The 1959 and 1960 eruptions of Kilauea volcano, Hawaii, and the construction of walls to restrict the spread of the lava flows.

GORDON A. MACDONALD

Senior Professor of Geology and Geophysics, Institute of Geophysics, University of Hawaii. Hawaii Institute of Geophysics Contribution No. 42.

Abstract

A summit eruption of Kilauea volcano took place in Kilauea Iki crater, immediately adjacent to Kilauea caldera, from November 14 to December 20, 1959. Approximately 61 million cubic meters of lava was poured into the crater during 16 short eruptive episodes. Following each of the later episodes nearly as much lava drained back into the vent as had been poured out.

On January 13, 1960, eruption commenced on the east rift zone of Kilauea about 40 kilometers east of the caldera. This eruption continued until February 19, liberating 113 million cubic meters of lava, and burying approximately 5.6 square kilometers of land surface, including much agricultural land and most of the village of Kapoho. Several walls were built, to try to prevent or lessen the southward encroachment of the lava. These walls were dams, impounding the lava, not diversion barriers. Lava overflowed the dams, but it is believed that the amount of southward spreading of the lava was sufficiently reduced to more than justify their construction; and it was demonstrated that such walls, properly constructed, will adequately withstand the thrust of even thick lava flows of the type characteristic of Hawaiian eruptions.

Introduction

The 1960 eruption took place on the east rift zone of Kilauea volcano, approximately 45 kilometers east of Kilauea caldera. The rift zone is a belt, 1 to 3 km wide, of numerous fissures that have served as channelways to bring lava to the surface. The 1960 eruption followed by only a little more than a month a summit eruption of Kilauea Volcano in Kilauea Iki, a smaller crater adjacent to the eastern edge of the main summit caldera. This pattern of a summit eruption followed a few weeks to a couple of years later by an eruption on the flank of the volcano is a normal one for Kilauea and Mauna Loa.

During the modern history of Hawaii (roughly 1 ½ centuries) few eruptions have caused serious trouble in inhabited areas. During several, lava flows have destroyed ranch lands and a few buildings, but the 1955 eruption, in the same general area as that of 1960, was the first to affect more intensively used land. During the 1955 eruption approximately 1,000 acres of land under cultivation for sugar, papayas, coffee, and other crops was destroyed, as also were 17 residences. The 1960 eruption destroyed 87 buildings, most of them dwellings, and approximately 400 acres of cultivated land, and damaged crops over a much wider area. Most of the destruction resulted from lava flows, though some buildings collapsed because of the weight of cinder and ash on their roofs, and some crops were damaged by falling tephra.

With rapidly increasing settlement and use of the land on the island of Hawaii the probability of lava flows doing serious damage in populated regions is increasing, and it is imperative that methods for alleviating the damage be considered and experimented with. The risk to the city and port of Hilo from lava flows of Mauna Loa long been recognized (Jaggar, 1931), and two methods have been suggested by which lava flows might be prevented from invading the area. These are: aerial bombing, to cause the lava to spread high on the mountainside where it will do relatively little damage; and construction of barriers to turn the course of the flows and divert them into areas where they will do less damage (Jaggar, 1945; Macdonald, 1958). Experiments in bombing lava flows have been carried on twice, in 1935 and 1942. Diversion barriers were tried in 1955, with a small measure of success, even although they were poorly located and inadequately constructed, and topography was not very favorable to their use. They have been discussed elsewhere (Macdonald, 1958, p. 266-269).

A diversion barrier, such as that suggested to protect Hilo, is in no sense a dam. It is intended simply to divert the flow, not to impound it. During the 1960 eruption conditions were adverse, or at the best only very slightly favorable, to the operation of diversion barriers. In part of the area, however, it appeared that there was a possibility of saving valuable property from inundation by lava through the construction of dams designed to actually impound the lava to a limited degree. The construction and operation of these dams is discussed in the present report, together with the lessons that can be derived from them applicable to the construction of other types of barriers.

Wall 1 (fig. 2), constructed in an attempt to prevent the destruction of the Warm Spring resort, was financed privately. The other walls were built for the Civil Defense Agency of the State of Hawaii. E. F. Morrison, District Engineer for the Highway Department, State of Hawaii, was in charge of construction. The writer was designated by General F. W. Makinney, Director of Civil Defense, State of Hawaii, to advise on volcanological matters.

The present paper contains only a summary of the events of the 1960 eruption, particularly as they were related to the wall construction, and as background a still briefer summary of the 1959 eruption. Detailed accounts of the two eruptions, the petrography of the lavas, and the composition of the gases, are being prepared by the staff of the U. S. Geological Survey's Hawaiian Volcano Observatory.

Acknowledgments

It is impossible to acknowledge individually the aid of the large number of persons who were of assistance during the eruption, or contributed information to this report, but to all of them I extend my sincere thanks. A few can be mentioned individually.

Reports of aerial observations from Capt. H. H. McNeill, Jr., Lt. Paul de Silva, and Lt. David S. Nobriga, of the Hawaii National Guard, and from William Stearns and William Beals of Murrayair, Ltd., and reports of ground observations by wardens of the Civil Defense Agency, were of great importance in keeping track of progress of the lava flows and new developments of the eruption. H. C. Marsh was particularly helpful during the hectic period between January 23 and 27. Arthur Lyman's keen observations and remarkable knowledge of the terrain were of great aid on many occasions.

The form of the lava flow, shown in figure 2, is taken largely from a map prepared in Civil Defense Headquarters from the observations of the aerial observers, the wardens, the staff of the Hawaiian Volcano Observatory, and the writer.

Leslie Payne and Norman Lyman served as construction foremen during the building of the walls. Harris Suyama, Karl Kami, and Samuel Kumukahi, of the State Highway Dept., served as project engineers and did the surveying for the wall construction.

Information on earthquakes and tilting of the ground surface have been compiled from previously published sources (Anonymous, 1959; Richter and Eaton, 1960), and from press accounts based on releases from the Hawaiian Volcano Observatory. The measurements of the depth of the lava in Kilauea Iki in table 1 were made by D. L. Richter, geologist of the Hawaiian Volcano Observatory. The writer's direct personal knowledge of events during the eruptions has been augmented from press reports, reports by the staff of Hawaii National Park, and the journal of the Hawaii Civil Defense Agency.

Perhaps more than anything else, tribute should be paid to the bravery, willingness, and determination of the bulldozer operators and supervisors who built the walls. These men voluntarily drove both themselves and their equipment continuously at high speed, constantly under great pressure, sometimes in the dark in rough dangerous terrain, sometimes in almost unbearable heat at the edge of active lava flows, sometimes boldly, if futilely, scooping up red-hot still-active lava on their bulldozer blades. Without their fine spirit, the work could not have been accomplished.

The summit eruption of 1959

After the end of the 1955 eruption on the east rift zone of Kilauea (Macdonald, 1959) there was no eruptive activity of either Kilauea or Mauna Loa until the outbreak of lava in Kilauea Iki crater in November, 1959. Kilauea Iki is a pit crater, approximately a mile in length, situated immediately adjacent to the eastern edge of Kilauea caldera and separated from it only by a low ridge known as the Byron Ledge (Macdonald, 1959, fig. 10). The last activity in Kilauea Iki crater had been in 1868, when a fissure part way up the southwestern wall of the crater poured lava onto the crater floor. Previous to that, in 1832, an eruption on Byron Ledge had poured lava into both Kilauea Iki crater and Kilauea caldera. (See Macdonald, 1959, p. 6-11, for a brief summary of activity of Kilauea volcano previous to 1951).

Measurements of tilting of the ground surface around Kilauea caldera indicated a slight tumescence of the summit of Kilauea volcano during late 1958 and early 1959, followed by a slight detumescence from about May to August. From late September until mid-November swelling of the mountain top was rapid (Richter and Eaton, 1960).

The earthquake prelude to the 1959 eruption started nearly 6 weeks before the outbreak, in early October. From October 7 to 20 there was an average of about 400 earthquakes a day, nearly all of

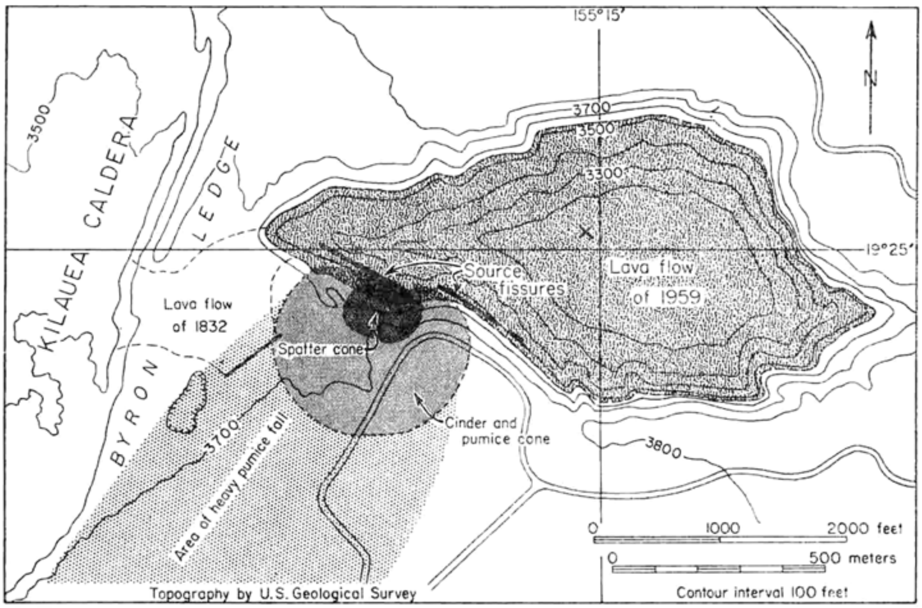

Fig. 1 - Map of Kilauea Iki crater, showing the area covered by lava, and the approximate distribution of cinder and pumice of the 1959 eruption. The X marks the approximate location of the hole drilled by the Lawrence Radiation Laboratory.

them very small. Most came from very shallow foci, many of them less than 1 km deep, very close to Halemaumau crater within the Kilauea caldera, and were recorded only on a very sensitive seismograph at the north edge of Halemaumau (Eaton, J. P., press reports). From the morning of October 17 to that of October 18 about 600 quakes were recorded. The number of quakes died down somewhat in late October and early November.

During October the volume of fume at the solfatara on the 1954 eruptive fissure at the northeast wall of Halemaumau also increased, and occasional puffs rising above the crater rim were visible from the Volcano House on the northeast rim of the caldera.

In the second week of November earthquakes increased greatly, as many as 1,500 being recorded in a single day. On November 12 the rate of tumescence of the caldera region increased, and tilting continued at an accelerated rate through November 13 and 14. On the latter day about 2,200 quakes were recorded (Eaton, S. P., press reports), of which 6 were large enough to be felt generally in the area around the caldera. Just before 20:00 on November 14 harmonic tremor started recording on the seismograph, and at 20:08 the eruption commenced. According to J. P. Eaton (oral statement, Nov. 27, 1959), earthquakes almost completely ceased when the outbreak took place; and although harmonic tremor was strong, actual earthquakes were very few during the next several days.

The outbreak was on the southwest wall of Kilauea Iki crater, roughly half way up from the floor to the crater rim (fig. 1), and very near the line of outbreak of the 1868 eruption (Macdonald, 1959, fig. 10). The fissures quickly lengthened both eastward and westward from the initial point of outbreak, and lava fountains up to about 15 m high played along them. There were soon two lines of fountains, each roughly 400 m long, lying slightly en echelon, and a smaller single fountain farther west approximately on the line of the western fissure. The eastern fountain chain poured a cascade of lava directly into the main part of Kilauea Iki. The western chain and the far-west fountain poured streams onto a platform that stood approximately 60 m above the main crater floor at the west end of Kilauea Iki. Thence the lava cascaded eastward down the steep slope to the crater floor, where it joined the streams from the eastern fissure to form a rapidly spreading pool of liquid lava (pl. 1). The eastern chain and the single western fountain lasted only a few hours, and activity was soon restricted to the western part of the central fissure.

By the morning of November 15 only one fountain 15 to 25 m high, and a smaller one nearby, were still in activity (pl. 1), and the volume of lava being poured out was small. Activity continued at a low level through November 16, but on November 17 it began to increase again and by that evening a single big fountain was reaching a height of about 75 m. By noon on the 18th it was 170 to 200 m high, (pl. 1, fig. 2), and by 15:00 it was reaching 230 to 250 m. During that evening and the early morning of the 19th it consistently exceeded 300 m, with some bursts reaching 350 m.

By the morning of November 19 the depth of the pool of lava on the crater floor was about 45 m, and the volume was about 11 million cubic meters. The cinder and pumice half-cone built on the crater wall behind the fountain was 300 m long at its base and more than 60 m high.

On the morning of November 20 the height of the fountain was reported to be down to about 275 m. The pool of lava was 68 m deep and D. L. Richter, geologist of the Hawaiian Volcano Observatory, estimated it to be rising about 1 m per hour, corresponding to a rate of extrusion of about 1,000,000 cubic meters of lava per hour.

Early on the morning of November 21 the fountain was reported to be 300 m high again, and the lava pool was about 92 m deep. During the morning the surface of the pool reached the level of the vent. The fountain was sporadic, and gradually getting smaller, at times dropping as low as 45 m. At 10:45 it shot up again very briefly to 345 m. At 10:46 another high burst reached 365 m, and at 11:10 it shot up to 380 m, showering hot pumice on the road just south of the crater. Olivine phenocrysts, blown clear of the lava and many of them trailing long strands of Pele's hair, fell in the area south and southwest of the vent.

During the afternoon the fountain was ejecting both the typical bright orange lava from a deep source, and deep red lava from the encroaching lava lake, to heights of 245 to 275 m, with a few bursts reaching 345 m. That evening the fountain very suddenly died, and for a short time it appeared possible that the eruption had ended. The dramatic cessation of activity was recorded thus by Claude Jendrusch, moving picture photographer who had been photographing the eruption (Honolulu Sunday Advertiser, No. 22): « Sometime after 7 (19:00) we noticed a loss of light all around us. The fountain was still going but was turning bloody red. Then we noticed that the details in the crater — the lava rivers — were more pronounced.

« Five minutes after we first noticed the loss of illumination, the height of the fountain began to decrease... In less than 40 seconds the fountain became level with the lava lake, then completely disappeared. The whole area turned so black that we all reached for our flashlights... There was no explosion or noise...

« The next thing we knew, the fountain emitted a billowing black cloud. It was thick and dense and about 60 feet high... The cloud lasted about a minute. It dissipated and the fountain gurgled about half a dozen times. It went up about 25 feet. Then it flattened out and disappeared ».

At 19:28 the Hawaii National Park staff reported the lava in the vent was merely bubbling; and at 22:00 J. P. Eaton reported that the eruption appeared dead.

For the next few days there was no surface activity. Seismographs recorded continuous harmonic tremor, but with decreasing amplitude. The surface of the lava pool gradually sank, and slump scarps more than 10 feet high formed around its edges.

Activity resumed at approximately 00.30 on November 26. A sightseer who chanced to be at the edge of the crater reported that without apparent warning the molten lava suddenly burst from the vent. The fountain quickly grew to a height of 100, then receded and held steady at 60 m, with a smaller fountain, about 15 m high, nearby. The larger fountain occupied the same vent as the large fountain of the previous eruptive period. A voluminous outpouring of lava rapidly spread over the crater floor. Harmonic tremor was reported by the Volcano Observatory staff to be of about the same magnitude as during the quiet period before the renewed outbreak. The activity continued for only 16 hours, and then again ended very abruptly. During the night the new lava floor sank 6 to 10 m, apparently largely due to drainage of liquid lava back down the feeding conduit.

On the evening of November 27 a river of bright orange-red lava, 3 m wide, was issuing from beneath the crust of the lava pool near the vent and flowing on the surface into the vent at a rate of about 3 km per hour. On the morning of November 28 the pool was completely crusted over right to the lip of the vent, but about 10 m below the level of the lip a stream about 2 m wide and estimated to be about half a meter deep was pouring into the vent at a rate of about 30 km per hour (pl. 2, fig. 3). At noon of that day the stream of lava was still pouring into the vent, but the fine incandescent spray of the very top of a spasmodic lava fountain was just visible in the vent about 35 m below the surface. Another eruptive phase was beginning.

The activity of November 26 was the first of 15 eruptive phases, each lasting only a few hours, and each ending with lava draining back into the vent with a spectacular whirlpool at the surface. The activity is summarized in table 1, based partly on a table issued by the Hawaii National Park staff that in turn was prepared partly from data furnished by the Hawaiian Volcano Observatory staff.

On December 17 the height of the lava fountain was reported to have reached 580 meters, — the greatest height ever recorded for a Hawaiian lava fountain.

The eruption finally ended on December 19. Fountaining stopped at 06:16, and lava immediately started draining back into the vent. This continued until 20:45, when lava again rose in the vent. However, fountaining did not resume; only a weak bubbling was visible in the lava pool occupying the vent, and only a very small amount of lava was poured out. Similar activity continued on December 20, by December 21 even that had ceased. The rapid backflow of lava into the vent after the end of extrusive phase 16 on December 19 lowered the surface of the pond as much as 6 meters. At the end of that period of drainage the total volume of lava emplaced in Kilauea Iki crater was approximately 61,000,000 cubic meters, and the thickness of the fill of new lava was 116 m. Over the ensuing months the level of the central part of the crater floor continued to drop very slowly until, by late August, 1960, the total sinking at some places was as much as 14 meters. High slump scarps formed around the edge of the floor. Some of the sinking may have resulted from continued slow oozing of lava back into the vent, but the amount (12 %) is well within the limits of shrinkage that apparently can result entirely from cooling and loss of gas (Macdonald, 1959, p. 38).

During July, 1960, the Lawrence Radiation Laboratory of the University of California, under their Plowshare Program, drilled a hole into the solidified crust of the lava pool at the location shown in figure 1. On July 25 viscous liquid lava at a temperature of approximately 1060° C. was encountered at a depth of 6 meters.

The rate of lava extrusion during the first 3 days of the eruption was only about 6000 meters per hour, but in the interval between the evening of November 17 and the morning of November 20 it increased to an average of 360,000 cubic meters per hour, and during the 24 hours ending on the morning of November 21 it averaged 905,000 cubic meters per hour. During the later phases the rate of outpouring was at times even higher (table 1), but the draining away of lava between eruptive phases resulted in the net rise of the crater floor being small. Average rates of extrusion and withdrawal of lava are shown in table 1. At times, however, both rates considerably exceeded the averages. Thus Richter and Eaton (1960, p. 996) estimate

Table 1 - Statistics on the 1959 eruption of Kilauea volcano
(in part modified after a table issued by Hawaii National Park).

Phase	Date	Duration (hours)	Maximum reported height of lava fountain (meters)	Maximum depth of pond at end of extrusion (meters)	Volume of lava extruded (cubic meters)	Average rate of extrusion (meters³/hour)	Volume of pond at end of extrusion (cubic meters)	Duration of quiet period between extrusive phases (hours)	Maximum lowering of pond crust (meters)	Depth of pond at end of withdrawal of lava (meters)	Approximate volume of lava drained back into vent (cubic meters)	Average rate of withdrawal of lava into vent (meters³/hour)
1	Nov. 14-21	167	380	102	50,000,000	300,000	50,000,000	101	2	100	1,500,000	15,000
2	Nov. 26	15	305	107	5,500,000	370,000	54,000,000	48	10	97	7,500,000	150,000
3	Nov. 28-29	29	520	104	5,500,000	190,000	52,000,000	101	4	100	3,000,000	30,000
4	Dec. 4-5	32	200	120	15,000,000	470,000	64,000,000	26	11	109	8,500,000	320,000
5	Dec. 6-7	9	380	123	10,500,000	1,100,000	66,000,000	15	9	114	6,500,000	430,000
6	Dec. 7-8	11	245	126	8,500,000	770,000	68,000,000	11	8	118	5,500,000	500,000
7	Dec. 8	7	425	125	5,000,000	700,000	67,500,000	42	11	114	8,000,000	190,000
8	Dec. 10-11	19	335	126	8,500,000	450,000	68,000,000	42	11	115	8,000,000	200,000
9	Dec. 13	8	245	126	8,000,000	1,000,000	68,000,000	17	13	113	9,500,000	560,000
10	Dec. 14	8	335	125	9,000,000	1,100,000	67,500,000	14	10	115	7,500,000	530,000
11	Dec. 15	4	365	123	6,000,000	1,500,000	66,000,000	9	7	116	5,000,000	550,000
12	Dec. 15	2	335	120	3,000,000	1,500,000	64,000,000	16	6	114	4,500,000	280,000
13	Dec. 16	4	350	120	4,500,000	1,100,000	64,000,000	9	5	115	4,000,000	450,000
14	Dec. 17	2	350	119	3,000,000	1,500,000	63,000,000	8	2	117	1,500,000	190,000
15	Dec. 17	4	580	121	3,500,000	900,000	65,000,000	35	6	115	5,000,000	140,000
16	Dec. 19	3	455	123	6,000,000	2,000,000	66,000,000	—	7[a]/	116	5,000,000	—

[a]/ Amount of sinking that took place within a few hours of the end of the extrusive phase 16. Slow sinking resulting probably largely from shrinkage of the lava caused by cooling and loss of gas, but possibly also by a continued small amount of drainage of liquid lava back into the vent, is still continuing at the date of writing, and by late August, 1960, had reached as much as 14 meters.

that at times the rate of backflow into the vent was more than 2,200,000 cubic meters an hour, — a good deal greater than the usual rates of extrusion. The maximum rate of extrusion, during phase 16, is among the highest observed in Hawaiian eruptions (table 2).

Table 2 - Estimated maximum rates of extrusion of lava during recent eruptions of Hawaiian volcanoes.

Eruption	Volume (cubic meters/hour)
1940, Mauna Loa	2,000,000
1952, Kilauea	1,400,000
1955, Kilauea	600,000
1959, Kilauea	2,000,000
1960, Kilauea	500,000

The temperature of the erupting lava ranged from 1120° to 1190° C. (Richter and Eaton, 1960, p. 996), the latter being the highest temperature ever reported for erupting lava in Hawaii. (Then only temperatures higher than these were observed in the throats of blowing conelets, where heating by burning gas was taking place). According to K. J. Murata (Anonymous, 1959, p. 1697), the highest temperatures were associated with the lava richest in olivine phenocrysts, presumably derived from the deeper parts of the underlying magma column.

The lava consolidated as pahoehoe. In composition it ranges from tholeiitic basalt with only a few scattered phenocrysts of olivine to picrite basalt of oceanite type containing as much as 30 percent olivine phenocrysts ranging in size up to about 8 mm long. Richter and Eaton (1960, p. 996) state that the silica content ranges from 46.3 to 49.5 percent. The olivine phenocrysts commonly show evidence of partial resorption, and it is clear that olivine crystallized at depth in excess of its stoichiometric ratio and has been only partly redissolved in the magma. The average composition of the entire mass of lava extruded during the eruption is probably tholeiitic olivine basalt slightly undersaturated with silica, containing 5 to 10 percent olivine.

The gas-rich character of the eruption resulted in large amounts of pumice (fig. 4, pl. 2) which drifted for several miles to leeward (fig. 1), forming a blanket as much as 1.5 m thick 1 km from the vent. Cinder and spatter falling on the rim of the crater southwest of the vent built a conical hill 300 m across at the base, and 45 m high.

The unusual features of the 1959 eruption were the many short eruptive phases, each followed by drainage of liquid lava back into the vent, and the great height reached by the lava fountain. The drainage is easily explained by the fact that the liquid lava accumulated in a deep pool to a level above that of the original vent opening. Most eruptions occur on the flank of the volcano or on the main caldera floor, and the lava flows away instead of accumulating in a pool over the vent. At the end of an eruptive phase of such an eruption the small pool of liquid in the crater of the cinder cone commonly drains back into the conduit, but the main flow cannot drain back. The behavior in Kilauea Iki more closely resembled that during a lava lake phase in Halemaumau crater, when lava alternately rises, producing a rise in the level of the lake surface, and sinks back again, the same opening commonly serving as both inlet and outlet.

The great height of the lava fountain correlates with an unusual abundance of gas in relation to the amount of liquid lava being extruded. The fountain differed from most during recent Hawaiian eruptions in being a spray of separated liquid blobs and solidified fragments, instead of a continuous jet of liquid. A spray of this sort commonly extends above the main body of the fountain in other eruptions, but because of the indefiniteness of its top it has been ignored in reporting the height of the fountain. The measured top of the fountain has been the top of the continuous core of liquid. However, during the 1959 activity no such continuous core was visible, and the height was measured to the top of the consistently visible rise of incandescent fragments in the spray. Thus, it is not strictly comparable with fountain heights reported from earlier eruptions. Attempting to determine the height of the fountain as nearly as possible in the same way as in previous eruptions, on November 27 the present writer made measurements by three different methods: reading the vertical angle to the top of the central, more nearly continuous, part of the fountain from a known horizontal distance from the base; comparing the height of the fountain with the approximately-known height of the crater wall behind it; and by measuring the proportion of the total field occupied by the fountain in a photograph taken from a known horizontal distance with a lens of known angular aperture. All three methods gave a height of approximately 350 meters, at a time when National Park Service observers reported the total height of the fountain to be 520 meters. Even making allowance for this difference, however, the fountain unquestionably was the highest ever measured during Hawaiian eruptions.

The flank eruption of January, 1960

Topography of the eruption area

The Kapoho area, in which the 1960 eruption occurred, before the eruption was a broad shallow trough, or graben, dropped down between two series of faults. (The name, Kapoho, means the depression, or sunken-in place). Both the faults and the graben trended approximately N 65° E, parallel to the east rift zone of Kilauea Volcano, at the crest of the broad ridge built by eruptions along the rift zone. The pre-eruption topography is shown on the map (fig. 2).

The north boundary of the Kapoho graben was the Koae fault, named after the village of Koae, which was situated just north of it. About 500 m west of the Koae road the fault scarp was 12 m high, but at the road and farther eastward it was only about 3 m high. North of the scarp in the vicinity of the road the ground surface rose gently another 10 to 12 m.

South of the Kapoho graben, Puu Kukii and Puu Kukae are a pair of prehistoric cinder cones. Half a kilometer to the west a smaller cinder cone protruded from encircling lava flows. (This hill was later entirely buried by the 1960 lava). Southwest of Puu Kukii the big Kapoho Hill is a tuff cone, resembling Diamond Head and Punchbowl cones on the island of Oahu, formed by explosions caused by hot lava rising into water or water-saturated rock. At the northwest edge of Kapoho Hill is a cinder cone (Puu Kea), with a row of small cinder and spatter cones stretching southwestward from it.

Along the south side of the graben a fault scarp 1.5 to 3 m high extended from the eastern part of Kapoho village toward the northwest edge of Puu Kukii, and increasing in height continued along the north side of Puu Kukii, and Puu Kukae and thence, decreasing again, to the Ipoho Lagoon (Higashi Pond). Warm Spring was an open crack extending down to the basal water table on this fault. The water was part of the Ghyben-Herzberg lens of fresh water floating on salt water that saturates the rocks below sea level, and owed its warmth to heating by shallow intrusive bodies in the rift zone.

The Kapoho graben had been formed in prehistoric times, but was increased in depth in 1924, when the ground at the foot of the Koae fault scarp inland from the road dropped as much as 2.4 m, and the region along the coast sank 4.2 m (Jaggar and Finch, 1924). The Ipoho Lagoon was formed largely at that time.

Running nearly eastward from the southeast edge of Puu Kukae was another small fault scarp, downthrown toward the south, and locally forming the southern side of a low ridge extending through Cape Kumukahi. South of the cape, at Waiakaea Bay and farther

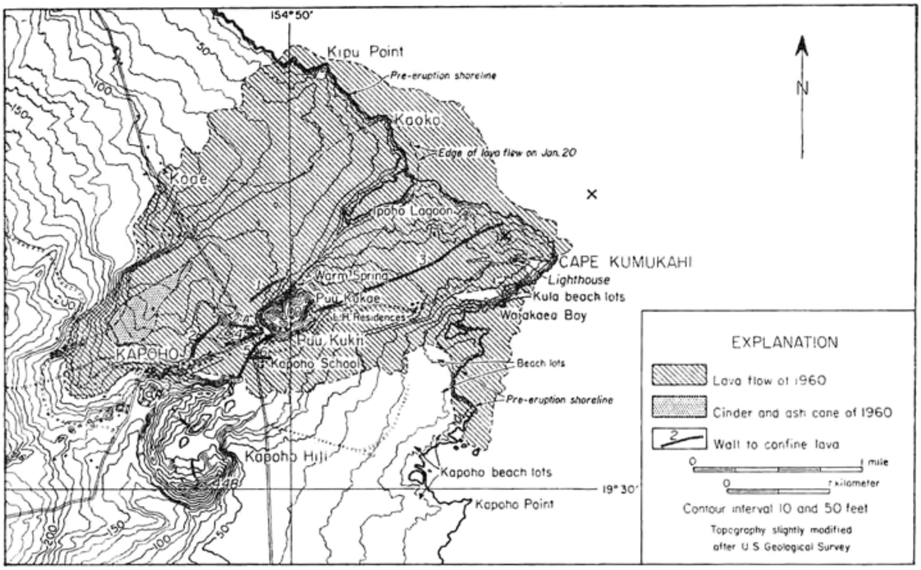

Fig. 2 - Map of the Kapoho area, east Hawaii, showing the pre-eruption topography, the distribution of the lava of the 1960 eruption, and the location of the walls built to prevent or reduce the southward spreading of the lava. The X's indicate the positions of the minor vents active on January 28, January 29, and February 3 (Modified after a map prepared by the Hawaii Civil Defense Agency).

south, the coastline had sunk 1 to 2 m during the violent earthquakes of 1868, submerging fishpond walls and other man-made structures.

The fault scarp and cinder cones, and the low ridge on which they were situated, formed a natural barrier along the south side of the Kapoho depression that tended to confine the 1960 lava flows to the depression and prevent them from spilling southward.

The general slope of the land surface in the graben was eastward, but at an angle of only about 5.7 meters per kilometer (less than 0.6 percent grade). Within the western part of the graben there was, in addition, a general northward slope of the land surface to the foot of the Koae fault scarp, tending to cause the liquid lava to flow northward, However, in the eastern part of the graben the slope of the surface was reversed, the lowest land lying along its southeast edge. Ipoho Lagoon was the lowest portion of the entire area.

The eruption

Late in December, 1959, very numerous earthquakes commenced on the east rift zone of the volcano in east Puna, 30 to 40 km east of Kilauea caldera. Some of them were felt by persons living in the area, but most were too small to be felt and were detected only by seismographs. At first the earthquake activity centered in the region west of Honuaula hill, in the vicinity of the first outbreaks of the 1955 eruption (Macdonald and Eaton, 1955; Macdonald, 1959, Fig. 12). However, about January 10, 1960, the center of earthquake activity shifted eastward to the vicinity of Kapoho village (Eaton, J. P., quoted in press reports). Many of the quakes were felt in the village, and persons who were working in the area north of the village on January 12 and 13 report that some were so severe that is was difficult to stand up during them. On these days east-northeast-trending cracks opened in the ground in and near Kapoho village. A crack across the paved road was about 2 cm wide on the morning of January 13, but had widened to 1 m by early afternoon, and the ground surface north of it had dropped about 30 cm. Along another crack, that extended east-northeastward for about 1.6 km to the vicinity of Warm Spring, the ground to the north had dropped 75 cm (fig. 6, pl. 4). Another zone of cracks, with a similar trend, opened along the foot of the Koae fault scarp, 0.8 km to the north, and the ground surface south of the cracks dropped in some places as much as 1.5 m. Thus there was a general subsidence of the graben floor between the two fracture zones. Similar graben subsidence had occurred in the same area in 1924 (Jaggar and Finch, 1924), and to a lesser degree again in 1955 (Macdonald, 1959, p. 56).

During the morning of January 13 Kapoho was declared a disaster area by the Civil Defense Agency, and evacuation of the village was begun. At 12:30 (Hawaiian standard time) Kongo Kimura, seismograph attendant at the Pahoa School, reported the appearance on the Pahoa seismograph of harmonic tremor, similar to that known to accompany the movement of molten lava in the volcanic conduits.

At approximately 19:30 molten lava broke out in a sugar-cane field half a mile northwest of the center of Kapoho village. The eruptive fissure opened gradually eastward, and a line of lava fountains along it gradually grew until it was more than half a mile long. By midnight the 3 westernmost fountains had ceased activity, but farther east a row of 15 to 20 fountains ranged from a few meters to about 100 m feet in height. Steam blasts accompanied the fountains (fig. 7, pl. 4), and showered the surrounding area, particularly to the north and northwest, with wet black ash containing abundant salt, which was left plastered on the vegetation. A lava flow advanced northeastward from the vents, and shortly after midnight crossed the road that led northward to Koae village.

By next morning a row of 4 to 7 lava fountains was still active along the east-central part of the fissure (fig. 7), centering approximately 600 m northwest of the center of Kapoho village. The edge of the lava flow was only 270 m from the village. During the day the fountains increased in activity, reaching as high as 150 m (fig. 8), and the volume of lava being poured out also increased. By evening of January 14 the lava flow was 300 m wide near the road to Koae, and its front was about 900 m from the ocean. At about 08:10 on the morning of January 15 it entered the ocean just south of Kaoko point, with a front about 300 m wide. Great clouds of steam rose from the water.

At first the slope of the pre-eruption ground surface directed the lava flow principally northeastward from the vents. On reaching the foot of the Koae fault scarp inland from the road, the flow bent east-northeastward along the foot of the scarp toward Kaoko point. Temporarily the fault scarp prevented the lava from spreading northward into Koae village, but by January 16 the flow had grown deep enough to overtop the scarp and begin to expand northward. Even although from that time on there was a progressive encroachment of the edge of the flow into the Koae area, the main body of the flow continued to move eastward south of the scarp, still guided by the buried scarp.

On entering the ocean the front of the lava flow turned southeastward, and advanced along shore toward the mouth of the Ipoho Lagoon. There was nothing in the pre-eruption topography just seaward from the shoreline that appears adequate to cause the flow to turn and advance almost along shore. Probably, the turn was caused by chilling of the flow front on entering the ocean on a very gentle slope, making it easier for the flow to spread laterally along shore than to continue seaward. The southward course was no doubt determined partly by the obstruction offered by Kaoko point, and perhaps partly by the fact that the southern edge of the flow was the last to reach the water. Once the course was changed and the seaward edge of the flow was well chilled by the water, it was easier for the flow to continue along shore than to advance seaward.

The slope of the pre-eruption surface east of the vents was very gentle, only about 20 m in 2.8 kilometers. This flat slope was insufficient to keep the lava flowing in the same channel. Lava extruded onto the surface of the earth has little or no superheat, and as it cools it quickly begins to crystallize and become more viscous, and tends to clog its channel. If the slope is great enough, the flow may be able to keep its channel clear in spite of the tendency for it to become clogged, but on gentle slopes the channel commonly becomes partly or completely blocked. This results in overflows to form distributary channels that carry part of the volume of the flow; or in a broad flooding, forming a pool of liquid lava that may spill in any direction depending on the routes of easiest release. The Kapoho flow did both. As early as January 15 distributaries were branching southeastward north of Warm Spring to feed flow tongues advancing toward the Ipoho Lagoon. This tendency continued throughout the eruption. On January 16 the lateral tongues had reached the lagoon, and another tongue was advancing toward Warm Spring. On January 17 a wall was hurriedly built to try to prevent the lava from entering and destroying the Warm Spring area. It is described on a later page. On January 17 also, the flow blocked the mouth of the Ipoho Lagoon and commenced filling the lagoon by flowing westward, up the valley.

On the morning of that day the principal lava fountain was reaching a height of 245 m, with a spray of incandescent fragments rising upward an additional 215 m.

By the afternoon of January 18 lava had covered the Warm Spring area and the entire margin of the flow was creeping southward. The main fountain ranged in height from about 45 to 245 m., and the volume of lava being poured out was estimated as about 5,000,000 cubic meters per day. A new finger of the flow had branched southeastward west of the Koae road, and was advancing toward the gap between Kapoho Hill and Puu Kukii. That afternoon, in a meeting with William F. Quinn, Governor of the State of Hawaii; Gen. F. W. Makinney, Director of the Hawaii Civil Defense Agency; T. K. Cook, Chairman of the Board of Supervisors of the County of Hawaii; Richard Lyman, State Senator and Manager of the Lyman Estate (on which the eruption was largely located); and other officials, it was decided to try to prevent the lava from spreading laterally into the area south of a line from Kapoho Hill to Cape Kumukahi, in which were located the Kumukahi lighthouse and the residences of the lighthouse keepers, the Kapoho School and school residences, and the Kula and Kapoho Beach Lots. For that purpose, walls were constructed along the lines shown on the map (fig. 2). The walls are described later.

Just before midnight on January 18 lava broke out near the top of the cinder cone that had been built around the fountains, and a very rapid flow coursed down the south slope of the cone into the valley between the cone and Kapoho village, and turned eastward. The overflow at the cone lip was 12 to 15 m wide, and lava poured through the gap at about 40 km per hour. By 01.30 on January 19 the flow front had advanced eastward about 300 m along the valley, and was approaching the base of wall 2, which was still under construction. On the morning of January 20 the lava of this flow and another overflow from the main river just east of the cone was against the western part of wall 2 for a distance of 245 m, but was almost stagnant. By the morning of January 21 it had advanced only about another 30 m along the wall, though its top was standing in places 1 to 1.5 m above the wall.

The north side of the flow remained essentially unchanged from January 17 to 20, but on January 21 lava began advancing northward into the forest seaward of the road. On the afternoon of January 22 the flow margin farther west also became active, and moved northward into Koae village, destroying several buildings on January 23. Northward encroachment continued irregularly until about the end of January.

By January 21 the cinder and pumice cone was about 55 m high, and 200 × 300 m across at the base. During the night of January 21 a new vent opened on the west side, and an irregular spattery fountain commenced buiding a steep-sided spatter cone against the end of the gentler-sloping cinder cone. On January 22 a broad pool of liquid had formed on the top of the lava flow north of Puu Kukii. That night a new flow tongue branched southward just east of the cone, and by 05:00 on January 23 it reached the eastern end of wall 2 (fig. 2). This tongue piled up against the wall and moved westward along it toward the edge of the earlier flow. Lava had also been moving slowly toward wall 2-A, and on the morning of January 23 came against it. By 09.30 the top of the flow stood 1 to 1.3 m above the wall, and at 10:30 lava started to spill over the wall. By late afternoon it had spread over wall 2-A, and reached the foot of wall 4. Another tongue was advancing rapidly toward wall 3, northwest of the lighthouse keepers' residences. This tongue came against wall 3 on January 24, turned, and followed the wall eastward. By midnight of that day it had moved eastward along the wall about 900 m. On the morning of January 25 the front of the flow had reached a point northwest of the lighthouse, about 360 m from the ocean, but was stagnating. Along much of the course of the wall the top of the flow was slightly above the wall.

On the afternoon of January 25 lava was against practically the whole length of wall 2, and had overflowed wall 2-A and made contact with wall 4.

During the night of January 25 a small overflow of lava occurred along wall 3 near the lighthouse residences, but by 09:00 on January 26 it was essentially stagnant. Bulldozers were still adding to the wall. By the morning of January 26 lava had piled up to the top of wall 4, and at about 08.30 a little tumbled over the wall. Movement then stopped temporarily.

At 09:30 on January 26 a crack opened across the Koae road 8 m south of the Kapoho road junction, about 230 m north of the Kapoho School, and by 10:30 it was about 30 cm wide. It extended east-northeastward up the western slope of Puu Kukii. Another zone of cracks opened parallel to the first, just north of the road junction. Between these two fracture zones the ground surface dropped irregularly, from 15 to 30 cm. A circular hole about 2.5 m across and 3 m deep caved in along the northern zone about 45 m east of the road, and shortly before 11:00 steam started to issue from it. By that time the main crack in the southern zone had opened and the sides caved in to form a yawning chasm 1.5 m across, and many other cracks were forming between the two main zones. Between that time and 14:00 cracking spread on southward to the base of wall 5, and steam poured abundantly from many of the cracks. The situation appeared so precarious that the bulldozers which had been working in the steaming cracked area were moved to the south side of the wall. At 15:00 the hole along the north zone of cracks had increased to about 6 m in diameter and red lava could be seen in it about 2 m below the surface.

For 3 hours early on the morning of January 27 construction of wall 5 had to be halted and the bulldozers moved out of the area because of a heavy fall of cinders, some of them red hot, in the region around Kapoho School.

By the early morning of January 27 lava was standing 1.5 to 3 m above the top of wall 2 along much of the length of the wall. About 07:00 it started to overflow the wall at a point midway along it. Lava was also standing as much as 2 m above the top of wall 4, and during the morning started to spill over it and advanced across the Kapoho road near the junction with the Koae road.

For several days the lava fountains had ranged from 75 to 250 m high, and had produced a large amount of pumice. The main cone had attained a height of about 75 m. South to southwesterly winds had blown much of the pumice, and some heavier cinder, to the north and northeast, building a long ridge extending northeastward from the main cone almost to the location of the former Koae road. This ridge reduced the flow of lava northward, and contributed to the southward spreading of the flow.

At 21:45 on January 27 the lava fountains suddenly stopped, but at 21:53 they started again. At 22:32 a loud explosion accompanied an outbreak which threw a shower of red-hot lava fragments 30 to 60 m in the air about 300 m east of the former main fountain. This place was approximately the location of the easternmost fountain during the first night of the eruption. A lava fountain immediately developed at that point, but remained small, generally less than 30 m high. Within the next few minutes a larger fountain, 100 to 150 m high, developed quietly just to the northwest. At 23:30 these two fountains, and 3 fountains in the main cone, were very active. Voluminous tongues of lava were diverging southward from the main flow just east of the cone and advancing toward the east end of Kapoho village and the Kapoho School. At 03:00 on January 28 lava had reached the foot of wall 5, which was still under construction. The zone of cracking that had developed in the vicinity of the Kapoho intersection on January 26 had become reactivated, and extended eastward across Puu Kukii, and the ground surface on the east side of the hill had started to cave in at some places.

At 04:10 a short-lived outbreak, with a row of low lava funtains, occurred on the line of the other vents approximately over the former Koae road.

Between 04:30 and 05:00 on January 28 the ground surface just north of the eastern end of wall 5 began to bulge upward. By 05:00 the top of the bulge stood 3 m above the top of the wall, and the bulging had spread eastward beyond the wall. A small lava fountain broke out just north of the wall, and threw sporadic showers of incandescent cinder and ribbon bombs to a height of 10 or 12 m. This continued for only a few minutes. The south side of the upheaved area was broken by faults, and one fault scarp crossed the wall and ran almost along its southern base, exposing the edges of prehistoric pahoehoe lava flows beneath the wall. Above this scarp the wall was elevated bodily, unbroken, as much as 790 cm. At 05:10 lava started to pour out of a tube in the prehistoric pahoehoe in the scarp at the south foot of the wall, 15 to 25 m from its east end. The lava was very fluid, but contained little gas. The lava spread rapidly southward, and destroyed the Kapoho School during the morning.

Upheaval across the eastern end of wall 5 continued. The bulge north of the wall took the form of an oval hill, 12 to 15 m high above the former ground level, and 6 to 7.5 m above the top of the new lava flow north of it. On its top trees still stood in position of growth. The northern slope of the hill was covered by a thin sheet of new lava, pushed up along with the old lavas beneath it. Just south and east of the eastern end of the wall a second hill was formed by upheaval of the lower slope of the Puu Kukii cinder cone. This hill was split open, a 10-centimeter dike intruded into it, and a thin sheet of lava was poured out, veneering the old cinder on the slope to the west. Minor explosive activity threw a few ribbon bombs over the adjacent surface. Later, a narrow graben formed, dropping part of the lava veneer about 2.5 m., and further upheaval elevated the side of the hill south of the graben an additional 5 to 10 m, revealing the thin dike on the south side of the elevated block. The top of the bulge attained a height of about 21 m above the former ground level. A portion of an old road remained on the south side of the bulge, 12 to 15 m above its former position, and tilted 30° southward. At some time between January 28 and 31 weak steam blasts scattered old cinder over the surface of the new lava flow south of the bulge.

The upheaval of the ground must have resulted from a small laccolithic intrusion at very shallow depth. The nature of the laccolith and overlying vent is open to some question. The gas-poor condition of the lava suggested that the vent might have been a secondary one, fed by lava draining through an old lava tube, or other openings, from the main vent about 1 km to the west-northwest. However, in view of the general east-northeastward course of flows in this area, a tube with an east-southeast trend is somewhat improbable. The line of fracture on which the vent developed is a major one, coincinding essentially with the ancient eruptive fissure on which Puu Kea and the row of cinder cones to the west were formed (fig. 2), and extending eastward into a fault scarp that continued from the south side of Puu Kukae toward Cape Kumukahi. Opening of the fissure was clearly indicated by distension of the ground surface, with cracking and graben formation in the zone from the Kapoho-Koae road junction eastward across Puu Kukii on January 26 and 27. Two other small outbreaks on later days were at least approximately on the same line of fissuring. From these facts, it appears to me that the vent almost certainly was a primary one, fed directly from depth. The fissure may have tapped the magma reservoir somewhat below the top, and therefore brought up lava poorer in gas than that issuing at the main vent. At any rate, whether it was primary or secondary, the vent liberated a lava flow on the south side of wall. 5.

During the afternoon of January 28 a small lava flow started from a vent on the west side of the spatter cone that had built against the west end of the main cone. Through that night and the next day it spread across a hollow west of the cone and threatened to spill over a low divide into the western end of Kapoho village.

At 06:40 on January 29, Arthur Lyman reported a lava fountain 6 to 8 m high a short distance north-northwest of the Kumukahi lighthouse, approximately at the point marked by one of the X's on the map (fig. 2). The fountain lasted only a few minutes, but lava continued to pour out of the vent, joining the general flow to the sea

During the night of January 29 lava started spilling over wall 3 in the area between the lighthouse residences and Puu Kukae, and entered a gully just south of the wall. It had been hoped that this gully would contain and channelize any small amount of overflow. It behaved as anticipated, and for the next 3 days the lava that overflowed the wall was directed eastward past the residences and lighthouse. Throughout this period the major part of the flow moved eastward north of wall 3, into the ocean north of Cape Kumukahi.

At 03:00 on January 30 Albert Wilson, Civil Defense Warden, observed the beginning of a new flow from a fissure in the southwest base of the cinder cone. This flow moved southward, destroyed one house in Kapoho village, and threatened others before it came to a stop the next day. The flow west of the cone also had stagnated.

On January 31 the edge of the main flow was crowding southward in the eastern part of the village, destroying houses and piling up a greater depth of lava behind wall 5.

By February 1 lava had accumulated to so great a depth along wall 3 that the top of the wall was completely hidden. Most of the flow from the main cone was moving eastward and southeastward around Puu Kukae toward the western part of wall 3. More and more lava was spilling over the wall west of the lighthouse residence, and moving sluggishly eastward along the gully. The latter had become overfilled, however, and in places the lava was edging southward from it. Two small tongues had crossed the road between the lighthouse and the residences, and a larger tongue had crossed about 400 feet west of the residence.

During the night the latter tongue advanced toward the lighthouse residences and the head of Waiakaea Bay. The residences burned at 08:30 on February 2, and by mid-morning half of the pond at the head of Waiakaea Bay had been filled. On the afternoon of that day the lava reached the mouth of the bay and turned southward along shore toward the Kapoho Beach Lots. This along-shore moment resembled that earlier, north of Cape Kumukahi. It was guided partly by a « reef » consisting of a ridge of lava an eighth of a mile or so off shore, and old fishpond walls drowned by subsidence of the coastline in 1868. However, these obstacles were so slight that is seems probable that much of the change in course of the flow must again be attributed to chilling of the flow front where it entered the ocean. By the morning of February 3 the flow front was in the northern edge of the Kapoho Beach Lots, 0.8 km north of Kapoho Point.

About 09:00 on February 3 a disturbance consisting of steaming and moderately strong turbulence was observed by a National Guard pilot and members of the staff of the Hawaiian Volcano Observatory in the ocean about 600 m northeast of Cape Kumukahi (X, in fig. 2).

This disturbance may have resulted from entrance of water into the hot lava flow beneath the ocean, though no similar disturbances were noted even where glowing red lava could be seen beneath the water. It is more probable that it was caused by a small eruption on the sea floor. The location was on a line passing approximately through the site of the small lava fountain that was observed by Arthur Lyman northwest of the lighthouse on the morning of January 29, and the vent at the east end of wall 5. The latter lay on a known eastnortheast-trending fissure, and it is probable that all three localities lay on the same fissure. Despite their smallness and paucity in gas, it is more probable that these outbreaks mark primary vents than that they represent merely secondary, rootless vents fed by movement of lava from the vents near Kapoho village through lava tubes near the surface in old pahoehoe flows.

On February 3 and 4 it was possible to cross the flows to the southern edge of the gap through which the lava was draining eastward from the cone. The main fountain ranged from 50 to 100 m high. West of it a smaller fountain was throwing showers of cinder barely above the rim of the spatter cone. A pool of lava in the main fountain pit was draining eastward over a sill, forming a cascade 3 to 5 m high and about 15 m wide. On the afternoon of February 4 the speed of flow across the sill was estimated at about 30 kilometers per hour, and the depth of the stream as 0.5 to 1 m. These figures correspond to a discharge of lava of 5 to 10 million cubic meters daily. Below the cascade the river slowed up and began to spread out into an oval pond approximately 1 km long and 0.5 km wide. From this pond lava was still flowing strongly into the ocean just north of Cape Kumukahi, and less abundantly at several points between there and Kipu Point and at Waiakaea Bay, but flow fronts in the Kapoho Beach Lots were essentially stagnant. Lava was still oozing from the vent at the east end of wall 5, and the flow front in the Kapoho School area was spreading slowly. This condition continued through February 5, when the school flow also became stagnant.

At about 15:00 on February 3 a small fountain broke out on the west flank of the spatter cone, and another flow started to spread over the flat west of the cone. This flow was still active the next morning, but stopped during the afternoon. At 22:00 on February 5 a row of small lava fountains broke out along a fissure extending westward from the cone, and sent a flow southeastward toward Kapoho village. This activity ended at 05:00 the next morning.

During the night of February 5 the main fountain occasionally reached a height of 200 m. At 05:30 on February 6 fountain activity practically stopped, and only weak spattering was visible. Early in the afternoon the fountain activity gradually resumed, and by late afternoon a single fountain was reaching a height of about 30 m. By the morning of February 7 the fountain was as much as 60 m high, but there was little evidence of flow of lava out of the cone.

For the next several days the fountain activity was very weak and irregular, with little or no sign of any new lava being added to the flow. Drainage of fluid lava from the interior of the flow into the ocean continued, however, and the top of the central part of the flow, formerly occupied by the big lava pond in the area north and northwest of Puu Kukii, sank as much as 10 m.

About 16:45 on February 10 a series of loud explosions, lasting about 3 minutes, threw ash and cinder 600 m in the air, accompanied by much steam. Smaller explosions continued intermittently during the night and on the morning of February 11, and incandescent cinder was occasionally thrown 30 to 60 m above the cone rim. At about 16:00, the main fountain increased to about 120 m in height, and a smaller one appeared in the vent to the west. The fountaining continued to increase in height and violence, and by 01:30 on February 12 a semi-explosive gas jet was throwing black pumice and cinder to a height of 180 to 250 m., accompanied by minor amounts of incandescent material. By daybreak, however, the main fountain was only 60 m high, with a fountain only 7 to 15 m high to the west of it. Little or no lava was being poured out; the activity was essentially only gas liberation. Through the day clouds of steam, black from their load of ash and fine pumice, accompanied mild explosive bursts.

On February 13 the explosive bursts were stronger, and a new cone of loose cinder and ash grew to a height of 60 m around the main vent. Through most of February 14 there was no lava fountaining and very little explosive activity, but at 18:15 a billowing black cloud of steam and ash shot up, and immediately afterward a lava fountain appeared that threw glowing cinder to a height of about 250 m. By 19:30 the fountain had died down again to 30 to 60 m.

Activity of a similarly variable nature continued for the next several days, with the cinder cone growing slowly to a height of 110 m. Fine cinder and ash was carried up as much as 1200-1500 m in the convection column above the volcano. No lava could be seen leaving the vent, but several small streams of liquid lava poured quietly into the ocean, and this together with continued harmonic tremor on the seismographs suggests that lava was still rising in the vent and draining away beneath the surface of the flow.

About 17:30 on February 18 the vent started to roar loudly, but about 18:30 it became quiet and activity essentially ceased. Then suddenly a ball of burning gas rose from the crater, followed by a billowing black cloud of ash, and the lava fountain resumed, shooting to 250 to 300 m. At 22:50 part of the western rim of the spatter cone around the smaller western fountain broke down, releasing a flood of lava that spread over the area just west of the cone. This overflow, which produced the first surface flow of lava for more than a week, ended before midnight.

At 07:30 on February 19 a dense black eruption cloud deposited wet ash over the Kapoho village area. Voluminous ash and cinder emission continued for 2 hours, ending about 09:30. During the rest of the day clouds of steam lightly laden with ash rolled gently out of the vent from time to time, but there were no more explosions.

On the morning of February 20 steam and fume emission was light (fig. 9), no liquid lava was present in either crater, and the cone was beginning to collapse. The eruption was over.

Volume and nature of the lava

The early lavas of the eruption were tholeiitic basalt containing numerous small phenocrysts of labradorite, but only a few small phenocrysts of olivine. The abundance of olivine phenocrysts increased more or less regularly through the eruption, and in the last-extruded lavas they constitute on the average about 15 percent of the rock. Gravitative settling of olivine phenocrysts occurred in some places and locally the rock is a picrite-basalt of oceanite type containing as much as 30 percent olivine phenocrysts. According to Richter and Eaton (1960, p. 997), the change in composition was accompanied by an increase in the temperature of the erupting lava, from about 1050° C. during early stages to 1130° during the last week of strong lava extrusion. It is noteworthy that the olivine content of the lava erupted from the minor vent at Puu Kukii on January 28 was distinctly richer in olivine than the lava erupted contemporaneously from the main vent.

Cinder, spatter, and pumice accumulating around the main vent built a cone 1,000 meters long, 300 meters wide, and approximately 110 m high above the former ground level. At the end of the eruption the summit of the cone was indented by a row of seven craters, some of them partly coalescing, and the easternmost breached toward the southeast.

The total volume of lava erupted was approximately 113 million cubic meters. The flows covered an area above sea level of approximately 7 square kilometers, in many places to a depth of more than 15 meters. Approximately 1.4 square kilometer is new land, built out beyond the former shoreline.

Origin of the steam

The principal ways in which the 1960 eruption differed from most eruptions of Hawaiian volcanoes was in the large amount of steam given off (fig. 7 and 10), the greater than usual explosiveness, and the large amount of cinder and ash produced (fig. 11 and 12). The three unquestionably are closely related, and indeed, the last two features very probably are simply the result of the first. The abundant steam unquestionably was derived from the water that saturates the rocks of the region up to a level a little above sea level, only about 25 m below the original ground level at the site of the eruption. On the first morning of the eruption the steam contained a large amount of salt, indicating that saline water was being brought up from below the thin lens of fresh ground water (Ghyben-Herzberg lens; see Stearns and Macdonald, 1946).

Steam rushing from the vents carried with it cinder and ash torn from the throat of the cone, and probably to a lesser degree from the walls of the conduit beneath it. Very probably, the steam also contributed to the unusually gas-rich character of the lava fountain itself, which produced far more « spray » of liquid lava shreds than do most Hawaiian fountains, and therefore formed a greater than usual amount of cinder.

The relative explosiveness of the eruption made it in many ways intermediate in charcter between typical Hawaiian eruptions and such more explosive eruptions as that of Paricutin, in Mexico, which in general are characteristic of continental basaltic eruptions.

It is expectable that hot lava rising throuqgh the body of ground water will convert some water into steam. Indeed, the surprising thing is not that steam is generated, but that a great deal more of it is not evident during Hawaiian eruptions. Ground water is almost ubiquitous in the Hawaiian Islands, and ni nearly all eruptions the magma must rise long distances through water-saturated rock. Yet it is rare that any large amount of steam is visible during the eruption, though moderate amounts commonly appear after the eruption has ended. The only eruptions which do produce large amounts of visible steam seem to be those that take place at low altitudes, where the ground-water body is close to the surface. Except near the surface the eruptive fissure is generally blocked by liquid lava, and any steam must find its way upward by tortuous and partly water-filled channels through the adjoining rocks. During eruptions at higher altitude the steam may be largely condensed in the cool rocks before it reaches the surface. Only when free channelways are open to ground-water level, as during collapses that produce phreatic eruptions, and after eruptions when the lava is withdrawn from parts of the eruptive fissure near the surface, do large volumes of steam appear.

Even in eruptions close to ground-water level the amount of visible steaf commonly is small. This was the case through much of the 1960 eruption. Large amounts of steam appeared only when the molten lava was locally and temporarily withdrawn from the surficial part of the fissure.

The small amount of steam may be in part, if not largely, the result of an insulating cushion of steam formed in the water-saturated rock directly around the hot lava, preventing contact of any large amount of water with the heating surface. This appears to have occurred at an observable level during the 1950 eruption of Mauna Loa, when the red-hot surface of a lava river plunged directly into the ocean with very little generation of steam except when occasional large blocks on the surface of the stream disturbed the overlying insulating layer (Macdonald, 1954, p. 166, pl. 21). In 1960, great clouds of steam rose where the lava flows entered the ocean, but practically all of it came from the shoreline, where waves were breaking on the hot lava. Very little of it rose from the water off shore, even though at several times during the eruption several different aerial observers, some of them certainly reliable, reported seeing brightly incandescent lava beneath the surface of water only a few tens of feet deep without any large amount of steam being visible.

Effects of water on flow margins

Where a lava flow enters the ocean there appears to be a checking of its advance, presumably because of chilling and partial congealing of the flow margin. Both south of Kaoko Point and south of Cape Kumukahi flows entering the ocean turned and advanced along shore, instead of continuing straight onward, apparently at least partly because of the chilling of the flow margin.

Even much smaller amounts of water may have a decided effect on slowly moving lava. On several occasions during the eruption the Hawaii Fire Department pumped water on the flow margin, in an attempt to find out what could be accomplished thereby. It was found that in the case of a stationary margin it is possible to cool the flow surface enough to prevent radiant heat from igniting wooden structures only a few meters away. It was also possible to locally check the advance of a flow margin. Although the check is temporary, it is sometimes possible in that way to gain the short time — up to several hours — that may be needed to remove furnishings or other materials from a building, or even to remove the building itself.

Much adverse criticism was heard of the firemen, for directing hose streams onto the flow margins. The criticisms seem totally unjustified! Efforts of this sort, to find out what can be done, should be commended!

Proposed bombing of the flow

Twice, in past years, lava flows of Mauna Loa have been bombed in efforts to divert them into different courses. The method appears to be legitimate under some circumstances (Finch and Macdonald, 1951, p. 128-131; Macdonald, 1954, p. 148-150), and it was suggested by several persons that it be tried during the Kapoho eruption. Actually, however, the situation was almost the reverse of that in which bombing can be useful. Bombing is employed to break down the walls of lava channels high on the mountainside, and clog them, causing the lava to spread there, thus reducing or eliminating the supply of liquid lava to a flow front advancing farther down on the flank of the mountain. At Kapoho, the lava was already spreading along the upper margins of the flow. It was desired to keep it from spreading, not to increase the spread. It was suggested that bombing near the shoreline might open up channels and allow the lava to flow more freely into the ocean, thus reducing its tendency to spread laterally. The idea was rejected because we could not identify any definite blocked channels the opening of which might accomplish the desired result, and because it appeared at least equally probable that indescriminate bombing might further clog what channels did exist and make the situation worse rather than better.

Events in the summit region

Eruption on the flank of the volcano was accompanied by sinking of the ground surface in and around the caldera, 40 kilometers to the west. Rapid tumescence of the volcano, indicated by measurements of ground tilting, had started just before the summit eruption in Kilauea Iki crater in mid-November, and continued following that eruption. By early January the Kilauea shield was markedly inflated (Eaton, J. P., press reports).

Reaction in the summit region did not commence immediately with the flank outbreak. For a few days there was little indication of change. By about January 19, however, sinking of the summit had started, and it continued throughout the eruption, accompanied by very numerous small to moderate earthquakes. On January 25 J. P. Eaton reported that the amount of sinking to that date equalled approximately half the swelling that had preceded the eruption (Honolulu Advertiser, Jan. 26, 1960).

On January 28 an ash-laden steam cloud was emitted from the 1959 vent in Kilauea Iki crater, probably as a result of subsurface cracking that admitted ground water to the still-hot conduits that had fed the 1959 eruption. The sinking also produced cracking beneath the main caldera area, and on February 5 dense steam clouds issued from Halemaumau crater. On February 7 the whole floor of Halemaumau crater suddenly sank, producing a broad basin about 40 m deep at the center surrounded by slump scarps up to 15 m in height. Within this there was formed an inner pit about 100 m across and 45 m deep. Lava drained from beneath the surface of the former crater floor into the inner pit, filling it to a depth of about 25 m. Dense clouds of steam and dust that filled the crater during the collapse made visibility very poor, but observers on the staff of Hawaii National Park report that the lava poured out quietly, without fountaining, and was cherry red in color. Trickling of lava into the pit continued until February 8.

No changes had been observed on the floor of Halemaumau that suggested any shallow intrusion of magma during the 1959-60 period of tumescence, and it appears almost certain that the lava that drained into the new pit had remained liquid at least since the 1954 eruption, and more probably since 1952. During the eruption of that year a deep lava lake was formed, and during later stages bodily elevation of the whole crater floor indicated injection of fluid magma beneath the floor (Macdonald, 1959, p. 28). Some of the latter appears more likely to have remained fluid for several years than does the thin layer, only 15 m thick, poured over the floor in 1954.

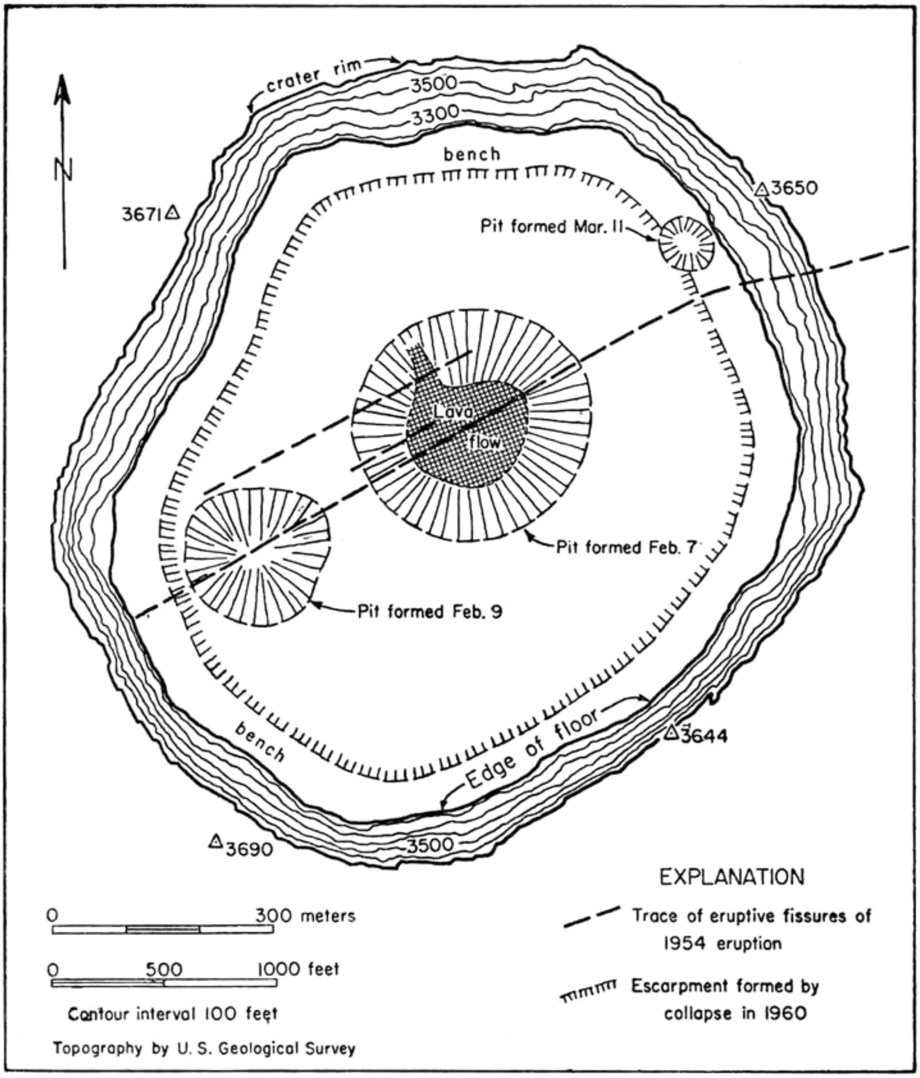

Fig. 3 - Map of Halemaumau crater, showing the position of the pits formed by collapse during February and March, 1960, and their relation to the eruptive fissures of the 1954 eruption.

On February 9 a second collapse formed another, smaller pit on the floor of Halemaumau just southwest of the first, but no additional drainage of lava was observed. The two craters lay approximately on the line of the 1952 and 1954 eruptive fissures. Heavy intermittent steaming continued at Halemaumau, but there was no further apparent collapse of the crater floor until March 11. On that day a third pit, about 60 m across, was formed at the base of the north wall of Halemaumau somewhat west of the 1954 eruptive fissure. The depth of the new pit was estimated by D. L. Richter, geologist of the Hawaiian Volcano Observatory, to be about 110 m (oral statement, March 11).

Despite the collapse on the floor of Halemaumau, the center of sinking in the summit region as a whole appears to have been a point somewhat northeast of Halemaumau (Richter and Eaton, 1960, fig. 2B), just as it was in 1955 (Macdonald, 1959, p. 58), and in 1950 (Finch and Macdonald, 1953, p. 86). It appears most likely that this general subsidence is related to deflation of a magma chamber at a depth of a few kilometers beneath the summit of the shield. In contrast, the localized collapse within Halemaumau probably resulted from withdrawal of magma from the still-fluid lower portion of the lava lake of the 1952 eruption and from small feeders of recent eruptions, probably of dike form, that were still liquid to a level very close to the surface.

Construction of dams to prevent spreading of lava

General plan. - As already pointed out, the walls constructed during the 1960 eruption were dams, not diversion barriers. For a diversion barrier to operate successfully there must be sufficient slope of the land surface to provide a reasonable flow gradient in the channel behind the barrier. Because the barrier must extend diagonally across the slope, the gradient in the diversion channel is necessarily less than the original slope of the land surface. In the Kapoho area the original slope was in most places too small to provide a good flow gradient. This was, indeed, the cause of the lateral spreading of the flows it was desired to prevent. Consequently, it was not practical to attempt the construction of diversion barriers.

However, the eruption was in the shallow trough of the Kapoho graben, and along the south side of the trough the Kumukahi ridge and the cinder and tuff cones on top of it formed a natural obstacle to the southward spreading of the lava flow. Furthermore, in the western part of the trough the initial slope of the ground directed the flow northeastward. It appeared possible that by raising the level of the lower parts of the natural barrier along the south side of the graben the southward spreading of the lava could be checked, or at least lessened, and the flow directed eastward into the ocean.

It should be remembered that in order to flow southward the surface of the lava flow must have a gradient in that direction. If the level of the south edge of the lava could be raised enough in relation to the surface of the flow farther north, the southward gradient would be too small to permit flowage in that direction. It was to be expected that, considering the flatness of the pre-eruption terrain, the lava would fill the Kapoho depression by the spreading of a series of flow units and tongues, the earlier of which would to some extent obstruct the movement of the later ones. It the eruption continued, later tongues would override earlier ones. Nevertheless, the general requirement of a southward gradient to permit southward spreading of the lava would remain. As Sen. Richard Lyman aptly expressed it, the situation was akin to slightly raising one rim of a cup full of liquid, causing any overflow that takes place to move in another direction.

Because of the low slope of the land surface, and because the direction of approach of the lava to the walls would be essentially at right angles to the line of the wall, the latter would operate in general as dams, not diversion barriers. As dam builders are well aware, if the depth of confined liquid behind any dam becomes too great, the liquid will overflow the dam. From the beginning, it was recognized that if the depth of lava behind the Kapoho dams became great enough, overflow would occur. A minor amount of overflow would cause little trouble, but a major overflow would spread on southward into the area it was desired to protect. In a sense, we were fighting against time. If the eruption continued long enough the lava in the depression was certain eventually to become deep enough to spill over the dam. On the other hand, if the extrusion of liquid stopped before the level of the lava became too high, overflow of the dams would not occur; and even if overflow did take place, the amount of lava moving southward would be reduced and the resultant damage lessened.

Along the south side of the flow the cinder cones supplied points to which to anchor the walls, and the Kumukahi ridge provided a natural barrier that could be increased by a reasonable amount of construction to a height that might be effective in preventing the lava from spreading. The possibility of dams on the north side of the flow, to protect the village of Koae, also was considered, but conditions on that side were far less favorable. The initial ground slope in the western part of the depression directed the flow northward toward Koae. The only good natural barrier was the Koae fault scarp, and that had already been overflowed before any wall construction could be started. The next natural barrier was the rather broad low ridge 0.6 km farther north, — too far north to provide protection for most of the village. For these reasons construction of walls on the north side of the flow was not considered feasible.

The construction of the individual walls is described on the following pages. Table 3 shows the approximate dimensions and volume of the walls, and their location is shown in figure 2. The material used in the construction was whatever was available to the bulldozers, except that an attempt was made to avoid the use of large amounts of light material, such as ordinary cinder. Most of the material was angular fragments of lava rock, though minor amounts of soil and vegetation were included, and locally some cinder. At two places the walls consisted largely of cinder, because adequate supplies of better material could not be obtained in the time available. The lava fragments consisted of both aa and pahoehoe. Aa clinker is easily handled with a bulldozer, and the angularity and spiny character of the fragments cause them to bind well, making it the ideal material for construction of this sort. In contrast, pahoehoe and the massive central layer of aa flows generally cannot be handled without prior ripping. In the Kapoho area aa clinker was far too sparse to supply the material needed for the walls. The great majority of the material emplaced had first to be torn up with rippers. The total volume of rock ripped and pushed into the walls by the bulldozers between the evening of January 18 and the morning of January 28 (9 ½ days) was in excess of 300,000 cubic meters !

Wall 1. - On January 16 lateral tongues of the lava flow were advancing southeastward toward the Warm Spring resort area. There appeared to be a very slight possibility that, provided the eruption ended soon, a wall north of the area would hold back the edge of the flow enough to cause the main volume to flow eastward past the resort. It was recognized that the chance was very slim, but the lessee of the resort decided to take that chance in an effort to save it from destruction. This wall was built entirely by private enterprise, not by any Government agency.

Table 3 - Data on walls built during the 1960 eruption.

Wall number	Length (meters)	Average height (meters)	Average width of base (meters)	Volume (meters^3)
1	400	3.6	7.6	10,500
2	810	6.7	30.5	70,000
3	2,295	5.2	24.4	153,000
4	305	6.7	25.9	26,400
5	565	7.6	30.5	53,400
6	150	1.5	6.1	660

The logical line for construction was the northern edge of a roadbed that had recently been constructed along a low ridge just north of the swale in which Warm Spring was located. Permission to build could not be obtained immediately, however, and by the time it was received the edge of the flow had at one place already passed the roadbed and started into the swale to the south. At approximately 02:00 on January 17 construction of the wall was started by two D-8 and one D-7 bulldozers, joined shortly afterward by two more D-8's and 2 D-9's. Construction material was sparse, and much of it had to be torn up with rippers. For the most part, fragments of pahoehoe lava were used. At the point where the tongue of lava had already crossed the roadbed a large amount of material was needed in a hurry, however, and there cinder was used. This bulge in the wall, constructed with light material, caused constant trouble, and bulldozers had to be diverted repeatedly from work on other parts of the wall to reinforce this weak spot and prevent the lava from breaking through by pushing the cinder ahead of it. At this point the wall eventually reached a height of about 8 meters.

Work went on continuously until about 22:00 on January 17, at which time a wall had been built approximately 400 m long, averaging about 4 m high and 8 m thick at the base. The cross-profile of the wall was approximately symmetrical, the slopes resulting largely from the tumbling down of loose rock fragments.

Lava was already against the central part of the wall when construction started. Early in the afternoon of January 17 another tongue came against the wall almost at right angles near its western end, turned, and moved eastward along the wall. Temporarily, the wall acted as a diversion barrier. However, the advancing tongue soon encountered the tongue that was already against the wall, and being obstructed by it commenced piling up behind the wall. By 20:00 the level of the top of the flow was several feet higher than the wall, and overflow was beginning. Eventually the edge of the flow stood as much as 3 m above the wall, still with relatively little overflow. Except in the portions built with cinder, the wall had not yielded at all to the thrust of the flow. Elsewhere, failure was completely by overflow.

At about 20:00 it became evident that further construction was useless, and work was discontinued. Extensive overflow began about 22:00, and lava reached the Warm Spring area at about 01:30 on January 18, and invaded the spring itself the next morning.

Wall 2. - The most vital gap to be filled along the southern margin of the valley was that between Kapoho Hill and Puu Kukii. Lava spilling through the gap would destroy the Kapoho School, and be guided by the topography directly into the Kapoho and Kula beach lots. It might also endanger the lighthouse and light-keepers' residences by encroachment from the south. Because, in addition, the edge of the lava flow was closer to that gap than any other place along the crest of the Kumukahi ridge, construction was started there.

It was obvious that the most effective place for a wall was along the crest of the ridge between the two hills (along the line of wall 5, fig. 2). However, if lava reached that level and was further impounded by the wall, causing the flow top to rise to a level higher than it would have reached if the flow had remained unobstructed, this might result in the inundation of parts of Kapoho village that would not have been inundated if the wall had not been built. Because of that, the wall could not be constructed without either legal releases from all property owners that might be affected, or appropriation by the State Government of the property involved. Neither of these things could at first be obtained. As an alternative, it was therefore decided to construct wall 2. The reasons for wall 2 were: (1) it was hoped that possibly even this low-level all might raise the level of the south edge of the flow in that area sufficiently to cause the lava to move eastward past Puu Kukii rather than southward through the gap; and (2), to delay the advance of the lava toward the gap sufficiently so that wall 5 could be built later if it proved necessary and permission was received to do so. Without wall 2, lava might advance so rapidly toward the gap that there would not be time to build wall 5. This fear was born out by later events.

The line actually chosen for wall 2 was determined partly by property ownership considerations, but largely by the fact that a wall at that level would be low enough so that it would not cause lava to back up over houses in the lower part of Kapoho village. During construction care was taken to keep the top of the wall at a level several feet below the lowest houses.

The most urgent threat appeared to be in the gap between Puu Kukii and the small cinder cone 0.3 km to the west (wall 2-A, fig. 2). Construction was started there with two bulldozers at about 16:30 on January 18. Two more arrived soon afterward, and others joined the work throughout the night. By the morning of January 19 a total of 24 bulldozers was on the job, five of them D-9's, and the rest D-8's and TD-24-s.

By 18:00 on January 18 a tongue of lava had started advancing rapidly toward the area west of the small cinder hill, and part of the bulldozers were moved to that area. The first construction was done by pushing material to the line of the wall from the zone just north of it. This made it possible to use the available material on that side of the wall before it was covered by the advancing lava; and also, by excavating, to increase the effective height of the wall on that side. (This excavation is of little or no importance in a wall intended to act as a dam, although it is important in the case of a diversion barrier in helping to create a channel for the flow to follow). Later, the bulldozers were moved to the south side of the wall and construction was finished with material from that side. At the west end the wall was built on top of a north-facing embankment about 3 m high.

Just before midnight a flood of fast-moving lava poured down the south side of the cone and eastward toward wall 2. By 01:30 on January 19 the lava was against the embankment beneath the west end of the wall, and by daybreak it had risen against the wall itself.

Bulldozers continued building the wall from the south side. So narrow was the time margin in the construction of this wall!

By the morning of January 19 a low pioneer wall (2-A) had been built most of the way across the gap between the small cinder hill and Puu Kukii, and because the flow margin in that area had stopped moving, all of the bulldozers were concentrated west of the hill.

On the morning of January 20 lava had come in contact with the westernmost 250 m of wall 2, and was still advancing slowly. Building of the wall continued. By that night most of the wall averaged about 8 m high (fig. 13), measured from the old ground level, and the width of the base was about 30 m. Because most of the construction was done from the south side the cross profile was somewhat asymmetrical, with the south side sloping more gently than the north side. Most of the wall was built of fragments of lava rock, but just west of the small cinder hill part of it was constructed with rather heavy cinder. In the latter area the wall was left low and incomplete, with the plan that if an overflow of the western end of the wall sent a tongue of lava down the depression south of the wall before lava reached the eastern end, the eastern cinder-built portion could be pushed back into a wing wall that might guide the flow back northward through the gap. If, on the other hand, lava first approached the eastern end, that portion of the wall could be quickly completed.

Extension of wall 2 westward, north of part or all of the village, was considered, but the idea was given up because of insufficient space in which to work, and inadequate construction material available locally. By January 20 the edge of the flow was only about 70 m from the edge of the village. Nearly all the material for the wall would have had to be hauled in trucks, and the only material readily available in sufficient volume was cinder, too light for effective lava-barrier construction.

During the night of January 22 a tongue of lava started to advance toward the east end of wall 2, and the gap in the wall was closed. By 05:00 on January 23 the lava was against the east end of the wall, and moving westward to close the space between it and the earlier flow (fig. 14). The westward, up-slope movement of this flow illustrates the very low gradient of the land surface north of the wall.

On the same morning lava came against wall 2-A, and by 09:30 the edge of the flow was standing as much as 1 to 1.5 m above the top of the wall. This wall was still low, averaging only 4 to 5 m high, and with a narrow base. A small amount of work was done to raise and strengthen the wall, but it was considered useless to build it much higher because it terminated eastward against the edge of a cinder pit at the base of Puu Kukii which would allow the lava to pass the eastern end of the wall and fill the pit, the southern rim of which was only at about the same altitude as the top of the wall. Instead, work on wall 2-A was abandoned, and construction of wall 4, at a higher level south of the cinder pit, was begun.

By 10:00 lava was standing more than 1 meter above wall 2-A in the vicinity of the Koae road. Just east of the road the wall was displaced slowly southward 1 to 1.25 meters over a length of about 6 m by the thrust of the lava, though lava did not actually push through the wall. At that place the wall was unusually thin and steep, probably only about 8 m broad at the base. Lava started to spill over the wall at about 10:30, first near the road, and then near the small cinder hill (fig. 15). The lava pouring over eroded the wall by picking up and carrying away the loose rock fragments. This erosive action cut gaps in the wall that greatly augmented the amount of lava crossing the wall.

Lava continued to accumulate behind wall 2 west of the small cinder hill, and by the morning of January 27 the edge of the flow stood 2 to 3 meters above the top of the wall. Overflow of the wall then started, and the hollow south of the wall was slowly filled with lava. The overflow produced very little erosion of the wall, probably because the lava moved slowly down the gently sloping south flank of the wall. In spite of the great depth of lava impounded behind it (about 12 m), the wall showed no signs whatever of mechanical yielding.

It should be noted that if the eruption had ceased at any time previous to that date, wall 2 would have accomplished its purpose of confining the lava to the region farther north. As it was, the wall succeeded in delaying the southward encroachment of the lava long enough to permit wall 5 to be built.

Wall 3. - Construction of wall 3, along the top of the ridge from Puu Kukae to a point near Kumukahi lighthouse, began on the morning of January 21. This wall varied somewhat in height, depending on the irregularities of the ridge. By the morning of January 24 the wall was approximately 2,300 meters long, and averaged 5.2 m high.

About 13:30 on January 24 a tongue of lava came against the wall just west of the lighthouse residences. The lava approached the wall almost at right angles, but on encountering the wall it turned and followed the north base of the wall eastward. Thus, temporarily this wall also acted as a diversion barrier. By midnight the flow had traveled along the wall for about 900 m, and along much of that distance the top of the lava was level with, or a little above, the top of the wall. On the morning of January 25 the flow became motionless, without having reached the ocean. The angle of approach, speed, and volume of this relatively fluid flow were such that it is quite probable that without the protection of the wall the lighthouse residences would have been destroyed on the night of January 24.

On January 25 bulldozers continued strengthening some parts of wall 3. During the afternoon and night new tongues of lava started advancing toward the wall between the residences and Puu Kukae, and the flow already against the wall continued to swell up as additional lava was forced into it. During the early hours of January 26 a small overflow commenced at a point about 300 m N 45° W of the residences. Bulldozers built a loop of wall around this overflow and succeeded in confining it. The loop was joined to the main wall and built to a height equal to it.

The voluminous outpouring of lava that commenced on the evening of January 27 sent a large amount of lava toward the western end of wall 3, gradually filling the hollow between the earlier flow and the base of Puu Kukae, and by the evening of January 28 lava was against nearly all of the wall and at many places was standing above it. During the night lava started spilling over the wall between Puu Kukae and the lighthouse residences. This lava entered a small gully between the wall and the residences and started flowing eastward along it. It had been hoped that if the volume overflowing the dam was not too great, this gully would contain it and divert it past the residences and the lighthouse, and at first it did indeed act in that way. As the lava continued to come over the dam, however, the gully gradually became filled to the point of overflowing. On the morning of February 1 lava was still moving slowly eastward along the gully, but two small tongues were diverging southward from it across the road between the residences and the lighthouse. Another tongue was moving slowly southeastward 500 feet west of the residences. The lava flow had become so thick that it had completely buried wall 3, no part of which was still visible from the air. General overflow of the wall was taking place, but by far the greatest volume of lava was still moving eastward north of the wall.

The tongue of lava west of the residences continued to spread, and increased in speed. On the morning of February 2 it destroyed the residences, and advanced into the pond at the head of Waiakaea Bay. By afternoon the bay was filled and the lava was advancing southward across the Kula Beach Lots, entering the Kapoho Beach Lots that night.

From February 1 to 3 most of the lava leaving the cone on the surface was flowing southeastward around Puu Kukae toward the west end of wall 3. The volume of outflow was estimated to be about 7,500,00 cubic meters per day. Just north of the wall, however, most of the volume turned eastward, forming a strong river that flowed east-northeastward north of the line of the wall and entered the ocean north of Cape Kumukahi. Thus, even though buried and overflowed, wall 3 was still contributing greatly to the eastward diversion of lava and reducing the destruction of property to the south.

Wall 4. - At the time lava started to overflow wall 2-A, on the morning of January 23, clearance had not yet been received to build wall 5. It appeared that if wall 5 were to be built, additional delay of the southward advance of the lava was necessary. At the same time, the additional wall might accomplish the purpose of permanently stopping the southward encroachment and make wall 5 unnecessary. For those reasons, construction of wall 4 was commendec at about 11:00 on January 23. The wall lay just north of the line of the Kapoho road, and extended eastward to the south edge of the cinder pit at the foot of the west slope of Puu Kukii. At the western end, it connected with the end of a north-facing fault scarp that trended toward the center of Kapoho village. The top of the wall was kept at or slightly below the level of the natural ridge south of it, so that it would not cause the lava to back up over any part of the village that would not have been inundated because of the effect of the natural topography. As finished, the wall was about 300 m long, and averaged 6.7 m high and about 26 meters thick at the base. Because it was designed largely as a delaying barrier, it was somewhat less substantial than is desirable for such walls. This was particularly true of its east end beyond the line of the Koae road, which was constructed in great haste, with insufficient time to work. Lava was already against this part of the wall about 4 hours after construction started.

The lava flow continued to accumulate and deepen behind the eastern end of wall 4, and to spread westward. By midday on January 26 it had filled the cinder pit at the east end of the wall and had reached the level of the top of the wall at places near the road junction. A small amount of lava had tumbled over the wall at about 08:30 that morning, but had not caused any trouble.

By 07:00 on January 27 the edge of the flow stood 1.5 meters, and locally more than 2 meters, above the top of the wall near the road junction, but no real spill- over had yet occurred. About 09:00 lava started to overflow the wall, and moved southward across the Kapoho road just west of the junction.

Walls 5 and 6. - Instructions to proceed with the building of wall 5 were received about 20:30 on January 25, as a result of a meeting at the Kapoho School participated in by Acting Governor James Kealoha; Attorney General T. Shigekane; General F. W. Makinney, Director of Civil Defense, State of Hawaii; John H. Felix, Administrative Assistant to the Governor of Hawaii; Ralph Burns, Director of the Natural Disaster Staff of the Office of Civil and Defense Mobilization; Edward R. L. Doty, Director of the Pacific Area Office, Region 7 Office of Civil and Defense Mobilization; Peter N. Pakele, Deputy Director of the Hawaii Civil Defense Agency; Wayne U. Ault, Geochemist of the U. S. Geological Survey; and the writer. At 21:00 construction commenced.

Several bulldozers were still working on wall 3. The rest began pushing rock from the north side onto the line of wall 5. This work continued until 14:00 on January 26, when the machines had to be shifted to the south side of the wall in the area near Puu Kukii because cracking and faulting of the ground and heavy steaming in that area made the situation dangerous for the machines and possibly for the operators. Work on the wall was continuous except for about 3 hours on the night of January 26, when a heavy fall of hot cinder made it necessary to move the equipment to a point farther south.

Lava reached the north base of the wall at approximately 03:00 on January 28. Work on the wall continued. About 04:30 the ground surface at the east end of the wall started to heave upward, and a new volcanic vent was formed directly beneath the wall. This vent has already been described. The wall above the vent was pushed up

7.9 meters, but was not broken, and save for a minor amount of tumbling down of loose rock fragments from the lower part of the southern slope it was not even deranged.

At 05:10 lava started to pour out of the vent at the south base of the wall and spread rapidly toward the Kapoho School, and at about 05:30 work on wall 5 was discontinued. At that time the wall was 567 meters long, averaged about 10 meters in height, and was approximately 30 meters thick at the base. It and wall 2 were by far the best built of the walls.

The opening of a vent south of the wall was not, and could not have been, anticipated. The outpouring of lava from it south of the wall in no sense represents a failure of the wall.

By 07:40 the lava flow from the vent south of the wall was approaching the Kapoho School. There appeared to be a slight possibility that the lava could be held back from the school and caused to flow eastward into the head of the gully south of wall 3. For that reason, at 07:42 several bulldozers started to build a low eastward-trending wall between the flow and the school (wall 6, fig. 2). The edge of the flow was only 23 m from the closest school building, however, and because of inadequate working space the material for the wall had to be heaped very close to the advancing lava, and at places directly against it. Construction material was scarce and difficult to obtain, and progress on the wall consequently was slow. By about 09:00 the lava behind the wall was growing in depth faster than the wall was increasing in height. It was apparent that further construction was useless, and work was discontinued. Lava soon overflowed this low wall, and the school burned during the morning. A large portion of the lava moved eastward, however, undoubtedly in part because of the wall. Without this initial eastward deflection of the lava, during the ensuing days the flow might have spread considerably farther southward and constituted a more serious menace to the Kapoho beach lots.

Lava came against wall 5 first near its eastern end, the toe of the flow turning and advancing westward along the wall. By 09:00 on January 28 the lava had nearly reached the western end of the wall at the base of Kapoho Hill (fig. 16). Over the next several days the lava against the wall continued to deepen, until on February 3 the edge of the flow stood as much as 1.5 m above the top of the wall, but without spilling over. By the morning of February 5 the edge of the flow top was as much as 2.5 m higher than the wall.

Fragments of a clinker had tumbled down on the south side of the wall in some places, but still no real overflow had occurred. At no time, either before then or afterward, did the wall show any indication of yielding before the thrust of the lava.

On February 5 lava extrusion resumed at the base of the east end of the wall, and the flow spread westward along the wall as well as in other directions. Over the next two days small amounts of lava from the flow to the north spilled southward over the wall. The flow south of the wall also gradually grew deeper until it also overtopped the wall, and in places small amounts of lava poured northward over the wall. The wall thus was engulfed from both sides, until finally it was almost completely buried, and the lava surface stood as much as 3.6 m above the top of the wall. The line of the buried wall is still clearly visible, however, as the boundary between the flow from the north and the flow that emerged south of the wall and moved eastward along it. Only negligible amounts of lava from the main flow to the north moved southward across the wall.

Analysis of behavior of the walls

The walls were kept under as close observation as possible, and repeatedly re-examined, to determine the effects of the lava on them. For the most part, the only effect was eventual overflow of the wall. Yielding of the wall before the pressure of the lava occurred only at a few places, where the wall was built of light cinder, or where the base of the wall was too narrow to provide adequate frictional resistance against the underlying ground. Walls constructed of heavy material and with a wide base showed no indication of displacement by the lava.

Conclusions drawn from the study of the walls are:

(1) The wall must have a broad base. If the flow against the wall is in the order of 10 to 12 m thick, the base should be in the order of 30 m wide.

(2) The wall must be constructed of heavy materials. Cinder is too light, and the lava tends to push it aside or burrow under it and heave it up.

(3) The wall should have adequate height to prevent overflow, so far as possible. Even small overflows can be serious, because they may erode the face of the wall and eventually cut a gap through the wall.

(4) The slope of the wall away from the lava should be gentle, so that any overflows that do occur will move slowly down the side of the wall and erode it less than if the movement were rapid.

(5) Sharp salients projecting into the flow should be avoided. Salients are equivalent to a low place in the wall, and invite overflows. If a salient is unavoidable, the wall should be built somewhat higher there than along the rest of its course.

(6) If a wall is to act as a diversion barrier, an unobstructed path should be provided along the side of the wall toward the lava. This clear path is nearly as important in directing the course of the flow as the wall itself. All vegetation larger than grass and small bushes should be removed. Even the trails of rock fragments spilled from the edges of bulldozer blades in building the wall constitute a noticeable obstacle to the advance of the flow and should be cleaned away so far as possible.

(7) Diversion barriers cannot operate successfully unless the gradient in the channel behind them is sufficient to cause the liquid lava to flow readily. The amount of slope necessary depends, of course, on the viscosity of the lava, more viscous flows requiring a steeper slope than less viscous ones. For flows of the sort ordinarily encountered in Hawaii, the minimum slope appears to be about 1.5 to 2 percent.

The behavior of the walls built during the 1960 eruption is encouraging, rather than otherwise, as regards the probability of success of walls that may be built as diversion barriers in other areas in the future. They have demonstrated that properly constructed walls will endure the thrust of even thick lava flows without yielding; and that walls with adequately sloping clear channels behind them will successfully change the course of a flow.

It is obvious that the walls were not completely successful in preventing the southward spreading of the lava. In my estimation, however, and in that of most other persons who had the opportunity of watching their operation during the eruption, they were partly successful, and that to a degree that fully justifies their construction.

The destruction of the Kapoho School cannot legitimately be attributed to the failure of the walls. Although it was overflowed, wall 3 greatly reduced the amount of lava that spread southward; and without wall 5 lava would have spread freely through the gap between the Kapoho Hill and Puu Kukii and on down the slope to the southeast, instead of piling up to a height of more than 12 meters behind the wall. Without wall 3 it is almost certain that the Kumukahi lighthouse would have been destroyed; and the remaining major portion of the Kapoho beach lots probably exists today only because of the reduction of southward spreading of the lava by walls 3 and 5.

REFERENCES CITED

ANONYMOUS - *Geological Survey volcanologists study new series of eruptions at Hawaii's Kilauea* - Science, vol. 130, p. 1695-1697, 1959.

EATON, J. P., and RICHTER, D. H. - *The 1959 eruption of Kilauea* - Geotimes, vol. 4, no. 5, p. 24-27, 45, 1960.

FINCH, R. H., and MACDONALD, G. A. - *Bombing to divert lava flows* - Volcano Letter, no. 506, p. 1-3, 1949.

JAGGAR, T. A. - *Preparedness agaist disaster* - Volcano Letter, no. 388, p. 2-4, 1931.

———— - *Protection of harbors from lava flow* - Am. Jour. Sci., vol. 243-A p. 333-351, 1945.

MACDONALD, G. A. - *Activity of Hawaiian volcanoes during the years 1940-1950* - Bull. volcanologique, ser. 2, vol. 15, p. 119-179, 1954.

———— - *Barriers to protect Hilo from lava flows* - Pacific Sci., vol. 12, p. 258-277, 1958.

———— - *The activity of Hawaiian volcanoes during the years 1951-1956* - Bull-volcanologique, ser. 2, vol. 22, p. 3-70, 1959.

MACDONALD, G. A., and EATON, J. P. - *The 1955 eruption of Kilauea volcano* - Volcano Letter, no. 529-530, p. 1-10, 1955.

RICHTER, D. H., and EATON, J. P. - *The 1959-60 eruption of Kilauea Volcano* - The New Scientist, vol. 7, p. 994-997, 1960.

STEARNS, H. T., and MACDONALD, G. A. - *Geology and ground-water resources of the island of Hawaii* - Hawaii Division of Hydrography, Bull. 9, 363 p., 1946.

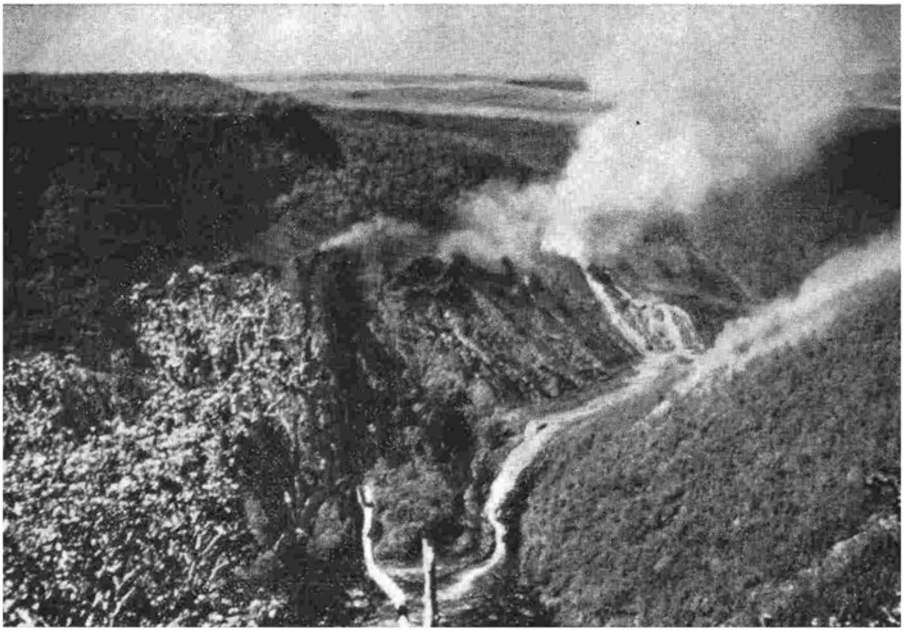

Fig. 1 - Row of spatter cones, and lava stream pouring onto the « mezzanine » platform at the east end of Kilauea Iki crater and thence onto the main crater floor, on the morning of Nov. 15, 1959. Photo by A. T. Abbott, University of Hawaii.

Fig 2 - Lava fountain, and stream of lava cascading westward into the main part of Kilauea Iki crater, Nov. 18, 1959. The main crater has been filled almost to the level of the « mezzanine » (Compare pl. 1, fig. 1).

Fig. 3 - Looking into the vent between eruptive phases 2 and 3, on the morning of Nov. 28, 1959. In the foreground a stream of brightly incandescent liquid lava is pouring into the vent about 10 meters below the level of the surface of the lava pool in Kilauea Iki crater.

Fig. 4 - Lava fountain and dark cloud of pumice, Nov. 29, 1959. The lava pool has risen not only above the level of the « mezzanine », but also above the level of the original vents (Compare pl. 1, fig. 2).

Fig. 16 - Wall 5, seen from the western end, Jan. 28, 1960. Lava is standing against the wall in the foreground and middle distance. In the far distance, at the base of Puu Kukii, the end of the wall has been elevated by faulting, and a lava flow is pouring from a vent at the south base of the wall and spreading to the right of the wall.