about 100 feet wide.

By 08^h59^m at the north edge of the 0.6-mile-wide graben, movement on the Koae or north-bounding fault had vertically displaced the Koae-Pohoiki road at least half a foot (south side down). In Kapoho, some of the thin cracks seen earlier in the morning had widened to 1-foot gashes by 09^h34^m, and renewed subsidence of the graben along the Kapoho fault was clearly discernible. Along the west end of the Koae fault, vertical movement was even more pronounced, and by 09^h50^m the old railroad-bed road north of Kapoho was rendered impassable by a 1-foot displacement (south side down) where the road crossed the old scarp.

Although the Kapoho fault ran directly through the village, little damage resulted from the earthquakes and faulting. One house, however, which had been built directly over the old fault scarp, was tilted northward (into the graben) approximately 15° before movement on the fault ceased (fig. 40). Because it appeared that an eruption might break out at any moment, inhabitants of the village, especially those living on the graben side of the fault, were urged to evacuate. Voluntary evacuation started

[2] In the text that follows many features of interest will be mentioned without specific reference to any figure. All are shown on at least one of the nine time-sequence maps that accompany the text. Generally, the next map following the mention of a specific feature will adequately identify it.

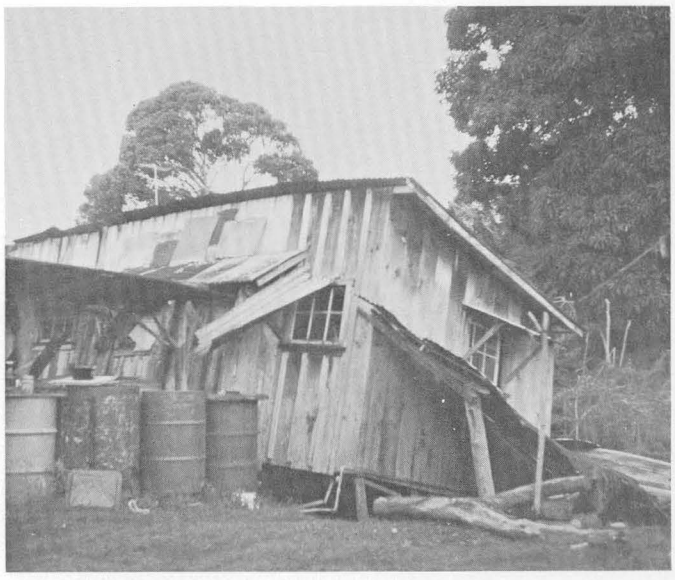


FIGURE 40.—January 13, 1960. House built directly over the Kapoho fault scarp tilts backward (north) into the graben. Photograph by Howard Pierce, Hilo, Hawaii.

about 10^{h}00^m and continued throughout the day; by nightfall most of the village was deserted.

Through the rest of the morning earthquakes continued to shake the area and the graben continued to subside slowly. By noon the maximum vertical displacement along the Kapoho fault was 1½ feet and along the Koae fault it was 2 feet. Elongate collapse pits, some as deep as 30 feet (see fig. 41, top photograph), marked the fault zone in areas overlain by poorly consolidated soil or fill; from one of these pits, at the west end of Kapoho south of the Pahoa-Kapoho road, steam was issuing feebly.

In the afternoon seismic activity gradually decreased, and by 15^{h}00^m only an occasional earthquake was being felt. The subsidence had virtually ceased by midafternoon, although cracks continued to form in the graben during the next few days. On the south side of the graben, renewed movement along 1.7 miles of the Kapoho fault extended east-northeast from a few hairline cracks on the old railroad-bed road to the base of Puu Kukae, where the fault branched into a number of weak fractures over a zone 300 feet wide. Along the north side of the graben, which was marked by a very pronounced scarp formed during earlier epochs of faulting and which exhibited greater displacement this time, the disturbed zone was slightly longer. It extended from southwest of the old railroad-bed road to at least 0.25 mile east-northeast of the Koae-Pohoiki road, a distance of 1.9 miles. The maximum vertical displacement along the Koae fault was approximately 4 feet (fig. 41, top photograph), and along the Kapoho fault it was about 3½ feet in the village of Kapoho (fig. 41, bottom photograph). Although movement on both faults was practically vertical, tensionlike gashes along the Koae fault west of the Koae-Pohoiki road indicated some minor right-lateral movement; that it, a relative westerly shift of the graben occurred.

With the decrease in seismic activity and cessation of movement along the faults, the course of future developments seemed highly uncertain. Was this ominous quiet merely the "lull before the storm," or might the disturbance subside without an eruption as in 1924? The uncertainty was soon resolved. At 19^{h}35^m, while we were discussing possible volcanic developments and plans of action with county officials in Pahoa, a red glow lit the night sky over Kapoho.

Rushing to the area, we reached the west end of the Kapoho fault on the old roalroad-bed road at about 20^{h}00^m. From atop a small spatter cone of the 1955 eruption just north of the fault, we looked out over a spectacular curtain of fire, an almost continuous line of lava fountains 3,000 feet long (fig. 42). Surprisingly, the erupting fissures were not along either of the two active faults which had suffered displacements earlier in the day but instead were aligned in a slight en echelon pattern, trending N. 63° E., just north of the center of the graben (A to J, fig. 43).

Conutinuing northward along the old railroad-bed road, we approached to within 100 feet of the westernmost fountains near A. A 5-foot-thick flow was moving slowly down the road toward us, and a veritable flood of lava from the vents farther east was pouring southward across the canefields into the topographic low along the center of the graben. Burning telephone poles protruding through the fiery flood stood like huge torches marking the course of the old road.

The erupting fissure continued to split toward the east, and by 20^{h}45^m the line of fountains had extended to C. In this area one of the new fountains was playing to heights of 200 to 300 feet, whereas along most of the curtain of fire the fountains were between 50 and 100 feet high. The erupting fissure attained its maximum development at about 21^{h}30^m, when a short 100-foot rift opened at D. Fountaining then was almost continuous from D to C, a distance of 3,500 feet.

Within half an hour fountaining began to abate noticeably. Along the west end of the initial out-

FIGURE 41.—Subsidence of the graben in the Kapoho area that occurred prior to eruption outbreak. *Top:* Koae fault cuts the old railroad-bed road north of Kapoho. Picture was taken January 14 (day after faulting) and shows the fine-grained salty ash deposit spewed out by the steaming vents earlier in the morning. View is toward the northeast. *Bottom:* January 13, 1960. View westward along the Kapoho fault scarp in the village of Kapoho. Maximum vertical displacement is about 3½ feet. Photographs by R. T. Haugen, National Park Service.

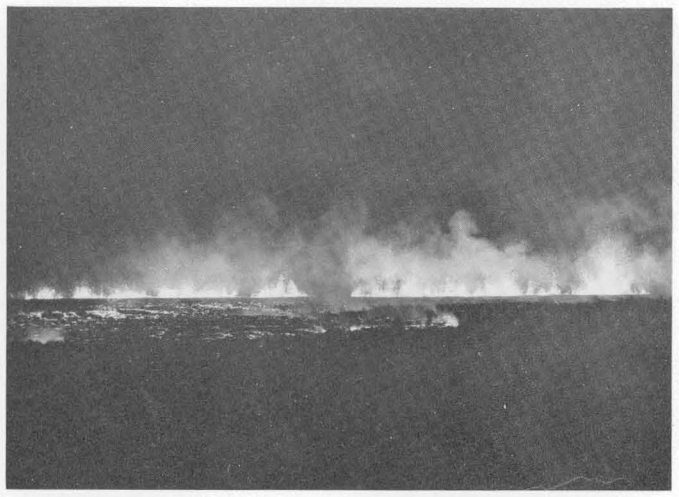


FIGURE 42.—January 13, 1960, 20^h00^m. Initial outbreak of flank eruption. View northeast toward curtain of fire and first lava flows, half an hour after outbreak. Erupting fissure is about 3,000 feet long and lava fountains are 50 to 100 feet high.

break, from A to H, and in the vicinity of F, fountaining became very feeble. At 22^h00^m the fountaining from the eastern vents, between B and C, ceased abruptly and a dark cloud of ash from these vents rose into the air. In spite of the extinction of many fountains, the rate of lava extrusion continued to increase; the greatest volume of lava was coming from the vents between B and F. Unlike the flows from the westernmost vents, which spread southward from the rift, most of the lava erupting from E and vents farther east flowed in a northerly direction to the north edge of the graben where it was directed east northeastward by the high fault scarp. Here it was confined in a narrow trough between the southward-facing fault scarp and the northward tilted graben floor, and the lava was funneled into a narrow flow that advanced rapidly toward the sea.

As the hot fluid flow advanced across cleared fields of nearly barren rock, small explosion cracks would open with loud reports. Gases, most likely derived from buried vegetation, burned vigorously with bluish flames up to a foot or more in height along these cracks until they were overrun by the advancing lava.

At 23^h45^m fires in the dense forest west of the Koae-Pohoiki road attested to the approach of the advancing lava. Twenty minutes later a thin 200-foot-wide aa flow, moving at an average speed of 700 feet per hour, crossed the road and continued down the graben.

Large quantities of brackish ground water (altitude of the vents ranged from 130 to 170 feet above

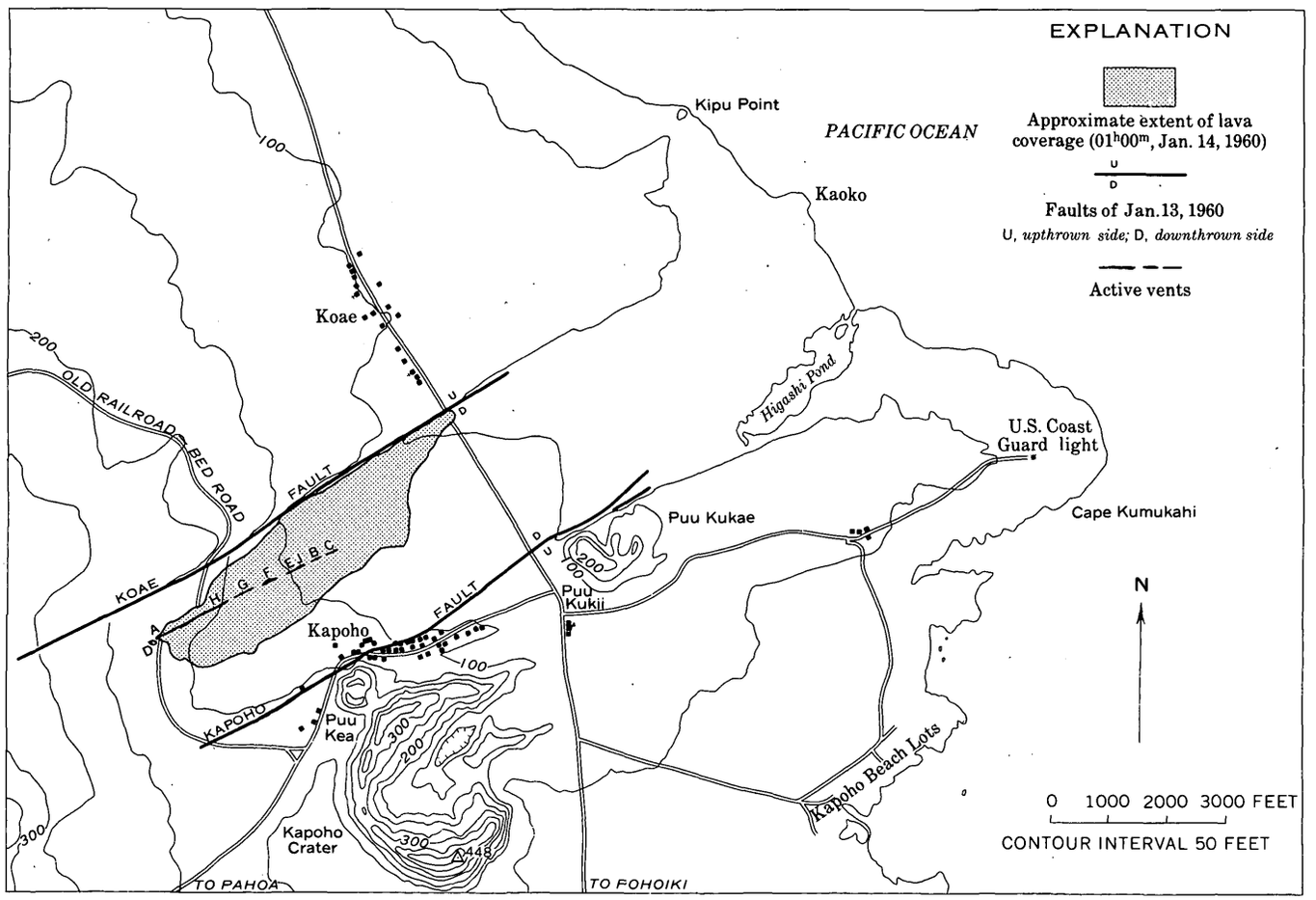


FIGURE 43.—Map of eruption area at 01h00m, January 14, 1960.

sea level) first gained access to the eruptive conduits at about 23h15m, when a loud roaring noise emanated from the vents near H. Although the area was illuminated only by light from the fountains, a few minutes after the noise was heard dark steam clouds could be seen spewing from the vents, much like the puffing of giant steam engines.

JANUARY 14, 1960

Through the night and the early morning of January 14 fountaining gradually decreased along the rifts, and ground water continued to gain entry to the hot lava conduits. The decrease in activity followed no orderly pattern, however, as many vents or groups of contiguous vents abruptly ceased fountaining, emitted steam for a short while, and then resumed normal lava fountaining.

At 01h00m the vents at C, which for 3 hours had intermittently produced light billowy ash clouds, suddenly began pouring out great quantities of ash and steam. This turbulent cloud spewed upward until 01h50m, when the steaming abated, and by 02h30m the vents were quiet again. During this time the fountains from B to E continued to erupt vigorously and showed no effect of the terrific rush of water into the conduits beneath the vents at C a short distance away.

Along the vents at F, fountaining ceased at about 02h00m and was followed by minor steam emission. The feeble spattering at D stopped altogether at 03h30m, but the vents continued to emit pale flames; at 04h00m a number of vents in the G area ceased fountaining.

At 04h15m dense black clouds of steam and ash again began to rise from the original steaming vents at H and the dead vents at F. Concurrent with this increased steam and ash production at H and F, the fountains between B and E, which had been spurting lava to heights of 300 feet, began to subside, and at 04h57m, after a few minutes of quiescence, water entered the conduit beneath the big fountain area at B. Rapidly expanding gas bursting from the vent ripped out pieces of incandescent

wall rock and shot them like projectiles into the mushrooming vapor cloud above. This spectacle was short lived, because at 05^{h}01^m lava fountaining revived at B, G, and F, and by 05^{h}30^m, B was again spurting lava to heights of 300 feet. Within minutes however, fountaining again subsided, and by 05^{h}50^m another turbulent column of steam was thundering out of vent B. These steam blasts lasted for only 2 minutes before fountaining started again. During this period of erratic activity at B, weak fountaining revived in the long-dead vents along H and produced a number of narrow lava tongues that flowed slowly southward over the older cooled flows.

Sounds similar to the roaring of a gigantic blowtorch began to emanate from the vents along F at 06^{h}00^m, and within seconds steam blackened by abundant ash boiled upwards (fig. 44, top photograph). This violent steam emission at F, bracketed by normal lava fountaining at G and B, continued for more than an hour. Hot gases that burst suddenly from the east vents at C at 07^{h}40^m were soon followed by copious steam and ash. Meanwhile, fountaining diminished at B but revived in the F area, and by 08^{h}15^m, when the steam blasts ceased at C, only an occasional burst of spatter issued from B whereas fountains up to 200 feet high played from the vents at F.

The vents at C, which again began to emit steam and ash profusely at 08^{h}50^m, continued in a very erratic manner until about 10^{h}00^m (fig. 44, bottom photograph). One or two vents "blew" for a minute or so and then reverted to fountaining. Steam and ash then roared from another vent and repeated the process. At 09^{h}45^m the vents at H were spouting steam again, and at 09^{h}50^m the vent at B, which had been quiet for more than an hour, revived with a big steam blast. Fountaining was then strong only at J and E. At F feeble spatter activity continued, and at C spatter mixed with steam occasionally issued from the vents.

Except for a short period of steaming from the C area during the afternoon, steam and ash production had virtually ceased by 10^{h}30^m. Most of the steam emitted from the vents was light brown to black, depending on the amount of vitric ash and comminuted wallrock that it contained. Frequently, however, uncontaminated white steam, which was in striking contrast to the darker ash-laden cloud, spewed violently from the vents. At times, narrow jets of white steam, which appeared to be almost totally liquid and resembled the spray stream of large fire hoses, spurted outward at relatively low angles from the same vents that were producing a steam-ash mixture. White steam trails also marked the graceful arcuate trajectories of large hot fragments that occasionally shot from the steam-emitting vents.

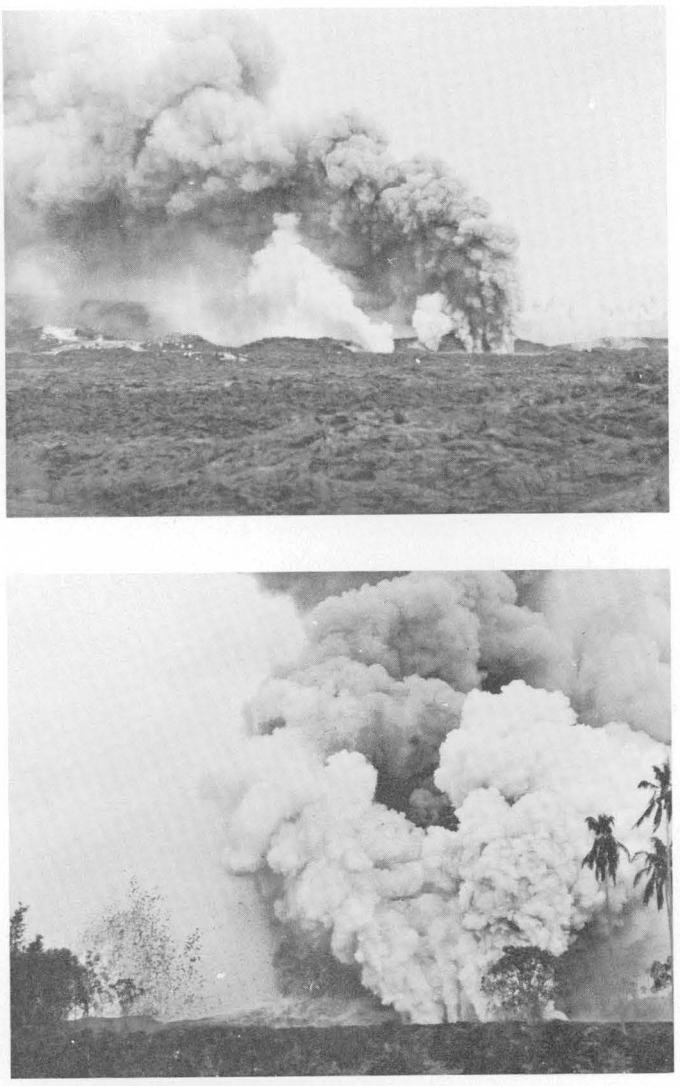


FIGURE 44.—Steam and ash production from the early vents. *Top:* January 14, 1960, 07^{h}00^m. Violent steam emission caused by ground water rushing into the subsurface eruptive conduits. Darker steam cloud is choked with fine ash particles. *Bottom:* January 14, 1960, 10^{h}00^m. Violent steam emission and adjacent moderate lava fountaining. Note the volcanic debris carried high into the steam cloud.

The fine-grained vitric ash produced during this episode of violent steam emission settled over hundreds of acres northwest of the vents. Along the Koae fault, about 1,000 feet from the vents, the ash deposit was ¼ inch thick, and as far as 5000 feet to the north it formed a thin film on plants (fig. 41, top photograph). Before it was washed by rain the ash had a strong salty taste due to occluded salt

particles that were carried along during the near-explosive vaporization of the brackish groundwater.

By 11^{h}45^m activity was confined to a number of fountains along a 700-foot segment of the original rift between B and E. Through the afternoon the fountains slowly grew in size, building a 20- to 30-foot-high spatter rampart that completely encircled the vent except for a gap along the north side from which poured a steady stream of lava. By midafternoon the front of the main lava flow, fed by the long, narrow lava river pouring from the vents, had advanced 1 mile down the graben and was within 0.3 mile of the ocean.

At 20^{h}00^m the fountains were playing steadily to heights of 250 to 300 feet, and most of the lava was coming from a broad massive fountain at B. Activity at E and J was more sporadic, and the lava, especially at J, appeared to be more heavily charged with gas.

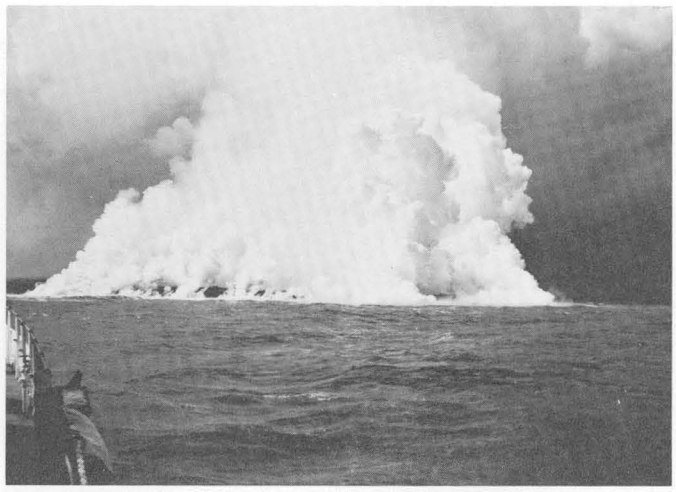


FIGURE 45.—January 15, 1960, 12^{h}00^m. Early lava flow pouring into the ocean behind a massive curtain of steam. Vessel is approximately 1,000 feet east of the front. Photograph by R. T. Haugen, National Park Service.

JANUARY 15, 1960

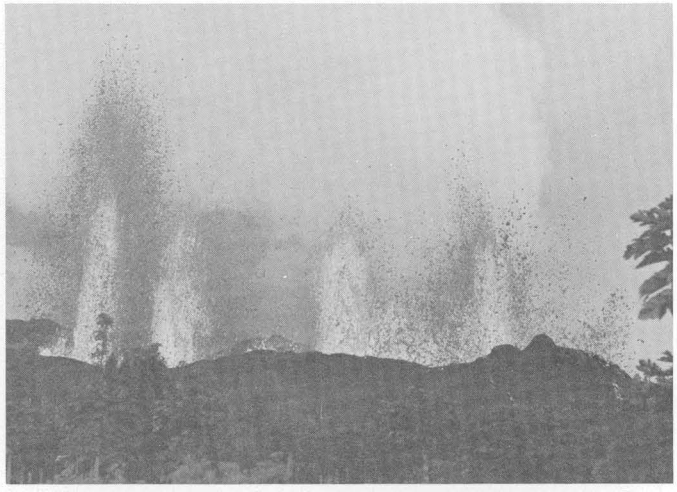
There was very little change in fountaining during the night. The main lava flow continued its advance toward the coast, gradually increasing in thickness and spreading laterally toward the center of the graben. At 01^{h}00^m, January 15, the flow across the Koae-Pohoiki road was more than 20 feet thick—its north edge was level with the top of the Koae fault scarp. South of the flow on the Koae-Pohoiki road, where the land surface rose gently toward the less pronounced Kapoho fault scarp, aa flows with local pahoehoe squeeze-out fronts were spreading southward from the main lava channel. By 07^{h}35^m the total width of the flow along the Koae-Pohoiki road was 1,000 feet, and its south edge was half a mile from the junction of the Kapoho road.

The main lava front first reached the ocean a few hundred feet south of Kaoko Point at about 08^{h}08^m and sent a large white steam cloud into the sky. The flow had advanced along the gently sloping 2-mile course from the fountains to the sea at an average speed of 290 feet per hour.

Four hours after the flow entered the sea, we inspected its steaming front aboard the Hilo-based U.S. Coast Guard cutter. Lava was flowing into the ocean along a 1,000-foot-wide front, from which rose an almost solid curtain of steam that was rapidly swept back over the flow by strong onshore winds (fig. 45). The steam generated at the flow front was so copious that during our 1½-hour stay in the area we never observed incandescent lava and only occasionally glimpsed the dark, craggy top or front of the massive aa flow. Between 1½ and 2 miles offshore from the flow front the ocean had a peculiar green roily appearance in contrast to its normal clear dark-blue color, and, at about this demarcation between disturbed and undisturbed water, the first noticeable increase in water temperature was observed. Water temperatures were recorded at the engine intake at 5-minute intervals, beginning approximately 2½ miles offshore, during the entire time we were in the area. As we approached the bank of steam clouds on a course perpendicular to the coast, the water temperature remained at 25°C (normal sea-water temperature) until about 1½ miles from the shore, where temperature increased abruptly to 28°C. From this point to 1,500 feet offshore the temperature gradually increased to 33°C, and during the 45 minutes we cruised at this distance from the flow front, water temperatures ranged from 28° to 38°C. On a quick trip to within 900 feet of the flow, our closest approach, we found the water temperature was up to 39°C. At this distance the air was warm and clammy; beads of moisture covered everything, and a peculiar odor, possibly from the decomposition of marine life, pervaded the area.

Back at the vent area, small aa flows continued to spread slowly across the low ground between the fountains and Kapoho and inundated a number of small papaya and orchid groves north and east of the village (fig. 46). Through the morning and early afternoon, fountain activity, which was still restricted to the area between B and E, slowly increased, and the old spatter rampart grew in height and bulk as cinder and pumice accumulated upon it (fig. 47).

FIGURE 46.—January 15, 1960, 15^h00^m. Lava flow moving slowly through papaya orchard northeast of Kapoho. Lava fountain in background is about 400 feet high.



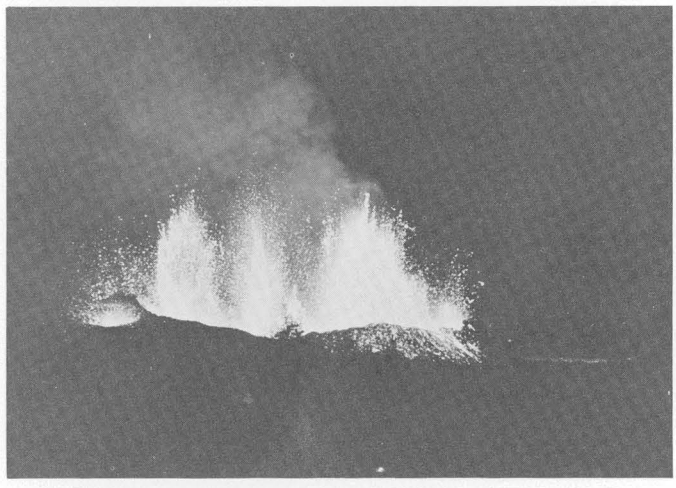


FIGURE 47.—Early views of main vent area. *Top:* January 15, 1960, 15^h00^m. Main fountain area (vents E–J–B) showing initial development of cinder-pumice cone. Note the fully leafed papaya trees in foreground. *Bottom:* January 15, 1960, 19^h00^m. View northward showing, left to right, the glowing orifice over vent E, two fountains in the J area, and the massive fountain in the B area.

In the afternoon, through the courtesy of the Hawaii Army National Guard, we obtained our first comprehensive view of the eruption from the air (fig. 48). A narrow river of incandescent lava pouring from a gap at the northeast end of the cone swerved first toward the north, until it encountered the high south-facing cliff along the Koae fault, and then toward the east-northeast along the fault scarp (fig. 48, bottom photograph). Confined between the straight fault scarp and the northward-tilted floor of the graben, the river of lava flowed in a straight narrow ribbon along the fault from the fountain to the sea, where its advancing front was hidden beneath turbulent clouds of steam (fig. 48, top photograph).

Fountaining from the vents at E and J became very sporadic during the afternoon and evening, and at about 18^h00^m, a spatter bridge developed between them, separating E from the rest of the active vents (fig. 47, bottom photograph). For a while strong fountaining continued at B and J, but by 20^h40^m the vents at J apparently ceased fountaining altogether and the principal activity was restricted to B, where a broad fountain shot to heights of 400 feet. With the increased fountain height, pumice and cinder accumulated rapidly on the new cone, and by 23^h45^m it was estimated to be 80 feet high.

At the seacoast the lava flow continued to broaden its front, and by 20^h55^m it was more than 300 feet beyond the original shoreline and had advanced southward to within a few hundred feet of the entrance to Higashi Pond. Billowing steam clouds rolling upward from the flow front were carried back over the flow by the onshore winds. Here, the steam clouds caught the glow from the incandescent river of lava and illuminated the countryside with a soft eerie red light.

JANUARY 16, 1960

Fountaining at B continued to increase through the night. At 02^h15^m, January 16, the fountain was consistently reaching heights of 550 to 600 feet, and at 03^h45^m, 600 to 700 feet; occasional bursts reached 900 feet.

An aa flow, creeping southward along the seacoast from the end of the main lava channel near Kaoko, advanced to the entrance of Higashi Pond during the night, but at 07^h30^m it had temporarily ceased

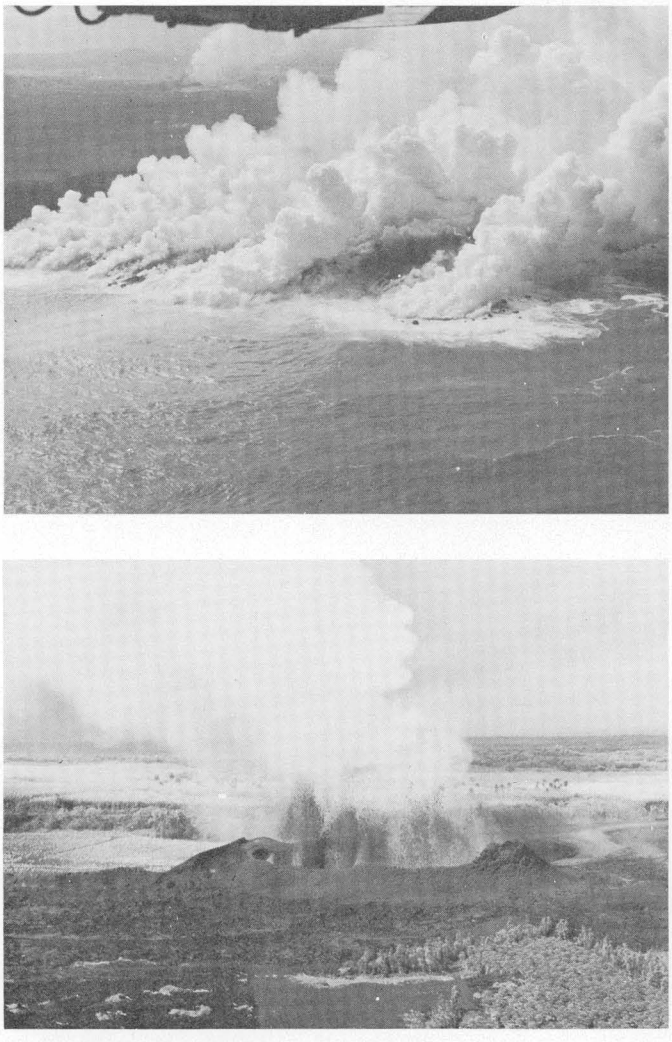


FIGURE 48.—Aerial views of eruption area. *Top:* January 15, 1960. View southwestward of steam clouds over the lava front at the ocean. In the background, under wing of plane, the lava fountains and fume cloud are visible. *Bottom:* January 15, 1960. View northward of the fountains and cone showing the lava river pouring from a breach in the cone and flowing against the Koae fault scarp north of the cone.

flowing. Elsewhere, the flows continued to spread southward across the floor of the graben (fig. 49). At noon many small pahoehoe tongues advancing through the forest ahead of a larger aa flowfront were only 800 feet north of Warm Springs, a small swimming and picnic area at the base of Puu Kukae. From the south side of the cone a 20-foot-thick aa flow advanced slowly through the stripped coffee and papaya groves toward Kapoho (fig. 50). Air reconnaissance between 14^h30^m and 16^h00^m disclosed moderate activity along the entire south edge of the lava field from Kapoho to Higashi Pond. The main lava river was beginning to spread out and pond over the old Koae road, but from there to within about 1,000 feet of the flowfront at the ocean, it still flowed in a narrow red ribbon parallel to the Koae fault.

Higashi Pond began to fill with lava at about 19^h45^m, when the south lobe of the lava front at the seacoast renewed its advance. The lava poured into the pond at its extreme eastern (outlet) end and spread slowly toward the south and west, sending a new steam cloud into the air.

By 21^h30^m the fountain was spurting to a height of 800 feet and was playing slowly back and forth through several degrees of arc. At 22^h50^m it was reaching 1,050 feet in occasional bursts, and glowing pumice was still discernible as high as 2,000 feet as it was wafted aloft by hot turbulent air currents.

The flow on the Koae-Pohoiki road, which had advanced southward along the road at an average rate of 33 feet per hour during the preceding 40 hours, had spread to within a quarter of a mile of the Kapoho road junction at 23^h00^m.

JANUARY 17, 1960

In the early morning of January 17 the height of the fountain decreased somewhat, but the rate of lava and pumice production remained large. By 03^h45^m the 300-foot-long crest of the cone had been built to a height of 100 feet. Lava, which found its way through tubes and channels in the wall of the cone, and spatter-fed rootless flows that oozed off the south flank of the cone continued to feed the large aa flow that advanced slowly through the papaya and coffee groves northeast of the village. About dawn fountaining increased again, and at 06^h35^m bursts as high as 1,200 feet were measured. Pumice fall was heavy in Kapoho throughout the day, and occasionally the strong easterly winds carried finer fire-fountain debris as far as Pahoa, 7 miles to the west.

Although most of the lava erupted still poured into the channel leading to the ocean along the north wall of the graben, the volume of lava pouring into the sea decreased during the night; by 06^h30^m only a few minor wisps of steam were rising from the flowfront at the ocean. Observations from the air at 08^h30^m revealed that a large lake of lava had ponded in the area between the fountain and the Koae-Pohoiki road, and no visible lava river was running to the sea. Spreading of the lava was restricted to small flows advancing southward between Higashi Pond, which was about two-thirds covered, and Warm Springs. By early afternoon the lake of lava east of the cone had risen about 10 feet, and increased movement was noted in the flowfronts near Warm Springs.

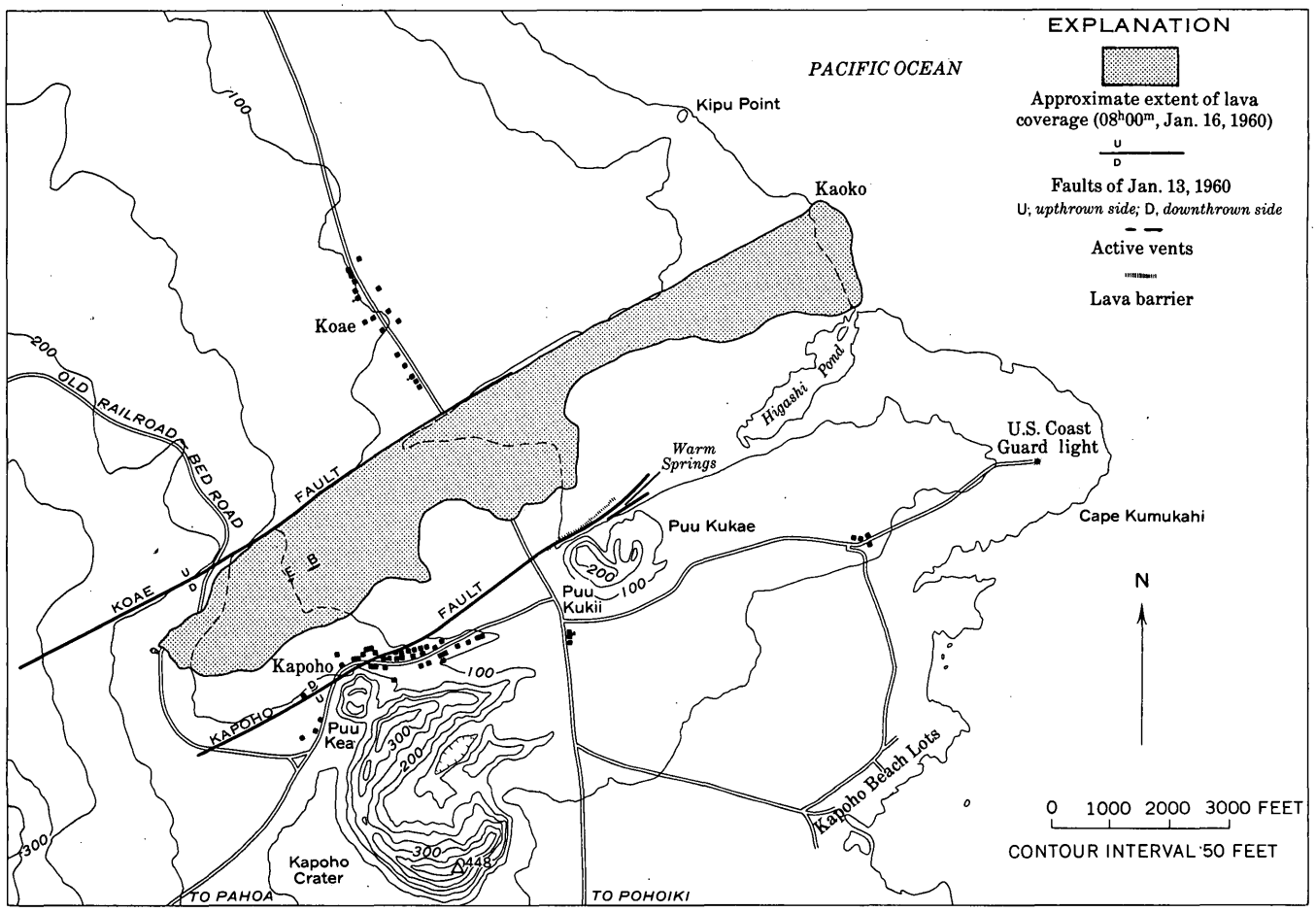


FIGURE 49.—Map of eruption area at 08h00m, January 16, 1960.

In an attempt to protect the Warm Springs picnic area from the rapidly advancing flows, bulldozers were brought in to scrape together a 1,500-foot-long rock dike around the north side of Puu Kukii and Puu Kukae. By 16h00m lava had reached the 4- to 10-foot-high man-made barrier in a number of places, and within an hour it had risen above the dike. The futile attempt to save the springs was soon abandoned, and by 20h20m most of the dike had been covered by new lava.

The fountain remained high (700 to 1000 feet) all through the day, and a further gradual increase in activity occurred late in the night. The heavy rain of pumice and cinder rapidly added to the height of the cone, and by 17h15m it was 170 feet above its original base. At 20h40m a small fountain west of the main fountain (between B and J) was active, and occasional bursts of spatter were being thrown from a depression in the cone over the old vent at E.

JANUARY 18, 1960

Flows advanced actively during most of the night in the area north of Puu Kukae. Long streams of incandescent lava, evidently originating from the crusted-over lake of lava, repeatedly broke through the blackened crust and poured rapidly toward the southeast. Lava reached Warm Springs shortly after midnight on January 18 and in the next hour slowly filled the small pool of water that gave the area its name. Farther west, activity was greatly subdued, and by 02h45m the large aa flow north of Kapoho had practically stopped.

Between 03h00m and 04h30m the fountain rose in a single straight plume to the greatest heights it attained during the entire flank eruption (fig. 51). For half an hour it played to heights of 1,200 to 1,400 feet; stronger bursts climbed to at least 1,700 feet, and still-glowing pumice reached 3,000 feet. During this episode of high fountaining at B, inter-

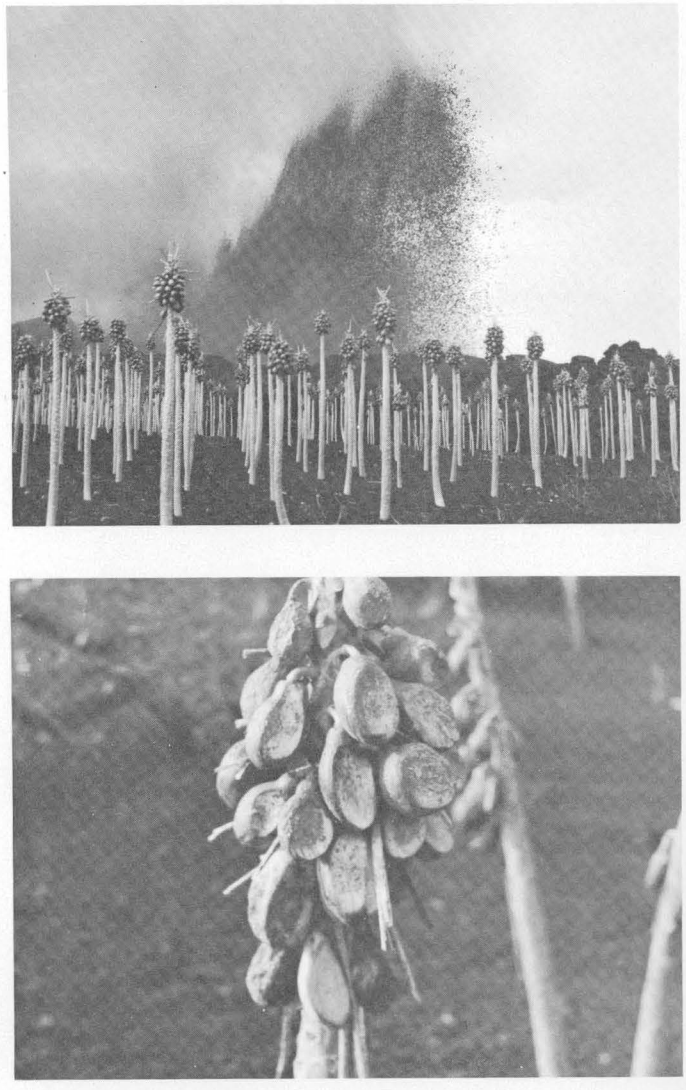


FIGURE 50.—Effects of lava and pumice on papaya. *Top:* January 16, 1960. Massive aa flow is advancing through papaya orchard; main lava fountain is in background. Compare denuded papaya trees with those in figure 47 (top photograph). View is toward northwest. *Bottom:* Closeup of papaya fruit cluster. The individual fruits have been cooked by the radiant heat of the fountain and flow and sheared away by falling pumice.

mittent spatter activity continued at E, and by 05^h15^m a small flow was issuing from that vent.

The main fountain was down to 400 to 500 feet by 05^h40^m, whereas the activity at the spatter vent (E) had noticeably increased. The lava flow from the spatter vent was also more vigorous, and by 06^h10^m it had covered several acres south and southwest of the cone and was threatening the west end of the village. About 07^h00^m, however, fountaining at E ceased and the flow it fed stagnated.

During the morning the main fountain split into two parts; one part jetted lava into the outlet channel, and the other boiled up through a pond in the vent and flung great quantities of lava onto the south slope of the cone. Seven successive flows fed by lava draining off the cone—the last at 11^h30^m—headed for Kapoho, but each flow died out when its limited supply of lava was interrupted.

During the day the top of the fountain occasionally dropped below the rim of the cone, but it generally played to heights of 400 to 700 feet. The rate of lava extrusion appeared to increase, however, and new flow fronts developed locally around the perimeter of the lava field. North of Puu Kukae, lava was still pouring rapidly eastward, and by 15^h30^m the advancing tongues were within 500 feet of the west end of Higashi Pond, which was more than two-thirds covered by the 20-foot-thick aa flow moving slowly westward from its east end.

In the morning, flows finally topped the graben wall along the north edge of the lava field, and by midafternoon two pahoehoe lobes, one east and the other west of the Koae road, were spreading northward across the buried fault scarp.

The large lava lake, which had built up gradually in the middle of the lava field for the past two days,

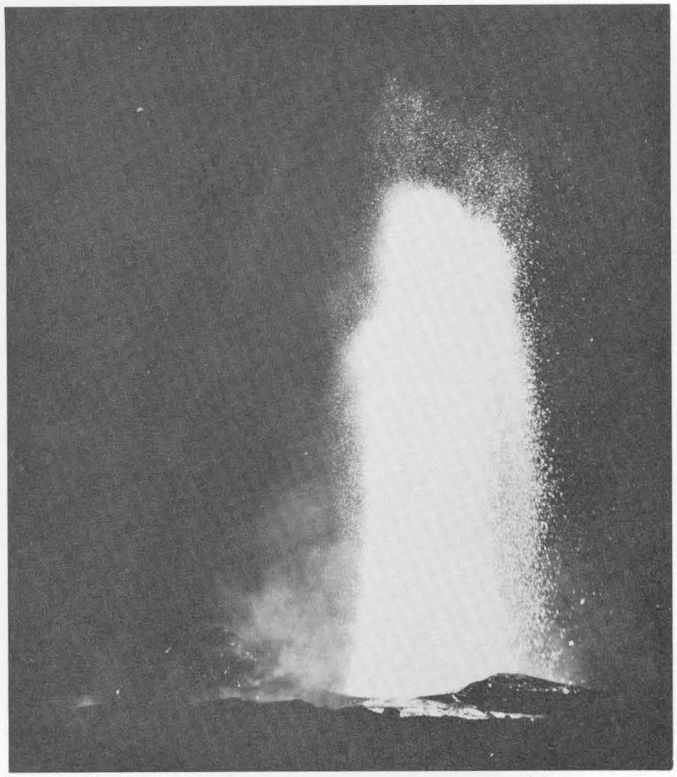


FIGURE 51.—January 18, 1960, 04^h00^m. Main lava fountain, 1,600 feet high, as seen from top of Puu Kukii, 4,700 feet east of fountain.

spawned a mammoth aa flow that branched early in the evening and sent flows toward the north, east, and south across the older flows in the graben. This breakdown of the high lava lake also appeared to augment the flows crossing the buried north graben wall, and by 18^h55^m a large stream was feeding the flow east of the Koae road.

Fountaining increased during the afternoon, and by 19^h20^m the main fountain was again reaching 1,100 feet and exceedingly heavy pumice showers from this high fountain pelted the papaya groves southwest of the cone. Sometime during the day intermittent spattering at vent E resumed and at 21^h00^m hot gases, with an occasional burst of spatter, issued from its glowing throat.

JANUARY 19, 1960

Through the night and the early morning of January 19 the fountain remained high, and great quantities of lava continued to pour from the vent. About midnight the south side of the cone collapsed. This collapse released a flood of lava toward Kapaho, but within an hour the cone had repaired itself and the flow had stopped. At 02^h00^m a lava flow angling southeastward across the graben reached the west end of Higashi Pond. By daybreak the two opposing flows in the pond had still not met, and a large area north of the pond remained uncovered (fig. 52). The main river from the fountain now flowed northeastward across the buried Koae-Pohoiki road and then split; one branch poured northward across the wall of the graben and the other moved eastward toward the Higashi Pond area.

The construction of a second lava barrier, between the east end of Kapoho and the west end of Puu Kukii, was begun in the morning. The announced purpose of the barrier was twofold: (1) to prevent lava in the vicinity of Puu Kukii from flowing southwestward into Kapoho, and (2) to keep lava from passing through the gap between Puu Kukii and Kapoho Crater, from where it could flow downslope to the area of expensive homes and real estate in the Kapoho Beach Lots. However, the site chosen

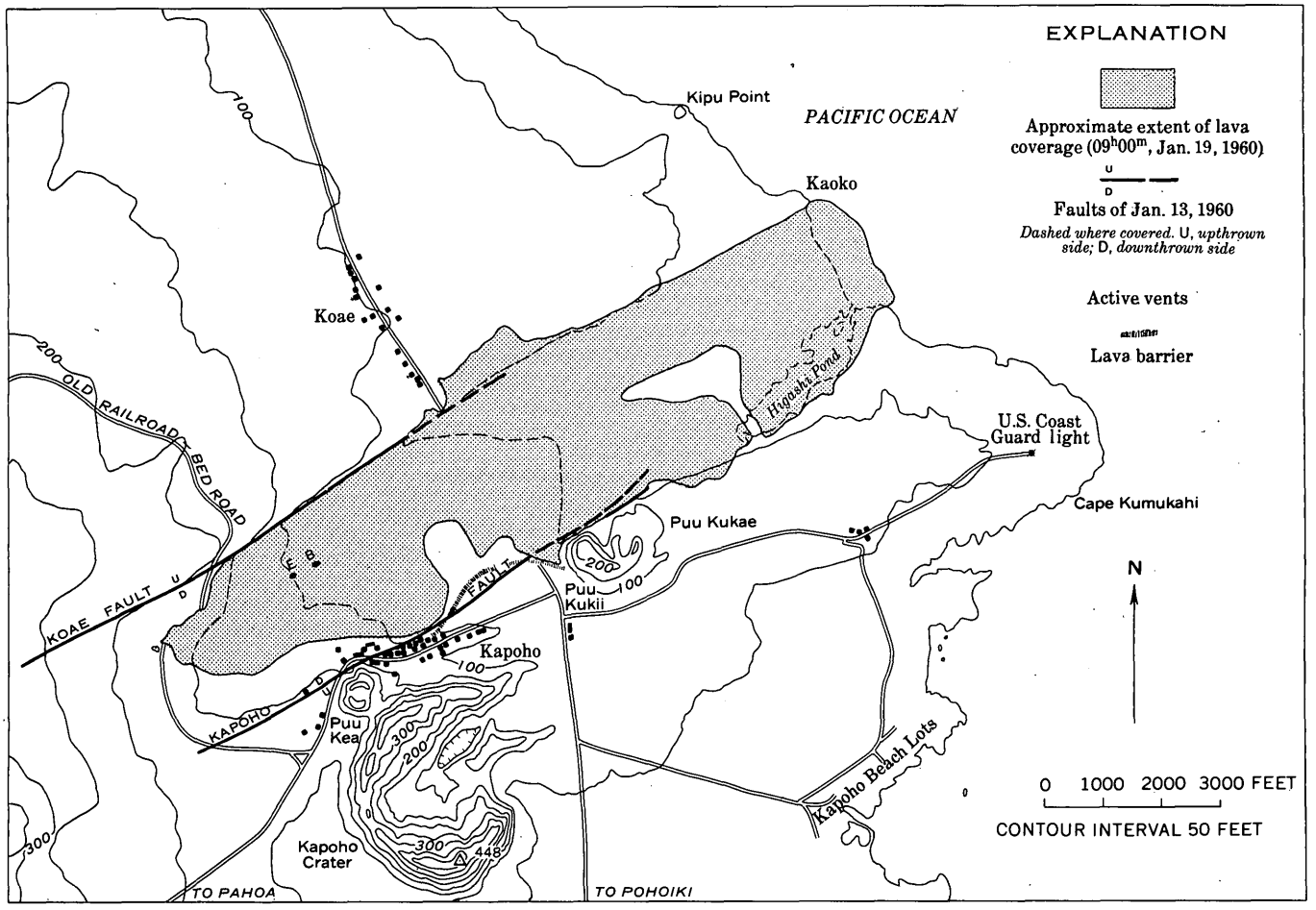


FIGURE 52.—Map of eruption area at 09^h00^m, January 19, 1960.

for the barrier was down slope from Kapoho and lay 20 to 40 feet below the natural barrier between Puu Kukii and Kapoho Crater a few hundred feet farther south. When the dike was completed to a height of 15 to 20 feet the following day, its top over most of its length was still below the level of the natural ridge. By 15^h30^m lava had reached the new barrier along its east end, and a massive 20-foot-thick aa flow was slowly approaching the barrier from the west. The same aa flow was inching southward toward the village along a 1,000-foot front west of the barrier.

The fountain continued in a very erratic manner through the day and night. Often it almost disappeared behind the rim of the cone, only to revive quickly and jet to heights of 900 feet (fig. 53, top photograph). The vent at E continued to throw out spatter sporadically, and by 23^h00^m a small rim of welded spatter had accumulated around its mouth.

JANUARY 20, 1960

The voluminous pumice production of the preceding 48 hours added more than 60 feet to the height of the cone, and by 02^h40^m, January 20, it stood 235 feet above its base. Through the early morning hours the fountain raged on, often as a broad V-shaped pulsating fan that appeared to oscillate slowly around the vent. By daylight this oscillatory motion had stopped, and the fountain continued as a slightly inclined jet spurting toward the east.

Strong flows continued to advance southward between Puu Kukae and the ocean. Higashi Pond had been completely filled, and by 03^h15^m two new fronts, each 1,000 feet wide, were working southward upslope toward the broad topographic ridge forming the backbone of Cape Kumukahi. The easternmost flow had apparently just poured over the small scarp along the south side of the buried Higashi Pond, and the other flow, at the east base of Puu Kukae, was advancing through the forest only 1,000 feet north of the road to the U.S. Coast Guard station. Near the village of Koae the flows pouring northward from the graben had abated considerably, and south of the fountain the thick aa flow advancing on Kapoho and the new barrier had stopped completely by 04^h45^m.

By midday a total of about 40 million cubic yards of lava, spread over approximately 750 acres of ground, had been erupted from the vents north of Kapoho since the beginning of the eruption.

Flows continued to move southward between Puu Kukae and the ocean throughout the day. Near the former inlet of Higashi Pond, considerable lava was once more entering the sea and sending up another billowing steam cloud. On the north side of the graben at 17^h00^m, pahoehoe flows with disrupted blocky surfaces had moved about 400 feet up the Koae road in advance of a larger aa front and were only 300 feet from the first house in the village. A more active flow across lower ground just east of the road, however, was already opposite the first few houses.

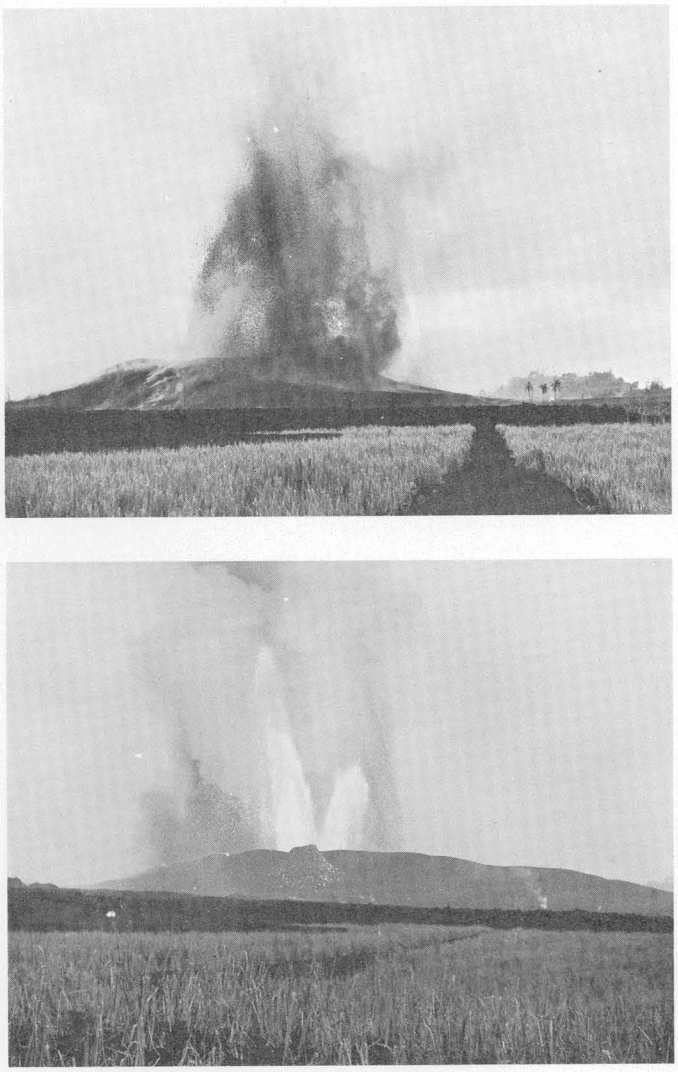


FIGURE 53.—Main lava fountain and cinder-pumice cone. *Top:* January 19, 1960. View eastward from old railroad-bed road showing pumice from vent B pelting southwest flank of cone. Flows in sugar cane field in the foreground are from vents (out of picture on the left) that were active briefly along the curtain of fire on January 13, *Bottom:* January 22, 1960, 16^h00^m. View eastward from old railroad-bed road showing main V-shaped lava fountain (vent B) and small parasitic spatter cone (vent E). Large fountain apparently originating from the spatter cone is actually rising from the main vent beyond. Compare features with those above, taken from approximately the same location 3 days earlier.

JANUARY 21, 1960

The small spatter vent at E, on the west side of the main cone, continued sporadically, and by 05^h45^m, January 21, a small parasitic cone had developed around its orifice. Spatter flung from this vent shot upward, inclined about 45° toward the west, and was generally accompanied by a loud shooshing sound. Between bursts of spatter, gases emanating from the vent burned with a large pale-blue flame.

The flow on the Koae road advanced 200 feet northward in 12 hours, and by 07^h00^m it was within 100 feet of the first house in Koae. Between Puu Kukae and the ocean, the two distinct flowfronts of the previous day merged into an irregular broad front which was advancing southward slowly.

Shortly after daybreak, lava began to ooze from a domed area on the pumice-covered flanks of the cone about 500 feet southwest of the spatter vent. The dome was undoubtedly pushed upward by the head of lava within the vent area; it had a maximum uplift of about 5 feet over a 10,000-square-foot area and was covered by at least 10 feet of pumice. Lava oozed from cracks in and around the periphery of the dome until about 08^h00^m.

The fountain remained relatively low throughout the day and rarely exceeded a height of 400 feet. By noon the lava flows in the Koae area had ceased to move and the massive aa flow immediately north of Kapoho was still dormant. Lava continued to pour into the sea at the site of Higashi Pond, however, where it generated a steam cloud that was considerably larger than the fume and steam cloud over the vent. At the shore, turbulent steam emission was frequently accompanied by violent blasts of rock-fragment-charged water and steam generated by large masses of incandescent lava tumbling into the water from the front of the aa flow (fig. 54).

Construction of a mile-long barrier between the east end of Puu Kukae and the ocean was begun in the morning. It was hoped that this barrier, which was placed atop the broad ridge extending inland from Cape Kumukahi, would prevent the spreading of lava across the ridge, from where it could pour down upon the Kapoho Beach Lots and the U.S. Coast Guard facilities at Cape Kumukahi. By late afternoon more than 2 dozen large D–8 and D–9 caterpillar tractors, some with earth rippers and others with dozers, were frantically engaged in the project.

By 21^h30^m the main fountain began to increase in height erratically, and at midnight it was reaching 1,000 feet. Meanwhile, little lava was pouring into the sea; only a few steam clouds were rising from the flowfront.

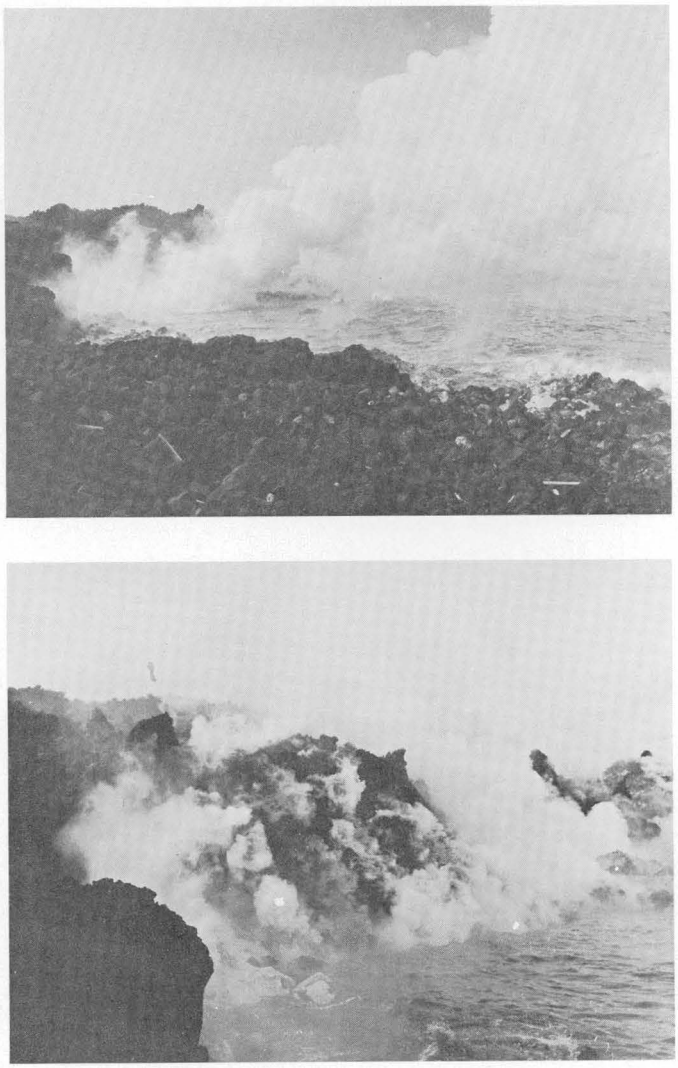


FIGURE 54.—Aa lava flow entering the ocean. *Top:* January 21, 1960. Heavy turbulent steam clouds rise from the front of a massive aa flow as it slowly pushes into the ocean. Small blasts of comminuted rock, which frequently exploded from the water, are not visible in the picture. *Bottom:* January 21, 1960. Closeup of same flow entering the ocean.

JANUARY 22, 1960

Conditions remained virtually unchanged during the early morning of January 22. Flows between Puu Kukae and the ocean advanced not more than 100 feet toward the barrier under construction, and in the Koae area, motion of flows along the road and in the forest east of the road revived slightly.

A flight over the area at 13^h00^m revealed very little movement around the entire periphery of the lava field, and only a small amount of material appeared to be entering the sea. In the middle of the

lava field, however, a great lava lake, which was higher and more ominous than the one of a few days earlier, was clearly evident.

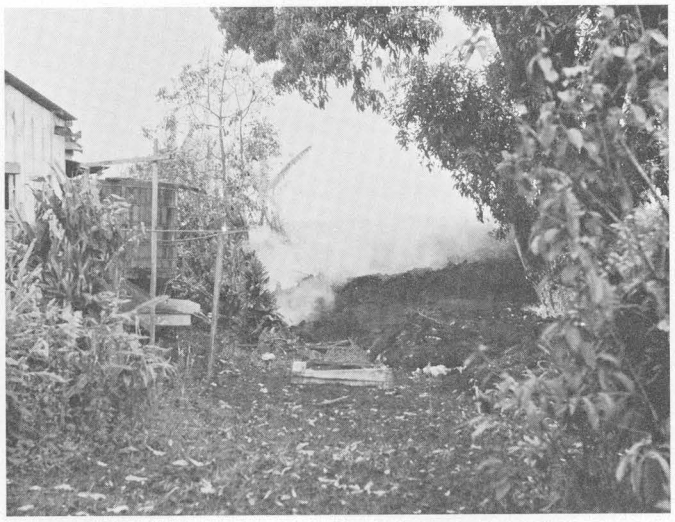
Spatter activity at vent E had gradually increased in intensity for about 24 hours, and by 14^h00^m showers of lava were blasted skyward every few seconds. The steep-sided parasitic spatter cone built by this very fluid ejecta grew very rapidly, and by late afternoon it was as high as the main cinder-pumice cone on the flank of which it perched (fig. 53, bottom photograph). Fountaining at the main vent increased at about 17^h00^m to a massive fountain, 1,000 to 1,400 feet high, which produced abundant pumice. Spattering at E also increased at this time, but there was no obvious synchronization of bursts from the two vents.

At 20^h10^m we watched the reactivation of a cold 5-foot-thick blocky flowfront near Koae. The first signs of revival, which we did not fully appreciate at the time, were peculiar rumbling sounds coming from within the flow. In the next few minutes cracks in the flow began to glow a deep red; gradually they became brighter and more orange as the temperature increased, and then, almost imperceptibly at first, the cracks parted and allowed small tongues of fluid lava to ooze out. By 20^h25^m a lobe about 200 feet wide had advanced as much as 5 feet beyond the old frozen front of the flow.

JANUARY 23, 1960

Activity at E continued to increase, and by 00^h30^m, January 23, spatter was shooting to heights of 300 feet. Moreover, by this time the western lip of the very steep spatter cone was visibly higher than the crest of the main cinder-pumice cone.

Flows immediately west of Puu Kukii revived about 01^h30^m and rapidly covered the area north of the first Kukii-Kapoho dike; by 07^h15^m lava was ponding behind the eastern half of the dike. In the Koae area lava slowly continued to advance, but at 04^h00^m it was still 50 feet from the first house in the village. Shortly before noon, however, the flows near Koae surged forward, and within 3 hours (13^h00^m to 16^h00^m) a house, a small community hall, and a church had been destroyed (fig. 55).



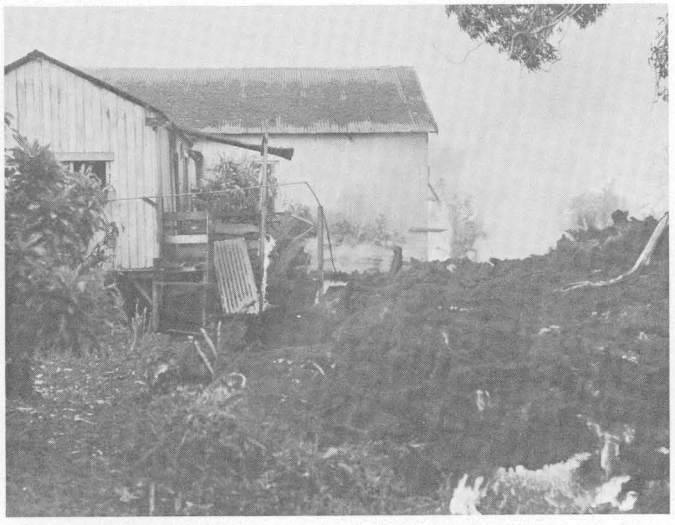


FIGURE 55 (left).—Flows in the Koae village area. *Top:* January 23, 1960, 12^h50^m. A slowly moving lava flow surrounds a large mango tree and is less than 30 feet from the first house in the village of Koae. *Middle:* 15 minutes later the lava reaches the house, flows underneath, and sets it afire. The water tank seen in the top photograph has collapsed. *Bottom:* 10 minutes later, as seen from the front yard, the house is a holocaust. Large mango tree behind house is the same one shown in the top photograph.

Between 15h50m and 16h10m the high lava lake in the middle of the lava field above the buried Koae-Pohoiki road was still distinguishable from the air, but only one lava stream, which fed the flow curving eastward past Koae, led directly from it. Other small aa tongues and short pahoehoe oozes, probably fed through tubes leading from the central lake, continued to smooth out irregularities on the older flows. A short wide stream of lava gushing from another subcrustal tube fed the flow around the west side of Puu Kukii which had breached the east end of the first Kukii-Kapoho barrier sometime earlier (fig. 56). At the seacoast many small tongues of lava bleeding from beneath the immobile aa crust covering the lava field were emptying into the water along the entire flowfront, but no zone of concentrated flow into the sea was visible.

Destruction of the first Kukii-Kapoho lava barrier spurred the construction of a second, slightly south of the old one and extending westward from the base of Puu Kukii about 1,500 feet along the Kapoho road. This dike, hurriedly erected during the afternoon and early evening, was intended to give State and civil defense officials time to erect a "last ditch" barrier along the high ground between Puu Kukii and Kapoho Crater.

Activity at both the spatter vent (E) and main vent (B) remained about the same during the day (fig. 57). The voluminous flow pouring through the gap in the northeast end of the cone near the base of the main fountain continued to raise the level of the lake in the middle of the flow over the Koae-Pohoiki road. At 21h15m a large flow from the lake was advancing rapidly around Puu Kukae toward the mile-long barrier complex east of the cone, and a smaller stream from the lake fed the slower moving flows east of Koae. In the village of Koae one more house was destroyed during the early evening, but at 21h35m only a few lobes of lava were still moving. At the west base of Puu Kukii, lava continued to pour through the breach in the old barrier and rapidly filled the area between it and the new barrier, which was still under construction.

Many times during the night the main fountain

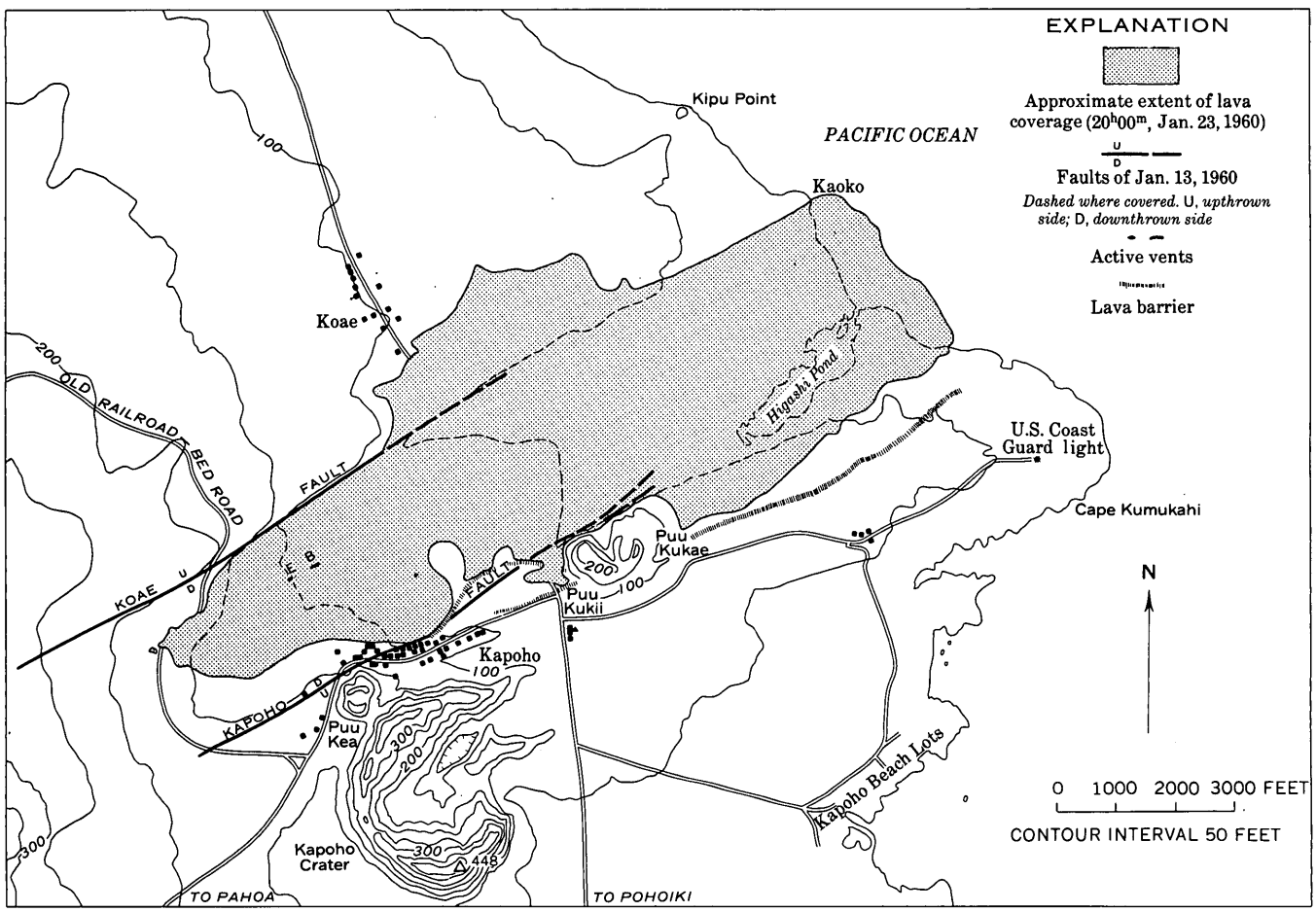


FIGURE 56.—Map of eruption area at 20h00m, January 23, 1960.

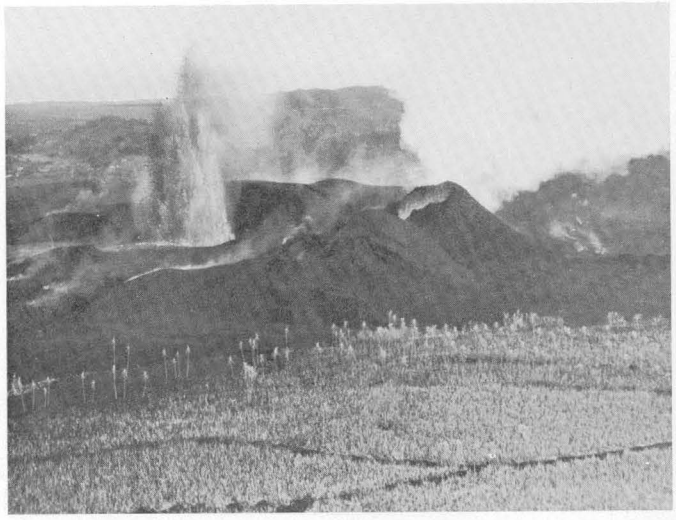


FIGURE 57.—January 23, 1960. Aerial view southeastward across the fountains and cone. Fountain at main vent B (left) feeds river flowing through breach in cinder-pumice cone. Spatter cone E (right) is higher than main cone. Defoliated coconut grove in foreground is dwarfed by growing 200-foot-high cone.

was reduced to a broad boiling mass of liquid lava less than 200 feet high. Generally, however, it played to heights of 400 to 700 feet. During these severe variations in the habit of the main fountain, the spatter vent continued undisturbed, blasting out a spray of liquid every few seconds.

JANUARY 24, 1960

At 01^h00^m, January 24, the large flow that had earlier begun to circle southeastward around Puu Kukae was spreading eastward along the axis of the old graben. From its point of most southerly advance, a narrow distributary lava stream was feeding the very active flows that were rapidly approaching the long barrier. Flows emerging from the massive front moving down the old graben, and overriding the older lava, apparently reached the ocean within a few hours, because by 04^h30^m a steady stream was pouring into the sea. This flow pattern remained unchanged during the morning, but by 13^h30^m activity had increased along the entire south side of the lava field between Puu Kukae and the ocean, where many local flowfronts were being fed by tubes bleeding southward from the main river.

At 12^h15^m a large jet of black smoke was first seen rising from the cone between the main fountain and the spatter vent. From the north, at 16^h00^m, it was evident that a new vent (J) had formed. Unlike the two old vents that flanked it, the new vent emitted a steady stream of hot gas charged with rock fragments and occasional shreds of incandescent lava that roared straight into the air. When night fell the cone and fountains were an incongruous spectacle—the main fountain was a mass of liquid ejecta pulsating to heights of 500 feet; over the new vent a slightly incandescent gas-cinder jet shot vigorously to 400 to 500 feet; and at the spatter vent, a sporadic shower of lava was blasting out toward the west.

By early evening flows containing approximately 60 million cubic yards of lava had covered about 1,080 acres. Cone-height measurements at 22^h40^m revealed no significant change in the height (235 feet above its base) of the main cone since 20 January, whereas the spatter cone, with 50° slopes on its west side, rose 65 feet above the main cone. Although the main cone had not grown in height during the last 4 days, it had increased greatly in mass and had compacted and spread laterally beneath the load of debris that rained down upon it.

Through the night the main lava river continued to pour into the ocean—its sinuous course from cone to sea was an ever-changing incandescent ribbon.

JANUARY 25, 1960

Activity in each of the three vents in the long high cone continued all night. By 04^h50^m, January 25, a small symmetrical cone had developed atop the main cone around the gas-cinder vent (J), and the west lip of the steep-sided spatter cone on the west appeared to be very unstable and ready to crumble.

From the air at 06^h40^m, a tremendous quantity of lava was observed entering the sea. From north of Kaoko to the east terminus of the long barrier, three rapidly flowing rivers and at least six smaller streams were pouring into the ocean behind a massive curtain of steam. The rivers and streams were very short; they were not fed by the active flows pouring into the ponding area northwest of Puu Kukae, but they were emerging from beneath the immobile crust of the lava field approximately along the original shoreline. Along most of the new coastline, flows had advanced about 500 feet into the ocean during the preceding 24 hours.

Bulldozers began work on the third Kukii-Kapoho barrier in the morning. This structure extended 1,500 feet from Puu Kukii to the east shoulder of Kapoho Crater on the high saddle between the two cones. When finished, it was 15 feet or more in height over its entire length and was by far the most massive barrier built during any Hawaiian eruption.

At noon only a few small local flows were still active in the village of Koae, but farther east an irregularly advancing flow fed by one of the main channels draining the high lava pond northwest of

Puu Kukii was creeping toward the ocean north of Kipu Point. Strong rivers of lava were also pouring into the region east of Puu Kukae, and by 15^h10^m lava was pushing up against the long barrier north of the U.S. Coast Guard residence area. West of Puu Kukii, however, the pahoehoe flows that had poured through the first Kukii-Kapoho dike the previous day had stagnated, and farther west the massive aa flow threatening Kapoho was still dormant.

Late in the afternoon a dark plume of ash began to evolve from the gas-cinder vent (J), and by 19^h50^m it had increased to a dense black convoluting ash cloud. This cloud bore much incandescent debris aloft over the cone and showered the countryside with fine ash as far as Puu Kukii.

The lava flow between the first two Kukii-Kapoho barriers at the west base of Puu Kukii was rejuvenated around 20^h00^m, and by midnight the entire flowfront from Puu Kukii to the west end of the first barrier had begun to thrust forward.

JANUARY 26, 1960

Shortly after midnight on January 26 the main fountain (B) increased from the 300- to 500-foot height, which it had held throughout the day, to 1000 feet, and it again showered the cone and nearby region with great quantities of pumice. The gas-cinder jet (J) had earlier ceased its vigorous ash production, and at times the pumice raining down from the main fountain completely obscured it. About 03^h00^m liquid lava in the spatter cone rose above the level of its rim, and two short-lived flows poured down its steep flank onto the gentle pumice-covered western slopes of the main cone.

During flights over the eruption area at 06^h30^m and 15^h00^m dozens of small lava streams were seen entering the sea along the entire flowfront. At 15^h00^m Kaoko was completely covered, and an impressive river flowed northward from the lava apron along the original shoreline toward Kipu Point.

At 14^h00^m a circular pit 15 feet in diameter collapsed at the base of Puu Kukii just south of the second Kukii-Kapoho barrier. Although steam issuing from the hole obscured its bottom, the rim continued to collapse, and the pit widened to more than 20 feet in half an hour. Cracks also opened across the Pohoiki road nearby, and a few hours later steam was evolving from the porous flank of Puu Kukii about 100 feet east of the collapse. These disturbances appear to have been caused by lava, impounded in the thick flow behind the dike, that was injected at a shallow depth into a zone of weakness leading from beneath the flow to Puu Kukii. Possibly the avenue of access was one of the many fissures that broke through the region when the graben subsided in 1924, or possibly an arm of the fragile cinder cone (Puu Kukii) that had been buried by later flows.

The massive aa flow west of Puu Kukii, which had slowly revived about midnight, was breaking through and pouring over a 300-foot section of the first barrier just east of Kapoho at 17^h30^m. The first Kukii-Kapoho barrier failed at still another point at 19^h05^m, and by 20^h30^m fluid pahoehoe pouring through the break had flooded the low ground between the first and second barriers.

During the afternoon or early evening the gas-cinder vent (J) stopped jetting, but at 20^h30^m it opened again and resumed activity as before. The main fountain (B) continued spewing lava to heights of 1,000 feet, and for a brief time at 19^h15^m, pieces of incandescent pumice, some as large as footballs, rained down on Puu Kukii 4,500 feet away. Sporadic activity at the spatter vent (E) continued unchanged.

JANUARY 27, 1960

Resumption of movement in the massive aa flow fronting Kapoho was heralded by weird crunching and rasping sounds emanating from the east end of the cold flowfront shortly after midnight on January 27. By 01^h00^m the flow had started to advance, and within 10 minutes a house at the northeast edge of the village was being crushed and pushed backward by a 20-foot-high wall of cold clinkery aa. The flow advanced as a tumbling wall of cold aa until about 02^h00^m, when fluid lava finally reached the front of the flow. Slightly toward the east, along the second Kukii-Kapoho barrier, the surface of the flow impounded behind the barrier loomed 15 feet above it, and blocks of new lava spalling from the flow tumbled down the south face of the barrier. At 03^h30^m incandescence was observed in the collapse pit in front of the barrier, and steam emission had increased between the pit and the west slope of Puu Kukii.

By 06^h00^m the aa flow east of Kapoho was pouring through the barrier and in places was halfway across the road. The collapse pit was covered rapidly, and just west of the pit the flow was shoving the barrier en masse across the road (fig. 58). In places, the asphalt surface of the road was crumpled and thrust forward in advance of the massive aa flowfront, which contained tabular blocks as large as $15\times15\times3$ feet (fig. 59). At 06^h40^m, 500 feet of roadway west of the junction had been covered, but within an hour the aa flows between Puu Kukii and Kapoho tempo-

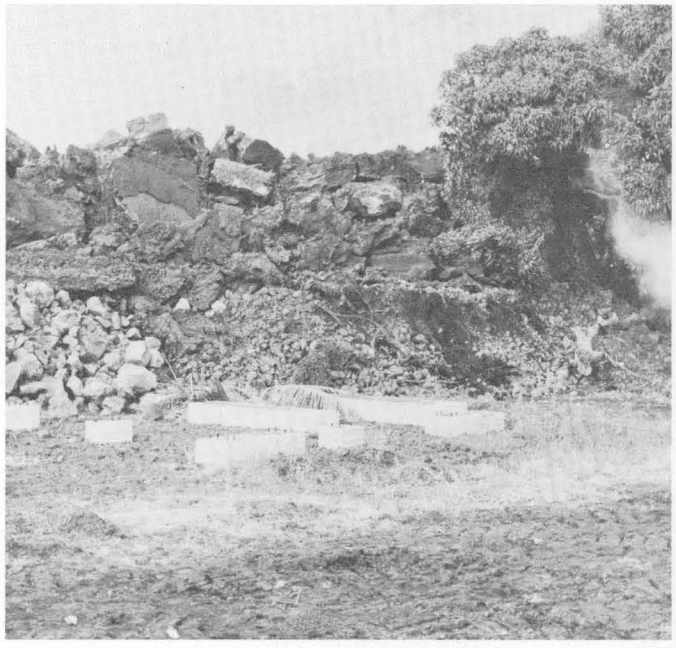


FIGURE 58.—January 27, 1960, early morning. Massive, blocky aa flow east of Kapoho overriding and shoving 8- to 10-foot high manmade barrier before it.

rarily halted, and only small pahoehoe lobes continued to ooze from the immobile aa flowfronts.

From the air, between 10^h00^m and 11^h00^m, it was observed that the flows east of Puu Kukae were against the mile-long barrier almost along its entire length (fig. 60). At the shore a host of small lava streams were entering the sea along a 1¼ mile front. East of Koae the flows appeared to be within 1,000 feet of the ocean, but haze from forest fires in that area limited visibility. The main fountain was relatively low and did not appear to be extruding much lava, but a large pool of liquid lava was boiling in the spatter cone and a small flow emerged from its base and slowly covered the older flows west of the main cone.

FIGURE 59.—January 27, 1960, 06^h40^m. Massive, blocky aa flow crossing Kapoho road east of the village. Note the burning telephone pole and the buckled pavement thrust forward by the flow.

In the early afternoon the main fountain increased greatly in size, and for the next 7 hours the heaviest pumice fall observed during the entire eruption rained down in the area northeast of the cone. At times the falling pumice formed an opaque wall as far east as the buried Koae road, and lesser amounts floated down in black lacy curtains extending far out over the ocean. The entire lava lake ponded northwest of Puu Kukii was rapidly covered with tens of feet of pyroclastic debris, and by 18^h20^m a broad pumice loaf almost as high as the main cone extended 3,000 feet northeast of the fountain.

Lava leaking from the base of the spatter cone continued to feed thin flows on the west side of the lava field, which by 16^h20^m were slowly approaching the west end of Kapoho. The massive aa flow just north of the village also revived during the day, and by 18^h20^m it was pressing into the backyards of houses on the north side of the main street. This flow seemed to be fed mainly by spatter from the main vent falling on the south flank of the cone. A more serious threat to Kapoho, however, was the high pumice-covered lava lake, which was impounded along its north edge by the immense still-growing pumice loaf northeast of the cone.

Through the early part of the evening, liquid lava continued to slosh in the spatter vent (E), and occasionally the gas-cinder jet (J) was visible through the screen of pumice falling from the main fountain. Then at 21^h40^m the main fountain sank abruptly below the rim of the cone. At the same time activity in the spatter vent increased markedly, but after a few minutes it too died and the countryside was plunged into darkness. At 21^h50^m, after 5 minutes of quiet, the spatter vent roared to life, expelling the pool of liquid lava in its throat and collapsing the thin, unstable rim of its cone. During the next half hour fountaining alternated between the vents at E and B, but at no time did the fountains exceed a few hundred feet in height. At 22^h20^m a new vent (L) opened 500 feet east of the main vent, and shortly thereafter still another new outbreak occurred 1,000 feet farther east near K (fig. 61). Fountaining near K began at a vent at the south base of the pumice loaf but was soon replaced by a more persistent fountain at K.

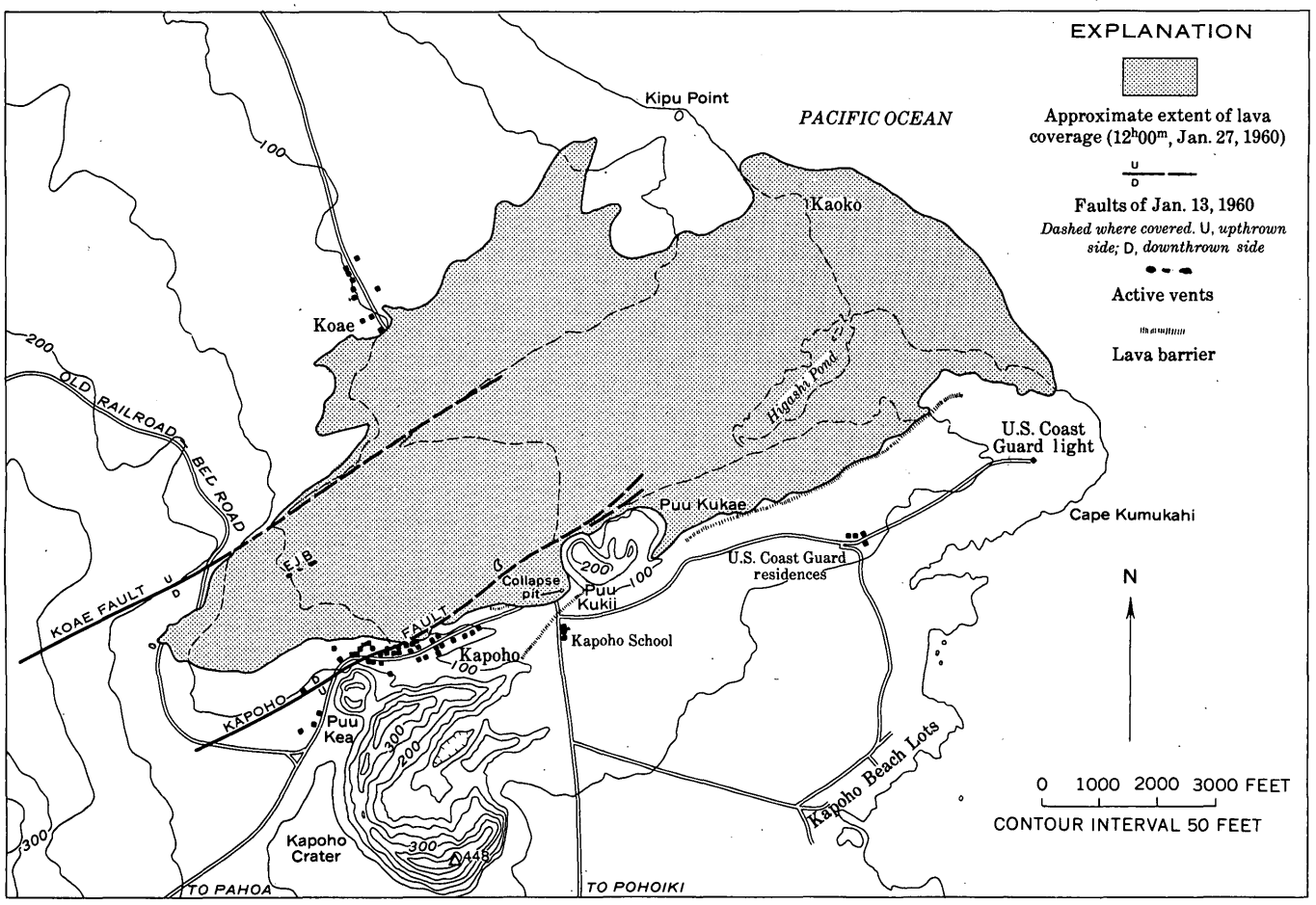


FIGURE 60.—Map of eruption area at 12h00m, January 27, 1960.

From the top of Puu Kukii at 23h15m, the spatter vent appeared to be dead, while extremely variable fountains played from B, L, and K. The old main fountain at B sputtered to heights rarely exceeding 100 feet, whereas the new fountains at vents L and K spurted as high as 700 feet. At times, activity appeared to alternate between K and the two fountains at B and L. Gases continued to blast from the vent at J, which was undisturbed by the variations among the other fountains. Very fluid lava pouring from all the active vents descended toward the south and fed the flows between Puu Kukii and Kapoho.

This new source of lava for the massive aa flow south of the cone spelled doom for Kapoho, and shortly after 23h30m the flow began to advance toward the village. Moving southwestward, the flow rapidly overwhelmed building after building, and by midnight most of Kapoho had been destroyed.

JANUARY 28, 1960

Through the night and the early morning of January 28 activity at all fountains was erratic. At 01h35m the principal activity was at K, where a 200-foot fountain erupted great quantities of lava that poured eastward along the south edge of the pumice loaf, whence it swept southward toward Puu Kukae. Beyond the east end of the pumice loaf a branch of this flow swung northeastward past Koae. Part of the lava from K and all of the lava from B and L flowed southeastward toward the Kapoho-Puu Kukii sector.

By 02h37m the fountain at B had increased in height to 1,000 feet, and its main discharge was directed toward Puu Kukii (fig. 61). The large flow southeast of the pumice loaf had slowed down by this time, but the branch flowing northeastward beyond Koae remained strong. By daybreak, flows fed by lava leaking intermittently from the base of the spatter cone had advanced beyond the earlier flows southwest of the cone.

A long crack extending about 1,000 feet northeast of K opened in the south flank of the pumice loaf about 02h55m. For a period of about half an hour

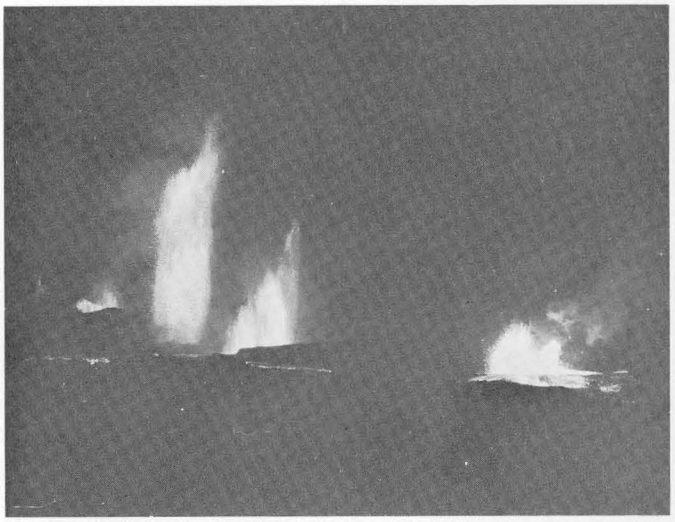


FIGURE 61.—January 28, 1960, 02^{h}40^m. Renewed fountaining along the extended active rift, as seen from Puu Kukii. From left to right the active vents are: the spatter vent (E), main vent (B), and the two new vents, L and K.

this glowing crack emitted fume and an occasional burst of spatter.

The aa flow in the Puu Kukii area reached the last barrier between Puu Kukii and Kapoho Crater shortly before 04^{h}00^m and very rapidly rose to a level even with the top of the barrier. By daybreak the lava ponding behind the barrier on the northwest flank of Puu Kukii reached a depth of more than 50 feet. The resulting high pressure at the base of the flow injected lava into the uncompacted cinder of the Puu Kukii cone (probably along the zone of weakness manifested by the collapse pit and steaming areas 2 days earlier) and drove it through the cone beneath the barrier to escape on the south slope of the cone near Kapoho School (fig. 62). The dense liquid squeezing through the cone floated a 500-foot-long part of the light cone as high as 30 feet above its original position; this left an island of cone partly covered by earlier lava high above the west end of the barrier.

A futile attempt using a small hastily built barrier was made to block the flows advancing toward the school, but at 10^{h}00^m the first of the school buildings was consumed. Lava continued to stream through the cinder cone, and by 12^{h}30^m three more buildings at the school had been destroyed.

The increased outpouring of lava from the fountains was soon noted along the south edge of the flow beneath Puu Kukae and the ocean. By midafternoon lava had breached the long barrier in four places; the largest breakthrough was only 800 feet west of the Coast Guard residence area. On the north side of the lava field, flows were actively advancing northwest of Kipu Point, but again smoky haze severely limited visibility in that region. By 16^{h}00^m only a few pahoehoe oozes were active along the front of the aa flow that had buried Kapoho, and near the school lava movement had virtually ceased. West of the main cone, however, lava still pumping from the base of the spatter cone was forming a large pond confined only by the cooled flows around its periphery.

At 16^{h}50^m another section of the west flank of Puu Kukii was raised by a fresh injection of lava through the cone, and lava began to ooze over the flows that poured beneath the barrier in the morning. As the flow spread across the schoolyard, shallow explosions rent the ground a few feet ahead of its leading edge, probably due to the ignition of hydrocarbon gases distilled from organic matter in the soil.

Through the afternoon and evening activity in all fountains continued erratically. At times all the fountains jetted to heights of 1,000 feet and showered the cone with pumice; frequently, one or more was high and the others were low; and occasionally all were low. The only vent that showed little variation was the gas-cinder jet at J, which continued to emit a straight plume of particle-charged gas.

The pond of lava fed by the vent at the base of the spatter cone gradually increased in thickness during the day, and by 21^{h}20^m it was above the level of the vent. The vent continued to erupt, however, burping through the overlying fluid and spraying the area with blobs of spatter. Above it, a heavy cloud of gas accompanied by an occasional shower

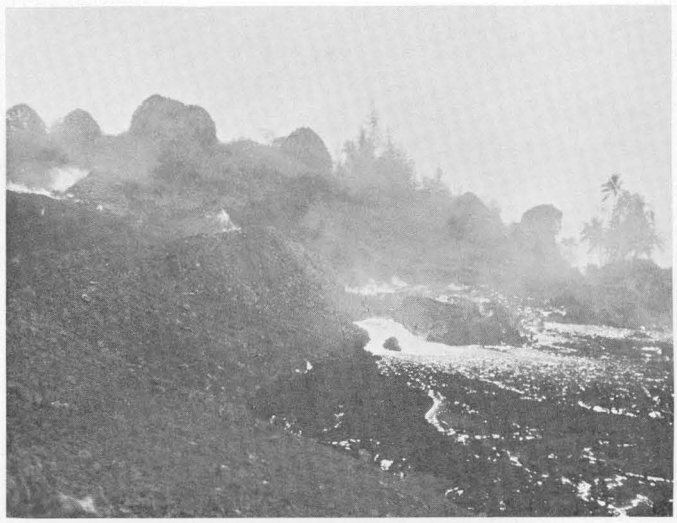


FIGURE 62.—January 28, 1960, early morning. Lava emerges from the base of Puu Kukii cone after pushing through the cone's flank behind the manmade lava barrier (left).

of spatter was discharging from the vent of the spatter cone.

Flows pouring through the large breach in the barrier between Puu Kukae and the ocean crossed the Coast Guard access road shortly before 22^h00^m. Farther west the flows that crossed the dike earlier had abated; only a few incandescent streaks marked their paths.

By nightfall, flows had covered about 1,280 acres with an estimated 85 million cubic yards of lava.

JANUARY 29, 1960

The fountain at L continued to be principal source of lava through the night. By daybreak, January 29, the once smooth pumice loaf was transected by sharp gullies and ridges showing the effect of the vigorous activity along the extended rift during the past 30 hours. Along the south flank of the loaf, where it was undercut by the lava river, huge blocks of bedded pumice, some 40 to 50 feet high and 100 feet across, had been plucked off and carried away by the moving stream. Many of these blocks, which formed much like the calving of a glacier, floated far downstream and eventually foundered along the main river channel or in the shallow extremities of the lava lake.

The advance of lava along the Coast Guard access road had practically halted by 06^h00^m. Northwest of the residence area, flows had approached to within 200 feet of the buildings; but here, too, all movement had stopped. In fact, flows had stagnated along the entire barrier east of Puu Kukae, and lava was no longer pouring across it.

By 11^h00^m the vent at L was quiet and only the old main fountain at B and the gusher at the western base of the spatter cone were active. Occasionally, the gusher rose through the thin layer of lava above its vent and sprayed lava to heights of 300 feet in the manner of a typical gas-charged fountain (fig. 63, top photograph). At 11^h10^m two explosions ripped through the liquid lava in the pond in the area of the dead vents along H, about 1,000 feet west of the spatter vent. These secondary explosions, possibly caused by the sudden expansion of ground water that had entered the old vents after cessation of fountaining on January 14, formed large dark clouds of steam and ash mixed with liquid lava carried up from the pond.

At the seacoast, lava continued to pour into the ocean along most of the flowfront; the greatest activity was northeast of the Coast Guard lighthouse and farther north along the shore east of buried Higashi Pond. From this latter area a tremendous cauliflowerlike steam cloud rose several thousand feet into the air.

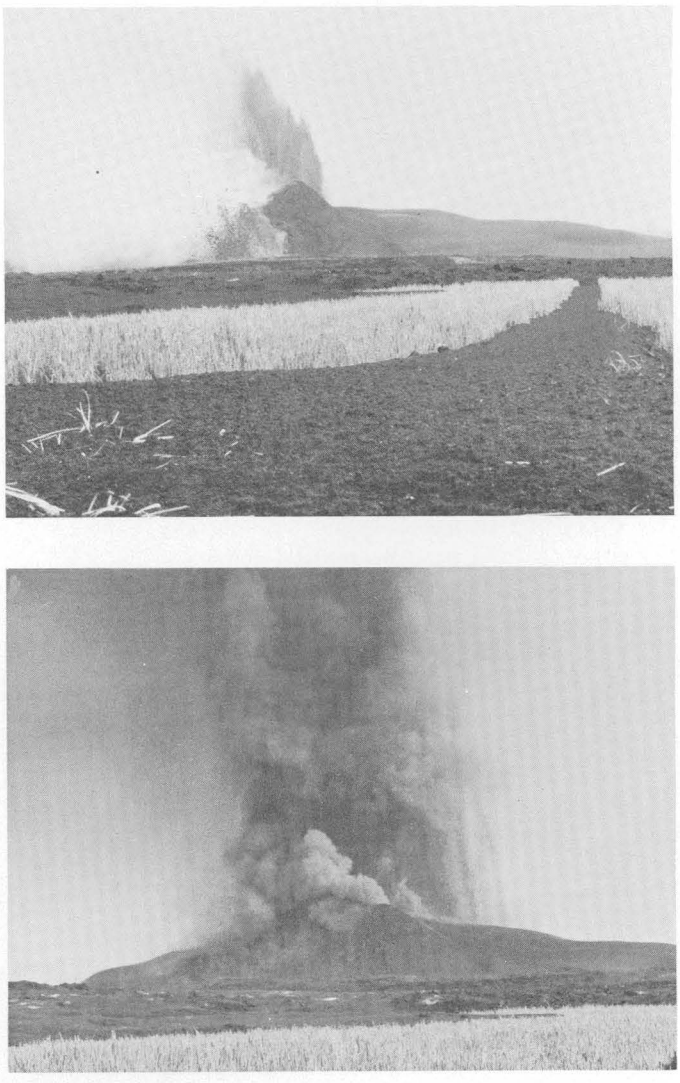


FIGURE 63.—Views of vent area. *Top:* January 29, 1960, 11^h00^m. Cone and fountain viewed from the west. Small gushing fountain at base of spatter cone (vent E) bursts through shallow lava lake. Fountain from the main vent B in cinder-pumice cone behind spatter cone is about 600 feet high. *Bottom:* January 30, 1960. Heavy pumice fallout from main fountain covers top of fuming spatter cone. View is from the west. Compare with activity in top photograph.

About 16^h00^m the vent pouring lava westward from the base of the spatter cone stopped erupting, and liquid lava from the pond immediately began to flow back down the vent. New lava from this vent had spread over almost all the area covered by flows from the original outbreak west of the cone; it had edged northward to the old railroad-bed road and had advanced southwestward into fresh cane and papaya land northwest of Kapoho. Drainback was

no longer apparent at 17^{h}00^m, but the surface of the pond, especially along its northern edge where it bordered the road, continued to subside slowly throughout the night.

As seen from the air at 16^{h}30^m, the main flow from the fountains was still directed toward the Puu Kukae area. From here it flowed under the surface, probably through a complex system of tubes, to all the active flowfronts.

Lava again began spilling over the barrier between Puu Kukae and the ocean late in the afternoon. At 17^{h}50^m flows were crowding southward east of the Coast Guard residence area, and, along almost the entire barrier, lava stood 5 to 10 feet above its top. West of Puu Kukii, lava behind the third Kukii-Kapoho barrier had risen about 4 feet higher than the dike, but in the Kapoho schoolyard in front of the dike all lava movement had ceased.

At about 19^{h}00^m fountaining revived at L and K. All fountains were relatively low—B, the highest, spurted eastward in a 300-foot-high arc, while the others played to heights of less than 200 feet. Later in the evening the fountains were even smaller, and by 23^{h}20^m the vent at K was emitting only an occasional shower of spatter. Meanwhile loud booming reports emanated from the cone but they were accompanied by no visible change at any of the vents.

JANUARY 30, 1960

Early in the morning of January 30 lava from the deep still-fluid pond west of the spatter cone began to ooze through the broad southwest pumice flank of the main cone and emerged northwest of Kapoho (fig. 64). After covering 3 or 4 acres, this secondary flow reached the west end of Kapoho, and by 09^{h}00^m it had destroyed two more buildings. The flow soon abated, and by early afternoon it was no more than a trickle. During the escape of lava through the cone, the level of the lava pond dropped about 10 feet and a number of "lava trees" were left along the northern shore.

Only the main vent (B) continued to fountain vigorously throughout the day, and frequently it produced abundant pumice (fig. 63, bottom photograph). Occasionally a small fountain or a shower of spatter emerged from the vents at L and K. Fuming from the spatter vent (E) was heavy, and the gas-cinder vent (J) was quiet.

From the air at 13^{h}30^m there was no major activity visible along any of the flowfronts on land. A small stream of lava continued to ooze from the pumice cone near the west end of Kapoho, and a few small tongues of lava were advancing east of the Coast Guard residence area. Along the coast, however, a large river of lava was pouring into the sea just north of Cape Kumukahi, and many short smaller streams were entering the water farther north. The large lava river, which was incandescent even in bright daylight, was at least 200 feet wide and flowed about 3,000 feet to the seashore from the old Higashi Pond area, where its identity was lost. Although the lava field from which the river emerged was extremely rough and broken, it probably was the edge of the huge lava pond that had been accumulating slowly over the buried graben for several days. A wider but more slowly moving river meandered southward from above the buried Koae-Pohoiki road toward Puu Kukae, where it turned eastward and disappeared in the stagnant crusted pond. Sometime during the last two days the flow north of Kipu Point had finally reached the ocean. At 13^{h}30^m, however, this flow was inactive after having sent a narrow tongue of lava less than 300 feet into the water (fig. 65).

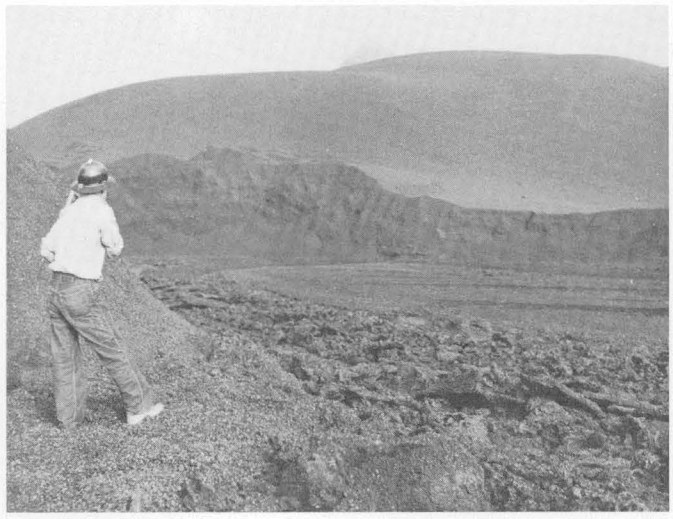


FIGURE 64.—January 30, 1960, 08^{h}00^m. Lava is oozing from the south base of the cinder-pumice cone and is flowing southward. Peak of spatter cone looms above main cone.

JANUARY 31, 1960

Shortly before midnight on January 30 and in the early morning hours of January 31, measured temperatures in the erupting lava were as high as 1,100°C; this was a significant increase over the 1,050°C to 1,080°C temperatures previously measured in the flank eruption. An increase in lava temperature had been suspected when fountaining resumed after the 5-minute lull in activity on January 27, but the increase was slight and erratic. The higher temperatures were also accompanied by a distinct change in the mineralogy of the lava. The

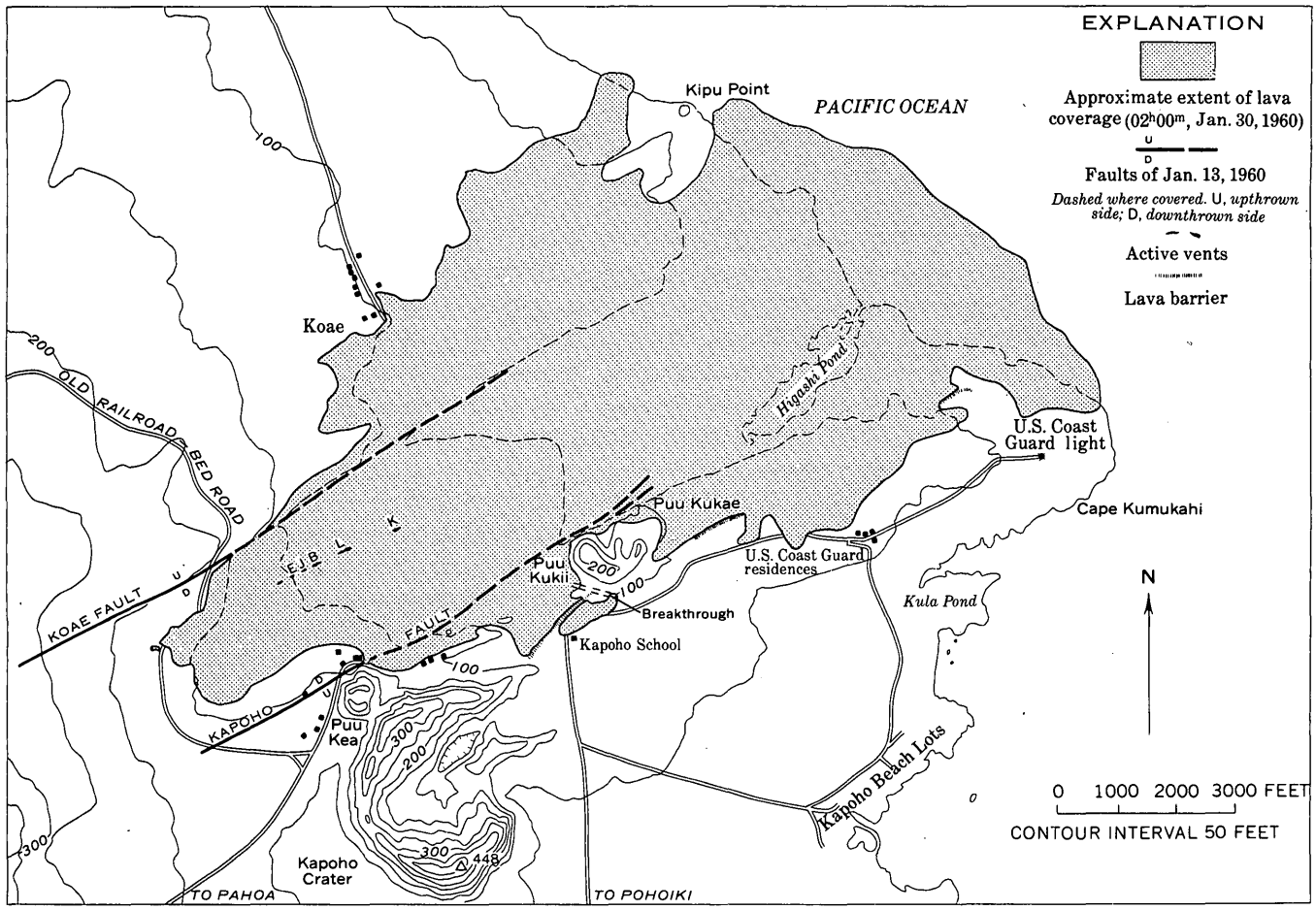


FIGURE 65.—Map of eruption area at 02h00m, January 30, 1960.

early cooler lavas contained abundant phenocrysts of clinopyroxene and plagiocase, and olivine was scarce or entirely absent. With the increase in temperature, olivine suddenly appeared, and within a few days it became the principal phenocryst of the lavas.

Throughout the day there was little change in the activity. At midnight the main fountain (B) was still predominant. Spattering was slowly reviving at E, and occasionally a spray of lava emerged from the vent at L. The easternmost vent (K), which had remained quiet for more than a day, was apparently dead.

FEBRUARY 1, 1960

At 00h45m, February 1, the main fountain (B) briefly surged upward and threw clots of spatter more than 1,300 feet into the air. It subsided quickly, however, and the orifice appeared to be wider than before. About 03h00m a short rift opened halfway up the west flank of the spatter cone in line with the old gushing vent at its base. For almost an hour a fountain spurted to heights of 600 feet from this vent, but by 04h45m only a sluggish flow issued from its glowing mouth. Several small flows were also pulsing over the lip of the spatter cone; these were fed by lava welling up within the liquid-filled caldron over the vent. By 11h00m an occasional dribble of lava still poured over the lip of the spatter cone, but fountaining from B and L was greatly reduced. The gas-cinder jet at J had revived by this time and was blowing a plume of fine particles 200 to 300 feet into the air.

West of the Coast Guard residence area, flow movement increased rapidly during the morning; some local 3- to 4-foot-high aa fronts were advancing as fast as 10 feet per minute. East of the residence area, a small slowly advancing tongue of pahoehoe cut the lighthouse road at 13h30m (fig. 66).

In the morning the main flow emerging from the cone area continued to feed the lake of lava over Higashi Pond. At 09h00m flows west of the Coast Guard residences were rejuvenated, and by 11h15m

lava was entering the shallow topographic trough leading southeastward down the south flank of the Kumukaki ridge toward Kula Pond. East of the residence area lava was also beginning to press southward, and small pahoehoe tongues were advancing along a front 2,000 feet wide less than 500 feet north of the lighthouse road. Elsewhere around the margin of the lava field no flows were moving. Fountaining at B and L continued through the afternoon and into the night.

Observation of the Kumukahi region from the air at 14^{h}00^m, revealed that a great stream of lava was pouring across the drowned barrier between Puu Kukae and the Coast Guard residence area (fig. 66). This vigorous stream was pouring into the trough that led to Kula Pond, and the rapidly moving aa front it fed had advanced to within 1,000 feet of the pond. Nearer the lighthouse, the flows were still sluggish, and only the one observed earlier in the morning had as yet crossed the road. On Puu Kukii, fresh lava was again emerging from the tunnel through the southwest flank of the cone and was flowing over and around the cooled flows of January 28. This renewed movement of lava through the cone disrupted more ground above its subterranean channel, and by late afternoon some of the small fault blocks had been thrust upward another 20 feet (fig. 67). Rejuvenated flows north of the third Kukii-Kapoho barrier were filling the remaining low ground east of Kapoho Crater.

Late in the afternoon only the main vent and the gas-cinder vent were active. By 17^{h}15^m the fountain

FIGURE 66.—February 1, 1960. Aerial view northeastward showing flows encircling the U.S. Coast Guard residence area. Flows have cut road leading to lighthouse out of picture on the right.

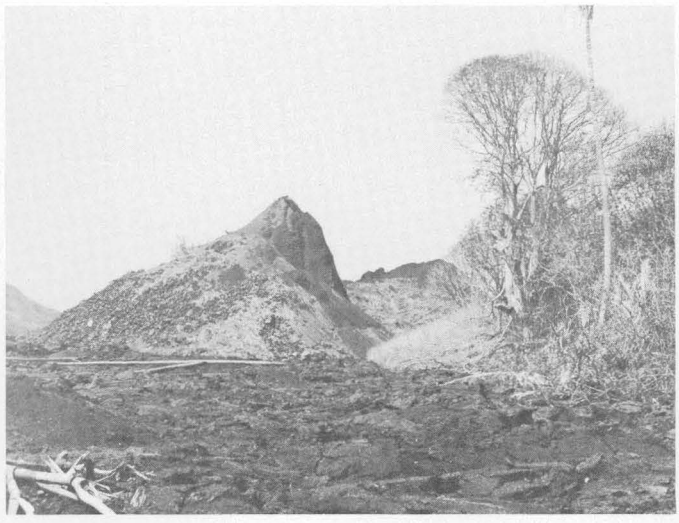


FIGURE 67.—Small fault blocks pushed upward and tilted by shallow intrusion of lava through old cinder cone (Puu Kukii) during the period January 28 through February 1. Photograph was taken March 23, 1960.

from the main vent was again up to 600 to 800 feet and was once more producing abundant pumice.

Flow activity continued to increase west of the Coast Guard residence area through the afternoon. At 17^{h}45^m the flowfront on the access road was only 150 feet west of the first house; just south of the road several isolated aa flows had merged into a single massive front advancing toward Kula Pond. When this front reached the steep slope in the trough leading to the pond shortly before 20^{h}00^m, the lava surged forward in a massive aa river. On some of the steeper slopes the flowfront advanced at speeds of 400 to 600 feet per minute (5 to 7 miles per hour), and bowled over large coconut trees like matchsticks. At 20^{h}35^m the flow crossed the last road into the Coast Guard area (from the beach lots), and by 22^{h}00^m it reached Kula Pond, where its extremely rapid advance was temporarily halted.

At 23^{h}00^m the main fountain was again low and there was only minor activity at the spatter and gas-cinder vents. The main lava river from the cone continued to pour into the crusted-over lake east of Puu Kukae, which in turn fed the flow into Kula Pond.

FEBRUARY 2, 1960

During the early morning hours of February 2 the vent at L revived, and by 08^{h}00^m it was producing the largest fountain in the cone group. Fountaining at B was minor; a thin plume of cinder-charged gas spewed upward from J, and an occasional spray of spatter was thrown out of the cone at E.

The first building in the Coast Guard residence area was overwhelmed by lava about 08^{h}00^m and the others were destroyed in quick succession. Farther south, the rapidly flowing river continued to pour into Kula Pond, where it fed an aa flowfront 10 feet high and 500 feet wide that slowly advanced seaward across the pond behind a dense curtain of steam. On the shore opposite the advancing lava, the water was so hot that we could not hold our hands in it for more than a few seconds; yet, great numbers of fish, including eels, were still alive and many were swimming in the near-boiling water at the very edge of the flow. They swam frantically about with head and back above water in a futile effort to escape the steaming waters.

Pahoehoe flows began to ooze from the cold aa flowfront in the Kapoho School area during mid-morning, and by 11^{h}00^m the entire flowfront from the barrier to Puu Kukae was advancing. Since lava had not yet actually poured down over the third Kukii-Kapoho barrier that separated the isolated "schoolhouse" flow from the main lava field, this new material must have found its way through the injected zone beneath the flank of Puu Kukii.

At 10^{h}48^m the fountain at L was playing to heights of 500 feet (fig. 68, top photograph), but by noon it had diminished till it only occasionally surged above the rim of the cone. Fountains at the main vent were also low, and the minor activity at J and E remained unchanged. Outflow from the fountains at this time formed a broad river, up to 500 feet wide, that continued to pour into the immense ponding area northeast of Puu Kukae. One small lobe of the river extended toward the Puu Kukii area, and out of the pond farther east emerged a narrow river feeding the aa flows in the Kula Pond area. The spatter cone was again very prominent, having been rebuilt since the collapse on the night of 27 January. Its rim stood about 370 feet above sea level or 270 feet above its base.

In the Kula Pond area, the massive aa flow split during the day—one tongue continued toward the ocean, and the other turned southeastward across the low peninsula separating Kula Pond from the next bay south. About 14^{h}00^m the southern branch, advancing about 100 feet per hour, entered the bay and began to move across the shoal waters toward the nearest houses in the Kapoho Beach Lots area less than 1,500 feet away (fig. 69).

By 16^{h}35^m vents B and L were both extruding an immense volume of very fluid lava with little fountaining (fig. 68, bottom photograph). The river pouring from the boiling fountains widened to about 300 feet after leaving the pumice-loaf area and then widened even more as it emptied into the ponding area north of Puu Kukii. Above the buried Koae road, the river was lower than its banks; downstream, both in the river and ponding area, the lava rose above the surrounding flows and was confined only by fragile levees of thin congealed pahoehoe overflows. At 19^{h}15^m the same flow pattern remained.

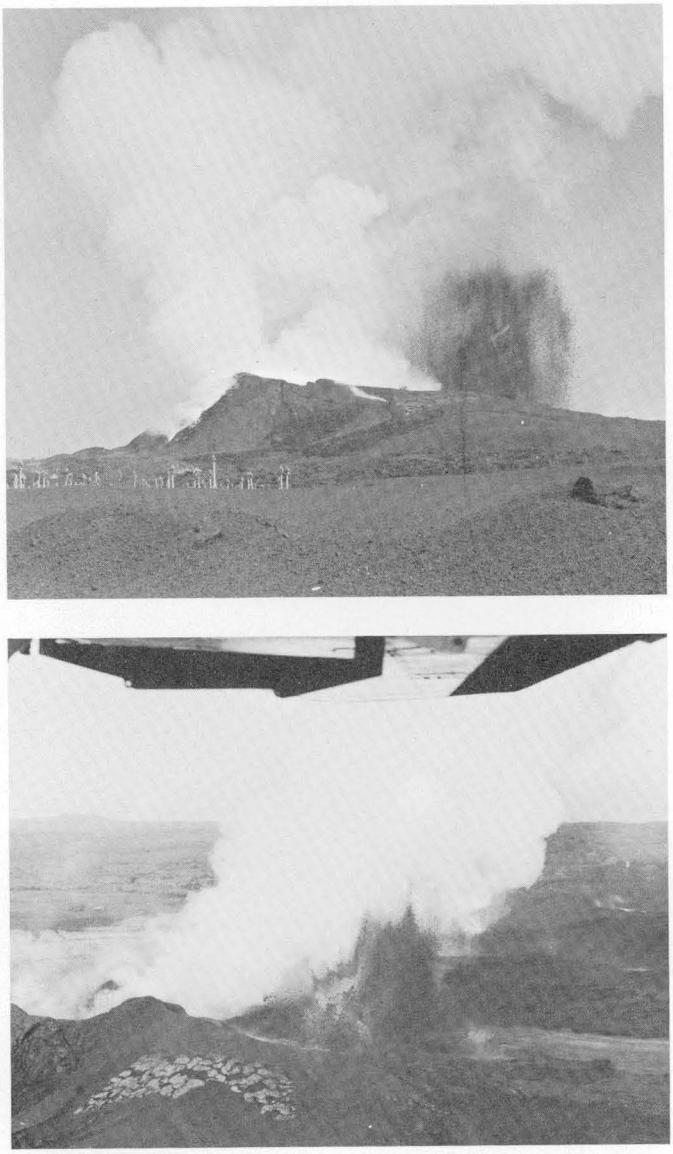


FIGURE 68.—Fountains and cone. *Top:* February 2, 1960. View northeastward from old railroad-bed road. Large fountain plays from vent L. Small fountain from main vent is barely visible above rim of cone, and spatter vent emits copious fume. *Bottom:* February 2, 1960. Aerial view northeastward showing large fountain playing from main vent (center) and the low boiling emission of lava from vent L (right). Note the patchwork pattern of congealed spatter on cone, formed by differential downslope movement.

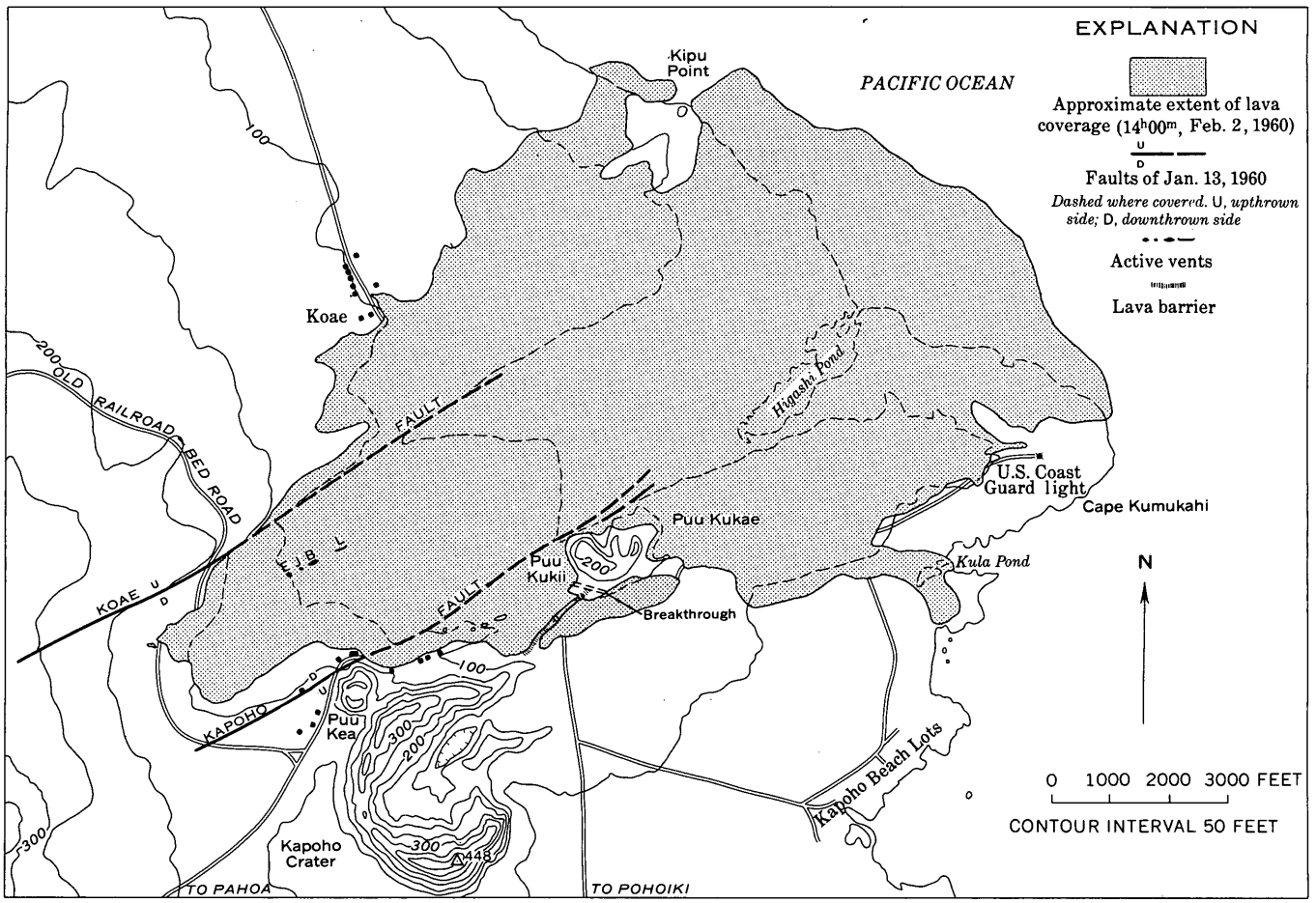


FIGURE 69.—Map of eruption area at 14h00m, February 2, 1960.

From Puu Kukii, which had not yet been completely encircled by lava, flows were seen entering the sea along an almost continuous front from Kipu Point to just north of the lighthouse and in the area north of the Kapoho Beach Lots.

North of the Kapoho Beach Lots, the two aa flows which had separated earlier over Kula Pond appeared to have rejoined by 23h55m, forming a single flow unit that extended to the surf zone about 1,000 feet offshore. The part of the flow that was advancing most rapidly was moving southeastward toward the open ocean. At the same time, however, the flow was broadening and creeping southward along the shore and was now less than 1,000 feet from the nearest houses in the Kapoho Beach Lots.

FEBRUARY 3, 1960

Early in the morning on February 3 the fountain at L was again high, sending up a candleflamelike plume of pumice. B was low but was still producing great quantities of lava. At the spatter vent (E) activity was mostly hidden within the cone, but the glow brightly illuminated the fume cloud that rose above it.

Between 06h35m and 07h35m aerial reconnaissance revealed that a large flow was entering the sea north of the lighthouse and that a second smaller flow was pouring into the shoal waters north of the Kapoho Beach Lots. The main flow could be traced an estimated half a mile beyond the shore by the narrow zone of turbulent upwelling water above it. In the Kapoho Beach Lots area the southward advancing flow was more than 1,500 feet wide and extended from the shore to beyond the breaker zone at the edge of the shoal waters.

Throughout the day flows remained strong in the Kapoho Beach Lots area and along the shore north of Cape Kumukahi. There was also minor movement in the flowfront south of Puu Kukae, but elsewhere around the periphery of the lava field there was no activity. The fountaining changed very little during the day; the vent at L generally predominated. In

the afternoon a small flow began to issue from another crack in the west flank of the spatter cone, and by 19h00m the crack was gushing lava profusely.

About 18h30m a large part of the main cone or part of the channel wall broke loose and partially clogged the outflow system at the upper end of the lava pond and caused the channel to overflow. One overflow headed toward Koae and another headed toward Puu Kukii. After this surface overflow, flow movement increased along the entire front from Kapoho Crater to east of Puu Kukae.

FEBRUARY 4, 1960

All vents except the gas-cinder jet at J remained active through the night. Occasionally a loud report emanated from the main vent, and an increase in fountain heights usually followed. At 02h05m, February 4, the gusher on the flank of the spatter cone had diminished to a dribble; yet, liquid lava continued to splash in the pool inside the cone above it.

By daybreak the Kula Pond flow was in the Kapoho Beach Lots area and had destroyed about six houses during the night. At 08h00m, however, the advance had practically stopped; only a few pahoehoe tongues were still creeping forward. Also, during the night flows had finally encircled the twin cones of Puu Kukii and Puu Kukae and had partially covered the Kapoho cemetery; between 03h45m and dawn lava advanced about 70 feet southward along the Pohoiki road.

A small aa flow oozed from a break through the north side of the dissected pumice loaf during the morning. When first observed at 11h30m it was still advancing slowly northward over the pumice-covered plain several hundred feet from its source.

Late in the afternoon only the main fountain, which was shooting to heights of 100 to 200 feet, and the spatter vent were active. Lava from the fountain flowed north toward Koae—this was probably in response to the clogging of the old channel—then it curved south toward Puu Kukae into the ponding area.

FEBRUARY 5, 1960

The southward advance of the flows through the Kapoho Beach Lots had stopped by 03h50m, February 5. However, lava must have continued to push seaward because at 04h00m the lava stream in the narrow defile above Kula Pond was still moving. Where the stream crossed the former south access road to the Coast Guard station it was approximately 200 feet wide and was flowing at an average speed of 2 feet per minute. Its surface was a jumbled mass of cooled blocks—some were the size of automobiles—that were continually readjusting and shifting their positions as the stream carried them along. Sharp vertical walls, continually plastered and reformed by red-hot pasty lava conspicuously marked the edge of the lava stream.

During the clear bright morning a magnificent steam cloud rose almost vertically above the area where the main flow entered the sea north of Cape Kumukahi. From a distance of 6.3 miles and at an altitude of 643 feet, the top of the billowing cloud was 23° above the horizon—a height of almost 15,000 feet.

At noon the fountain at L began to increase in size while the fountain at B diminished. Copious fume with an occasional splash of liquid rose from the spatter vent, but the gas-cinder vent remained quiet. On land, flow advance was restricted to a mile-long zone extending eastward from Kapoho and possibly to the inaccessible area near Cape Kumukahi (fig. 70). North of the third barrier between Kapoho Crater and Puu Kukii, however, the flows continued to increase in thickness and finally rose far above, and covered all but the very ends of, the barrier.

Shortly before 21h00m, after a period of subdued activity in the vents at B and L, the long-dead rift west of the spatter cone reopened (fig. 71). Along a line extending about 700 feet from the base of the spatter cone to the east end of the old vents at H (fig. 43), at least 18 small fountains spurted from the new rift in a short curtain of fire. By 22h40m the new fountains, all between 25 and 50 feet high, had developed to a maximum, and within minutes they began to subside slowly. At the same time activity at the old vents began to decrease, and by 23h25m only an occasional shower of spatter was being thrown out of the vent at L.

FEBRUARY 6, 1960

Very fluid lava from the curtain-of-fire vents quickly formed a small pond around the erupting rift, and some lava spread northward to the old railroad-bed road. At 00h15m, February 6, only a few vents along a 300-foot section of the new rift were still fountaining, and by 03h00m activity was restricted to a 100-foot-long low boiling area. Meanwhile the vent at L had died completely and the old main vent (B), for the first time during the eruption, evolved into a gas producer. This activity resembled a giant roman candle; gases roared from the vent and carried incandescent blocks that had been ripped from the walls of the conduit to heights of 1,700 feet, where they lazily reversed direction and plummeted back onto the cone. During the next few hours activity at the main vent alternated between this

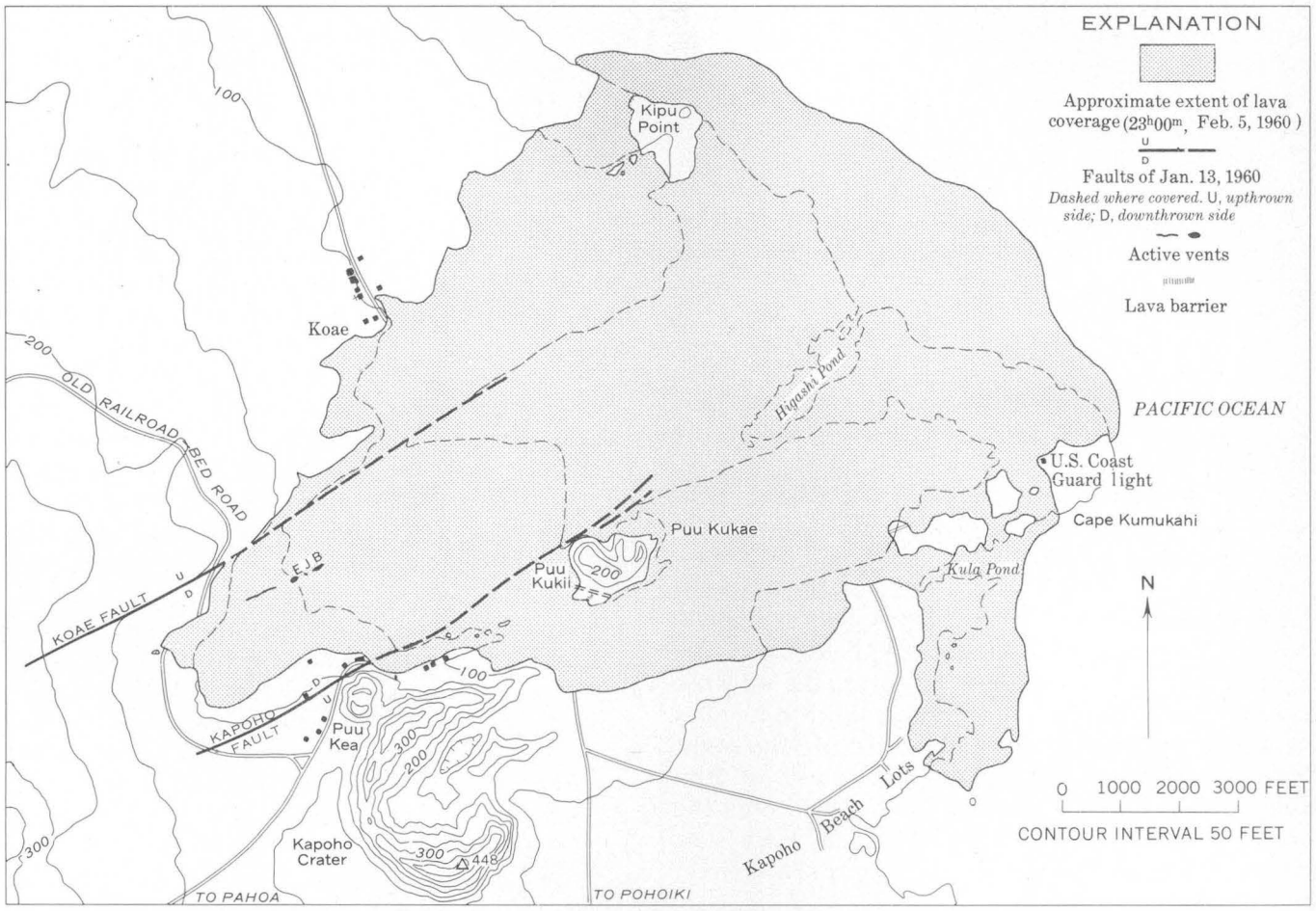


FIGURE 70.—Map of eruption area at 23h00m, February 5, 1960.

almost explosive expulsion of gas and cinders and quiet fuming.

At 05h15m the vents along the new rift were completely quiet, and by 07h05m both the main vent and spatter vent continued only feebly. After weeks of constant noise—whooshing, booming, roaring, and clattering volcanic sounds—the quiet was strange and almost ominous.

FIGURE 71.—February 5, 1960, 22h30m. Renewed outbreak west of the spatter cone (left) along original fissure. Very fluid lava pours northward toward the old railroad-bed road.

As we surveyed the eruption area from the top of Puu Kea at 10h45m, and later from the air, it was apparent that the vents had ceased extruding lava. By looking directly into the vents from the plane, an occasional fling of spatter would be seen rising from the main vent, and in the spatter cone lava flowed into the crater from a hole on the east side and drained away through a hole on the west side. Between the main and spatter vents a bright orange hole, probably over the gas-cinder jet, was spewing out a small amount of black ash. During a later flight, at 16h00m, there was still no visible lava outflow from the vent area. The vent at J was predominant, shooting a vertical jet of ash with occasional spatter as high as 100 feet. A moderate amount of lava was still flowing into the sea north of Cape Kumukahi, and the broad front south of Puu Kukii and Puu Kukae continued to advance slowly.

Through the rest of the afternoon and evening the vent at J continued to jet except during short periods of explosive detonations from within the vent. Detonations usually began when the jetting weakened, built up to a maximum while the jetting stopped altogether, and then decreased as jetting revived.

FEBRUARY 7, 1960

From February 7 until February 20, when all activity except minor fuming ceased entirely, there were only minor changes in the activity at the eruptive vents. Moreover, only twice during this period did appreciable lava flow from the vents. Weak flows that drained into the ocean and oozed forward along the south edge of the lava field were undoubtedly supplied by lava draining from beneath the high central part of the field north and northeast of Puu Kukii.

Early in the morning of February 7 the old main vent (B) revived weakly and threw out spatter sporadically. The strongest activity was at J, however, where a particle-charged gas jet continued to spew from the vent. In the spatter cone a pool of liquid lava boiled and splashed throughout the day.

FEBRUARY 8, 1960

A small vent opened about half way up the steep west flank of the spatter cone during the night, and by 01^h45^m, February 8, a few short flows and small bursts of spatter were issuing from it. The vent inside the main spatter cone became active at this time also, and some of its bursts flung material to heights of 500 feet.

At 02^h15^m, during a lull in the effusive activity, burning gases were first observed rising from the small new vent on the west flank of the spatter cone. Like those seen over the dying vents at Kilauea Iki, the gases burned with a pale-yellowish-blue flame which flickered to heights of 20 or 30 feet.

During the day and evening activity was much feebler than during the morning and was restricted to the spatter vent and the small vent on the side of the spatter cone. After dark, flames were once more visible, and the glowing interior of the spatter cone brightly illuminated the dense fume rising above it. Lava was still oozing forward in a few areas along the ocean front, but on land all flow advance had stopped.

FEBRUARY 9, 1960

There was very little change in activity throughout February 9. The spatter vent (E) continued to throw liquid lava 50 to 100 feet above the lip of the cone, and the small vent on its flank still emitted flame (visible only at night), which was extinguished occasionally for short periods of time when it was supplanted by copious emission of dense fume.

From the air at 14^h00^m, lava was observed flowing sluggishly into the sea at four small areas from Cape Kumukahi northward to beyond Kipu Point. At each area a number of very small streams, generally branching from one larger stream, constituted the active flowfront.

FEBRUARY 10, 1960

The main vent (B) began ejecting spatter feebly about 01^h00^m, February 10, and, like the spatter vent (E) and the small flaming vent on the side of the spatter cone, it continued with little change through the day. By daybreak, a small rampart, built by the sporadic emission of spatter and by small overflows from the flaming vent, clung to the west flank of the spatter cone.

At 16^h45^m billowing black clouds of ash boiled upward from the elongate crater in the spatter cone. This emission of ash lasted for only a few minutes and was followed shortly by loud detonations from the main vent, which continued intermittently until at least 23^h20^m. At about the same time the vent at J revived and began spewing out a small plume of gas and fine rock particles.

FEBRUARY 11, 1960

During the morning of February 11 and the early part of the day, the vents that were active the previous night continued their activity, but with diminishing vigor. About 14^h00^m a furious discharge of gas began to ream out the conduit of the main vent (B) and formed a plume of black ash with filaments of incandescent particles and larger glowing clots that pulsed to heights of 700 feet. At 16^h30^m, as this apparently anhydrous gas discharge waned, white steam began to spew from the vent with almost explosive violence. At vent J, black ash clouds billowed upward about 18^h30^m, and for the next 12 hours these contrasting phreatic discharges continued from the two vents.

FEBRUARY 12, 1960

Shortly before 08^h00^m, February 12, the main vent (B) stopped its violent gas discharge and a steady flow of very fluid lava began to pour from it down the old river channel toward the east. When the low boiling fountain producing this flow stopped abruptly at 08^h25^m, the lava level in the vent dropped and explosive bursts recommenced. At J the erratic gas-cinder discharge continued, unaffected by changes at B.

For 2 days activity in the crater of the spatter cone had gradually decreased until only dense fume

emanated from its interior. The smaller vent on the west flanks of the spatter cone was also quiet; no flames had been observed since the previous night.

FEBRUARY 13, 1960

By 16^h15^m, February 13, the main vent at B was completely quiet. At J, however, a vigorous gas jet was spewing a thin plume of cinder to heights of 300 to 500 feet and was rapidly building a small cone around the vent. From the air 1,000 feet above the cone, the main vent was no longer visible; apparently it had been covered by ejecta from J. By looking directly down into the mouth of the active vent, no fluid lava could be observed; the cinder-charged gas burst from a very small aperture deep in the glowing interior of the cone.

Except for a few sluggish streams of lava that still dribbled into the ocean north of Cape Kumukahi, the entire flow looked cold and dead. A few wisps of blue fume rose from cracks in the old flow channel and from the pumice loaf, but not even the flow of the previous day showed any movement or incandescence.

During the night, the jet occasionally sprayed cinder as high as 1,100 feet; at other times it was barely visible above the lip of its cone. During some of the higher bursts, the impelling gas column seemed to rotate as it rose; this gave the jet a spiral form.

FEBRUARY 14, 1960

The cinder jet spewed upward with little change throughout February 14.

FEBRUARY 15, 1960

With the continued emission of ash, cinder, and blocks from the vent at J, the small steep-sided cone developed rapidly. By midday on February 15, it towered above the old spatter cone on the west and the cinder pumice loaf extending toward the east. At 15^h30^m a thin spray of incandescent fragments accompanied by a loud hissing roar was still pulsing to heights of 1,000 feet.

FEBRUARY 16, 1960

Activity at J continued unchanged. Rain during the night and the morning of February 16 transformed the new lava field into a vast steaming plain. During the afternoon a moderate ash cloud drifting from the top of the high jet over J (fig. 72) deposited a thin film of fine-grained vitric and lithic ash west and southwest of the vent. At 20^h00^m on the top of Puu Kea, a dense low-hanging fume cloud, probably originating from the spatter vent (E), accompanied this light rain of ash. The fume had a strong hydrogen sulfide odor in contrast to the dominant sulfur dioxide odor detected earlier during the eruption. This fume irritated the mouth and throat but was not acrid to the taste.

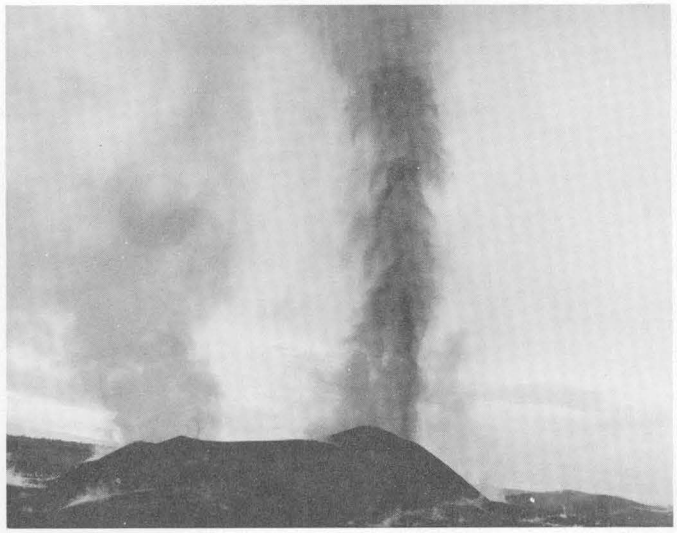


FIGURE 72.—February 16, 1960. Gas-cinder jet shooting to 1,000 feet from vent J as viewed from Puu Kea. Spatter vent E (left) emits strong fume cloud. Steam rising from flows and cone is from recent heavy rain.

FEBRUARY 17, 1960

Activity at vent J on February 17 remained virtually unchanged from the preceding several days, and the cone continued to grow. Measurements during the afternoon indicated that the top of the cinder cone was about 450 feet above sea level—this was more than 50 feet above its base on the old cinder-pumice cone. Impact craters formed by the larger blocks and clots of cinder expelled from the vent (J) dotted the ash-cinder covered slopes of the new cone and the broad pumice flank of the old cone (fig. 73, top photograph). Many of these craters, some of which were as much as 5 feet in diameter, still contained the blocks that formed them; in others the blocks had disintegrated on impact or had buried themselves in the soft surface (fig. 73, bottom photograph).

FEBRUARY 18, 1960

On February 18 the vent at J still continued to pour out a steady stream of gas and rock particles. From the air at 14^h30^m two very small sluggish streams were observed entering the ocean, but elsewhere only a few wisps of bluish fume and a minor amount of steam rose from the cooling lava flows.

At 20^h00^m the gas jet gradually began to weaken, and soon it was very low. Shortly thereafter liquid lava welled up in the crater of the spatter cone, and

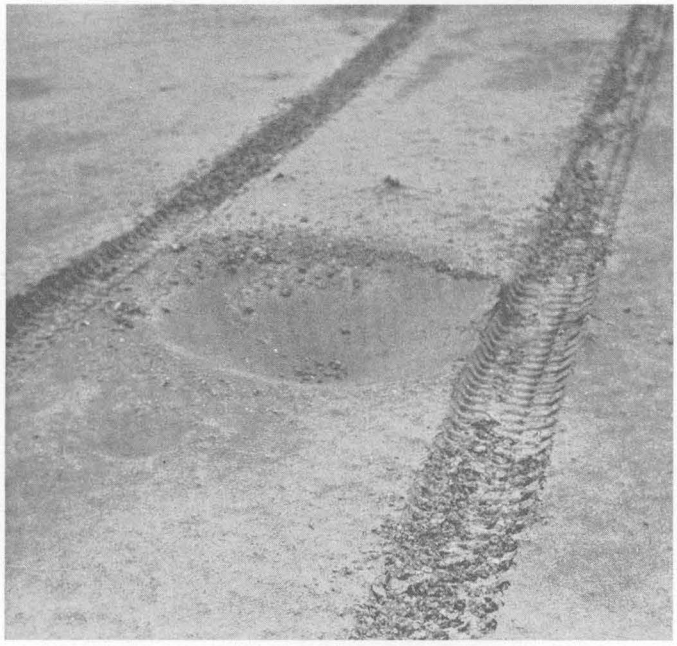


FIGURE 73.—Impact craters. *Top:* View north from top of new cone showing the impact-scarred pumice and cinder blanket. Old railroad-bed road crosses Koae fault scarp in background. *Bottom:* Closeup view of large impact crater. Block that formed the crater disintegrated when it struck the ground.

about 22^h00^m very fluid lava poured out over the cone's northwest lip (fig. 74). The flow was voluminous but brief. The 70-foot-wide river on the flank of the cone spread rapidly over the ash-pumice field at its base and within minutes reached the old railroad-bed road north of the vent.

FEBRUARY 19, 1960

The February 18 flow was the last gasp of the dying eruption. Minor intermittent bursts of gas and cinder continued to discharge from vent J through the night and the morning of February 19, but by 14^h00^m only a gentle billowing fume cloud rose from the vents. The eruption was over.

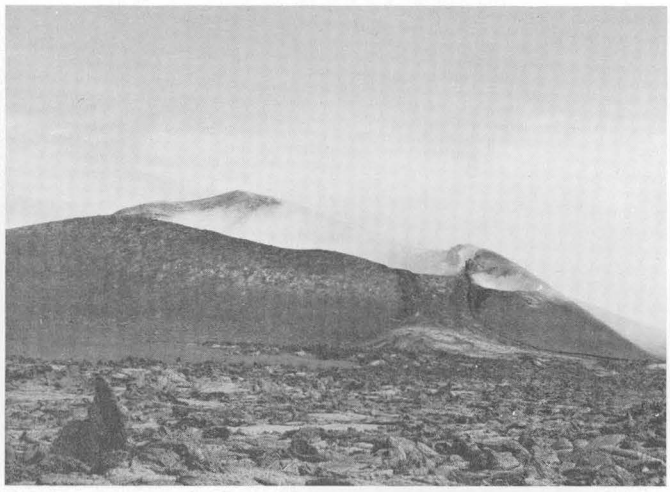


FIGURE 74.—February 20, 1960. Flow of February 18 that poured out over lip of spatter cone. Minor fume still emanates from the now quiet vents.

The black lava flows covered 2,510 acres, including about 500 acres of new land built beyond the original shoreline (fig. 75). North of Cape Kumukahi, once the easternmost tip of the Island of Hawaii, the new land extended the island a few hundred feet still farther eastward. A conservative estimate of the volume of lava extruded, based on areal coverage and thickness and including the lava beyond the new shoreline, is about 160 million cubic yards. The widespread pumice blanket, exclusive of the area overlain by new lava, covered a total of 2,750 acres to a depth of 0.1 foot or more, including 820 acres with more than 1 foot of pumice and 55 acres with more than 5 feet of pumice (fig. 75). This pumice plus the huge pyroclastic mass of the cone and pumice loaf constitute an estimated additional 10 million cubic yards of lighter effusive material ranging in density from 0.08 to 2.0 grams per cubic centimeter.

SUMMIT COLLAPSE

On January 17, 1960, 4 days after the beginning of the flank eruption, magma in the great reservoir beneath Kilauea caldera, which had refilled slowly during the years following the 1955 eruption and which had fed the multiphased summit eruption in Kilauea Iki, began to drain rapidly away through the east rift zone toward Kapoho. Thus began the dramatic, and at times frightening, subsidence of the Kilauea dome which was climaxed on February 7 with a major collapse of the floor of Halemaumau

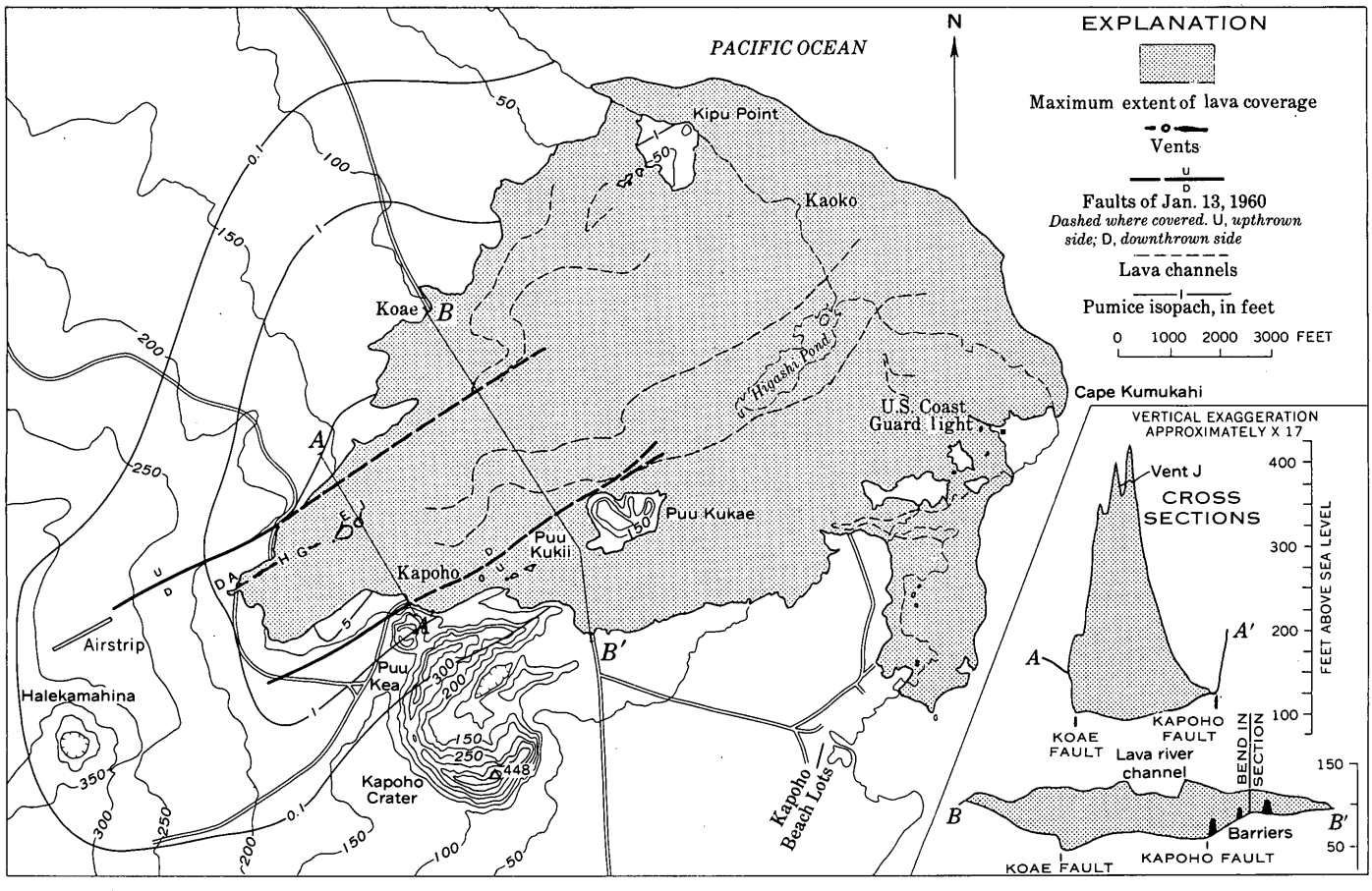


FIGURE 75.—Map and cross sections of the eruption area showing maximum extent of lava coverage and isopachs of the pumice blanket.

(fig. 76). Very feeble harmonic tremor had continued to emanate from beneath the caldera after the Kilauea Iki eruption ceased, and as the escape of lava and consequent subsidence of the summit of the volcano intensified, the tremor steadily increased. By January 23 small shallow earthquakes announced the beginning of failure in the rock enclosing the deflating reservoir. Within a few days the number and intensity of earthquakes increased, and by the end of January the seismograph on the caldera floor was recording thousands of quakes a day. Hundreds of these quakes were strong enough to be felt and apprehension mounted as the swarm intensified day by day. Old peripheral cracks around Halemaumau and Kilauea caldera widened, and many new cracks developed. Avalanches from the precipitous walls of Halemaumau became very frequent, and on February 5 new steaming areas were observed in a 200-foot-wide ring encircling Halemaumau's 450-foot-deep floor.

FEBRUARY 7, 1960

Park Ranger R. T. Haugen, on patrol around the caldera on the night of February 6–7 to warn of any dangerous change that might develop, reported a night of unnerving solitary vigil. Through the night and early morning the entire caldera region shuddered frequently as earthquakes rent the roof over the shrinking magma reservoir. Near the south rim of Halemaumau the ground was in almost incessant motion. From the dark interior of the pit (moonset was approximately 01^h40^m) strange booming sounds accompanied the constant clatter of rocks raveling off the walls and the occasional jetlike roar of an avalanche spilling onto the floor.

By daybreak, collapse of the 140-acre nearly flat floor of Halemaumau was already in progress. Around the entire floor, 100 to 300 feet in from the base of the crater wall, a 20- to 30-foot scarp, formed during the preceding hours of darkness, marked the outer limit of a broad saucer-shaped

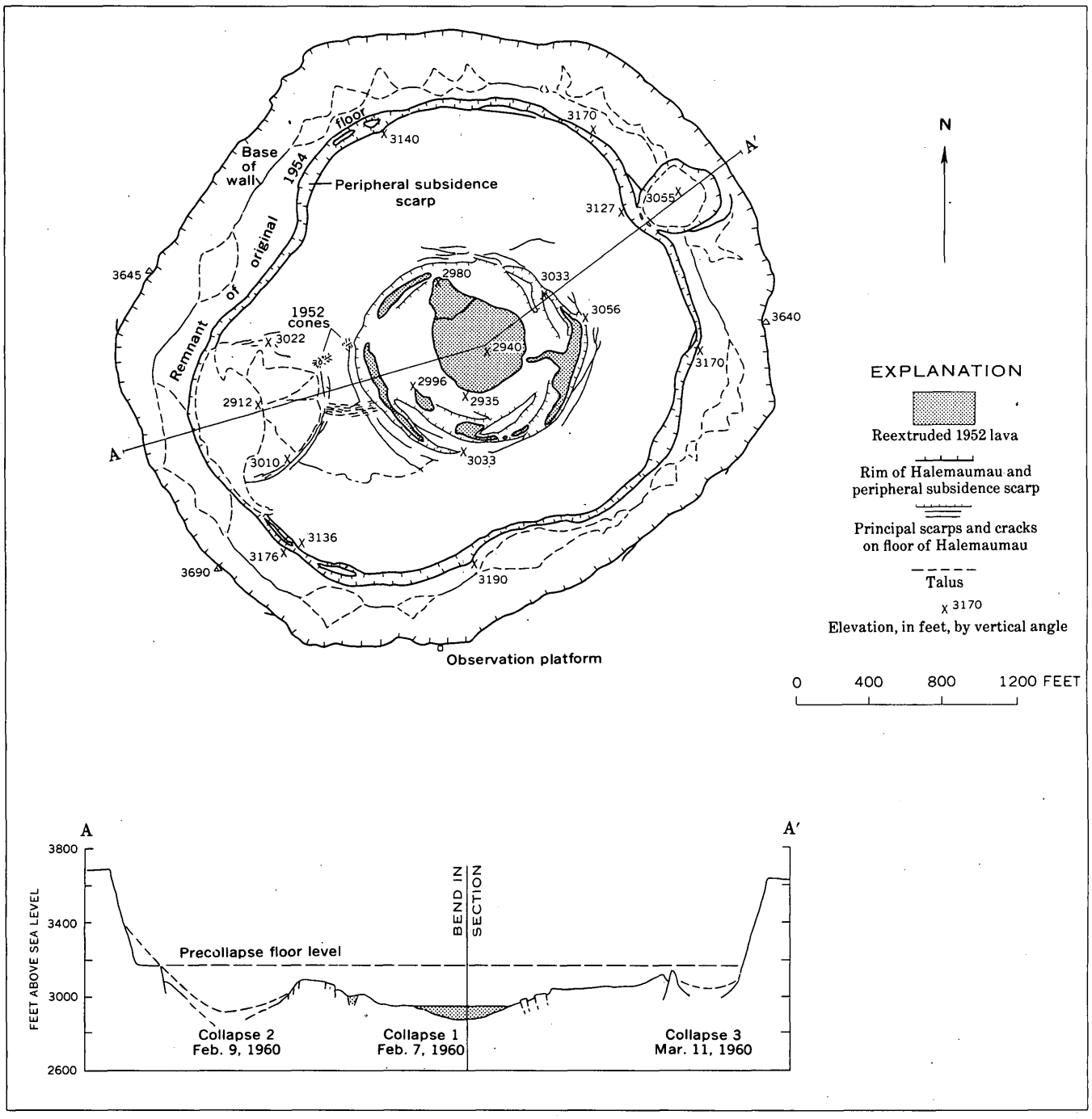


FIGURE 76.—Map and cross section of Halemaumau showing principal features of the 1960 collapse.

depression. Unseen cracks had evidently opened beneath the 300-foot-deep lava lake erupted into Halemaumau in 1952, and the still-liquid lava in its core had drained away (fig. 77).

As we watched, the floor continued to sink; great quantities of steam rose from new cracks on its concave floor, and clouds of dust rolled upward from avalanches along the main peripheral scarp. By 10^h00^m displacement along the scarp was as much as 40 feet, and the center of the floor had sunk much lower. The elevated apron around the sinking floor sagged inward as the center sank deeper, and many cracks that were formed during the earliest stages of subsidence were reshaped by the resulting com-

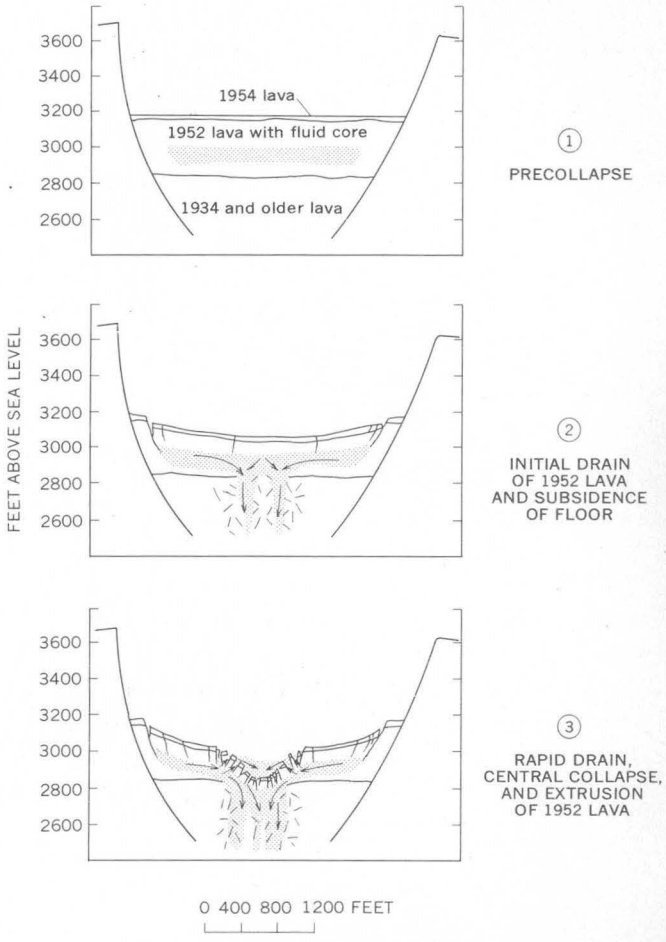


FIGURE 77.—Hypothetical east-west sections through Halemaumau showing development of principal collapse features.

pressional forces into prominent pressure ridges.

By 11^h15^m, when a transit was set up on the rim of the crater to follow the progress of the collapse, the lowest part of the floor had subsided about 100 feet; in the next half hour it sank an additional 13 feet. Then at 11^h51^m, with a mounting roar and a voluminous rising cloud of steam and rock dust, a circular area 1,000 feet in diameter in the deep central part of the crater floor suddenly began to fall as though a gigantic plug had been pulled deep within the crater. In less than 9 minutes the huge pit collapsed more than 200 feet, and at 12^h00^m viscous lava began to pour from a ring fracture along the northwest quadrant of the pit's rim. As the floor of Halemaumau continued to subside, more and more lava was squeezed from beneath the crust of the 1952 lake and into the new pit. By 12^h10^m a broad stream flowed slowly into the collapse from the northwest fracture, a smaller stream cascaded down the rubbly east side of the pit, and a number of small ponds accumulated in moats formed by the collapse along the south and west rim of the pit (fig. 78).

By 12^h15^m, the bottom of the central pit had subsided approximately 314 feet below the level prior to collapse. Through the afternoon the pit filled slowly with viscous gas-free lava, and by 17^h10^m a small pond $3\frac{1}{2}$ acres in area and 60 feet deep had

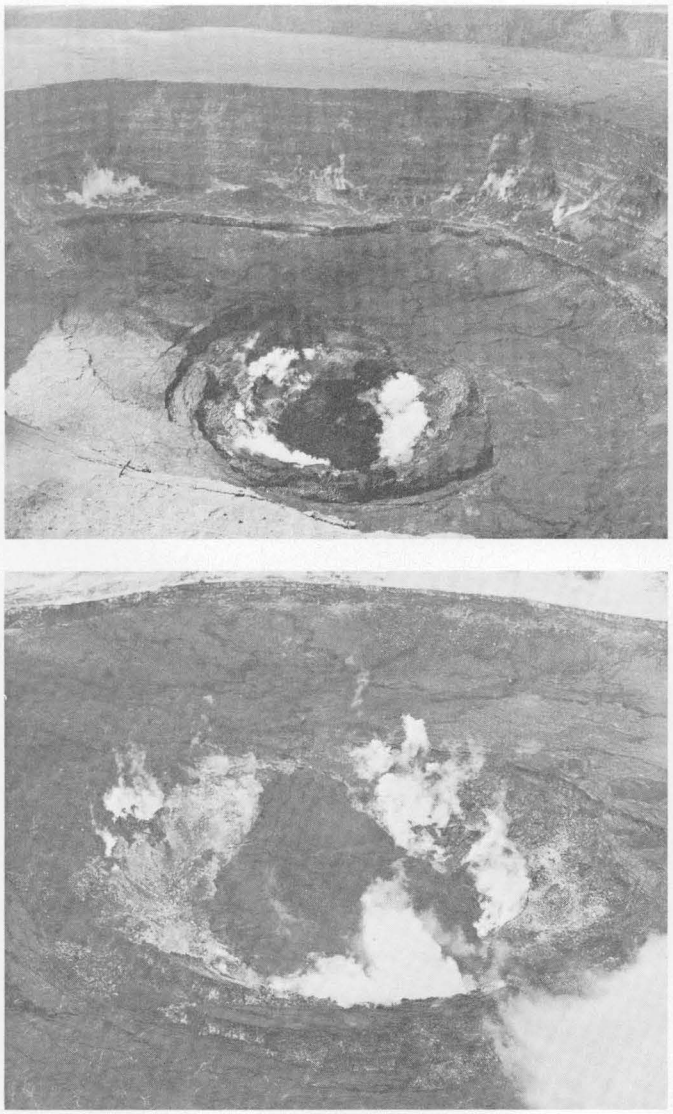


FIGURE 78.—Early collapse features in Halemaumau. *Top:* February 9, 1960. Aerial view northwestward across Halemaumau. Scarp encircling floor of crater marks outer limit of saucer-shaped subsidence. Steam rises from periphery of central collapse pit, partially filled with reextruded 1952 lava. Note wormlike pressure ridges crisscrossing floor. Diameter of central collapse pit is about 1,000 feet. *Bottom:* February 13, 1960. View of central collapse pit from south rim of Halemaumau. The small dark lava pond merges imperceptibly with the steep lava delta on far wall of pit.

formed (fig. 78). At night many incandescent spots, but no fluid lava, were observed in the 40- to 80-foot deep crack at the foot of the scarp that encircled the sunken floor of the crater.

FEBRUARY 8, 1960

Small oozes of lava continued to bleed from the walls of the inner collapse pit during the night. The principal activity was along the northwest wall where lava first began to spill into the pit, and by the morning of February 8 a small steep lava delta had formed on the side of the pit below the extrusion orifice.

Although local earthquakes continued to shake the summit area, their number and intensity decreased considerably after the collapse. Harmonic tremor, which had increased to a maximum during the draining of the 1952 lake, also diminished greatly after the collapse.

FEBRUARY 9, 1960

At 08^h20^m, February 9, three small rivulets of lava continued to ooze down the lava delta on the northwest slope of the inner pit. The streams appeared to be extremely viscous, almost like toothpaste squeezed from a tube, and they all congealed before reaching the small pond deep in the bottom of the pit. When Halemaumau was inspected from the air during the afternoon only one small tongue of lava was still moving (fig. 78, top photograph).

Concurrent with a strong earthquake at 17^h28^m, a second smaller collapse pit formed in the sunken floor of Halemaumau along its margin southwest of the central collapse (fig. 79). (Also see fig. 76.) As with the central pit two days earlier, the collapse was very rapid; nearly continuous slides, which generated dense clouds of dust, "poured" into the new 700-foot-diameter pit for almost 10 minutes. At the time of the collapse, a few short-lived fresh lava oozes appeared around the closest rim of the central pit, but none was squeezed into the new southwest pit. By 18^h25^m all was relatively quiet; a few small rockfalls clattered down the walls of Halemaumau, and a number of incandescent spots glowed in the large crack around the main sunken floor.

FEBRUARY 10 TO MARCH 10, 1960

By February 12 extrusion of lava at the lava delta in the central collapse pit had ceased. A few cracks near the apex of the delta continued to glow throughout this period, however, and early in March a slight glow was observed for the first time on the steep rubbly slope on the west side of the pit.

The number of earthquakes from the summit of Kilauea further decreased after the second collapse. Many were still felt, however, and two were strong enough to cause considerable damage. The first of these occurred along one of a group of east-west faults 4 miles south of the caldera at approximately 16^h35^m on February 12. Uprooted trees, freshly exposed soil, and new talus were observed for about a mile along the fault, and cracks were very abundant in a zone 500 feet wide on both sides of the scarp. Where the fault was crossed by the Hilina Pali road, the north (caldera) side was downthrown 6 inches and a gaping 4- by 6-foot-wide hole had engulfed a part of the road. The other earthquake that caused damage occurred at approximately 03^h20^m on March 7 at a shallow depth beneath the east end of the caldera. Although the earthquake was felt rather strongly by all residents in the summit region, damage was restricted to a small area in the community of Volcano, 2 miles east of the caldera. Kitchenware, lamps, toiletries, and other small objects were overturned or broken in about six houses; at one house the fireplace and chimney were cracked; and at another house, the water tank was slightly damaged.

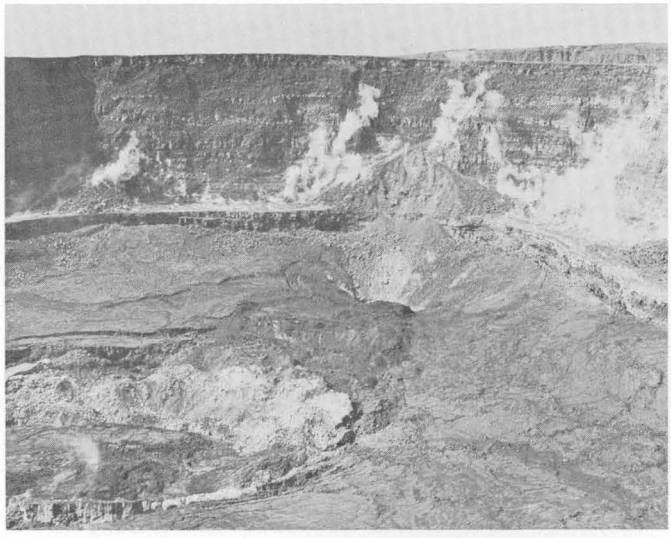


FIGURE 79.—View southward across Halemaumau showing saucer-shaped subsidence of floor, central collapse pit (left), and second (southwest) collapse pit at base of large talus pile in background.

On February 28 the main vent in Kilauea Iki, which had emitted fume and steam in diminishing amounts since the beginning of the year, began to expel a dark convoluting cloud of steam and dust. Emission of fine black ash was strongest during the afternoon, when a thin layer was deposited around the north and northeast rim of the caldera. By

morning the next day, only steam was rising from the vent, and its volume had diminished greatly.

MARCH 11, 1960

The third and final collapse of the floor of Halemaumau began about 08^{h}00^m, March 11, when a dust-laden steam cloud boiling up out of the northeast corner of the crater was seen from the Hawaiian Volcano Observatory. By 08^{h}25^m when we arrived at the rim of Halemaumau, the collapse was virtually over. A pit, 300 by 400 feet in diameter and about 100 feet deep, had formed at the northeast corner of the crater on the remaining level ledge of 1954 lava that still encircled the sunken main floor at the base of the crater wall (fig. 80). Steam clouds smelling slightly of hydrogen sulfide and sulfur dioxide continued to rise from the collapse, and frequent rock slides tumbled down its steep walls. The dust generated by the collapse formed small pisolitic mudballs up to an eighth of an inch in diameter that fell on the crater rim above the northeast pit. A thin film of fine dust was deposited on the north and northeast rim of the caldera more than 2 miles from Halemaumau. At nightfall steam still evolved from the collapse, and within the pit the lowermost wallrock was brightly incandescent.

The total volume of the 1960 collapse in Halemaumau was approximately 29 million cubic yards; this volume was slightly less than one-half of the 64 million cubic yards of lava that poured into Halemaumau during the 1952 eruption.

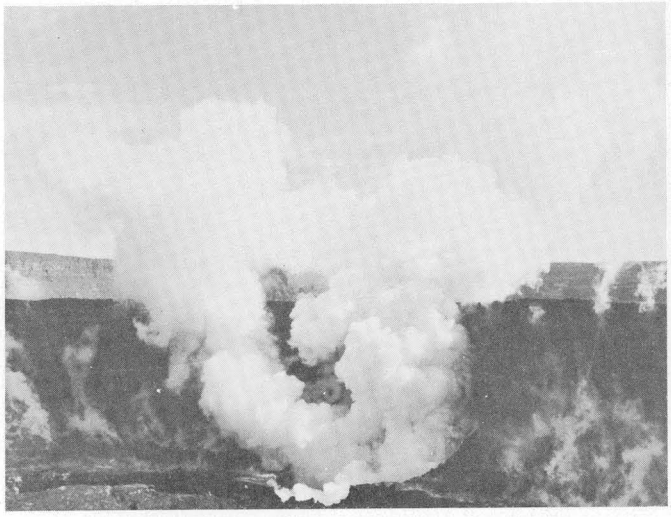


FIGURE 80.—March 11, 1960, 08^{h}30^m. View northward of steam rising from third (northeast) collapse pit in floor of Halemaumau. Main caldera wall is in background.

MARCH 12 TO NOVEMBER 3, 1960

Rocks in the third collapse pit remained incandescent until about the third week of April. At night, steam rising from the pit was often brilliantly illuminated from below, and occasionally the reflected glow could be seen from the northeast rim of the caldera. Although the few incandescent spots in the west wall of the central collapse pit were very weak and were visible only at night, they persisted much longer and were last observed glowing very feebly on the night of November 3.

On June 4 bluish fume was first observed emanating from the southeast side of the collapse pit. Daily the fuming increased, and the choking odor of sulfur

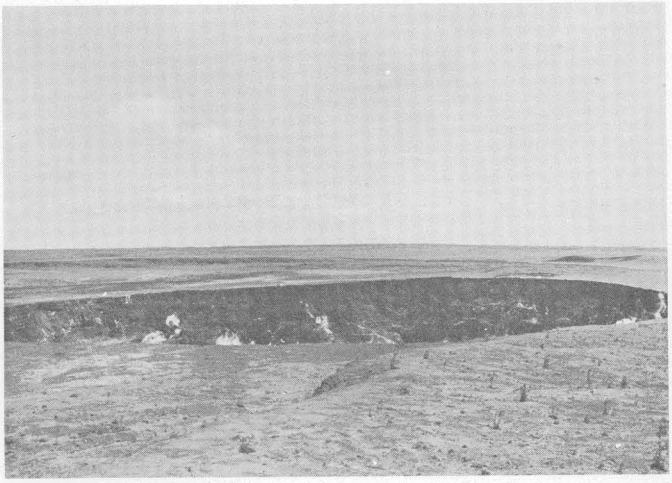


FIGURE 81.—Views of Halemaumau from the U.S. Geological Survey's Hawaiian Volcano Observatory. *Top:* April 26, 1960. Halemaumau before the period of fuming after the collapse. Steam escaping around rim is from vaporized ground water. *Bottom:* June 26, 1960. Halemaumau during the period of strong fume emission from central collapse pit.

dioxide was at times very pronounced on the rim of Halemaumau 700 feet above source of the fume. By June 14 the entire inner face and rim of the central pit was emitting fume, filling the crater with bluish-white haze (fig. 81, bottom photograph). This strong emission of fume, which was preceded by feeble harmonic tremor, suggested that the liquid core had drained from a part of the reservoir labyrinth beneath the caldera and had allowed the hot interior to degas.

Fume emission reached a maximum during the last two weeks in June, and throughout this period a heavy fume cloud drifted leeward over the Kau Desert as far as the southwest rift of Mauna Loa. By the middle of July fuming had visibly abated, and by early August it had virtually ceased.

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