Report of the Hawaiian Volcano Observatory for 1948 and 1949

By R. H. FINCH *and* GORDON A. MACDONALD

CONTRIBUTIONS TO GENERAL GEOLOGY, 1950

GEOLOGICAL SURVEY BULLETIN 974-D

Including sections on the 1949 eruption of Mauna Loa and the bombing of lava flows

UNITED STATES GOVERNMENT PRINTING OFFICE, WASHINGTON : 1951

UNITED STATES DEPARTMENT OF THE INTERIOR

Oscar L. Chapman, *Secretary*

GEOLOGICAL SURVEY

W. E. Wrather, *Director*

For sale by the Superintendent of Documents, U. S. Government Printing Office
Washington 25, D. C. - Price 20 cents (paper cover)

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By R. H. FINCH and GORDON A. MACDONALD

ABSTRACT

This report, the first of its kind, summarizes the work of the Hawaiian Volcano Observatory for the years 1948 and 1949. A short history of the observatory from its founding in 1912 by the Massachusetts Institute of Technology and the Hawaiian Volcano Research Association is given.

At the present time five seismograph stations are maintained on the island of Hawaii. In addition there are two stations at which tilt only is measured. Instruments are repaired and new ones are built in the observatory shop. One project of the shop is the building of semiportable tiltmeters that can be housed in a 20-inch cubical box.

Records and investigations during 1948 and 1949 are discussed under the following headings: earthquakes, tilting of the ground, cracks, radiation, temperature, rainfall, and volcanic conditions. The number of earthquakes per week is given by a graph that shows the increase in earthquake frequency preceding the January 1949 outbreak of Mauna Loa. Tilt curves for 1948 and 1949 also are shown by means of a graph. Measurements on two sorts of cracks are described, rainfall statistics summarized, and steam and lava temperatures given. Radiation studies, using both X-ray film and a Geiger-Müller counter, indicate no appreciable radioactivity at either Kilauea or Mauna Loa.

Special sections in the report are devoted to the eruption of Mauna Loa, January 6–June 1, 1949, and the possibility of diverting lava flows by bombing.

INTRODUCTION

The Hawaiian Volcano Observatory was founded in 1912 by T. A. Jaggar under the joint sponsorship of the Massachusetts Institute of Technology and the Hawaiian Volcano Research Association. The latter, with headquarters in Honolulu, was organized with the broad purpose of promoting volcano investigations and specifically to help establish and maintain an observatory at Kilauea volcano. It is composed of members and patrons in Hawaii and elsewhere. The observatory was taken over by the United States Weather Bureau in 1919 and transferred to the Geological Survey in 1924. In 1935 it was transferred to the National Park Service, which supported it until the Geological Survey again took it over on December 28, 1947.

This report, the first of its kind, summarizes the work of the observatory under Geological Survey sponsorship during 1948 and

1949, when the staff consisted of Ruy H. Finch, volcanologist in charge; Gordon A. Macdonald, geologist; Burton J. Loucks, instrument maker; Brother B. T. Pleimann, seismograph operator, Hilo; Howard M. Tatsuno, seismograph operator, Kona; Chester K. Wentworth, geologist, part-time; Ruth C. Loucks, assistant. It is proposed to issue similar reports, annually, in future years.

PHYSICAL PLANT

From the time it was established until 1941 the Hawaiian Volcano Observatory was located in a frame building on the northeast rim of Kilauea caldera. In 1941 the old observatory structure was razed to make room for a new hotel, and the observatory was moved to newly built quarters about 600 feet northeast of the original site (fig. 32). In 1948 the building that housed the observatory was taken over for the headquarters of Hawaii National Park, and the observatory was moved to the old museum originally built in 1927 by the Hawaiian Volcano Research Association at Uwekahuna, on the west rim of Kilauea caldera. The new location (fig. 32) affords an excellent view of Kilauea and, during clear weather, of the entire profile of Mauna Loa.

SEISMOGRAPHS AND TILTMETERS

The first seismographs installed at the Hawaiian Volcano Observatory were of special design, built in Tokyo. One was intended for recording teleseisms and had only a single horizontal component. The other was a three-component instrument for recording local earthquakes. A Bosch-Omori two-component horizontal pendulum seismograph was installed a little later and is still the principal instrument of the observatory. Operated with a period of 7.7 seconds and a magnification of 115, it gives satisfactory records of short-period local earthquakes and is a sufficiently sensitive tiltmeter.

The seismographs were purchased through an allotment from the Whitney fund for geophysical research of the Massachusetts Institute of Technology. Consequently the station was named the Whitney Laboratory of Seismology. The laboratory is a cellar, 18 feet square, that originally was under the main observatory building (fig. 32). The cellar was dug through 5½ feet of volcanic ash and pumice to the upper surface of basalt. It is only 20 feet from the cliff that forms the inner wall of Kilauea caldera. Steam cracks beneath the concrete floor in the badly fissured basalt keep the cellar at a temperature of nearly 90° F.

A vertical seismograph was installed at the Whitney station late in 1929. In 1941, when the original observatory building was torn down, the cellar housing the Whitney Laboratory was covered with a concrete slab and 18 inches of soil. The vertical seismograph was moved to a cellar under the new observatory building (second location, fig. 32),

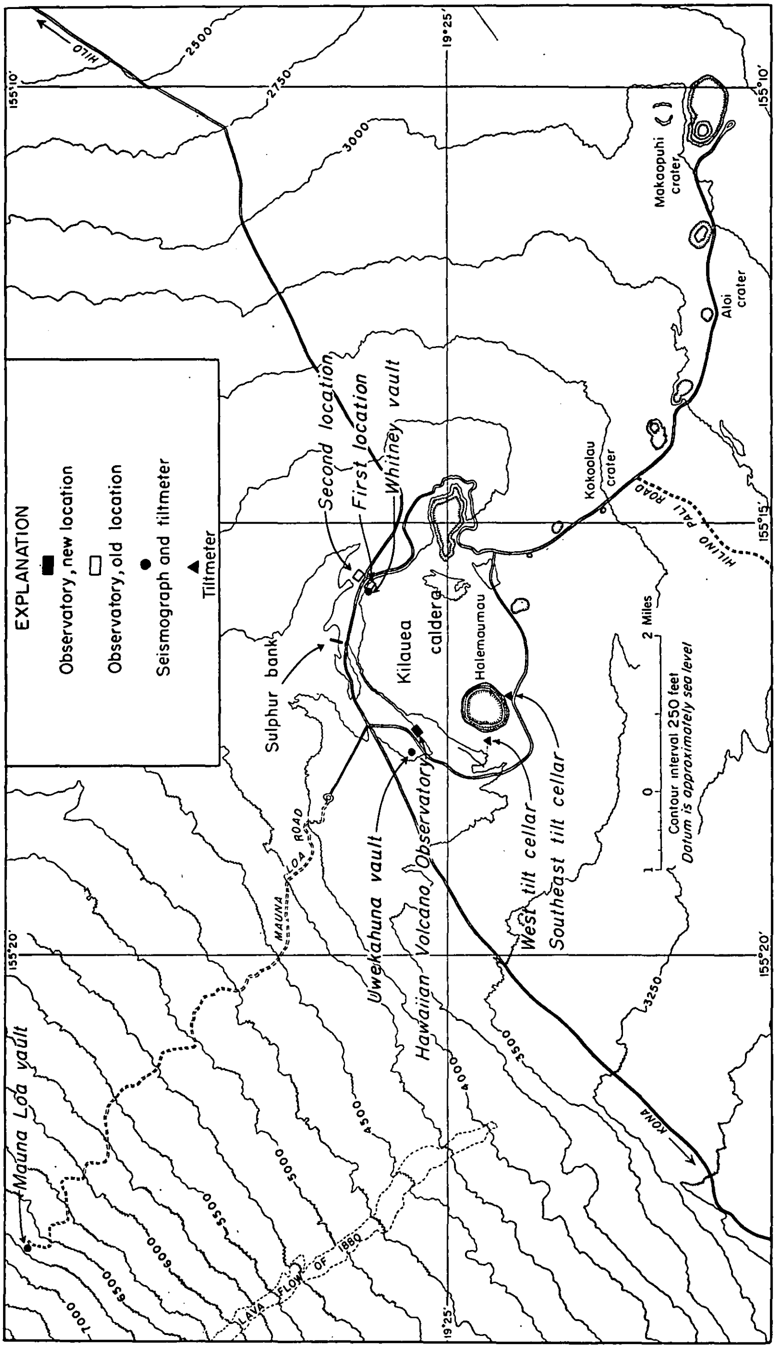

FIGURE 32.—Map of the vicinity of Kilauea caldera, showing the successive sites of the Hawaiian Volcano Observatory and the location of the principal seismograph and tiltmeter installations.

but the Bosch-Omori instrument was left in the Whitney vault. In 1948, when this building was taken over by Hawaii National Park, the vertical seismograph was moved to a new vault about 1,000 feet west of the present observatory building at Uwekahuna (fig. 32).

During 1948 and 1949 the Hawaiian Volcano Observatory maintained three seismograph stations in addition to the Whitney and Uwekahuna stations, as well as two stations on the floor of Kilauea caldera at which only tilting of the ground is measured. The locations of the seismograph and tiltmeter stations are shown in figures 32 and 33. In the Uwekahuna vault, in addition to the vertical seismograph, there is a pair of horizontal pendulums for measuring north-south and east-west tilting of the ground. It is planned to convert these tiltmeters into seismographs and install them in the newly constructed building of St. Joseph's School in Hilo. Space has been provided in the Uwekahuna vault for installing a high-magnification seismograph with photographic registration.

The Hilo, Kona, and Mauna Loa stations (fig. 33) are equipped with two-component "Hawaiian"-type seismographs. The Hilo station is located at St. Joseph's School, the Kona station at Konawaena School in Kealakekua, and the Mauna Loa station at an altitude of 6,600 feet on the eastern slope of Mauna Loa. The heavy mass of the Hawaiian-type seismograph is a section of 8-inch pipe 27 inches long, which when filled with sand weighs approximately 225 pounds. The mass is suspended as a horizontal pendulum by means of short piano-wire links at the top and bottom.

All the seismographs mentioned record on smoked paper. The vertical seismograph has a magnification of 250, and all the others have magnifications of approximately 115. The Bosch-Omori recording drum is driven by a synchronous A. C. motor, and the other drums by spring-powered clocks. Time control for the Whitney station, and (normally) the Uwekahuna and Mauna Loa stations as well, is supplied by a Howard pendulum clock.

The Bosch-Omori seismograph has a fixed stylus used to scratch a reference line at the beginning of each record from which tilt of the ground is measured. Tilting of the ground is a change in the angular relation between a part of the earth's surface and the horizontal (Jaggar and Finch, 1929). Any tilting of the ground causes a shift of the position of the pendulum, which in turn results in a displacement of the recording stylus. As the instrument is now operated, a displacement of the recording stylus of 1 centimeter indicates a tilt of 1.2 seconds of arc. Tilt is measured in a similar manner on the Mauna Loa instrument, but the values obtained are much smaller than those from the instruments in the vicinity of Kilauea caldera. Tilt is not measured at the Hilo and Kona stations because

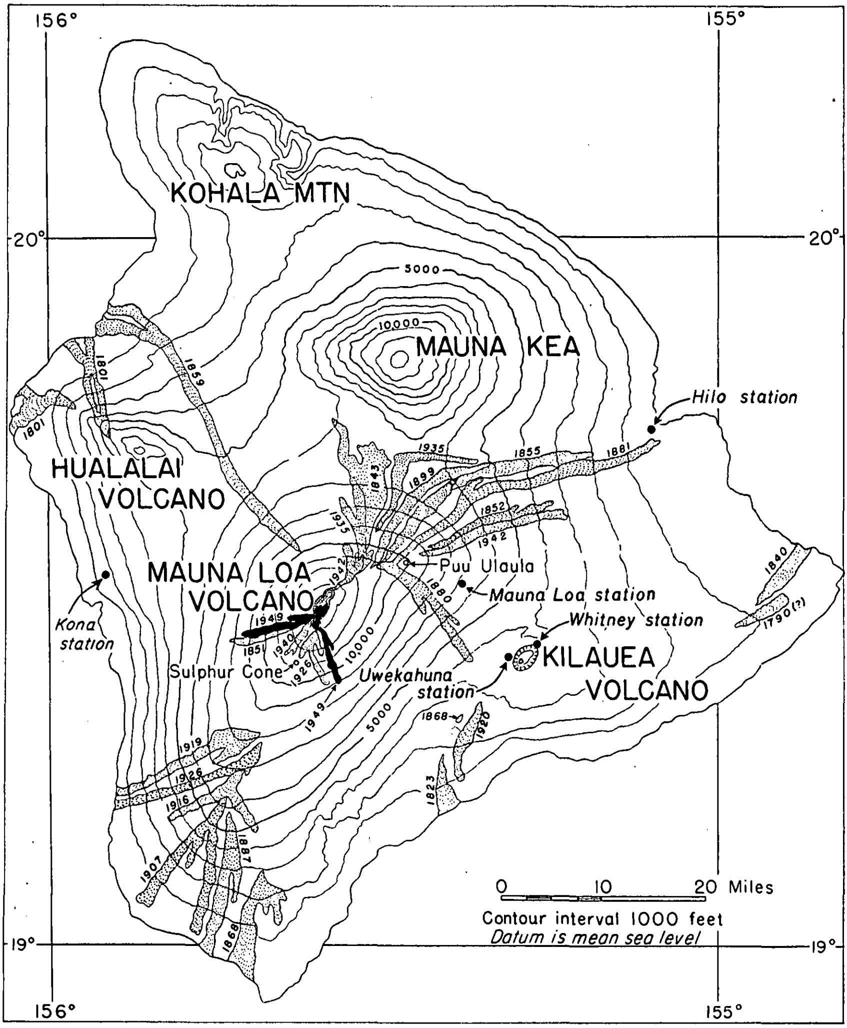

FIGURE 33.—Map of the island of Hawaii, showing the location of the seismograph stations of the Hawaiian Volcano Observatory and the distribution of the historic lava flows of Mauna Loa and Kilauea. The lava of 1949 is shown in solid black, and the older historic flows are stippled.

experience has shown that they are subject to little tilting other than diurnal and seasonal.

Two tiltmeters are housed in vaults on the floor of Kilauea caldera near Halemaumau crater (fig. 32). Each of these tiltmeters is a normal pendulum 206 centimeters long, suspended from a tripod resting on leveling screws. By means of a pivot arrangement the magnifying lever projects vertically upward to a point just below a horizontal disk that is graduated in degrees and ruled with concentric circles spaced 2 millimeters apart. Readings are obtained by means of a mirror. The instrument indicates both the amount and the direction of tilt, a shift of the pointer of 1 millimeter corresponding to a tilt of 1.3 seconds of arc.

None of the tiltmeters is of the recording type. They are read at various intervals, some once a day and others only monthly unless rapid tilting indicates the desirability of more frequent readings. The accumulation of tilt from day to day, and over longer intervals, as shown by plotting on millimeter cross-section paper, has been found useful in making correlations with results obtained by precise leveling and in the study of earthquakes and volcanic activity both at the surface and in depth (fig. 36).

A list of the seismographs and tiltmeters operated by the Hawaiian Volcano Observatory, with some of their constants, is given in table 1.

TABLE 1.—*Seismographs and tiltmeters operated by the Hawaiian Volcano Observatory*

Station	Instrument	Period of pendulum (seconds)	Magnification (approximate)	Sensitivity to tilt (seconds of arc per millimeter)
Whitney Laboratory of Seismology (northeast rim of Kilauea caldera).	Bosch-Omori seismograph and tiltmeter.	7.7	115	0.12
Mauna Loa (altitude of 6,600 feet on east slope of Mauna Loa).	Hawaiian-type seismograph.	7.1	115	.14
Uwekahuna (1,000 feet west of west rim of Kilauea caldera).	Vertical seismograph.	.4	250	----------
	North-south and east-west horizontal pendulum tiltmeters.	34.0	7	.1
Hilo (St. Joseph's School)	Hawaiian-type seismograph.	7.3	115	.13
West tilt cellar (floor of Kilauea caldera west of Halemaumau).	Normal pendulum tiltmeter.	3.0	100	1.3
Kona (Konawaena School, Kealakekua).	Hawaiian-type seismograph.	7.3	115	.13
Southeast tilt cellar (floor of Kilauea caldera southeast of Halemaumau).	Normal pendulum tiltmeter.	3.0	100	1.3

SHOP

A machine shop for the building and repair of instruments is housed in one wing of the observatory building. It is equipped with a 10-inch screw cutting lathe, a 9-inch high-speed precision lathe, a jeweler's lathe, a milling machine (Van Norman No. 12), a drill press, a 16-inch stroke shaper, a power hacksaw, and assorted hand and bench tools. Power is obtained from a 25-kilowatt Diesel-driven generator.

The power plant and most of the heavy machinery are loaned to the observatory by Hawaii National Park, and appreciation is hereby expressed to the park officials for their use.

Several two-component semiportable tiltmeters are being built for use locally and in Aleutian volcano investigations. They are designed for installation on a concrete base in a 20-inch cubical weatherproof box. The small housing requirements and light weight of the instruments (about 90 pounds each) permit their installation in rather inaccessible places. They have a lever magnification of 15, and when they are operated with a period of 20 seconds a 1-millimeter shifting of the lever pointer indicates a tilt of 0.08 seconds of arc. The instruments are nonrecording, although a chronograph could be installed with only slight modifications. Figure 34 is a photograph of one of these instruments.

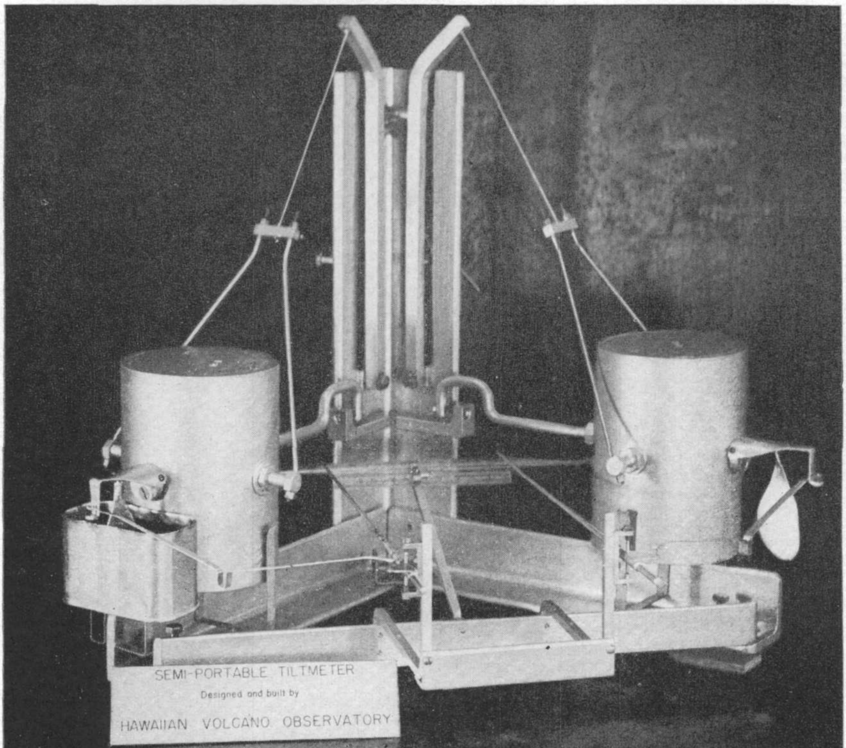

FIGURE 34.—*Semiportable tiltmeter designed and built at the Hawaiian Volcano Observatory for use locally and in Aleutian volcano investigations. The height of the upright post at the back of the instrument is 16 inches. Each of the heavy masses weighs 35 pounds.*

RECORDS AND INVESTIGATIONS, 1948–49

EARTHQUAKES

The number of earthquakes recorded per week on the Bosch-Omori seismograph for the years 1948 and 1949 is shown graphically in figure 35. The weekly totals that occur most frequently are four, five, and six. Normally about five earthquakes per week can be expected. An appreciable excess over this total occurs at times of local superficial adjustments along the active rifts of the volcanoes

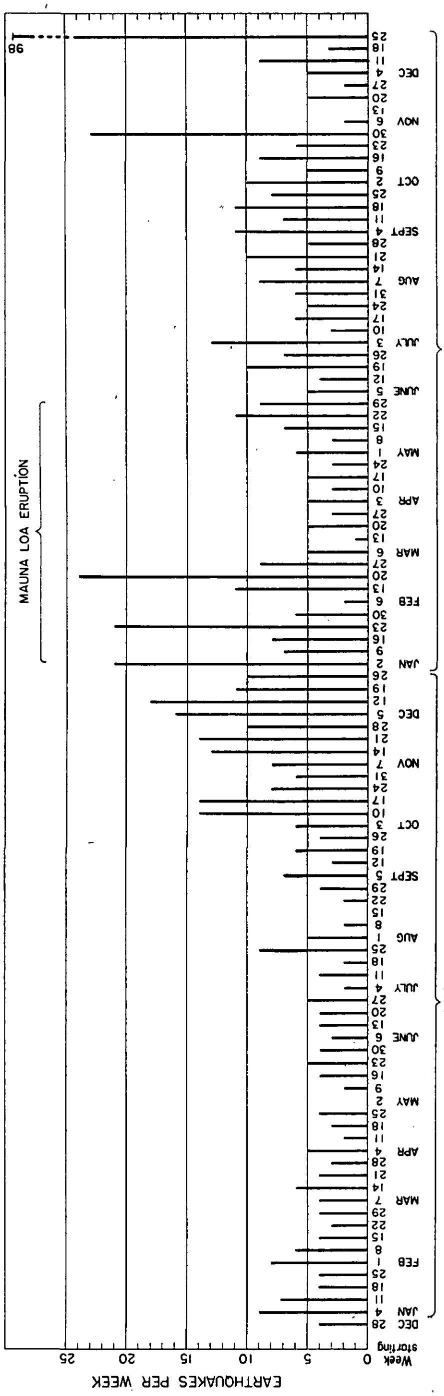

FIGURE 35.—Graph showing the number of earthquakes recorded each week at the Whitney vault of the Hawaiian Volcano Observatory during the years 1948 and 1949. The duration of the 1949 eruption of Mauna Loa is indicated by the bracket. During the week starting December 25, 1949, a total of 98 earthquakes was recorded.

and may have little volcanic significance. Such earthquakes are shallow-seated. An equal number of quakes, with at least the earlier quakes of the group originating at greater depth, especially under volcanic vents, commonly is an indication of volcanic uneasiness.

The large totals shown in November and December 1948 were premonitory symptoms preceding the January outbreak of Mauna Loa. The number of earthquakes remained large during the first week of the eruption. This is common, especially during flank eruptions when there is motion along a rift system often several miles long.

The large totals for the weeks starting January 23 and February 20, 1949, probably accompanied resumption or increase of lava extrusion.

The 24 quakes that were recorded during the week beginning October 30, 1949, originated deep under Mauna Kea, a volcano that has been quiescent for several thousand years.

During the week beginning December 25, 1949, a total of 98 earthquakes was recorded. Most of these originated at a shallow depth beneath the 12,000-foot contour along the northeast rift of Mauna Loa. The Mauna Loa seismograph, which is about 9 miles closer to the epicentral region than the Whitney station (fig. 33), recorded 274 tremors during the week. These earthquakes were all small and of rather uniform amplitude, suggesting the possibility that they may have been caused by a shallow intrusion under the upper end of the northeast rift of Mauna Loa.

TILTING OF THE GROUND

Tilt curves for the Whitney station for 1948 and 1949 are shown in figure 36. Records show that there is a distinct seasonal tilt on the northeast rim of Kilauea caldera. The east-west seasonal curve closely parallels that of the air temperature. The north-south curve, though definitely showing seasonal effects, is somewhat out of phase with that of the air temperature. Southward tilting is usual from January to April, inclusive, and northward tilting from May to December. Accordingly, seasonal southward tilting is more rapid than the northward tilting. An allowance for normal seasonal tilt must be made before estimating the amount of tilt resulting from volcanic processes. Northward and eastward tilting in excess of usual seasonal amounts means a doming up of the Kilauea edifice. Southward and westward tilting means a sinking. The summit of Mauna Loa lies nearly west of the Whitney station (fig. 33), and there are some indications that Mauna Loa eruptions are preceded by eastward tilting.

The north-south tilt curve for 1948 showed the usual rapid southward tilt for the first 4 months and a northward tilt in about the same amount during the next 8 months. Southward tilt at the begin-

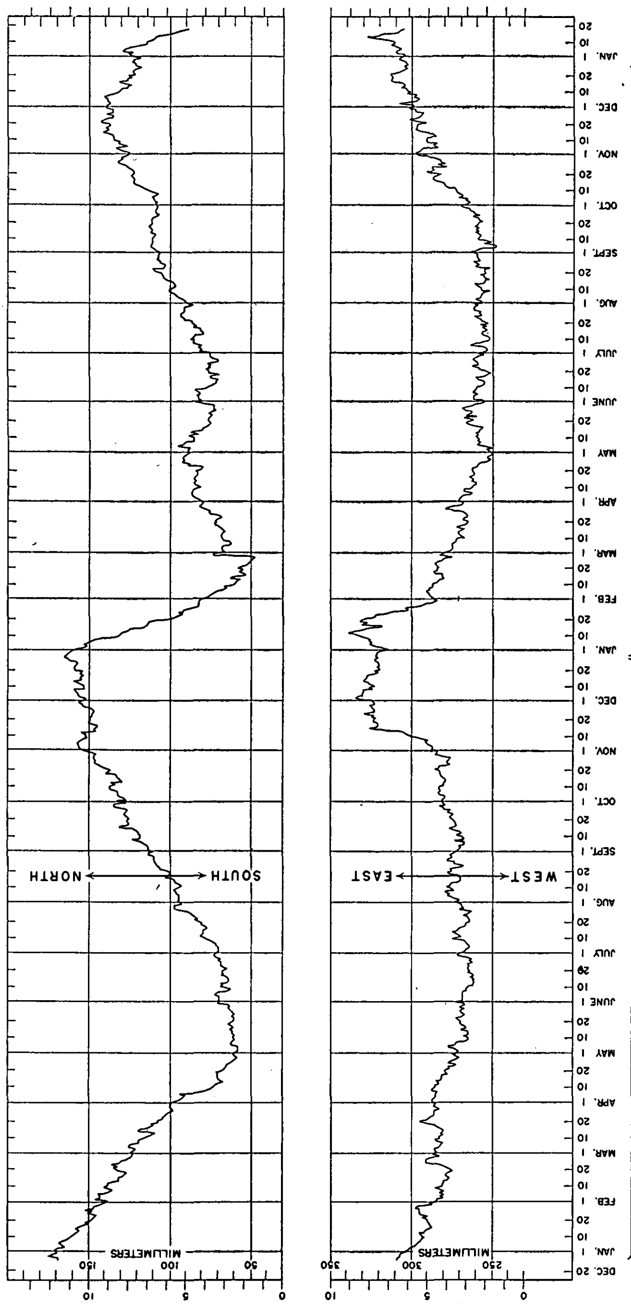

FIGURE 36.—Graph showing tilting of the ground at the Whitney vault, northeast edge of Kilauea caldera, during the years 1948 and 1949. The upper curve represents tilting in a north-south azimuth, and the lower curve tilting in an east-west azimuth. At the ends of the diagram, the inner scale represents millimeters of actual measured movement of the writing stylus on the tiltmeter, and the outer scale represents the amount of ground tilting, in seconds of arc, necessary to produce the observed linear shift of the stylus.

ning of 1949 was more rapid than usual; it stopped on February 26, about 2½ months earlier than usual. The reversal followed a strong earthquake under the east slope of Mauna Loa, and the tilt during the single day February 26–27 amounted to 3.2 seconds of arc, many times the amount resulting from instrumental lag. The accumulation of northward tilt during the rest of 1949 was a little less than usual, and the net tilt for the 2 years was 5.6 seconds to the south.

Except for a rapid eastward tilting during the first 2 weeks of November 1948 and a nearly compensating westward tilting from January 11 to January 30, 1949, the east-west tilt curve shows the usual seasonal characteristics. The rapid eastward tilt preceded the January 1949 eruption of Mauna Loa by a little more than 2 months. There was no significant accumulation of tilt in the east-west direction for the 2 years.

CRACK MEASUREMENTS

Periodic measurements are made of the width of certain cracks in and near Kilauea caldera. A brass stud has been set on each side of the crack at the measuring point, and the top of each stud marked with an indented point or a cross. Measurement of the distance from the mark on one stud to the mark on the other is made directly with a steel tape graduated in millimeters, or for longer distances by means of a large pair of calipers having a span of about 1.5 meters.

At one time more than a hundred such cracks were measured once a week. It was found, however, that the number of cracks and frequency of measurement were much greater than necessary under ordinary conditions. The number of cracks measured has now been reduced to 13, and during times of volcanic quiescence measurements are made only once a month.

The cracks now being measured are of two sorts. Cracks that lie back of blocks of rock on the rim of Halemaumau are measured purely as a matter of safety. Any widening of these cracks indicates a movement of the block toward the center of the pit. If such movement becomes large or rapid, warning can be given that the block is likely to collapse into the pit. A crack of this sort crosses the platform at the Halemaumau tourist lookout, about 20 feet back from the edge of the pit. During the interval from July 1948 to December 1949 the width of this crack at measuring station 5 (table 2) increased 1.8 centimeters.

Cracks of the second category are of greater significance volcanologically. Some of these cracks lie on the floor of Kilauea caldera away from the rim of Halemaumau, and others along the east rift zone. Although there are some variations because of differences in the movement of individual blocks, in general these cracks open up

TABLE 2.—*Width of cracks at Kilauea caldera, Hawaii (in centimeters)*

Date	Measuring station number													
	Halemaumau rim cracks						Cracks on floor of caldera					Cracks on east rift		
	5	6	7	8	9	27	37 N.-S.	37 E.-W.	37A	40	41	101A	106	DT-1
1948														
July 31	104.8	57.8	34.5	-----	-----	64.0	49.6	44.9	64.5	33.0	33.4	127.8	-----	-----
Aug. 31	104.9	57.8	34.5	57.7	77.8	-----	-----	-----	-----	-----	-----	-----	-----	-----
Sept. 30	105.0	57.8	34.4	57.7	77.6	64.1	49.5	44.8	64.5	33.1	33.4	127.7	101.6	35.6
Oct. 31	105.0	57.8	34.5	57.7	77.6	64.1	49.5	44.9	64.6	33.0	33.4	127.8	101.7	35.6
Nov. 28	105.1	57.7	34.5	57.7	77.6	64.0	49.5	44.8	64.5	33.0	33.4	127.8	101.6	35.6
Dec. 31	105.4	57.8	34.5	57.7	77.7	64.1	49.5	44.8	64.5	33.1	33.4	-----	-----	-----
1949														
Jan. 31	105.4	57.8	34.5	57.8	77.8	64.1	49.4	44.8	46.5	33.0	33.4	127.8	101.6	35.6
Mar. 1	105.7	58.1	34.5	57.7	77.9	64.1	49.3	44.8	64.4	33.0	33.4	127.7	101.6	35.9
Mar. 31	105.9	58.0	34.5	57.8	-----	-----	-----	-----	-----	-----	-----	-----	-----	-----
Apr. 30	105.9	58.2	34.5	57.8	-----	-----	-----	-----	64.4	-----	-----	-----	-----	-----
June 1	106.2	58.2	34.4	57.8	77.8	64.1	49.3	44.7	64.4	33.1	33.4	-----	-----	-----
July 1	106.1	58.2	34.6	57.8	77.8	64.2	49.3	44.7	64.3	33.0	33.4	127.5	101.6	35.8
Aug. 1	106.2	58.3	34.6	57.9	77.8	64.1	49.2	44.7	64.4	33.0	33.4	127.4	101.6	35.9
Sept. 1	106.4	58.4	34.6	57.9	77.9	64.1	49.2	44.7	64.3	33.0	33.4	127.6	101.5	35.9
Sept. 30	106.4	58.4	34.6	57.9	77.9	64.1	49.2	44.6	64.3	33.0	33.4	127.5	101.5	35.9
Oct. 31	106.5	58.5	34.6	57.9	77.9	64.1	49.2	44.6	64.[illegible]	33.0	33.4	127.6	101.5	35.9
Nov. 30	106.6	58.5	34.6	57.9	77.9	64.2	49.2	44.6	64.3	33.0	33.4	127.7	101.6	35.9
Dec. 30	106.6	58.4	34.6	57.9	77.9	64.1	49.2	44.6	64.3	33.0	33.4	127.7	101.6	35.9

during the tumescence that accompanies the subsurface rise of magma and close during the sinking that accompanies a decrease of volcanic pressure. Of the cracks on the floor of the caldera, crack 40 is west of Halemaumau (about 400 feet west of the West tilt cellar), crack 41 is south of Halemaumau, and the others are southeast of Halemaumau. All appear to be part of the continuation of the southwest rift zone across the caldera floor. The interval from July 1948 to December 1949 was one of volcanic quiet at Kilauea, and from late December 1948 to mid-February 1949 marked southerly tilt at the northeast rim of the caldera (fig. 36) indicated a decrease in volcanic pressure. A decrease in pressure and the resultant sinking are indicated, also, by a closing of the cracks southeast of Halemaumau (table 2).

RADIATION

A series of experiments was started in August 1948 by Ruth C. Loucks in an attempt to determine to what extent X-ray film can be used to record radiation from volcanic sources (Loucks, 1949). Because X-ray film is affected by radiation both longer and shorter than the X-ray range, it appeared possible that it might be of use in detecting any short-wave radiation that might be present. No X-radiation is to be expected, but both ultraviolet and gamma radiation can be recorded on X-ray film. Dental pack film was used because of the ease of handling.

To obtain control for the experiment, several series of films were exposed at times and places where they would not be directly affected by volcanic eruption. One series was exposed for 10 weeks, some of the films at Puu Ulaula, 10,000 feet above sea level on the northeast rift zone of Mauna Loa, and some at the rim of Mokuaweoweo caldera, more than 13,000 feet above sea level. Of this series, unshielded films showed pronounced fogging, but films that were only slightly shielded were unfogged. Even a strip of masking tape produced a shadow on the film, indicating that the radiation that affected the film was of relatively long wave length. Of two films exposed back to back, the front one was fogged, but the one behind, which was shielded by the two lead-foil backing sheets, was not fogged.

A second series of films was tested in the Kilauea region. Film tested for tightness of the film pack to visible light showed no darkening. Cosmic radiation also produced no detectable darkening on any of the films tested. Other film exposed for 5 weeks at a distance of 12 to 15 feet from tiltmeter masses, containing slightly radioactive lead, in the Uwekahuna vault showed slight darkening, thus serving as a check of the sensitivity of the film to gamma radiation.

A third series of films was exposed for nearly 6 months at Puu Ulaula, with various degrees of shielding. The unshielded film was darkened. Films covered respectively by 0.11 millimeter of aluminum foil and by sheets of lead 1.75 and 3.5 millimeters thick all were undarkened. It therefore appears that the darkening was caused by ultraviolet radiation and that the radiation can be excluded by enclosing the film in even a thin covering of aluminum foil. During future eruptions lightly shielded films can be exposed to radiation from the lava fountains to see whether any darkening results from gamma radiation.

Two series of X-ray films were taped to the stone monument in front of the summit rest house on Mauna Loa and exposed for periods ranging from 17 hours to 17 days during the high-lava-fountain stage of the 1949 eruption. The films, which were unshielded, showed darkening that was probably caused by ultraviolet radiation. However, the films were more than a mile from the lava fountains, too far away for gamma radiation to be expected. Because of bad weather and inaccessibility it was not feasible to place them closer. At that time the tests with shielded films at Puu Ulaula had not yet been made.

A Geiger-Müller counter was received by the Hawaiian Volcano Observatory late in January 1949. The instrument is a type SGM–18A Survey Meter, manufactured by El-Tronics, Inc. It arrived too late to be used in testing for radiation from the high lava fountains of the early phase of the 1949 eruption of Mauna Loa. However, observations were made on hot lava flows in and near South Pit on February 5. The number of clicks in the earphones ranged from 38 to 45 per minute with the shield on the counter tube both open and closed. This is approximately the same number of clicks as was obtained on nearby prehistoric lavas and is approximately the number to be expected from cosmic radiation alone. This work was purely preliminary and does not constitute a conclusive test of radiation associated with volcanic activity. It is especially desirable to test for the possible presence of radioactive materials in the gases liberated during the early lava-fountain phase. Such tests are planned for future eruptions. In the meantime, it is planned to obtain a series of counts at various altitudes to determine the background effect of cosmic radiation.

TEMPERATURE

Frequent measurements of the temperature of the steam escaping from the shallow drilled wells at Sulphur Bank were started on September 10, 1949. Sulphur Bank is a solfatara in a small graben at the foot of the outermost boundary fault at the northeast edge of Kilauea caldera, but outside the main caldera depression. During 1922, two holes were drilled in the floor of the graben. The more westerly of these was drilled to a depth of 50 feet. In 1923 it was deepened to 70 feet, and a 15-foot hole was drilled on each side of it, about 4 feet away, to increase the output of steam. The three holes are cased and are connected above the ground surface by a manifold 6 inches in diameter. After some experimenting a uniform procedure of temperature measurement has been adopted. A half-inch plug at the top of the east end of the manifold is removed, and the well is allowed to blow freely for 10 minutes. A maximum thermometer is then inserted all the way into the aperture and allowed to remain 5 minutes, with steam escaping around it.

Weekly readings made in this way gave a temperature of 96.5° C. from September 10 to October 9. On October 15 the temperature was found to have dropped to 96.0°, which was maintained until November 13. On November 30 the temperature was 95.5°, and it remained the same at each reading for the rest of the year. Other readings at natural steam vents in the Sulphur Bank area ranged from 95.0° to 97.5°.

When the holes at Sulphur Bank were first drilled, in 1922, the temperature was found to average 96.0° C. In 1923 readings with a thermocouple gave an average temperature of 95.5°, which is close to the boiling point of pure water at the altitude (3,950 feet) of Sulphur Bank.

On November 4, 1949, temperature measurements were made in two prominent steaming areas near the Chain of Craters road, on the east rift zone of Kilauea. The highest temperature found in the steaming area just south of Kokoolau crater was 88° C., and that in the Aloi steaming area was 90.0°.

In regions where rainfall is high, such as Sulphur Bank and the east rift zone of Kilauea, it is to be expected that ground water will almost always be present in excess of the amount that can be converted into steam and therefore that temperatures in the steam much in excess of the boiling point of water are not commonly to be observed. The temperatures measured at Sulphur Bank do not show any immediate change in response to variations in the amount of rainfall, but this probably indicates merely that the transformation of ground water into steam occurs at a depth greater than that to which the amount of water present in the rocks is much affected by short-term variations in rainfall. However, noteworthy changes in the steam temperature do occur. In March 1886 the steam at Sulphur Bank became so hot that the steam baths could not be used (Brigham, 1909, p. 162). Such changes are most probably the result of increases in the amount of subsurface heat and therefore of subsurface volcanic episodes such as shallow intrusions. It is hoped that systematic measurement of temperatures at Sulphur Bank, and possibly at other localities, may aid in the interpretation of subsurface changes.

Little new information was obtained on lava temperatures during the 1949 eruption of Mauna Loa. Estimation based on their color at night indicates the temperature of the lava fountains to have been in the vicinity of 1,000° C. Temperature measurements with an optical pyrometer were made on the glowing interior of a thick aa flow in South Pit on the afternoon of February 5. The glowing part of the flow was well exposed in a large crack. Three observations were made, all yielding readings close to 760° C. This temperature is believed to be accurate within 50°. The flow was essentially motionless but was still creeping ahead a little on a very low slope. Thus aa lava with a temperature in the vicinity of 760° is still capable of flowing.

RAINFALL

A rain gage was set up approximately 75 feet west of the Uwekahuna seismograph vault in October 1948. Since that time daily records of rainfall have been kept. The monthly totals are as follows:

Monthly rainfall at Uwekahuna, west rim of Kilauea caldera, Hawaii

	Inches		*Inches*
1948:		1949—Continued	
November	11. 16	June	0. 85
December	4. 87	July	. 81
		August	. 63
1949:		September	. 22
January	31. 52	October	3. 61
February	6. 04	November	4. 94
March	3. 14	December	12. 19
April	. 49		
May	1. 01	Total for 1949	65. 45

In comparison, the total rainfall for the year 1949 at Hawaii National Park headquarters (second site of Hawaiian Volcano Observatory, fig. 32) was 95.63 inches.

VOLCANIC CONDITIONS

Kilauea.—Kilauea volcano erupted in Halemaumau in September 1934. Since then there has been no surface activity, although in 1944 the pattern of earthquakes and occurrence of harmonic tremor on the seismographs indicated the movement of magma underground (Finch, 1949). Except for occasional small avalanches from the walls of Halemaumau, there have been no visible surface changes during 1948 and 1949.

Solfataric activity has continued with no apparent change at Sulphur Bank, which is at the northeast edge of Kilauea caldera, and along the inner boundary cliff of the caldera east of Halemaumau. Steam vents have continued active on the flats west of the Whitney vault at the north edge of the caldera, on the caldera floor, and at several localities along the east rift zone between the caldera and Makaopuhi crater. The two most prominent of the steaming areas along the east rift zone are the one crossed by the Chain of Craters road at Aloi crater and another that lies southwest of the road just south of Kokoolau crater. The latter area, which is roughly circular and about 1,500 feet across, first appeared in 1938 and almost certainly can be attributed to the emplacement of a body of magma at a fairly shallow depth beneath it.

Mauna Loa.—Mauna Loa was in eruption at the summit from January 6 to June 1, 1949. During 1948 and the rest of 1949 it was quiescent. A swarm of earthquakes on December 28, 1949, may have accompanied the intrusion of magma at a shallow depth along the upper part of the northeast rift zone, unaccompanied by surface activity. The eruption of Mauna Loa is described on pages 119–128.

Steam vents are constantly active along the northeast rift both above and below the prominent cinder cone at an altitude of 11,750 feet. The conspicuousness of the steam varies greatly, owing in part to changing visibility with changing weather conditions but probably also to variation in the abundance of the water supply. The steam is especially prominent during and just after the melting of heavy snowfalls. Steam vents and solfataras are present on the southwest rift in the vicinity of Sulphur Cone at an altitude of 11,300 feet. Comparison of photographs taken at Sulphur Cone by Macdonald in October 1949 with others taken by Finch in 1926 shows no apparent change in the degree of activity. During October 1948 Macdonald and Howard A. Powers observed light fume at the 1940 cinder cone in Mokuaweoweo caldera and light but conspicuous sulfurous fume at fissures on the caldera floor north of the 1940 cone, at about the position where the 1949 eruptive fissure later opened. Fume continued to issue from numerous secondary fumaroles on the flows within Mokuaweoweo caldera for a few weeks after the end of the 1949 eruption. At the end of 1949 the 1940 cone and the new cone of the 1949 eruption were still fuming lightly, as were fissures on the caldera floor half a mile north of the 1940 cone.

SPECIAL STUDIES

ACTIVITY OF MAUNA LOA DURING 1949

A summit eruption of Mauna Loa began at about 4 o'clock in the afternoon of January 6, 1949. The last previous activity had been noted during 1943, when from November 21 to 24 volcanic tremor on the seismographs and a fume cloud at the summit of the mountain indicated weak activity.

The 1949 eruption has been described in detail elsewhere (Macdonald and Finch, 1949a and 1949b; Macdonald and Orr, 1950). Only a brief summary account will be given here.

The early activity was characterized by explosive violence. Rumbling was audible at the Hawaiian Volcano Observatory, 20 miles east of the site of eruption. Fragments of pumice were carried by the wind 7 miles northeastward, and Pele's hair was drifted about 20 miles.

The lava broke out along a series of fissures en echelon (fig. 37) that crossed the floor of Mokuaweoweo (the caldera at the summit of Mauna Loa), split the 1940 cinder cone, cut the cliff at the southwest edge of the caldera, and extended about 1.2 miles down the southwest slope of the mountain (fig. 38). The total length of erupting fissure was about 3 miles. On the morning of January 7 lava fountains were still playing from the fissures at four localities. One of these was near the center of Mokuaweoweo (fig. 38), north of the 1940 cone, another was at the southwest boundary of the caldera (fig. 39), and the other two were on the southwest slope of the mountain outside the caldera. The rest of the fissures had become inactive except for the emission of fume. On the morning of January 9 very weak intermittent fountaining was still going on at one place outside the caldera, but by that evening lava liberation was entirely confined to the caldera.

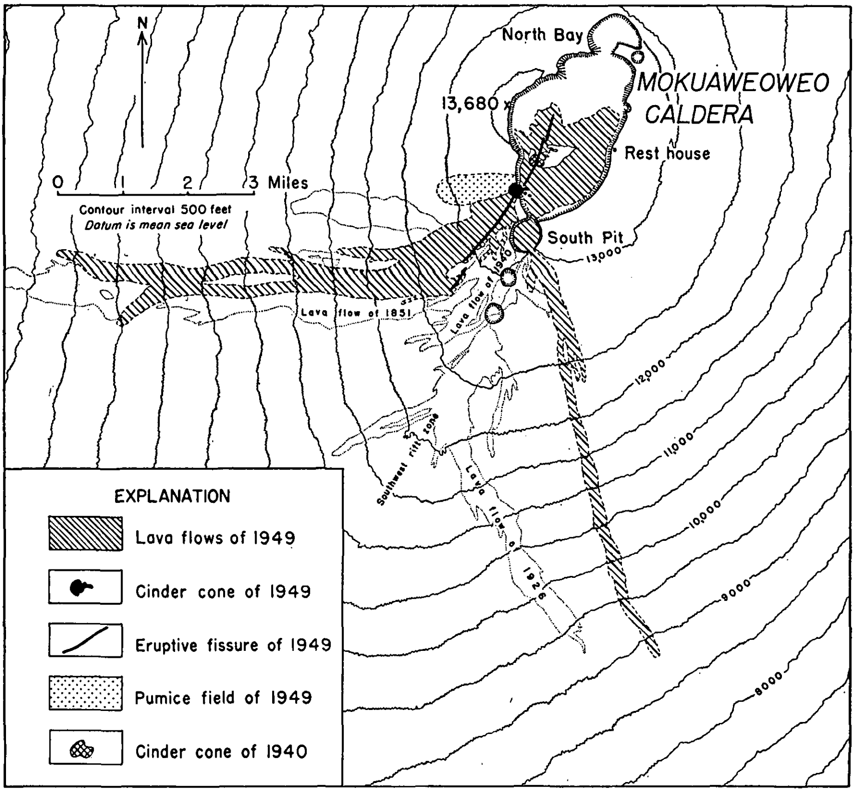

FIGURE 37.—Map showing the approximate outlines of the lava flows and the location of the vents of the 1949 eruption of Mauna Loa.

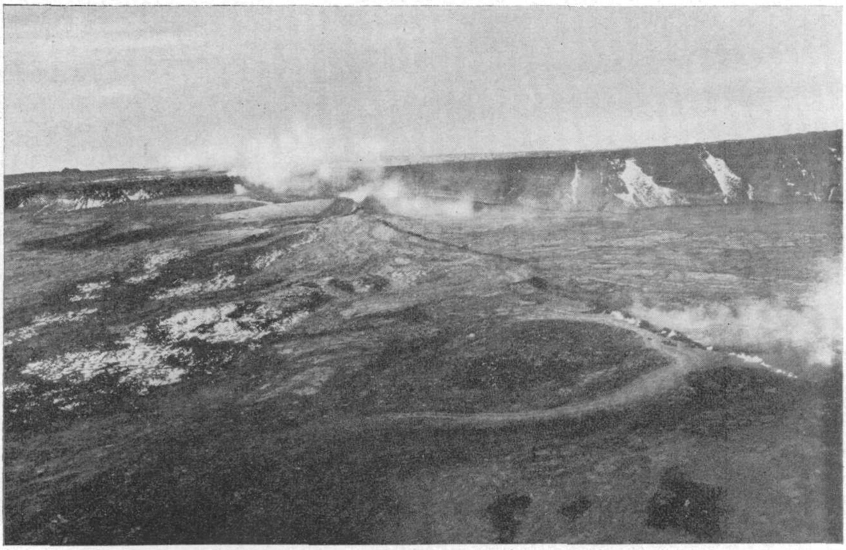

FIGURE 38.—Aerial photograph looking southwestward across Mokuaweoweo caldera, January 7, 1949. In the right foreground a chain of small lava fountains is playing along the eruptive fissure and sending a flow of lava to the left across the caldera floor. In the middle ground the fissure can be seen crossing the 1940 cone, which is fuming. In the left background clouds of fume are rising from the fissure, which cuts the caldera wall and extends on down the flank of the mountain. Lava fountains are playing at the base of the caldera wall. Official photograph, United States Navy.

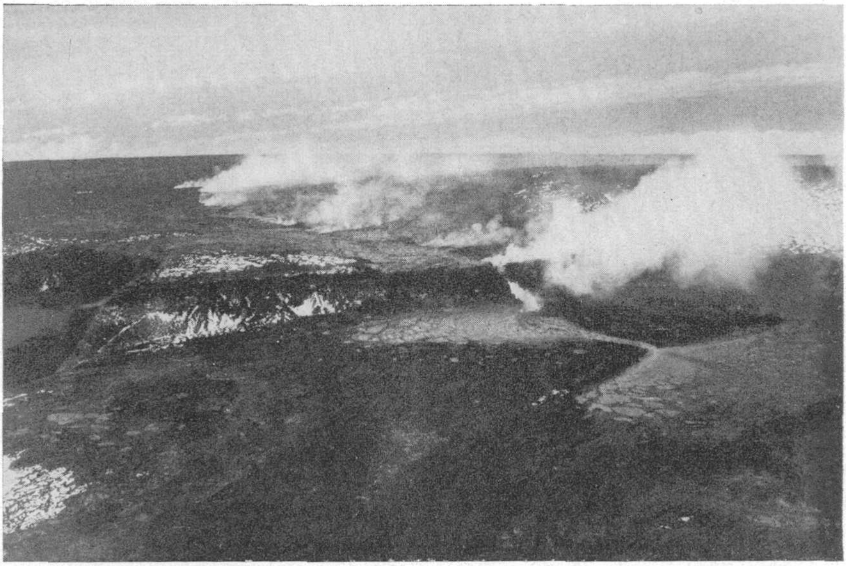

FIGURE 39.—A closer view, on January 7, of the southwest wall of Mokuaweoweo caldera and the upper flank of the mountain shown in the background in figure 38. Lava fountains are spurting from the fissure in the wall and on the floor of the caldera close to the wall. A pool of molten lava has formed just to the left of the base of the fountains and is spilling northward over the escarpment at the edge of the South Lunate platform to form another pool at the right of the picture. The edge of South Pit is visible at the left. The white patches on the caldera walls and outer slope of the mountain are snow. Official photograph, United States Navy.

The fountains outside the caldera gave rise to a lava flow down the west slope of the mountain, just north of and partly overlying the flow of 1851 (figs. 33 and 37). In its first 24 hours this flow advanced about 6 miles and occasioned some alarm in the Kona district, despite reassurances from the observatory staff that danger was not imminent. With the cessation of fountain activity outside the caldera the supply of lava was cut off, and by January 8 the flow appeared to be essentially motionless. The total length of the flow is about 6.8 miles.

The first ground observers reached the scene on the afternoon of January 7. At that time a nearly continuous line of lava fountains half a mile long was playing from the fissure near the center of Mokuaweoweo. The average height of the fountains was about 50 feet, but occasional bursts rose as high as 150 feet. Flows of lava were spreading both eastward and westward over the caldera floor, but the principal flow moved eastward. The other active area was at the southwest edge of the caldera. There a small fountain played intermittently from the fissure at the base of the cliff, with occasional spurts part way up the wall, and a much larger and steadier fountain played a short distance out from the cliff on the caldera floor. The larger fountain shot constantly to heights of 150 to 200 feet, with occasional bursts as high as 300 feet. From the southwestern fountains a stream of lava flowed northward, west of the 1940 cone, and joined the lava from the central fountain chain. Another lava stream flowed eastward, then divided, sending one branch northeastward across the caldera and another southward into South Pit.

The eruptive fissure split the 1940 cone, which was fuming strongly (fig. 38). Later examinations showed that lava had risen in the crater of the cone and had issued from the fissure on both sides of the cone, but by the afternoon of January 7 all this activity had ceased. Early on the morning of January 8 the observing party was driven off the summit by a heavy blizzard, and for the next 2 weeks the only observations were made from the air.

On January 9 the central fountains had stopped playing. For a week or more the southwestern fountains appear to have remained small, although variable in size. After that they increased greatly in height. On January 19 the larger fountain was reported to be 400 to 500 feet high (fig. 40). On January 21 Frank Hjort and James Orr, of the National Park Service, reached the summit and reported that the fountains were playing to heights of 300 to 500 feet. On January 23 Orr and D. H. Hubbard estimated the height of the larger fountain to be well over 500 feet, with some bursts reaching 800 feet or more. This great height, possibly the greatest yet observed on Mauna Loa, is roughly confirmed by comparison in photographs of the height of the fountain with that of the cliff behind it (fig. 40).

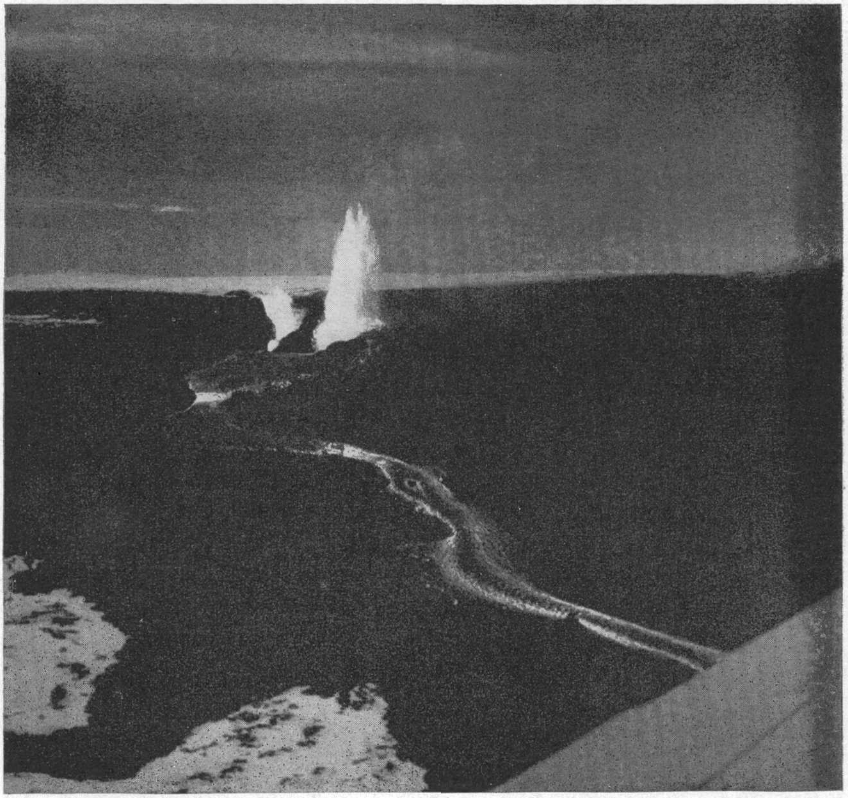

FIGURE 40.—Looking nearly west toward the lava fountains and flow at the southwest edge of Mokuaweoweo caldera on the evening of January 19, 1949. The smaller fountain on the left is issuing from the fissure part way up the wall. The fountain on the right is about 500 feet high. Photograph by K. Otaki, Ace Portrait Studio, Hilo.

These very high lava fountains, together with strong shifting winds, resulted in a light distribution of Pele's hair all over the southern part of the island. The fountains produced, for Mauna Loa, exceptionally large amounts of pumice, which accumulated around them to form a large cone and was drifted westward to form a blanket of pumice a mile long, half a mile wide, and about 20 feet thick near the cone (fig. 37).

The lava fountains were inclined somewhat eastward, and most of the ejecta fell into a pool at the east edge of the cone. From the pool the lava flowed eastward, over the surface of the old South Lunate platform. Lava spilling northward almost completely obliterated the scarp that formerly separated the Lunate platform from the central pit of Mokuaweoweo (fig. 39). During late January flows poured part of the time into the main caldera and part of the time into South Pit.

Lava pouring into South Pit gradually filled it. On January 25 the lava reached the level of the low southeast rim of the pit, and late on the same day the pit overflowed. A new lava stream flowed southeastward down the outer slope of the mountain, and by the evening of January 26 it had attained a length of about 2 miles. On the evening of January 31 the flow front was about 5.5 miles from South Pit (fig. 37). On January 29 or 30 a new branch of the flow broke out near South Pit, and this appears to have robbed the older branch of its supply of lava. After January 31 the older branch advanced very little. The new stream moved down slope just east of the older one and partly overlapped it, eventually attaining a length of about 2 miles.

During the night of February 4 lava-fountain activity was still moderately strong, but by the morning of February 5 it had become weak and irregular and on the afternoon of that day it ceased altogether. The cone was climbed on February 6, and the vent was found to be completely inactive except for the liberation of fume. On February 7 the flows on the south flank of the mountain were still found to be moving slowly. This continuation of movement in the flows after the cessation of lava extrusion at the vent probably resulted from draining of the still-fluid lava from the feeding tubes in the flows on the upper slopes of the mountain.

Thus the first phase of the eruption came to an end on February 5. It had buried about two-thirds of the floor of Mokuaweoweo with new lava, filled South Pit to the level of its southeast rim, sent two new flows down the west and south flanks of the mountain, and built a large cone at the southwest margin of the caldera (fig. 41). The cone is compound. An outer cone, breached on its east side, consists largely of fine cinder and pumice. It rests partly on the outer slope of the mountain and partly on the caldera floor and against the boundary cliff. The top of the outer cone is about 100 feet above the former rim of the caldera, and the maximum diameter of the cone is about 1,500 feet. At the east edge of the large cone, and partly enclosed within it, is a small double cone of coarse cinder and spatter. This inner cone probably was built during the stage of reduced gas pressure and lower fountains that directly preceded the end of the first phase of the eruption.

The area and volume of each of the major divisions of the 1949 lava are shown in the accompanying tabulation. Except for that in Mokuaweoweo and an almost negligible amount in South Pit, all the lava was poured out during the first phase of the eruption. It is estimated that, of the 44 million cubic yards of new lava in Mokuaweoweo, less than 4 million was extruded during the second phase of the eruption.

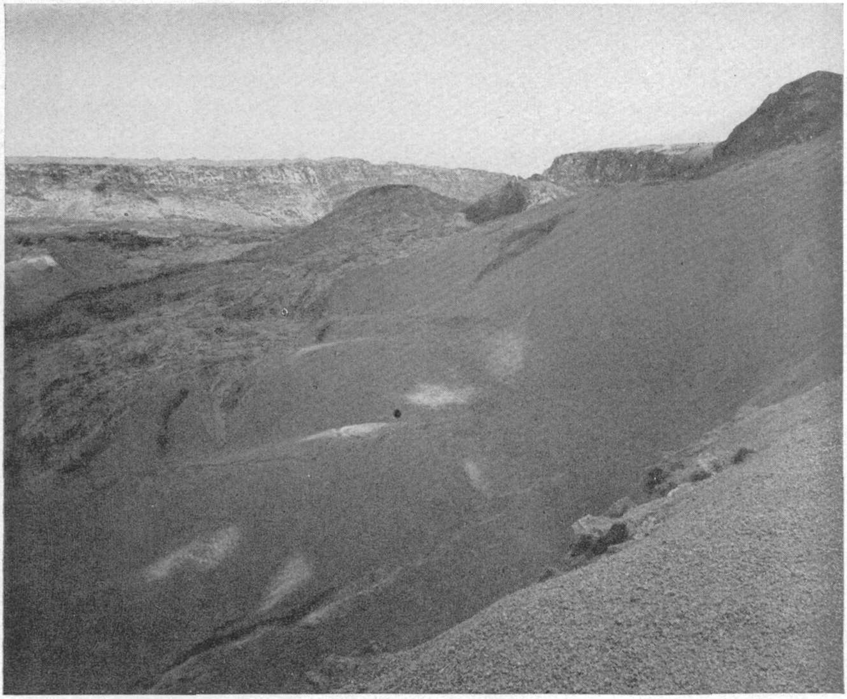

FIGURE 41.—View of the cone area of the 1949 eruption on July 26, from the top of the caldera wall to the north. In the foreground and on the right can be seen the big pumice cone built on and against the caldera rim during early stages of the eruption. The fissures are the result of partial collapse and slumping of the cone, and the white areas are the result of alteration of the pumice and deposition of salts by escaping gases. In the middle distance can be seen the hollow cinder-and-spatter cone, and to its left the lava cone. Photograph by G. A. Macdonald.

Area and volume of 1949 lava of Mauna Loa

Division	Area (square miles)	Volume (cubic yards)
Mokuaweoweo caldera	1. 5	44, 000, 000
South Pit	. 2	8, 000, 000
Western (Kona) flow	3. 1	16, 000, 000
Southern (Kau) flow	. 8	9, 000, 000
Total	5. 6	77, 000, 000

Lava fountaining ended on February 5, but fume rising from Mokuaweoweo was visible almost constantly during the remainder of February and March. It was obvious that the magma column must be standing at a very high level in the conduit. On several different nights a distinct glow was reported at the summit of the mountain. Although at no time when observers were able to see into the caldera was there any sign of lava fountaining or flow, there can be no doubt that the reported glows were the result of brief, quiet outpourings of lava.

During late March or early April the quiet outflow of lava became essentially continuous. On April 8 the cinder-and-spatter conelet inside the crater of the large pumice-and-cinder cone was emitting great puffs of fume, but no lava. About 250 feet east of the fuming conelet a small lava cone had been built (fig. 41), about 80 feet high and 150 feet across at the base, with a crater 40 feet in diameter containing a small surging pond of molten lava. The surface of the lava pond heaved slowly up and down, from a few inches to 15 feet below the rim of the crater. From the vent area liquid lava moved through tubes beneath the surface, emerging about a mile east-northeast of the cone to feed two sluggish flows of aa. Another sluggish aa flow was moving southeastward into South Pit.

On May 5 the height of the lava cone had increased to about 95 feet (fig. 42), and the cinder-and-spatter conelet had liberated some short flows of lava that partly veneered its flanks. A small pahoehoe flow was spreading near the base of the lava cone. Another, larger stream moved through tubes to issue a mile northeast of the cone as a moderately active pahoehoe flow.

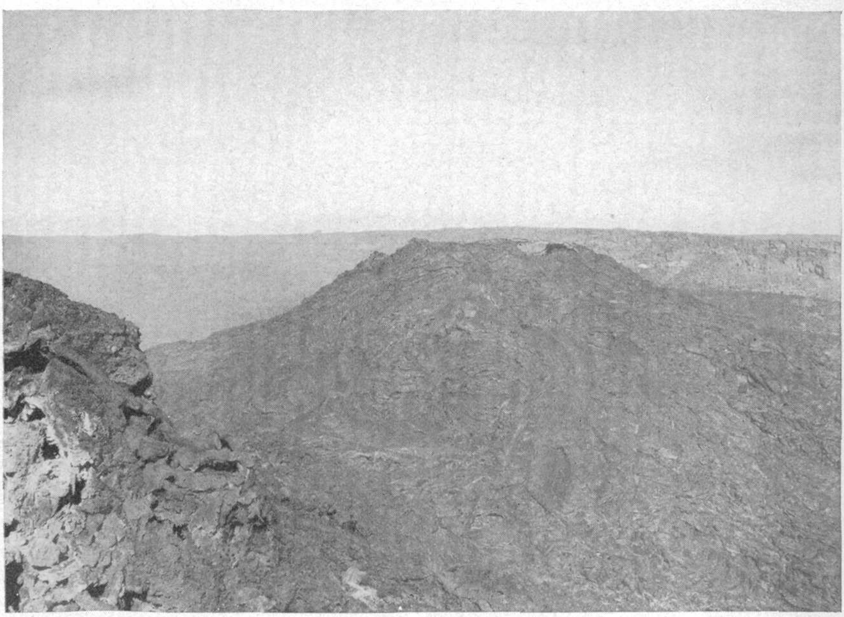

FIGURE 42.—The small lava cone built within the crater of the big cinder-and-pumice cone during the late stage of the 1949 eruption. The cone is about 100 feet high. The view was taken looking nearly east from a point near the summit of the cinder-and-spatter conelet on June 3, just after the end of the eruption. Hawaii National Park photograph by James B. Orr.

On May 7, J. B. Orr observed a distinctly cyclic pattern in the behavior of the two small cones. Each cycle began with a loud hissing and roaring within the cinder-and-spatter conelet, accompanied by copious liberation of fume. This lasted about 5 minutes and was followed by rapid outpouring of gas-rich pahoehoe. The lava effusion continued about 45 minutes, the rapidity of extrusion gradually decreasing until all flows ceased. Within about 5 minutes after the lava ceased to flow the hissing and roaring within the cone began again, and a relatively violent escape of gas continued for about 10 minutes. Immediately afterward the lava cone, which had been quiescent, started to fume copiously, and shortly thereafter fluid lava entered its crater, which had been empty. Within 10 minutes the crater was completely filled. The fluid lava gradually bulged up above the crater rim; confined within its tough crust, it formed a flat dome a foot or two high. Then the crust ruptured and the lava poured down the flanks of the cone. This phase of overflow continued for about an hour. Then the lava in the crater drained away, accompanied by liberation of large volumes of fume at the lava cone and hissing and roaring in the cinder-and-spatter conelet. This was followed by a period of quiet lasting about an hour, after which the entire cycle was repeated.

The eruption ended about the first of June. Flows were still moving actively on the caldera floor on May 19. On June 2 there was no further sign of movement in the flows; but a weak glow was still visible in the cone, which was fuming strongly. By the afternoon of June 3 the fume was very light and contained less sulfur dioxide than it had earlier. During the remainder of June no glow, and only weak fuming, were reported. On July 26 the 1949 cones were still hot, and both they and the 1940 cone were fuming weakly.

Later visits, in October 1949 and March 1950, showed no further changes in Mokuaweoweo except partial collapse of both the cinder-and-spatter conelet and the lava cone. The collapse revealed the cinder-and-spatter conelet to be partly hollow. In the center of the cone is an open chamber, about 25 feet across, with nearly vertical walls arching inward to a point at the top. The opening is about 40 feet high but was formerly higher, as the visible floor is formed of loose rubble that resulted from the collapse of the cone. The walls of the chamber are lined with a layer of pahoehoe 2 to 4 feet thick, in which the flow lines and flow planes are arranged parallel to the walls of the chamber and are nearly vertical. At the apex of the chamber the pahoehoe lining is prolonged upward as a 3-foot dike leading to two small spatter conelets at the summit. Apparently the lava rose into the cone, making room for itself by removing the material that in earlier stages formed the core of the cone. There is no evidence whether the removal was by stoping or by redissolving the hot cinder, or both. At the end of the eruption the magma column withdrew, leaving the center of the cone empty and the walls of the cavity veneered with a thin layer of lava.

BOMBING TO DIVERT LAVA FLOWS

Probably the first attempt to alter the course of a lava flow by artificial means occurred during the 1669 eruption of Etna volcano. The flow was advancing toward the city of Catania and seemed likely to destroy it. In an attempt to save the city, several dozen men covered themselves with wet cowhides for protection against the heat and dug a channel through the wall of hot lava at one edge of the flow. The operation was initially successful. A stream of lava escaped through the gap thus created and moved away at a high angle to the direction of the original flow, partly relieving the pressure on the stream moving toward Catania. Unfortunately, however, the new flow moved toward the town of Paterno, and some 500 irate citizens of that town descended upon the men of Catania and drove them away from the newly dug lava channel. Left unattended, the gap in the flow wall soon clogged up with cooled lava, and the main branch of the flow continued toward Catania, partly destroying it (Rittmann, 1929). This early attempt, although it ended in failure, demonstrated the possibility of diverting part or all of a lava flow to a new course by artificially breaking down the confining wall of the flow.

Digging away the edge of the flow, by hand or by machine, is a difficult and possibly dangerous procedure. It is easier and quicker to blast away the lava by means of explosives. Lorrin A. Thurston suggested orally in the early 1920's that, in the case of pahoehoe lava flows descending gentle slopes, high explosives might be thrust out over the flow on long poles and dropped through windows in the feeding tube near the flow source, shattering the tube, forcing the lava to spread out again near the source, and removing the supply of lava from the advancing lower end of the flow. He later published the suggestion (Thurston, 1929). Similar methods had been under discussion for several years by members of the staff of the Hawaiian Volcano Observatory. Thurston's suggestion was accepted and advocated by Jaggar (1931), and during the Mauna Loa eruption of 1935 Jaggar introduced the method of emplacing the explosive by dropping military bombs from airplanes (Jaggar, 1936). This generally is the most practical way of transporting and emplacing the explosive. In some instances shells from nearby big guns might be more effective because of the greater accuracy with which they can be directed, but for the most part potential diversion sites are too inaccessible to be reached conveniently or quickly by artillery.

There are three principal ways in which bombing can bring about diversion of the fluid lava, thereby robbing the older flow front of its supply of lava and causing stagnation of the lower end of the flow. These are: (1) bombing of the natural levees along the open lava river of an aa flow or a young pahoehoe flow in which tubes have not yet formed; (2) bombing of the main feeding channel of a mature pahoehoe flow in which tubes have become well developed; and (3) bombing of the walls of the cinder cone at the source of the flow.

In well-established lava flows on little-dissected terrain the liquid lava of the main feeding channels commonly is confined within tubes or between natural levees and is at a level several feet higher than that of the land surface adjacent to the flow. Where the lava river is still open and confined between levees, the breaking down of the levee therefore will allow the liquid lava to escape to one side and form a new flow, robbing the old flow of part or all of its supply of liquid lava. If topographic conditions are favorable, the new flow may move off at a high angle to the direction of the older flow and reach some entirely different destination. More commonly, however, because the older flow was guided by the direction of steepest slope or preexisting topographic depressions, the new flow follows the same direction and moves down slope along the edge of the older one. If it does so, it may eventually reach the same place at which the older flow terminated. However, the advance of the lava as a whole is greatly delayed, because the diverted flow may take days, or even weeks, to reach the point attained previously by the older flow. When the second flow has reached the danger point, it also can be bombed, thus delaying the advance of the lava front still further.

A long stretch of the flow, or several separate points on the flow, may be suitable for bombing. If so, in general it appears advisable to select the lowest suitable site for bombing first. If it then becomes necessary to bomb the flow again at a later date, the higher sites are still available. On the other hand, if the higher sites are bombed first the new lava streams advancing along the edges of the older one may so alter conditions that the lower sites are no longer suitable. Generally speaking, it is wise to wait as long as is safely possible before bombing the flow. Every day during which bombing is delayed brings the eruption that much closer to an end and, in general, sees the rate of lava output diminished. Premature bombing may result in a need for repeating the process, whereas a single bombing might have sufficed had it been delayed a little longer. Care must be taken, however, to allow a sufficient margin of time to cover the possibility of periods of bad weather with low visibility (when bombing is impossible) and rapid forward spurts of the flow.

The practicability of breaking down the levee of an open lava stream by aerial bombing was demonstrated during the 1942 eruption of Mauna Loa (Finch, 1942, p. 4). Disruption of the levee by bombs resulted in at least one new lava stream that poured out through the break in the wall. Topography was not favorable for directing the new flow away from the course of the older one; consequently it flowed along the edge of the older one for a short distance and then rejoined it. Even such a brief diversion may have some effect, however, in retarding the advance of the front of the major flow, owing to the rapid cooling of the channel of the main flow below the point of diversion and the consequent chilling of the next lava to enter it, with the accompanying tendency to clog the channel.

The method of bombing the main tubes of a pahoehoe flow was tried successfully during the 1935 eruption of Mauna Loa (Jaggar, 1936). Bombs dropped on the roof of the tube may break in the roof and cause the tube to become clogged with solid fragments, or bombs dropped into the liquid lava within the tubes through the roof or through windows in the roof may cause sufficiently violent stirring of the liquid to transform it from pahoehoe to aa, with an increase in viscosity or even local congelation. If it is not swept away with the current, this mass may cause a plugging of the tube. If in either way the tube becomes clogged, the result is an overflow of liquid lava from the tube at the point of clogging and a partial or total removal of the supply of liquid from the tube farther down slope. The lava that overflows at the break forms new tongues, which advance down slope on top of, or alongside, the older flow. If the eruption continues long enough, these tongues may develop new major tubes and may in time reach or pass the terminus of the older flow, but the advance of the lava as a whole will have been delayed and the end of the eruption will be that much closer. It may be possible to repeat the bombing if necessary.

The cinder-and-spatter cones formed at the source of lava flows commonly contain pools of lava that are held at levels several feet above the surrounding land surface. Likewise, the liquid surface of lava flowing in a well-established channel issuing from the cone is generally several feet above the adjacent terrain. The breaking down of the cone walls, either naturally or by bombing, therefore will allow the liquid in the cone to escape over the surrounding ground, robbing the established lava flow of its supply of new lava. Many of the cones on the rifts of Mauna Loa have a form especially favorable for bombing. They are built by rows of lava fountains spurting from fissures and are long and narrow, with relatively thin walls that probably would be quite easy to break down by bombing. Bombing of the walls of the source cone has been suggested (Finch, 1942, p. 6; Macdonald, 1943, p. 255) but has not yet been tried. However, during the 1942 eruption of Mauna Loa there occurred a natural breakdown of the cone walls, liberating floods of pahoehoe, one of which formed a new flow advancing seaward parallel to the older channel. A day later, forward movement at the front of the older flow had practically ceased.

Successful diversion of lava flows by bombing depends upon a combination of several favorable circumstances, including a lava river flowing in a channel or lava held in the source cone at a level higher than the adjacent land surface; narrow levees, thin cone walls, or thinly roofed tubes that can be broken open by bombs; and favorable topography. The first two conditions are commonly present during eruptions of basaltic lava, but favorable topography is not so general. On the slopes of volcanoes that have been appreciably dissected by erosion, flows may be confined within valleys, and diversion may be difficult or impossible. Even under those conditions, however, it may be possible to delay greatly the advance of the flow front by repeated bombing and spreading of the lava in the upper reaches of the valley. On the undissected or little-dissected slopes of young volcanoes, where erosion has not yet cut valleys, bombing to divert the flow is both possible and practical.

It must be pointed out that successful diversion is possible only where the flow has continued long enough to establish well-defined channels or build at least moderate-sized cones. Probably little can be done with the voluminous bursts that occur during the early hours of Mauna Loa eruptions when the flows are spreading rapidly in several directions and moving through many shifting and anastomosing channels. Fortunately these early floods are generally high on the mountain, where they constitute no danger. It must likewise be realized that time is required to prepare the planes and load the bombs, as well as to select the targets and put the plan into operation. Therefore, diversion by bombing may not be possible in time to avert catastrophe where the flow is advancing rapidly down steep slopes or where the point of outbreak of the flow is too close to the area whose protection is desired. It is difficult to place any definite limit on the distance of the vent from the endangered area within which time is insufficient to permit bombing to divert the flow. This depends on the fluidity of the particular lava stream, on the slope, and on the general character of the terrain. For average Hawaiian eruptions, with average slope conditions, it may be about 7 miles. Where the distance is less than that, or where slopes are steep and flow of the lava rapid, only lava barriers such as those suggested by Jaggar (1945) can furnish protection.

REFERENCES CITED

BRIGHAM, W. T., 1909, The volcanoes of Kilauea and Mauna Loa: Bernice Pauahi Bishop Mus. Mem., vol. 2, no. 4.

FINCH, R. H., 1942, The 1942 eruption of Mauna Loa: Volcano Letter 476, pp. 1–6.

———, 1949, Volcanic tremor (pt. 1): Seismol. Soc. America Bull., vol. 39, pp. 73–78.

JAGGAR, T. A., 1931, Preparedness against disaster: Volcano Letter 338, pp. 2–4.

———, 1936, The bombing operation at Mauna Loa: Volcano Letter 431, pp. 4–6.

———, 1945, Protection of harbors from lava flow: Am. Jour. Sci., vol. 243–A (Daly volume), pp. 333–351.

JAGGAR, T. A., and FINCH, R. H., 1929, Tilt records for 13 years at the Hawaiian Volcano Observatory: Seismol. Soc. America Bull., vol. 19, pp. 38–51.

LOUCKS, R. C., 1949, Report on preliminary work for radiation survey: Volcano Letter 505, p. 1.

MACDONALD, G. A., 1943, The 1942 eruption of Mauna Loa, Hawaii: Am. Jour. Sci., vol. 241, pp. 241–256.

MACDONALD, G. A., and FINCH, R. H., 1949a, The Mauna Loa eruption of January 1949: Volcano Letter 503, pp. 1–7.

———, 1949b, Activity of Mauna Loa during April, May, and June 1949: Volcano Letter 504, pp. 1–4.

MACDONALD, G. A., and ORR, J. B., 1950, The 1949 summit eruption of Mauna Loa: U. S. Geol. Survey Bull. 974–A.

RITTMANN, A., 1929, Der Ätna und seine Laven: Naturwissenschaften, vol. 17, pp. 95–96.

THURSTON, L. A., 1929, On the use of high explosive to divert lava flows: Honolulu Daily Advertiser, September 27.

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