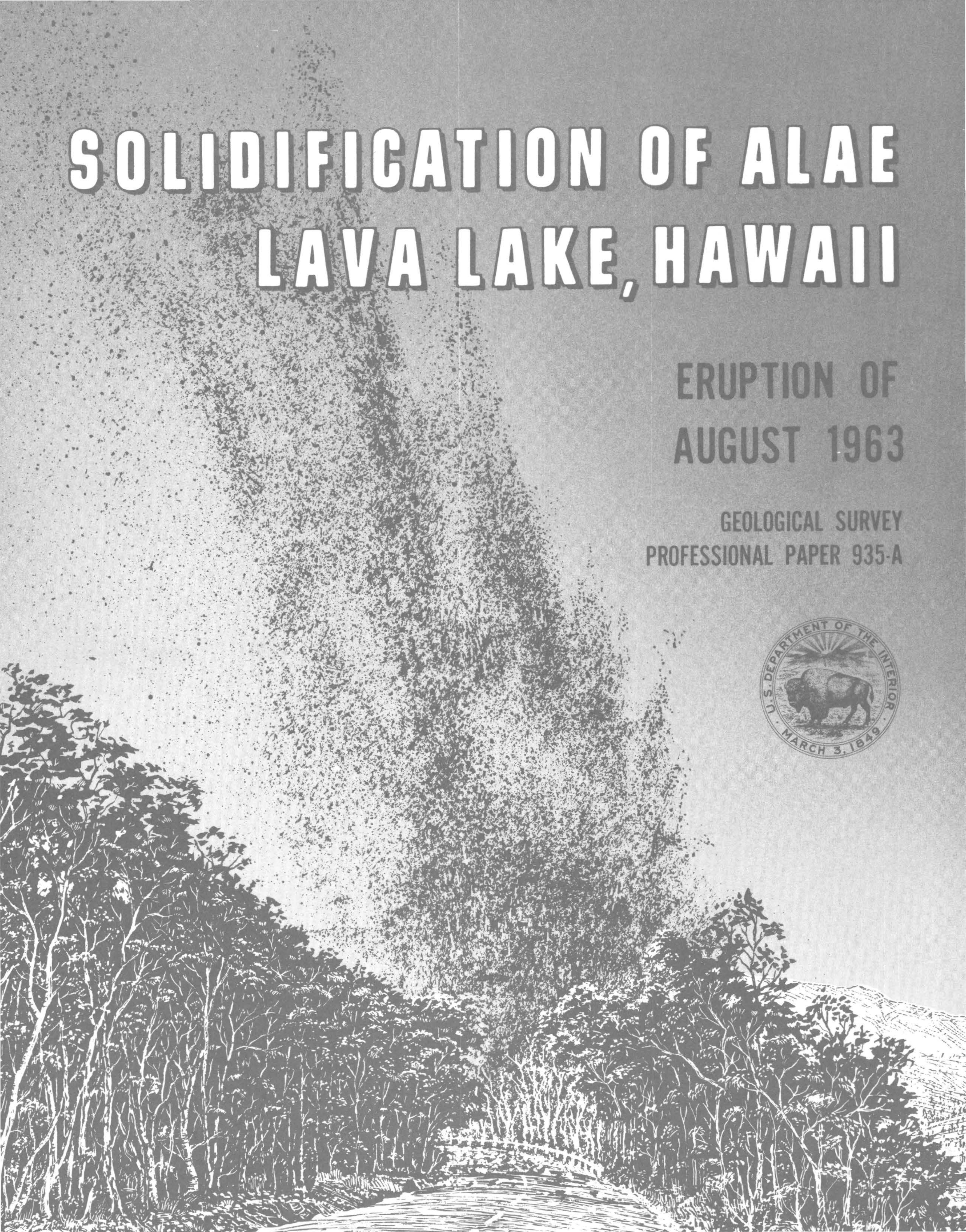
SOLIDIFICATION OF ALAE LAVA LAKE, HAWAII

ERUPTION OF AUGUST 1963

GEOLOGICAL SURVEY PROFESSIONAL PAPER 935-A



The Eruption of August 1963 and the Formation of Alae Lava Lake, Hawaii

By DALLAS L. PECK and W. T. KINOSHITA

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A detailed description of the formation and surface features of a thin, ponded basalt flow

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ILLUSTRATIONS

METRIC-ENGLISH EQUIVALENTS

Metric unit		English equivalent	
Length			
millimetre (mm)	=	0.03937	inch (in)
metre (m)	=	3.28	feet (ft)
kilometre (km)	=	.62	mile (mi)
Area			
square metre (m^2)	=	10.76	square feet (ft^2)
square kilometre (km^2)	=	.386	square mile (mi^2)
hectare (ha)	=	2.47	acres
Volume			
cubic centimetre (cm^3)	=	0.061	cubic inch (in^3)
litre (l)	=	61.03	cubic inches
cubic metre (m^3)	=	35.31	cubic feet (ft^3)
cubic metre	=	.00081	acre-foot (acre-ft)
cubic hectometre (hm^3)	=	810.7	acre-feet
litre	=	2.113	pints (pt)
litre	=	1.06	quarts (qt)
litre	=	.26	gallon (gal)
cubic metre	=	.00026	million gallons (Mgal or 10^6 gal)
cubic metre	=	6.290	barrels (bbl) (1 bbl=42 gal)
Weight			
gram (g)	=	0.035	ounce, avoirdupois (oz avdp)
gram	=	.0022	pound, avoirdupois (lb avdp)
tonne (t)	=	1.1	tons, short (2,000 lb)
tonne	=	.98	ton, long (2,240 lb)
Specific combinations			
kilogram per square centimetre (kg/cm^2)	=	0.96	atmosphere (atm)
kilogram per square centimetre	=	.98	bar (0.9869 atm)
cubic metre per second (m^3/s)	=	35.3	cubic feet per second (ft^3/s)

Metric unit		English equivalent	
Specific combinations—Continued			
litre per second (l/s)	=	.0353	cubic foot per second
cubic metre per second per square kilometre [$(m^3/s)/km^2$]	=	91.47	cubic feet per second per square mile [$(ft^3/s)/mi^2$]
metre per day (m/d)	=	3.28	feet per day (hydraulic conductivity) (ft/d)
metre per kilometre (m/km)	=	5.28	feet per mile (ft/mi)
kilometre per hour (km/h)	=	.9113	foot per second (ft/s)
metre per second (m/s)	=	3.28	feet per second
metre squared per day (m^2/d)	=	10.764	feet squared per day (ft^2/d) (transmissivity)
cubic metre per second (m^3/s)	=	22.826	million gallons per day (Mgal/d)
cubic metre per minute (m^3/min)	=	264.2	gallons per minute (gal/min)
litre per second (l/s)	=	15.85	gallons per minute
litre per second per metre [(l/s)/m]	=	4.83	gallons per minute per foot [(gal/min)/ft]
kilometre per hour (km/h)	=	.62	mile per hour (mi/h)
metre per second (m/s)	=	2.237	miles per hour
gram per cubic centimetre (g/cm^3)	=	62.43	pounds per cubic foot (lb/ft^3)
gram per square centimetre (g/cm^2)	=	2.048	pounds per square foot (lb/ft^2)
gram per square centimetre	=	.0142	pound per square inch (lb/in^2)
Temperature			
degree Celsius (°C)	=	1.8	degrees Fahrenheit (°F)
degrees Celsius (temperature)	=	[(1.8×°C)+32]	degrees Fahrenheit

THE ERUPTION OF AUGUST 1963 AND THE FORMATION OF ALAE LAVA LAKE, HAWAII

By Dallas L. Peck and W. T. Kinoshita

ABSTRACT

After the seismic episodes and summit collapses of May, July, and early August 1963, Kilauea Volcano, Hawaii, erupted along the east rift zone in and near Alae Crater from August 21 to 23, only 8½ months after the December 1962 eruption in nearby Aloi Crater. The eruption started at 18^h10^m, August 21, after nearly 4½ hours of summit deflation, low-amplitude tremor, and many small earthquakes. Fountains on the floor and north wall of Alae Crater fed lava, at rates as high as $2.3 \times 10^5 m^3$ per hour and at maximum temperatures of about 1,160°C, into a growing lava lake in the southeast pit of the crater. During the last 12 hours of the eruption, a decrease in the rate of extrusion to near zero, accompanied by a decrease in temperature to 1,140°C, led to stagnation of the lava lake at its maximum volume of $8.4 \times 10^5 m^3$. Near the end of the eruption at 08^h10^m, August 23, $1.8 \times 10^5 m^3$ of lava drained back into the vents leaving a stagnant lake 305 m long, 245 m wide, and as much as 15 m deep, composed of homogeneous tholeiitic basalt containing 3.5 percent olivine. A low spatter ridge partially covered and bordered the northwest side of the lake and continued as coalescing spatter cones on the north wall of the crater. The flat central floor of the lake was 14.0 m deep, but the northern part thinned to 11.3 m over a buried spatter ridge.

The surface of the lake was complex in detail and showed a variety of flow features, which are a record of the many events that took place during and after the eruption. A 30-m wide levee of discontinuous slabs and pressure ridges bordered all but the northwest margin of the lake and was in turn bounded for most of its length by a moat as deep as 5 m. The main part of the lake was crossed by pressure ridges and linear oozeups, which marked the position of glowing cracks during the eruption. Shear zones marked the boundaries between crust formed on relatively static lava and crust formed on lava flowing out from the vent area. Observation during the eruption and later mapping of the surface features indicated that during the later part of the eruption, the lava lake consisted of an outer stagnant part and an inner part marked by active lava circulation; lava flowing outward from the vent rafted crust against the stagnant margin, shoving up piles of broken slabs and buckling the crust along lines of weakness.

The surface of the lake was broken by cracks formed largely as the result of stresses induced by thermal contraction of the cooling lava. Cracks that developed near the end of the eruption formed a random, orthogonal network outlining 0.3- to 0.7-m-high hummocks, which were divided by orthogonal cracks into 3- to 6-sided polygons averaging 1½ m in diameter. Many new cracks, mostly short ones near the crests of hummocks, opened during a period of heavy rainfall 5 to 9 months after the eruption. Most of these cracks were sites of deposition of sublimates of sulfur and calcium sulfate. Between 1 and 2 years after the eruption, when the lake had completely solidified, the surface was broken by long swarms of short cracks that originated in the zone of maximum cooling at depths of 5 to 10 m in the lake and propagated upward to the surface.

Field studies of the August 1963 lake ended in February 1969, when the lake was covered by 72 m of new lava.

INTRODUCTION

Kilauea Volcano erupted in and near Alae Crater from August 21 to 23, 1963, 8½ months after the eruption in nearby Aloi Crater. The eruption left in Alae Crater a lava lake about 15 m deep of tholeiitic basalt, which solidified during the following 10 months and cooled to less than 90°C by August 1967, 4 years after the eruption. This report describes the eruption and surface features of the lava lake.

Three eruptions of Kilauea Volcano during the last 2 decades ponded flows in accessible pit craters, forming stagnant lakes of molten lava that have been intensively studied—the 1959 eruption in Kilauea Iki Crater, the August 1963 eruption in Alae Crater, and the March 1965 eruption in Makaopuhi Crater. These lava lakes are natural laboratories that have provided unique opportunities to learn more about the properties of basaltic lava and the cooling processes of ponded flows. They have been the target of a major continuing effort by the U.S. Geological Survey's Hawaiian Volcano Observatory.

Studies begun in the 111-m-deep lava lake in Kilauea Iki Crater included precise-level measurements, core drilling, temperature measurements, chemical and petrographic study of drill core, ground magnetic studies, and field electromagnetic surveys. These have been described by Ault and others (1961, 1962), Macdonald and Katsura (1961), Decker (1963), Rawson and Bennett (1964), and Richter and Moore (1966).

When the August 1963 eruption produced a shallow ponded flow in Alae Crater, a variety of similar studies were begun. Drilling equipment was lowered to the lake surface by an aerial tram, and the first of many drill holes through the crust was started on August 29, 6 days after the end of the eruption. Temperature measurements in the drill hole were begun on the following day. During the following months many different studies were started, some of which were continued until August 1967, when the lake had approached ambient temperature. These included the following: repeated core drilling through the crust and into melt; sampling of gases and melt, and measurement of temperatures in the drill holes; study of drill core, including examination by binocular microscope, measurement of density, petrographic study, chemical analysis, mineral separation, and measurement of magnetic susceptibility; installation of a grid of stations on the lake surface and repeated measurement of the altitude and intensity of the magnetic field at the stations; recording of rainfall at the rim of the crater; and mapping of surface features and joint cracks.

Previous reports on Alae lava lake include: a preliminary description of the eruption and of temperatures in the lake (Peck and others, 1964); analysis of volcanic tremor associated with the eruption (Shimozuru and others, 1966;) descriptions of crystallization of basalt in the lake (Peck and others, 1966); magnetic properties and oxidation of iron-titanium oxide minerals (Grommé and others, 1969); the formation of joint cracks (Peck and Minakami, 1968); sulfide-rich blebs in an ooze sample from the lake (Skinner and Peck, 1969); lava coils on the surface (Peck, 1966); and a report on infrared radiation from the lake (Decker and Peck, 1967).

In March 1965, an eruption of Kilauea Volcano produced a new lava lake 83 m deep in Makaopuhi Crater (Wright and others, 1968). Studies of this lake, which have been carried out under the direction of T. L. Wright, include microprobe study of core samples (Hakli and Wright, 1967; Wright and Weiblen, 1968), measurement of oxygen fugacity in drill holes (Sato and Wright, 1966), collection of molten lava samples from beneath the crust (Wright and others, 1968), collection of gas samples from drill holes (Finlayson and others, 1968), and the measurement of viscosity in molten lava beneath the crust (Shaw and others, 1968). The prehistoric lava lake that was exposed in section on the mezzanine cliff face of Makaopuhi Crater has also been studied in detail (Moore and Evans, 1967; Evans and Moore, 1968). Some of the interpretations of the present series of papers on Alae lava lake have benefited from these later studies. The studies of all three recent lava lakes have been summarized by Peck (1974) and Wright, Peck, and Shaw (1976).

Later eruptions of Kilauea Volcano, starting in February 1969, have buried the lakes in Alae and Makaopuhi Craters with new lava (Swanson and others, 1971), bringing field studies of these lakes to a close. Alae Crater was later completely filled with lava during a series of episodic and complex eruptive events (Swanson and others, 1973; Swanson and Peterson, 1972), and by 1972 the site was covered by a broad, 100-m-high, basaltic dome, satellitic to the new shield, Mauna Ulu. In this report, accordingly, we refer to the crater and its 1963 lava lake in the past tense. As of 1974, studies including level measurements and core drilling of the still partly molten lake in Kilauea Iki Crater were continuing.

ACKNOWLEDGMENTS

We are indebted to many who helped observe the eruption in Alae Crater, and carry out the program of studies of the lava lake. These included a visiting group of Japanese scientists under the direction of Prof. T. Minakami of the Earthquake Research Institute, Tokyo University. Other members of the group were Profs. D. Shimozuru, S. Aramaki, and K. Kamo and Messrs. T. Miyasaki and S. Hiraga. The work reported here was a team effort of the staff of the observatory under the general guidance of the successive Scientists-in-Charge, J. G. Moore and H. A. Powers. Directly concerned with the studies are the following: T. L. Wright, B. J. Loucks, W. H. Francis, J. C. Forbes, E. T. Endo, R. T. Okamura, R. Y. Koyanagi, and G. Kojima. The Hawaiian Volcano Observatory and Alae Crater are in Hawaii Volcanoes National Park; the Park Superintendent at the time of the study, F. T. Johnston, and other personnel of the Park Service helped facilitate the studies. The U.S. Weather Bureau supplied the continuously recording rain gauge for the study. Major P. K. Nakamura, Commander of the Air National Guard unit in Hilo, made aircraft available for photographing the eruption area. Many of the problems encountered in the study have been clarified as the result of discussions with our colleagues of the Geological Survey, particularly H. R. Shaw, D.

B. Stewart, R. S. Fiske, M. Sato, and A. H. Lachenbruch.

GEOLOGIC SETTING

The basaltic shield volcano Kilauea is one of five volcanoes on the island of Hawaii (fig. 1), at the southeast end of the Hawaiian Archipelago. Kilauea has erupted repeatedly in historic time in its summit caldera and along the two rift zones that stretch from the summit to the east and southwest.

After nearly 18 years of quiescence, Kilauea began the current series of eruptions in June 1952 (Macdonald, 1955), with activity in Halemaumau Crater, in the summit caldera (fig. 2). In each of the next

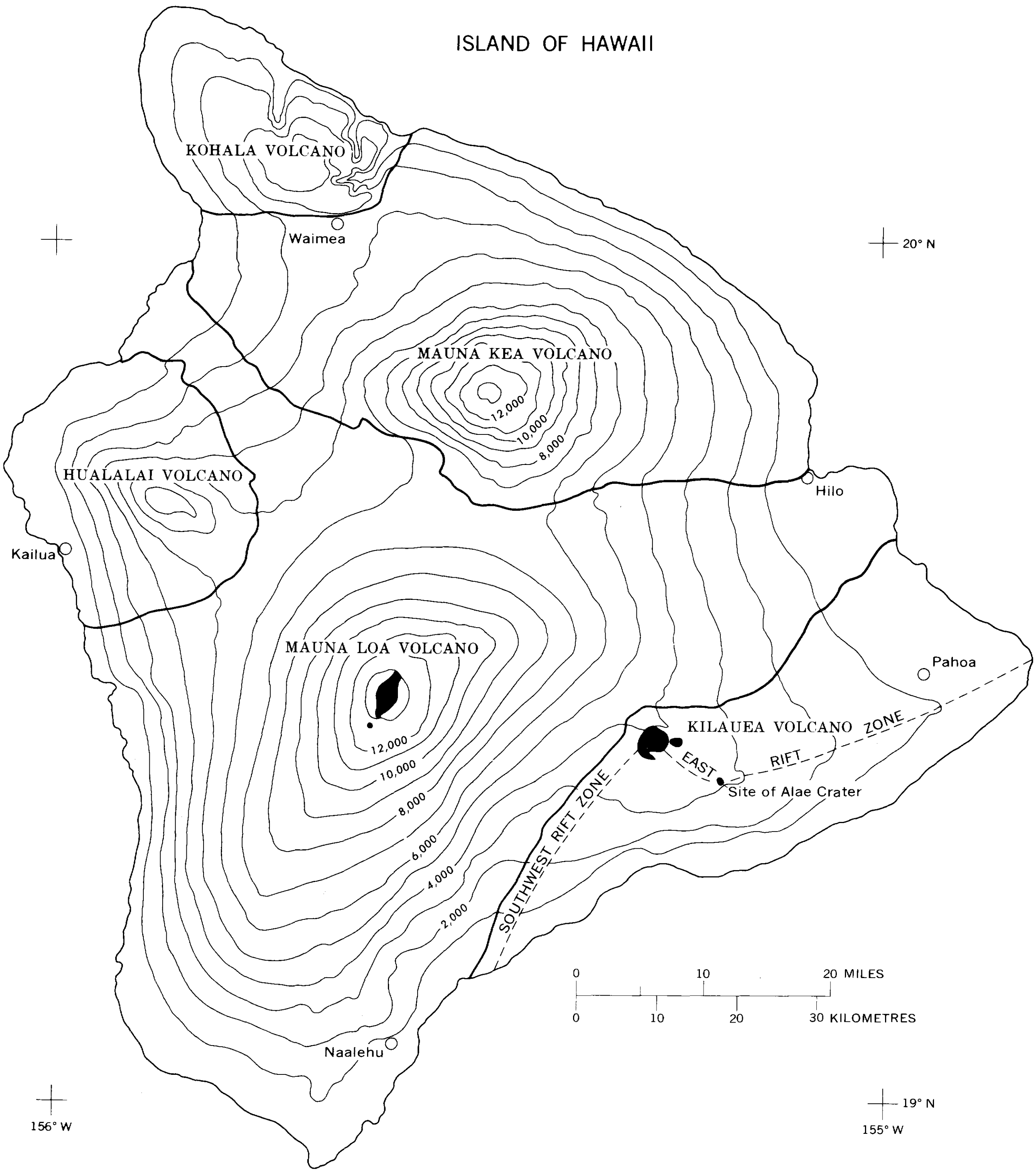

FIGURE 1.—Map showing the five volcanoes constituting the island of Hawaii.

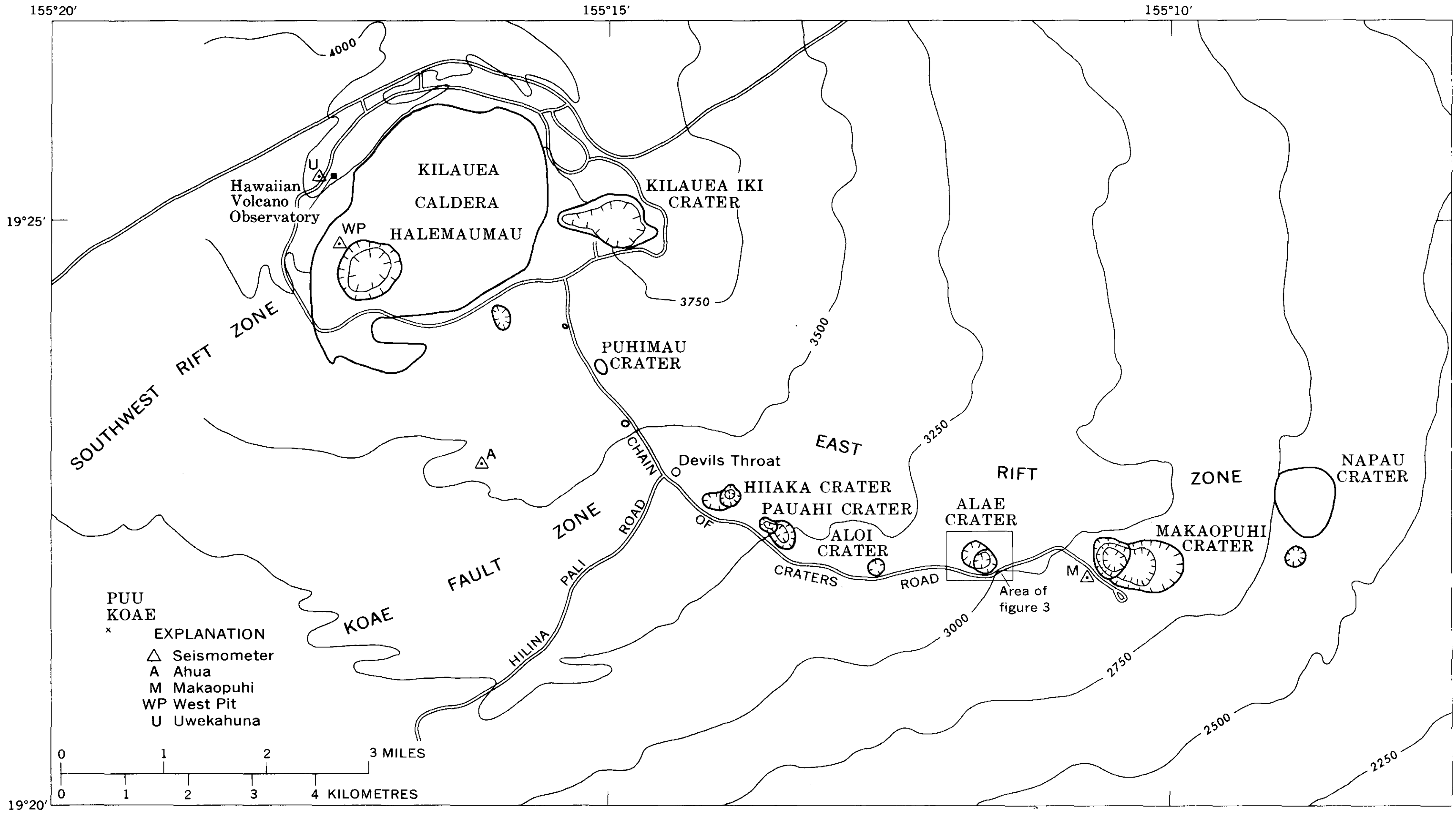

Figure 2.—Index map of the summit and upper east rift zone of Kilauea Volcano as it appeared in 1963. Boundaries of craters and Kilauea caldera are shown as heavy lines.

three pairs of eruptions, a summit phase was followed by a flank eruption along the east rift—in 1954–55 (Macdonald and Eaton, 1957, 1964), 1959–60 (Richter and Eaton, 1960), and in 1961 (Richter and others, 1964). During the next 5 years, all eruptions were from fissures along the east rift zone with no intervening summit phases: in Aloi Crater in December 1962 (Moore and Krivoy, 1964), in Alae Crater in August 1963 (this report), in Napau Crater and along the middle part of the east rift in October 1963 (Moore and Koyanagi, 1969), in Makaopuhi Crater and along the middle part of the east rift in March 1965 (Wright and others, 1968), and in Aloi Crater again in December 1965 (Fiske and Koyanagi, 1968). Lava also moved into the east rift zone from the summit reservoir, but without attendant eruptions during three seismic episodes in 1963 (Kinoshita, 1967). Since 1965, Kilauea has erupted repeatedly, both at the summit and along the two rift zones. The week-long eruption in February 1969 fed flows into Alae Crater (Swanson and others, 1973) covering the August 1963 lava lake.

Alae Crater was on the east rift zone of Kilauea Volcano, about 8 km southeast of the summit caldera (fig. 2). The filled crater now underlies the eastern flank of Mauna Ulu. Alae was an elliptical pit crater elongate in a northwesterly direction, 640 m long and 460 m wide (fig. 3). Most of the observations and measurements of the 1963 eruption were made from a turnout and observation point on the Chain of Craters Highway at the south edge of the crater. Alae Crater was a double crater formed by two overlapping collapse pit craters. The first and larger pit was filled by a prehistoric lava lake and by an overlying 6-m-thick lava flow to within 100 m of the crater rim. At the time of the 1963 eruption, this old crater fill was still preserved as a bench on the northwest side of the crater. A second prehistoric collapse of the southeast part of the first crater dropped the original crater fill at least 60 m, producing an approximately circular pit 160 m deep and 300 m in diameter. In 1840, lava erupted from fissures in the crater (Dana, 1849, p. 188), formed a spatter rampart on the mezzanine and floor of the southeast pit, spread as thin shelly flows over parts of the floor and cliff face of the mezzanine, and ponded in a shallow flow on the floor of the southeast pit.

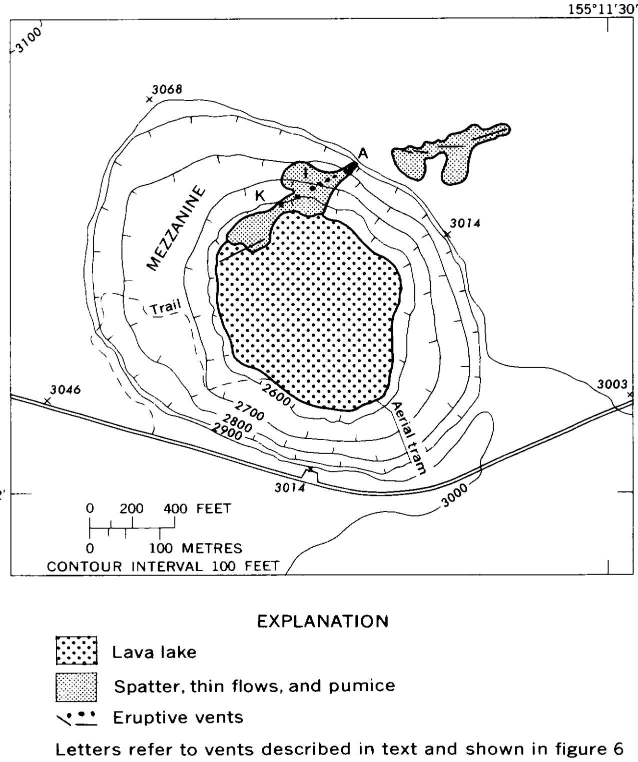

FIGURE 3.—Map of Alae Crater showing distribution of volcanic rocks from the August 1963 eruption. Location of crater is shown in figure 2.

PRE-ERUPTION UPLIFT OF THE SUMMIT REGION AND SEISMIC ACTIVITY

Uplift of the summit region of Kilauea Volcano resumed almost immediately after the collapse associated with the small flank eruption of December 1962 (fig. 4) and continued until May 9, 1963, when about 8 million m^3 of lava moved from the summit reservoir into the southwest rift zone, accompanied by harmonic tremor and many shallow earthquakes (Kinoshita, 1967). The intrusion of lava produced extensive new cracking along a zone extending 5 km from Puu Koae to a point 3 km south of Halemaumau. Collapse of the summit ceased on May 12, and rapid reinflation began. This continued until July 1, when about 8 million m^3 of magma moved from the

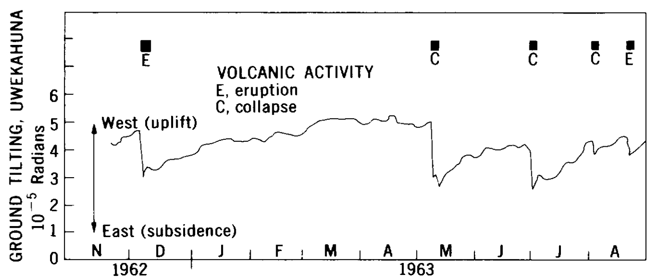

FIGURE 4.—East-west ground tilting of the Kilauea summit area as indicated by daily readings of the short base water-level tiltmeter at Uwekahuna from December 1962 to September 1963. Periods of eruption (E) and collapse (C) are shown at top.

summit reservoir into the eastern part of the Koae fault zone. The intrusion produced extensive cracking and deformation along the Koae fault near its junction with the east rift zone. Uplift began again on July 2 and continued until August 3, when nearly continuous tremor and earthquakes were recorded at Kilauea as about 2 million m^3 of magma moved from the summit reservoir into the upper east rift zone near the junction with the Koae fault zone. If the volume calculations are even approximately valid, we can infer that most, perhaps all, of the lava erupted into Alae Crater from August 21 to 23 was derived from lava stored in the rift zone after the collapses of May, July, and August 1963. After this episode, uplift began again, slowly, and continued until August 21. During this period, local caldera quakes averaged about 70 per day.

DESCRIPTION OF THE AUGUST 21–23, 1963, ERUPTION

The first indication of the impending eruption was the onset, at *$13^{h}46^{m}$ August 21, 1963, of nearly continuous small-amplitude tremor that recorded more strongly on a seismograph near the Makaopuhi Crater than on seismographs near Kilauea Caldera (fig. 5). Beginning at the same time, many small earthquakes, one to four per minute, were recorded. Many of these were from epicenters near Makaopuhi, which yielded *S* minus *P* intervals of 0.5 and 0.6 seconds at Makaopuhi. More than 800 distinct earthquakes were recorded from the upper east rift zone during the remainder of August 21. At $13^{h}50^{m}$, displacement of the traces of the Press-Ewing seismographs in the Uwekahuna vault near the Hawaiian Volcano Observatory indicated the beginning of a distinct tilt to the east and a less distinct tilt to the south. Tremor died down to a low level after $15^{h}00^{m}$, but at $18^{h}00^{m}$ it began to increase again. A sharp increase in tremor amplitude at $18^{h}10^{m}$ probably marks the beginning of the eruption. A swarm of small earthquakes began at about $13^{h}50^{m}$ after three earthquakes of magnitude about 2 on the Richter scale. The frequency of earthquakes increased to about 5 per minute at $14^{h}30^{m}$ and then decreased to 0 at $18^{h}15^{m}$.

When the eruption was first observed, shortly after $18^{h}15^{m}$, vigorous lava fountains on the floor of southeast pit and on the north wall had already formed a pool of lava covering most of the floor of the southeast pit. At $19^{h}20^{m}$, the fountains on the floor formed an almost continuous curtain 5 to 10 m high extending 80 m N. 65 E. from near the east

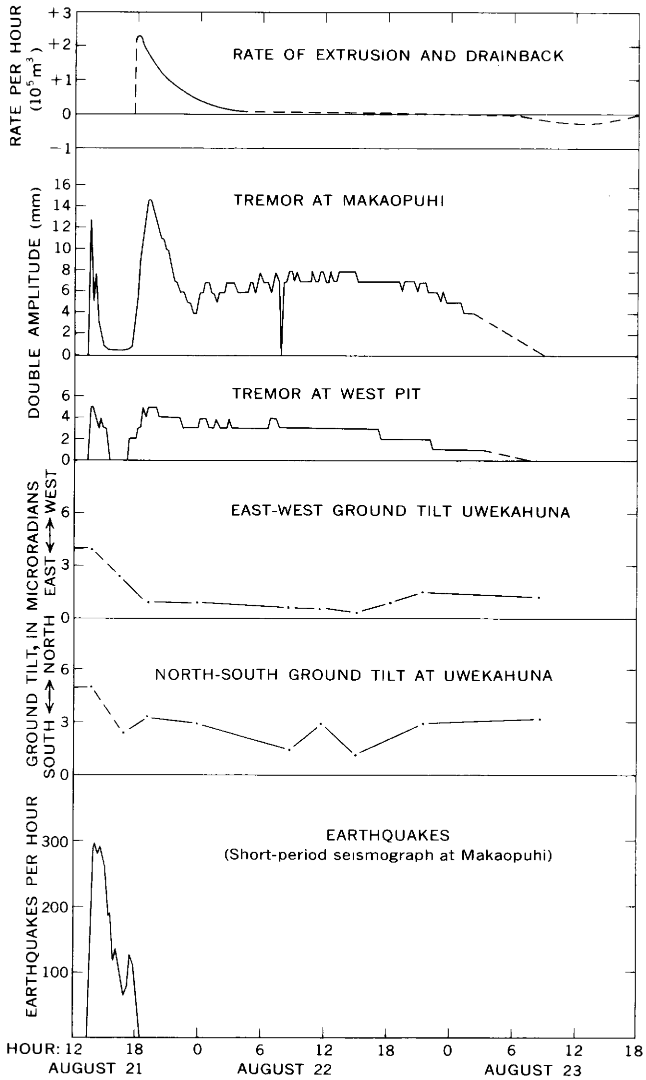

FIGURE 5.—Chronology of events during the August 1963 eruption of Kilauea.

edge of the southeast pit (long eruptive vent, fig. 3). Lava was erupting from 11 vents on the north wall along a fissure parallel to the fissure on the floor of the crater but displaced 30 m to the northwest. This lava cascaded down the cliff and plunged beneath the surface of the growing lake of lava (fig. 6). The most rapid discharge was obliquely upward and westward from one of the vents in the middle of the line, about 100 m below the north rim (vent H of fig. 6). The dark crust of the lake was broken by glowing zigzag cracks that splayed outward from the curtain of fire and from the base of the lava cascades. At this time the lake had an estimated depth of almost 10 m and had completely covered the floor of the southeast pit, an area of about 65,000 m^2, with almost 400,000 m^3 of lava (fig. 7). The level was

* All times given are in hours and minutes, Hawaiian standard time.

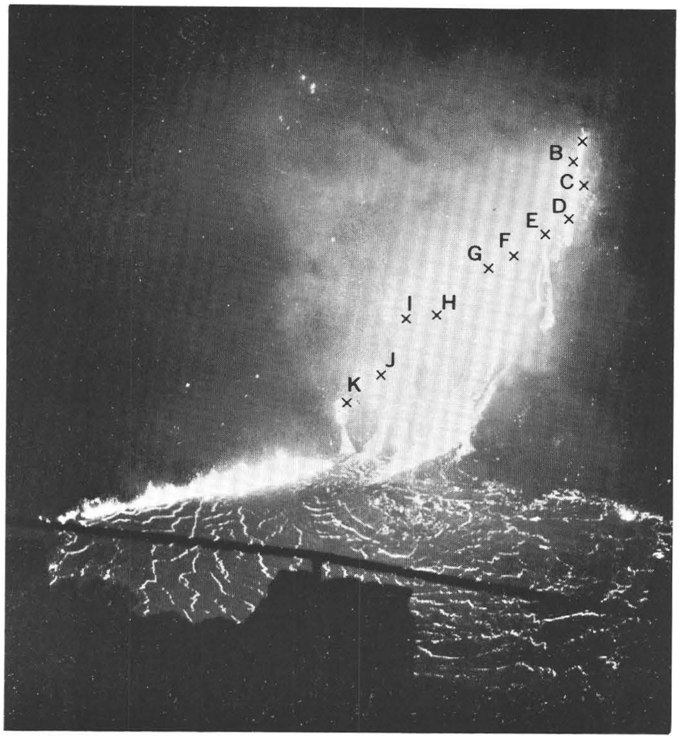

FIGURE 6.—Eruption in Alae Crater at $19^{h}20^{m}$ August 21, 1963, as viewed from overlook at south rim of crater. Letters refer to vents described in text. Fountains extend over a vertical distance of 100 m on the north wall of the crater.

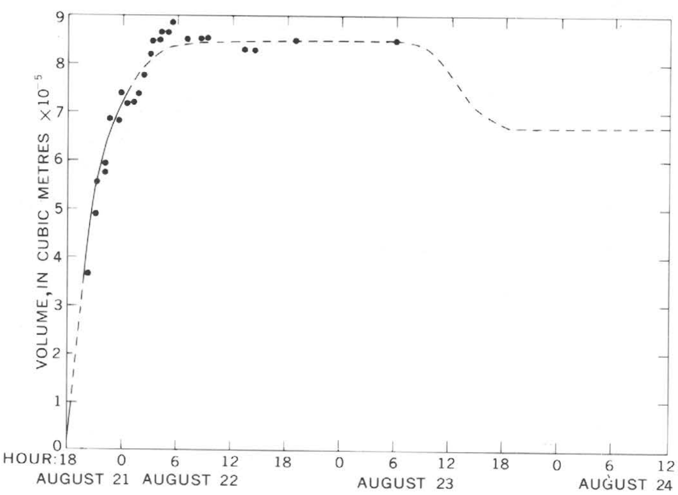

FIGURE 7.—Volume of lava in Alae lava lake during the August 1963 eruption, as determined by transit sightings (dots) from the rim during the eruption and by triangulation and level measurements after the eruption.

rising at an estimated rate of about 2 m per hour, indicating a rate of extrusion of approximately 230,000 m^3 of lava an hour (fig. 5). Spatter from a 150-m-long en echelon line of fountains in the jungle, 60 m beyond the north rim, was visible above the trees. These fountains died by $19^{h}45^{m}$ after sending thin flows of shelly pahoehoe over an area of 7,000 m^2.

By $20^{h}00^{m}$, the uppermost vents on the north wall (A, B, and C, fig. 6) had died, and the thin lava streams that had issued from them were dark. During the remaining 4 hours of August 21, many of the other vents on the north wall of the crater died —vent D at 21^{h} and E and F at 22^{h}; vent F emitted bluish gases for several hours after it had stopped spattering. By midnight only three vents were still erupting vigorously. The line of fountains on the floor of the crater had become discontinuous; the fountains were playing to a height of 8 m over a length of 40 m, and an isolated fountain at the southwest end of the original line was bubbling weakly. As determined by transit sightings from the overlook, the surface was rising at a decreasing rate—1.5 m per hour at 21^{h}, 1 m per hour at 22^{h}, and 0.6 m per hour at 23^{h}. The rate of extrusion had dropped from about 200,000 m^3 per hour at 20^{h} to 45,000 m^3 per hour at 23^{h}. As the rate of extrusion from the vents on the north wall decreased, the apparent viscosity of the lava increased (probably because of a decrease in temperature), and lava cascading down from the fountains formed a noticeable delta at the edge of the lake. At $01^{h}40^{m}$ on August 22, surges in the fountain on the floor of the crater produced waves in the lake with a frequency of 22 cycles per minute; these broke like surf on the shore northwest of the fountain and traveled 70 to 100 m to the southwest in the lake before dying out. Through the night, the lake had been broken by glowing zigzag cracks that radiated out from the vents. Photographs taken at 10-minute intervals between $01^{h}50^{m}$ and $02^{h}10^{m}$ show correspondence in the crack pattern between successive photographs, indicating that the crust of the lake was being rafted outwards on lava flowing from the vents at a rate of about 200 m per hour, to be piled in a narrow slabby levee at the edge of the southeast end of the lake.

By $03^{h}00^{m}$, the line of fountains on the floor of the crater had become erratic, momentarily dying back to a length of 15 m, and then lengthening to 35 m. The fountains on the north rim continued to diminish in vigor. The lake was about 17 m thick and probably was rising at an hourly rate of about 0.3 m (15,000 to 20,000 m^3 of lava per hour). Transit sightings to the foot of the lava cascade on the north shore of the lake continued to show a decrease in the angle of depression with time, suggesting continued extrusion of 30,000 m^3 of lava per hour until $05^{h}30^{m}$. However, the later increase in the angle of depression between $05^{h}30^{m}$ and 07^{h}, indicating an apparent subsidence of the lake surface, and observations of the north shore the following morning, suggest that the transit sightings were reflecting the slow buildup and lowering of the surface of a broad lava delta at the foot of the cascades, rather than changes in altitude of the surface of the lake.

By 06^h00^m, the lava lake had reached almost its maximum depth (18 m) and volume (8.4×10^5 m^3). The increasing volume of lava in the lake for the rest of the eruption was so small that it was not measurable. The vent on the floor of the crater had begun to fountain irregularly; instead of throwing up a curtain of flowing lava 7 to 10 m as before, it erratically spewed bursts of spatter to heights as great as 50 m, accompanied by great booming noises. The change in activity of the fountains at this time, and the lack thereafter of any substantial increase in volume of the lake, probably recorded a change in the type of material being supplied to the fountains from the rift zone. Before 06^h, this included a significant proportion of lava, the quantity of which steadily decreased with time; after 06^h, it was mostly gas. The lava thrown up by the fountains may largely have been lava from the lake, blown out by expanding gases rising upward through the lake from the underlying vent. The three remaining fountains on the north wall (H, J, and K of fig. 6) were spattering weakly and sending two sluggish rivers of aa down to a small low delta on the lake. In the morning light, we could see that the vents on the north wall had built a row of coalescing spatter cones and that spatter and cinders from the fountains on the floor of the crater had accumulated to form a low spatter and cinder cone along the northwest side of the lake.

The eruption continued at a diminishing rate during the morning. At 11^h, a party circled around to the north side of the crater, where they could look down directly into the two remaining active vents on the north wall. One, vent K (fig. 6) was spattering weakly within its cone and sending a red ribbon of lava down to the lake. The other, vent H, was emitting much fume but only a little lava. This lava formed a sluggish stream which at times had a rough dark aa crust that first formed at the lower end and appeared to grow upstream, only to be repeatedly dislodged and carried downstream by the red lava.

Two major fountains and several minor ones played on the floor of the crater (fig. 8). The lava lake was impounded behind a slab levee, but occasionally it overflowed or undermined the levee, producing festooned flows or tumuli on the lake margin.

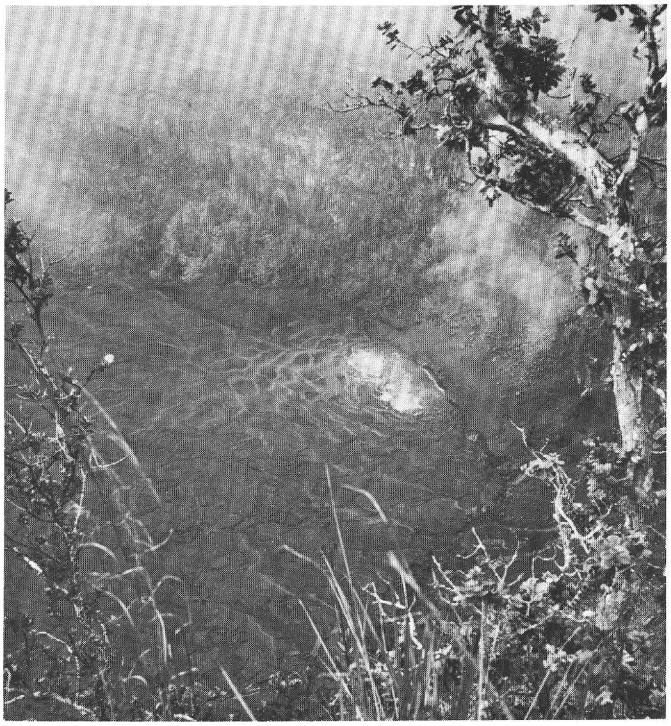

FIGURE 8.—Eruption in Alae Crater at 11^h10^m, August 22, 1963, as viewed from the north rim. Incandescent bubbling areas (light colored) are about 10 m in diameter.

The crust of the lake continued to founder locally, mostly along cracks near the edge of the lake or above the former southwest end of the curtain of fire. Pumice that had been erupted during the night was collected from the ground near the north rim, and samples were gathered from the spatter rampart and shelly pahoehoe flows in the jungle beyond the north rim of the crater.

By 15^h, the line of fountains on the floor of the crater had shortened to 30 m; they bubbled to an average height of 3 m but sent occasional bursts of spatter to 50 m. The vents on the north wall were almost dead, and lava rivers from them were crusted over. The slabby rim of the lake increased in width from the new slabs of crust that were continually added to it from the lava lake. The crust of the lake had a distinctive mosaic appearance (fig. 9) caused by patterned differences in surface texture that appeared as alternating light and dark bands parallel to the glowing cracks. These textural differences are discussed on page 22.

At 17^h, the fountains on the floor of the crater were seen from the mezzanine to bubble vigorously with whooshing and thundering noises from two large and several small intermittent centers along a length of 35 m (fig. 10). At each center, the activity

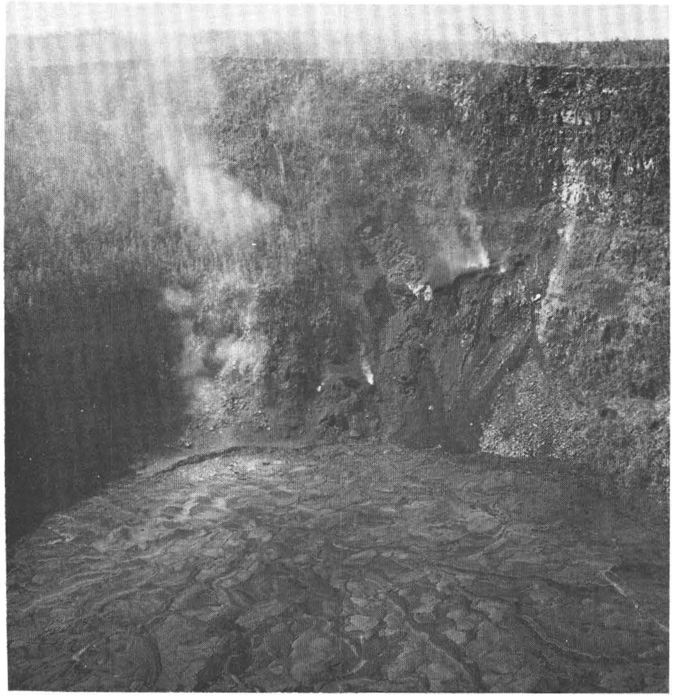

FIGURE 9.—Eruption in Alae Crater at 15^h, August 22, 1963, as viewed from overlook at the south rim of the crater. Behind and to the left of the vent is a 50-m cliff at the end of the forested mezzanine. The degassing vents on the far wall are almost dead, but the inconspicuous line of fountains on the far floor are bubbling to an average height of 3 m. The lake surface looks like a mosaic because of patterned differences in surface texture parallel to glowing cracks.

resembled the bubbling of a mud pot; a bubble of lava 1 m or so in diameter would appear, grow rapidly larger as the gas inside expanded, and then break into long ribbons of lava that were cast as high as 50 m. Gases rising from below the lake apparently provided the driving force for the fountaining. Spatter was not thrown evenly in all directions; more than half fell to the west on the lakeshore behind the fountains, forming a spatter and cinder cone that was about 2 m high at this stage. Possibly this unevenness reflected only the prevailing wind direction, which is typically a counter-trade wind direction on the floor of the crater; from the mezzanine, however, the fountaining appeared to be inclined in that direction, perhaps because lava in the lake impinged on the breaking lava bubbles.

The dark surface of the lake was broken by glowing cracks; these consisted of two sets, one of concentric cracks near the fountains and the other of thin cracks that radiated out from the fountains. The latter cracks diverged farther away and divided the lake surface into distinctive lobate areas (fig. 11). The outer margins of the lobate areas were bordered by wider glowing cracks, which were the sites of foundering at many localities.

We scrambled down the talus to the southwest edge of the lake and found that the lake was brim full behind a 15-m-wide levee of folded and faulted pahoehoe slabs. The surface of the lake was not flat; it rose as much as 0.5 m from the edge of the lake to the site of the fountains, reflecting the hydraulic gradient of the viscous fluid. Small outflows and foundering took place at the distal end of the lobate areas, which were commonly about 0.3 m higher than the lake surface at its margin. Foundering was related to outflows of fresh lava from these cracks. The weight of the outflowing lava would cause a slab of crust to bend down and break off. This slab would glide inward and tilt down toward the center of the lake until the leading edge would sink and the trailing edge rise up in the air—looking for all the world like a sinking surfboard. Crustal foundering on a much larger scale was observed during the formation of Makaopuhi lava lake (Wright and others, 1968, fig. 10).

The levee was separated from talus mantling the crater walls by a moat 15 m wide and about 3 m deep. Inside the moat were several small tumuli about 8 m long and 2 m high; the medial crack of each was filled by a snakelike mass of lava, still glowing red in marginal cracks. At many places the levee had been breached and overflowed by small festooned flows of pahoehoe. We marked the level of the lake surface on the talus mantling the walls of the crater by sighting with a compass level. Later surveying with a transit from the floor of the lake fixed this level at 785.5 m (2,577 feet), 3.0 m above the present floor of the lake and 18.0 m above the base of the crater before the eruption.

Beginning at about 21^h, the glowing cracks at the south and east edges of the lake began to darken (fig. 12) as the actively circulating part of the lake shrank because of diminished vigor of fountaining. By 22^h45^m (fig. 13), the southeast half of the lake was dark; by 23^h16^m (fig. 14), only two small lobate areas were left; and by 23^h55^m, the lake was dark except for the fountain. The position in plan of the glowing cracks was later determined by examination of photographs taken during and after the eruption and by mapping the surface features of the lake. These studies provide clues to the pattern of lava circulation in the lake during the evening of August 22, as discussed on pages 22–24.

The activity of the line of fountains on the floor of the crater decreased through the evening of the

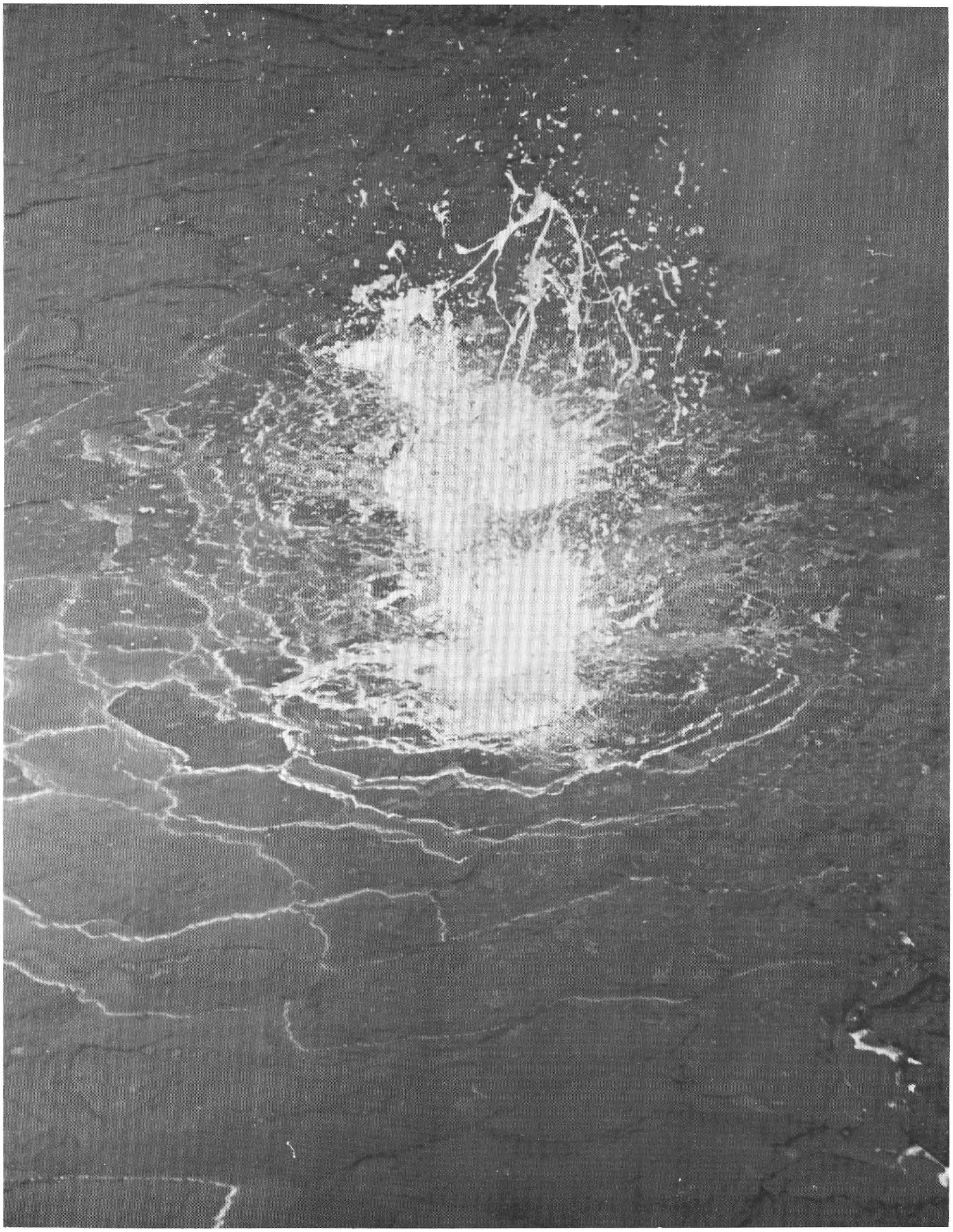

FIGURE 10.—Fountain in Alae Crater at 17^h45^m, August 22, 1963, as viewed from the mezzanine. Height of fountain about 5 m. Ribbon spatter on top was produced by bursting of a bubble of lava an instant before the photograph was taken (compare with fig. 23). Photograph by S. Aramaki.

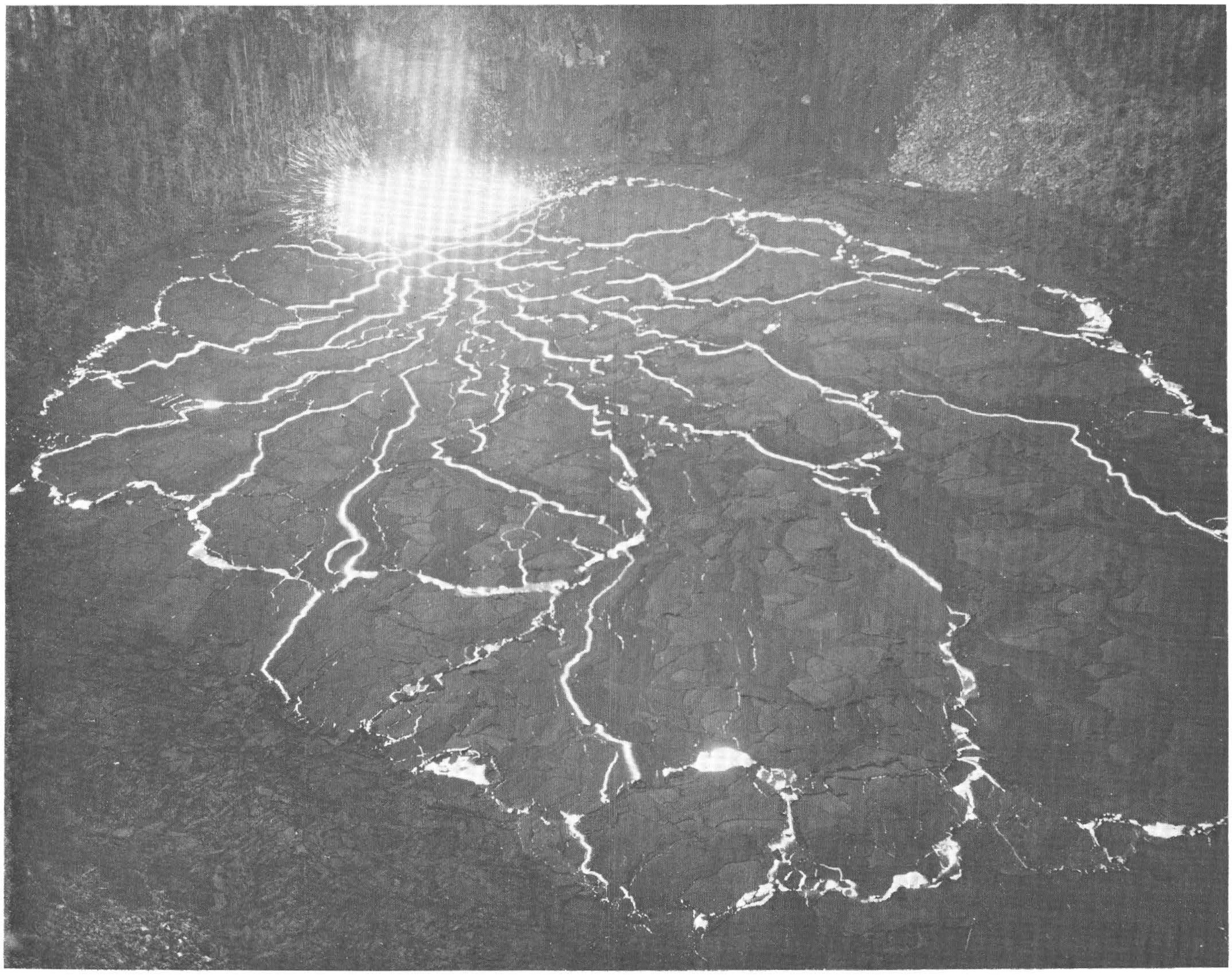

FIGURE 11.—Eruption in Alae Crater at about 18^h, August 22, 1963, as viewed from overlook. Two sets of glowing cracks break the dark crust, one near to and concentric with the fountain, which was about 35 m long, and another radial to the fountain which outlines lobate areas of crust. Crustal foundering (light spots) occurs at the distal ends of the lobes. A marginal levee of slabs and small festooned flows can be dimly seen in the left foreground. Photograph by T. Miyasaki.

22d and the early morning hours of the 23d. By 23^h30^m of the 22d, fountaining was taking place at 5 centers along a length of 25 m. By midnight, the fountains became more erratic and died completely for a second or two before resuming again. By 02^h10^m of the 23d, only three areas were bubbling, and the periods of quiet had increased to 5 seconds. By daylight, at 05^h30^m, only one bubbling area was left; it burst slowly about every 5 seconds. At this time the lake surface was at the same level as at 19^h the previous evening, when the level of the lake surface had been marked with a sample bag on the talus mantling the lower crater walls after sighting on the lake surface with a brunton compass level. By 07^h30^m, the vent was still bubbling every 5 to 7 seconds; drainback had lowered a semicircular area about 30 m (100 ft) in diameter around the vent. By 08^h10^m, the bubbling at the vent had stopped. The eruption was over. Slow drainback into the orifice beneath the lake at the vent, however, apparently continued for several hours.

Vertical-angle transit sights from the rim of the crater on August 24 showed that the surface of the flow had been lowered about 3 m by drainback since the end of the eruption. Later, precise level measurements from the flow surface to the marker on the talus and more precise triangulation from the rim

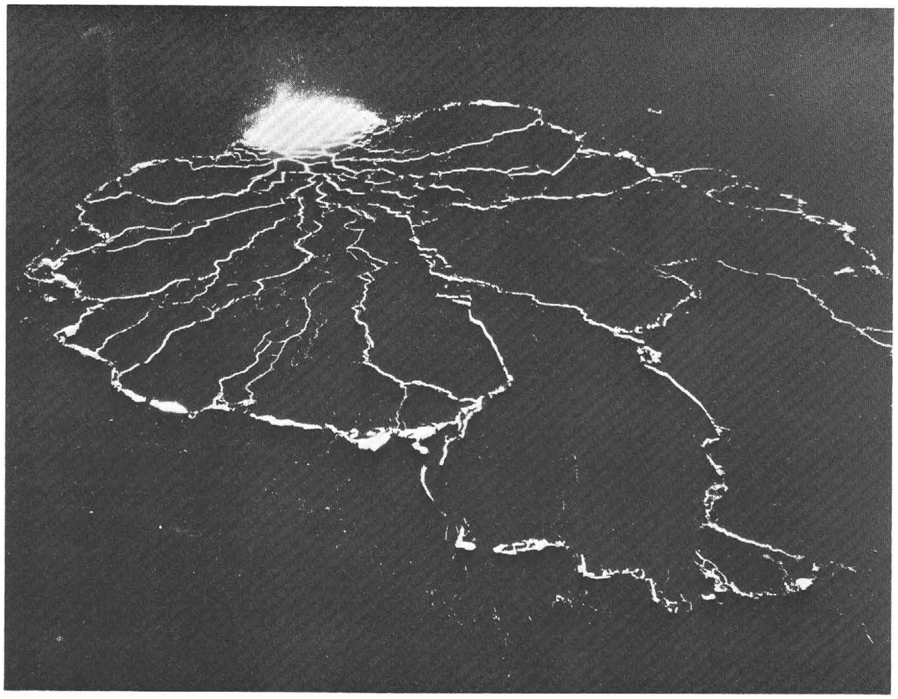

FIGURE 12.—Eruption in Alae Crater at about 21^{h}, August 22, as viewed from the overlook. Stagnation of the lava lake in the foreground has resulted in the nearly complete darkening of glowing cracks visible earlier there (fig. 11).

FIGURE 13.—Eruption in Alae Crater at 22^{h}45^{m}, August 22, as viewed from the overlook. Glowing cracks in the entire outer part of the lake have darkened because of continued stagnation of the lake.

FIGURE 14.—Eruption in Alae Crater at 23^{h}16^{m}, August 22, as viewed from the overlook. The actively circulating part of the lake has become restricted to an area less than 100 m long adjacent to the fountains.

showed that the average elevation of the surface had fallen 3.0 m below the marker—a loss of 180,000 m^3 of lava. The lake was left with a volume of 660,000 m^3. An additional 30,000 m^3 of flows, spatter, and pumice had accumulated in the jungle beyond the north rim of the crater and in the low spatter ridge that covered and bordered the northwest side of the lake and continued as coalescing spatter cones up the north wall of the crater (fig. 15).

TEMPERATURE MEASUREMENTS

Temperatures were estimated during the eruption with a glowing-filament optical pyrometer. These estimates have been supplemented by temperatures deduced from a study of pumice from the eruption and by temperatures measured with thermocouples later in the Alae lava lakes.

Heavy fume obscured the view of the fountains during much of the eruption, making pyrometer measurements of little value. When the fume was moderate to light, repeated pyrometer measurements of the fountains were made from the overlook at the south rim of the crater—a distance of 350 to 400 m from the fountains. During the evening of August 21, from 20^h to 23^h, maximum readings were repeatedly found to be 1,090° to 1,100°C The actual maximum temperatures of the fountains were probably substantially higher. Pumice from this fountaining, which was collected August 22 from the north rim of the crater, contains only 7 percent crystals—2.0 percent olivine, 4.1 percent augite, and 0.9 percent plagioclase (sample H 186, T. L. Wright and D. L. Peck, unpub. data). Laboratory melting studies of drill core from Alae lava lake (Tilley and others, 1967) and data from the 1965 eruption in Makaopuhi Crater (Wright and others, 1968) indicate that the temperature of first appearance of plagioclase in these lavas is 1,160±5°C. The scarcity of plagioclase (and other crystals) in pumice from the early stage of the Alae eruption, accordingly, suggests a maximum eruption temperature of about 1,160°C.

During the evening of August 22d, maximum temperature measurements showed a steady increase, from 1,085°C at 19^h30^m to 1,115°C at 20^h15^m and finally to 1,140°C at 21^h20^m. This increase very likely resulted from a decrease in radiation-absorbing fume between the fountain and the observers (as a result of the decrease in activity), allowing more accurate temperature measurements, rather than an actual increase in temperature of the dying fountains. Pumice from this late fountaining, which was collected near the vent after the eruption (sample DPH–77, T. L. Wright and D. L. Peck, unpub. data), contains 13 percent crystals—2 percent olivine, 8.5 percent augite, and 2.5 percent plagioclase. Comparison of this abundance of crystals with the abundance in samples of known temperature from the 1965 Makaopuhi lava lake (Wright and others, 1968) indicates a temperature of about 1,140°C; this is in excellent agreement with the maximum pyrometer readings.[1]

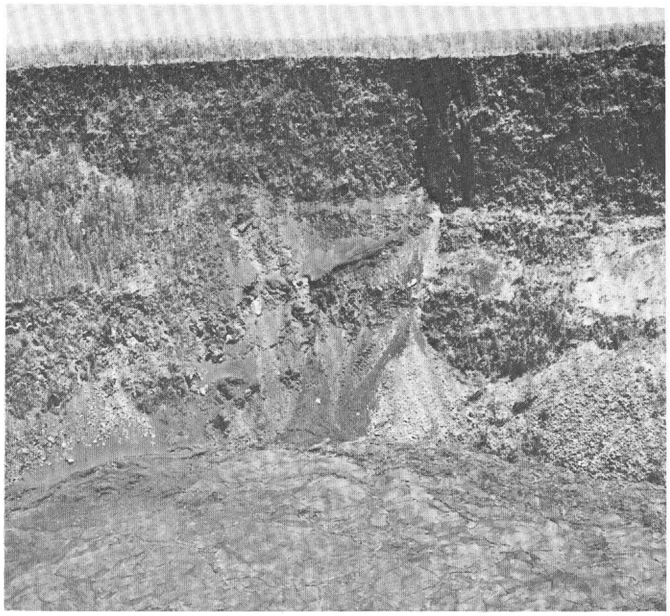

FIGURE 15.—Northwest part of Alae lava lake as viewed from overlook on August 31, 1963, showing low spatter ridge near former vent on floor of crater and coalescing spatter cones marking positions of former vents on north wall. Forested mezzanine atop a 50-m-high cliff can be seen to the left of the spatter cones on the north wall of the crater.

The maximum initial temperature of the lava lake at the end of the eruption can be inferred from temperature data collected with thermocouples in drill holes in the lake after the eruption (Peck and others, 1964). The highest temperature measured in the lake was 1,136°C. This value was obtained on November 8, 1963, 2½ months after the eruption, at a depth of 5.46 m, 2.2 m below the base of the crust. Extrapolation of the temperature gradient downward 2 m to the estimated depth of the maximum temperature in the lake suggests a temperature of about 1,140°C. Maximum temperatures in the central part of the lake were measured starting July 2, 1964, and contact temperatures at the base of the central part of

[1] On the basis of the MgO/MgO+FeO+Fe_2O_3 content of analyzed glass from sample DPH–77 and the calibration of Tilley and others (1964, fig. 23), the temperature of the later stage of the eruption has been estimated to be 1,065°C (Wright and others, 1968, table 5). We favor a lower temperature that is more in accord with the temperature and crystallinity measurements in Makaopuhi lava lake.

the lake were obtained beginning on December 8 from drill holes that pierced the lake. These values were, respectively, 1,050° and 700°C. Analysis of these and later values using the heat-conduction theory (J. C. Jaeger, written commun., 1967) indicates initial maximum temperatures in the lake of 1,140°C.

Thus we conclude that during the early vigorous part of the August 1963 eruption, the maximum temperature of the fountains was 1,160°C. During the waning stages of the eruption, the maximum temperature fell to 1,140°C. By the end of the eruption, the maximum temperature of the resulting lava lake was 1,140°C.

DEFLATION OF THE SUMMIT REGION AND SEISMIC ACTIVITY DURING AND AFTER THE ERUPTION

The sharp collapse of the Kilauea summit area that began at 13^h50^m on August 21 was completed by about 19^h, August 21 (fig. 5); thereafter the summit subsided slightly until 15^h, August 22, when renewed inflation took place.

Precise level measurements of benchmarks along the Chain of Craters Highway after the August 21 to 23 eruption (fig. 16) showed inflation of the rift zone between Aloi and Makaopuhi Craters since mid-July. The maximum uplift measured was 0.131 m at the overlook at Alae Crater, relative to the YY22 benchmark at the junction of the Kilauea Crater rim and the Chain of Craters Highway. The level measurements also showed deflation of the rift zone near Hiiaka Crater, at the intersection of the Koae fault zone and the east rift. Several lines of evidence indicate, however, that this subsidence took place during the August 3 collapse and not during the August 21 to 23 eruption: (1) measurements of the altitude of about one-half the benchmarks after the August 3 collapse but before the eruption in Alae crater; (2) the location, during the August collapse, of epicenters of shallow earthquakes that cluster near Hiiaka crater; and (3) the distribution of cracks formed during the collapse.

After the outbreak of lava at about 18^h10^m on August 21, earthquake activity at Alae Crater and beneath the summit and upper east rift zone of Kilauea decreased to a very low level. Later, at

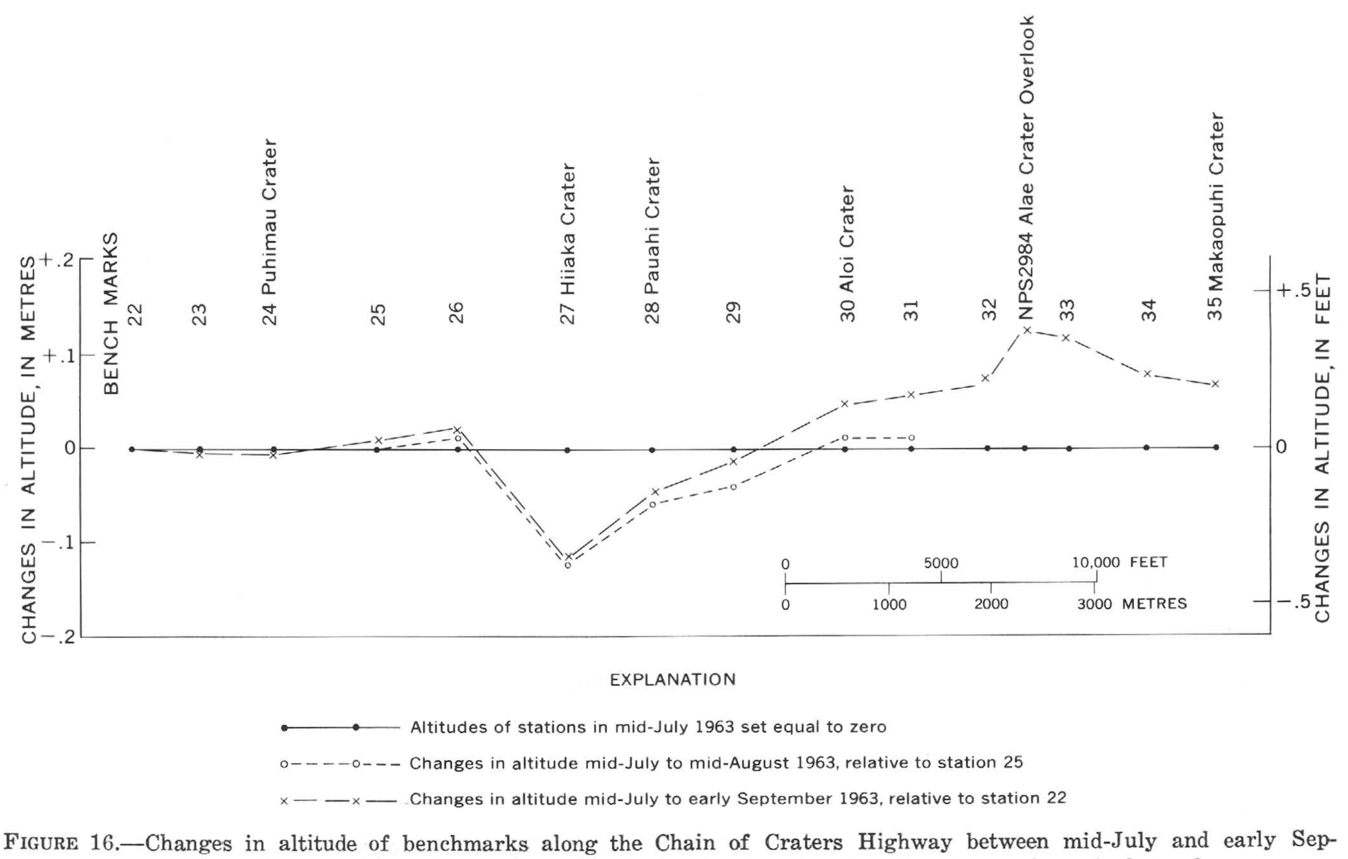

FIGURE 16.—Changes in altitude of benchmarks along the Chain of Craters Highway between mid-July and early September 1963 on the basis of second- and third-order leveling. Location of craters is shown in figure 2.

about $02^{h}00^{m}$ on August 22, earthquake activity increased, centered mostly beneath Kilauea caldera. From August 24, the day after the eruption was over, to September 1, only 10 earthquakes occurred along the upper east rift. The number of Kilauea caldera earthquakes during the rest of August averaged about 65 per day.

Harmonic tremor recorded during the August 1963 Alae eruption was unusual in its attenuation pattern and maximum amplitude. The highest amplitudes were recorded by the seismometer at Makaopuhi Crater, only 2½ km from the site of the eruption. The tremor attenuated rapidly as distance increased, however, and was never recorded at the Desert and Mauna Loa seismometers, which were 21 km west and 24 km northwest, respectively, of the eruption. This attenuation pattern is similar to that of shallow-focus earthquakes beneath the summit of Kilauea. The maximum amplitude of tremor recorded by the Makaopuhi seismometer was one-third to one-fourth of that recorded during the October 1963 and March 1965 upper east rift eruptions, even though the eruptive vents were closer to the Makaopuhi seismometer during the Alae eruption than were some of the vents of the October 1963 eruption (Shimozuru and others, 1966). A possible explanation for this observation is that the amplitude of tremor recorded at seismometers within 3 km of a vent is an indication of the rate of extrusion at that vent. Thus, the amplitude of tremor recorded by the Makaopuhi seismometer was much higher during the October 1963 eruption (Moore and Koyanagi, 1969) and the March 1965 eruption (Wright and others, 1968), when the rates of extrusion at the vents near Makaopuhi Crater were much higher.

PHYSICAL FEATURES OF THE LAKE

SURFACE FEATURES OTHER THAN JOINT CRACKS

The lava lake in Alae Crater, formed from August 21 to 23, 1963, was an elliptical lens 305 m long, 245 m wide, and as much as 15 m thick. The lake was composed of homogeneous tholeiitic basalt containing 3.5 percent olivine (Peck and others, 1966). The outline of the lake and the location of surveying stations and a study area are shown in figure 17, together with cross sections along the major and minor axes of the lake. The pre-1963-eruption topography of the bottom of the crater (fig. 17) was prepared by photogrammetric methods from aerial photographs taken February 1963 by the U.S. Geological Survey and supplied to us by William A. Fischer. The lake deepened inward from the edge to an average maximum thickness of 14.0 m. The floor of the lake was nearly flat but sloped at a small angle to a low area beneath the northcentral part of the lake. The northern part of the lake thinned to 11.3 m over a buried spatter ridge formed during the eruption of 1840.

The surface of the lake was surprisingly complex and showed a great variety of features recording events that took place during and after the eruption. Many of the features which were observed forming, as described earlier in this paper, were studied in detail because they are potentially important in understanding the physical regimes of flowing lava and cooling basalt flows. Similar features on well-preserved flows formed elsewhere during eruptions that were not observed, may provide clues to the temperatures, viscosities, and flow patterns of the erupting lava, the relative chronology of eruption, and the conditions under which the flows cooled.

Many of the surface characteristics of Alae lava lake are shown in an aerial photograph (fig. 18) taken 1 month after the eruption. The southeast half of the lake was separated from talus flanking the crater walls by a moat (cross-section *A–A′*; fig. 17) of August 1963 lava. The moat was 8 to 15 m wide and about 2 m deep for most of its length, and the base sloped irregularly southeast to a maximum depth of 5 m below the levee at the southeast end of the lake. In many places it was partially filled by small festooned flows that broke through or over the levee. Judging from the altitude of the base of the moat at the southeast end of the lake [778.8 m (2,555 ft)], the moat was formed within the first few hours of the eruption. Two pressure domes, or tumuli, rose from the floor of the moat (fig. 19); each was about 10 m long, 5 m wide, and 2 to 3 m high and had an axial crack partly filled with bulbous lava. These domes were formed by lava forced along channels beneath the levee by hydrostatic pressure from the lake inside the levee. After the eruption, the crests of the domes were at or above the present surface of the main body of the lake; when the domes formed, however, the crests were below the surface of the lake.

The main body of the lake was separated from the moat and from the talus flanking the crater walls by a levee about 30 m wide that borders all but the northwest end of the lake. Figure 20 shows the levee and moat as viewed from the talus at the south edge of the lake, and they are indicated on the map (fig. 21), which shows all major features of the lake surface except for joint cracks. The map was prepared using an aerial photograph (fig. 18) and pace and compass methods from a grid of stations on the lake

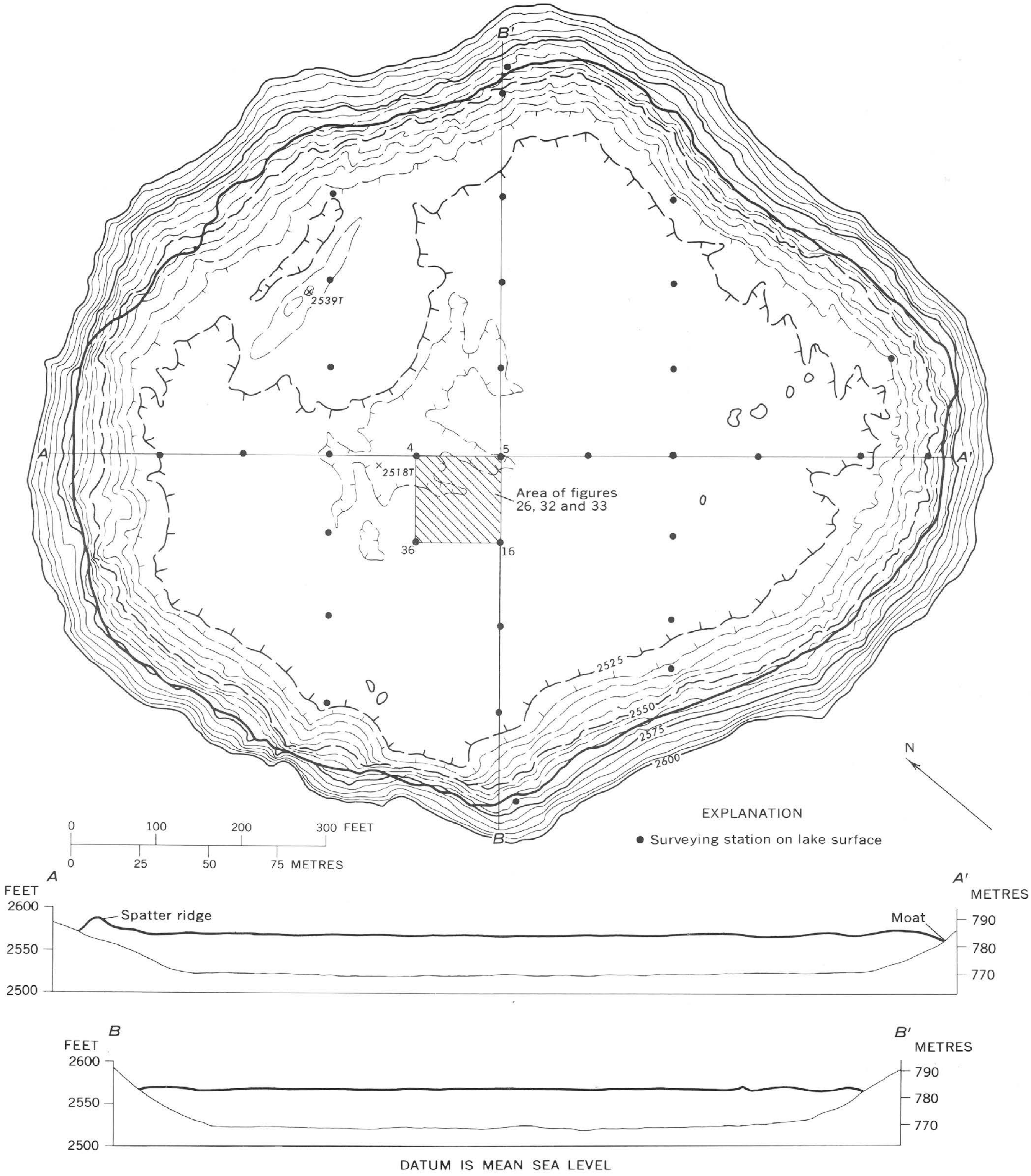

FIGURE 17.—Map of Alae lava lake showing contours (in feet above sea level) at the base and margin of the lake. Shaded area was studied in detail. Cross sections along the major axis (*A–A'*) and the minor axis (*B–B'*) of lake have the same horizontal and vertical scales. Topography prepared by photogrammetric methods from aerial photographs taken February 15, 1963, by the U.S. Geological Survey.

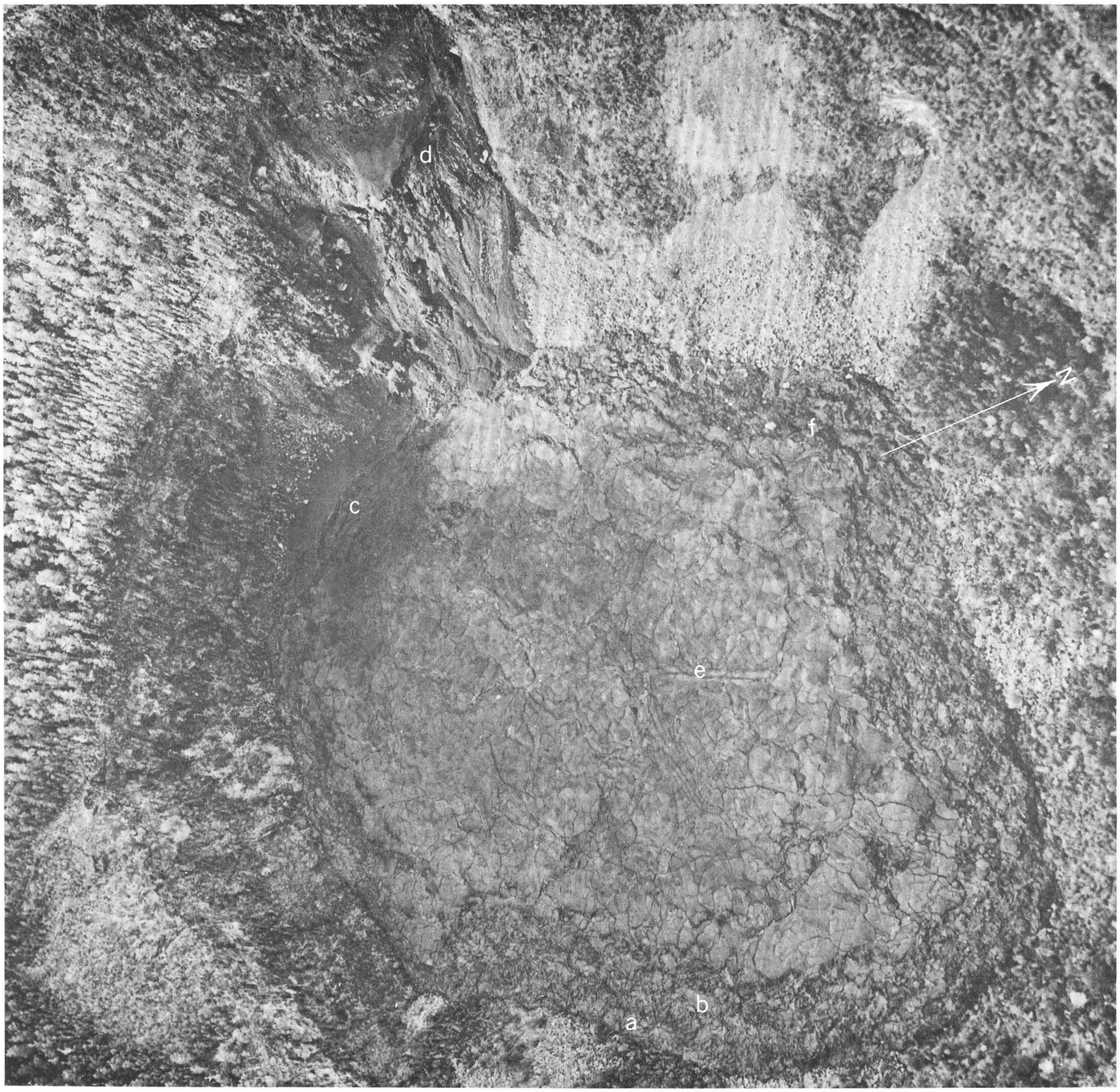

FIGURE 18.—Aerial photograph of Alae lava lake taken September 25, 1963, from an altitude about 900 m above the east rim of the crater. Letters designate features as follows: a, moat; b, levee; c, spatter cone formed by fountains on floor of crater; d, spatter ridge formed by vents (*A–K*) on north wall of crater; e, shear zones; f, landslide block thrown down by an earthquake on September 21, 1963.

surface, which were laid out by means of a transit and steel tape. The panorama of figure 20 was photographed from near point A of figure 21. The levee was made up of discontinuous pressure ridges—mostly symmetrical anticlinal folds, but also folds overturned away from the center of the lake, faults overthrust toward the edge of the lake, and jumbled piles of broken slabs of crust. The average height of the levee rose and the width narrowed as the levee was traced from near point A around the west side of the lake toward the vent. In the same distance, the pressure ridge between the levee and the main

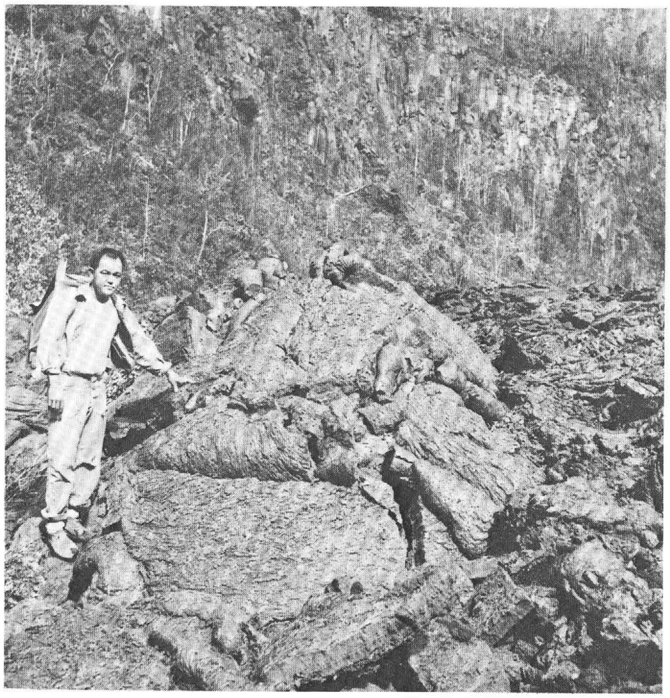

FIGURE 19.—Pressure dome in the moat at the south edge of Alae lava lake.

body of the lake changed northwestward from an anticlinal fold to a fault with a scarp as high as 2 m facing inward toward the center of the lake. This change probably resulted from a greater and more abrupt withdrawal of lava from the lake near the vent during drainback at the end of the eruption. Lava in the lake farther from the vent had stagnated earlier (p. 8) and hence was colder and more viscous. The levee was formed from slabs rafted across the lake by lava flowing from the vent beneath the crust during the eruption. When first noted at 02^h30^m, August 22, the levee was 6 to 10 m wide. The pressure ridges and thrust faults were formed by the push of lava-rafted crust against the static crust of the levee, which yielded by folding and faulting along lines of weakness.

The central part of the lake had a hummocky filamented surface that sloped almost imperceptibly toward the vent. Along the north side of the lake were several domes which consisted of jumbled piles of slabs of crust and were as high as 2 m (fig. 22). These domes are similar in origin to the levee rather than to the pressure domes in the moat formed by hydrostatic pressure. They were formed at the intersection of convergent streams of flowing lava, mostly where lava flowing from vents on the floor of the crater converged with lava from vents on the north wall of the crater.

Near the former position of the vent on the floor of the crater was an asymmetrical spatter ridge (cross section *A–A'*, fig. 17) that mantled the northwest end of the lake and the adjacent talus and continued as coalescing spatter cones up the north wall of the crater. Below the vents, the wall of the crater was mantled by drapery, which led downward to rough aa flows of oxidized cindery blocks overlying the talus. Beyond the spatter cone (which on fig. 21 is arbitrarily bounded where the spatter cover is less than 30 cm thick), the lake was mantled by a thin layer of spatter, which consisted mostly of cowdung bombs and twisted-ribbon bombs (fig. 23). Formation of ribbon bombs such as that shown in the figure is captured in the photograph of the fountains on the evening of August 22 (fig. 10). Still farther from the vent the spatter cover was discontinuous. The greater the distance from the vent, the smaller the proportion of surface covered. The quarter of the lake farthest from the vent had almost no spatter. Because all the crust formed near the vent was covered by spatter, the decreasing proportion of spatter on the lake at greater distances from the vent recorded the decreasing proportion of original crust. By the time the crust was rafted three-fourths of the way across the lake, all of it had either foundered or been covered by thin flows of lava that spread through cracks from beneath the crust.

The surface of the central part of the lake was crossed by pressure ridges and linear oozeups that marked the position of glowing cracks during the eruption. These are shown on the map of the lake (fig. 21) and also on the cross sections of figure 24. The undisturbed oozeups had a thin shell of crust, usually less than 2 cm in thickness, enclosing a central gas cavity. When they formed, gas exsolved from the underlying molten lava was escaping through cracks in the crust; when the incandescent lava filling a crack crusted over, some of the gas was trapped, forming the central cavity. The pressure ridges rose as much as 1 m above the surface of the surrounding lava and ranged from faulted anticlinal folds to piles of broken slabs of crust formed from the thin crust of oozeups (fig. 25). During the eruption, many overflows and squeezeups could be seen forming along glowing cracks at the distal ends of the lobate areas of dark crust (fig. 11). When the cracks darkened as a result of stagnation of the underlying molten lava, the oozeups formed lines of weakness because of the thinness of their crust. Most of them were soon folded and faulted as a result of the pressure of lava-rafted crust nearer

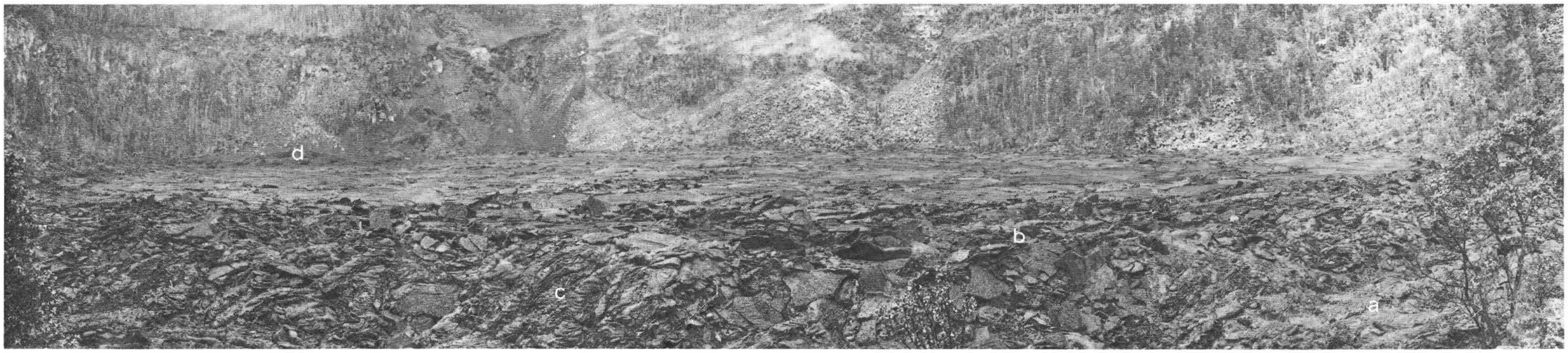

FIGURE 20.—Panorama of Alae lava lake from the talus at the south edge of the lake. Photograph taken August 31, 1963, from near point A of figure 21. Lettered features are as follows: a, floor of moat; b, levee; c, festooned pahoehoe flows partially enclosing slabs of crust; d, spatter cone formed by fountains on floor of crater.

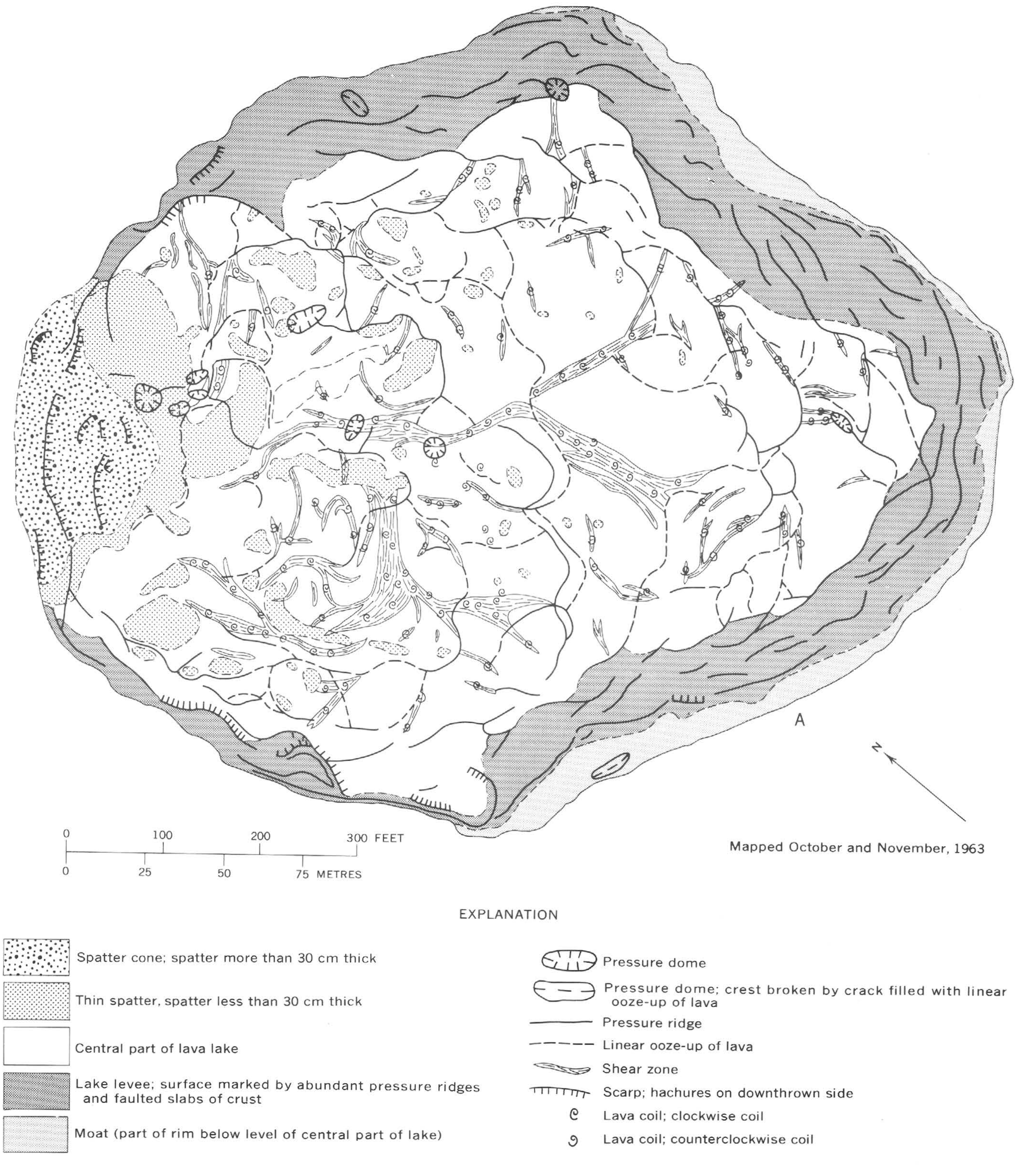

FIGURE 21.—Map of the surface features exclusive of joint cracks of Alae lava lake.

the vent against the crust of the stagnant part of the lake.

The lake surface was also broken by shears (Peck, 1966, fig. 3), which were formed at the contact between relatively static crust and crust moving above a flowing stream of lava. Voluted strips of lava (lava coils, Peck 1966, fig. 2), as high as 30 cm, were found along the shears together with irregular

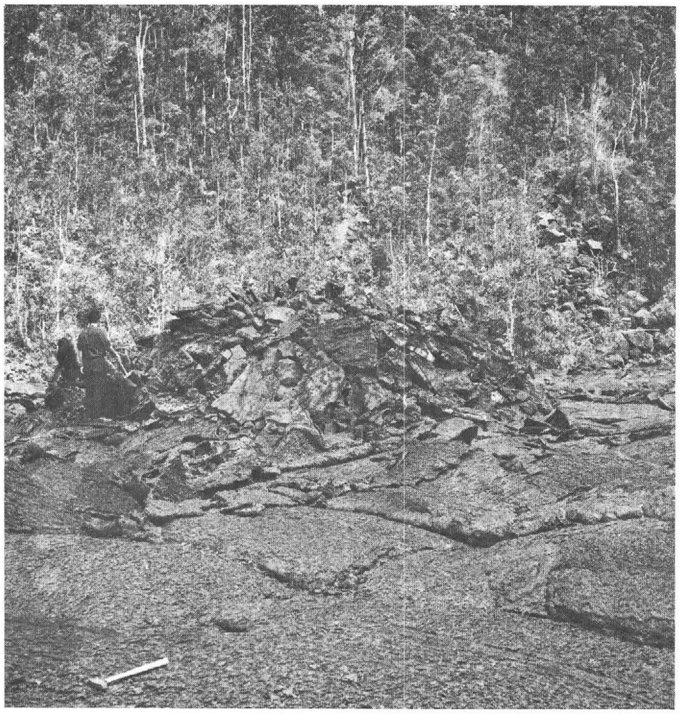

FIGURE 22.—Pressure dome of jumbled slabs near the northwest edge of the lava lake.

FIGURE 23.—Twisted ribbon bomb (1 m long) on the surface of Alae lava lake.

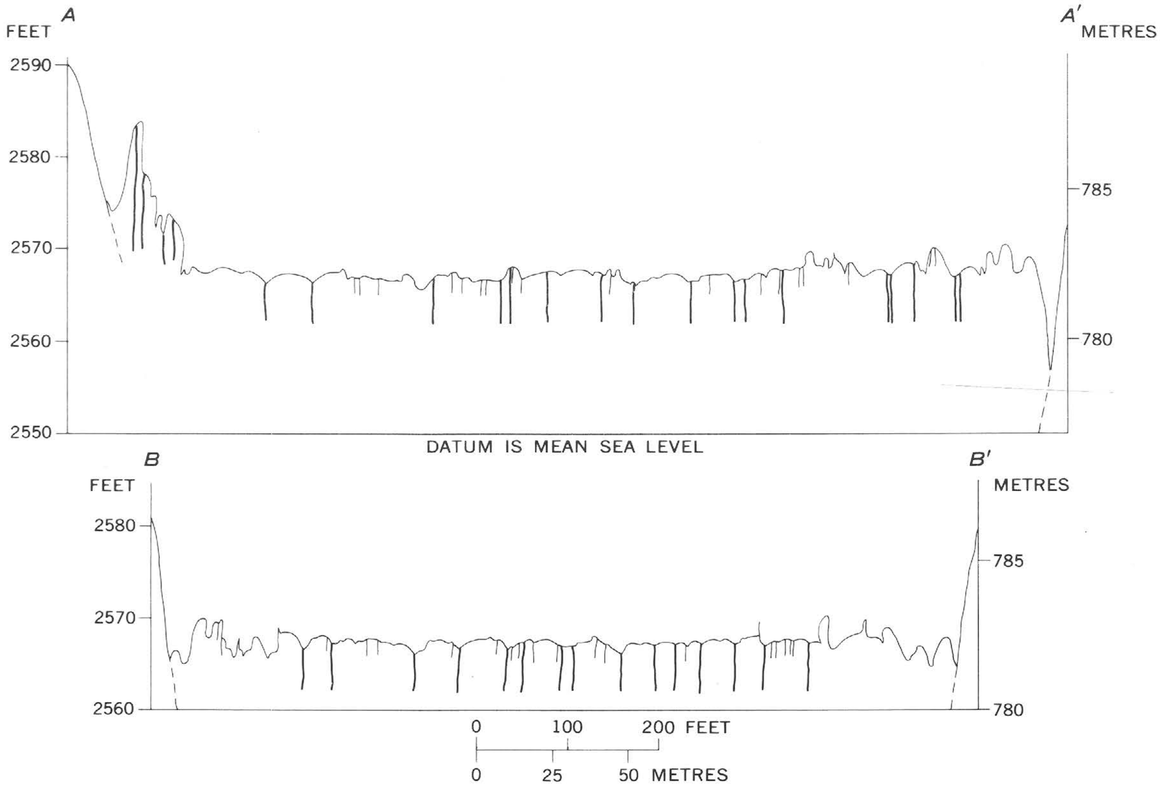

FIGURE 24.—Cross sections of the surface of Alae lava lake. Vertical scale exaggerated 10 times. Section A–A' is along the major axis of the lake, and section B–B' is along the minor axis of the lake, as shown in figure 17. Short cracks shown as light lines; long cracks as heavy lines.

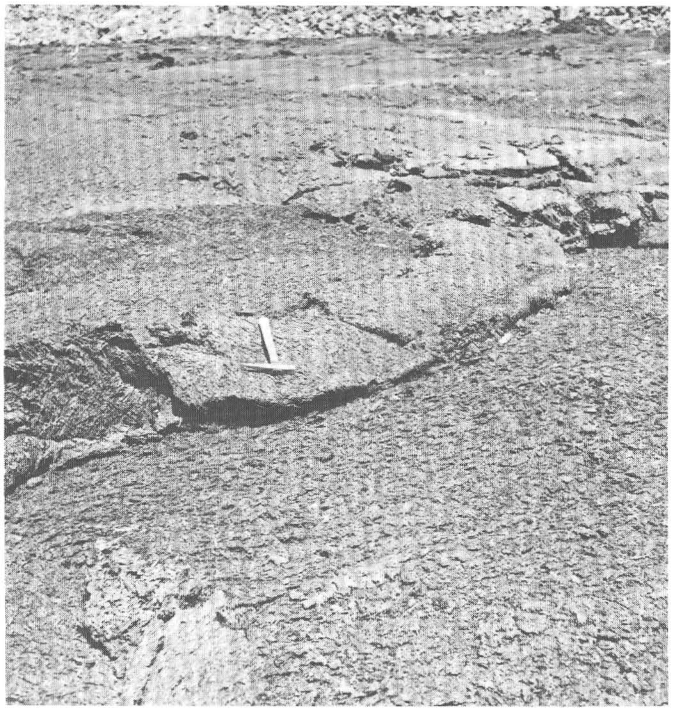

FIGURE 25.—Pressure ridge formed from the crust of a linear oozeup on Alae lava lake.

clots and strips of lava and indicated the relative direction of movement of the lava. Coils that spiral inward in a clockwise direction record right-lateral shear; coils that spiral inward in a counterclockwise direction indicate left-lateral shear. Other coils, mostly broad coplanar forms as large as 1 m in diameter, do not occur along recognizable shear zones.

The surface features of the lake were studied in more detail in an area approximately 30 m (100 ft) square near the center of the lake (fig. 17). The features were mapped at a scale of 10 feet to the inch (1:120). Nails were driven into the lake surface at 3-m (10 ft) intervals along two opposite sides; steel tapes were stretched between the nails, and the features mapped by inspection. Figure 26 shows the distribution of the surface features except for joint cracks. The area was bisected by a northwest-trending shear zone consisting of two offset segments. This zone marked the position of a glowing crack that, during the eruption, was the source of many small flows of slightly different age on each side of the zone. The northwest side of the area intercepted a major zone of pressure ridges and linear oozeups formed from lava in the glowing crack at the margin of the active part of the lake at 23^h16^m on August 22. The northeast edge cut across the flank of a low pressure dome. Several different ages of crust were present; the oldest crust, which had a thin spatter cover, was at the north corner. The area was crossed by many narrow linear oozeups, which occupied cracks formed near the end of the eruption.

Several minor features are shown in figure 26. Fine lines over most of the map indicate the trend of filaments of the surface crust. The surface of the lake consisted of 1-cm-thick layer of highly vesicular froth made up of intertwined filaments or threads of glassy lava (fig. 27). The filaments on each small flow were generally alined parallel to the direction of flowage or stretching of the crust; this was particularly clear on the crust of linear oozeups. The filaments appear to have formed by the drawing out during flowage of vesicles in the still-plastic glassy crust until only threads of glass were left between vesicles. A filamented surface is characteristic of many Kilauea flows extruded at moderate temperatures (1,150°C ±); at higher temperatures (1,175° to 1,200°C), a smooth or sharkskin surface is formed, such as that on the lava lakes in Kilauea Iki and Makaopuhi craters. The filamented surface bent near the medial shear zone in the area of detailed study, particularly at the south end of the north segment, indicating a left-lateral displacement along the shear. The sense of lava coiling along the shear suggested the same relative displacement. The filamented surface was also offset by fractions of 1 cm or sharply bent along obscure lines(marked by long dashes on the map), which indicated the same sense of movement. Apparently these lines were minor shears marking interruptions in the extrusion of the small flows. These discontinuities, together with shears and the fronts of small flows, outlined bands parallel to the cracks from which the flows issued. The bands were obscure after the eruption, except when viewed under oblique illumination early and late in the day, but were conspicuous during the eruption (fig. 9).

INFERRED CIRCULATION OF LAVA DURING THE ERUPTION

Clues to the pattern of lava circulation in the Alae lava lake during the latter part of the August 1963 eruption are provided by observations made and photographs taken, particularly during the evening of August 22 (figs. 11 to 14), and by the distribution of pressure ridges, linear oozeups, shears, and lava coils on the lake (fig. 21). Early in the evening of the 22d, lava was circulating beneath most of the surface of the lake. The lava flowed from the fountains to the inner margin of the levee along a surface that sloped gently outward at a gradient of 1 or 2 to 1,000. The rafted crust above the circulating lava

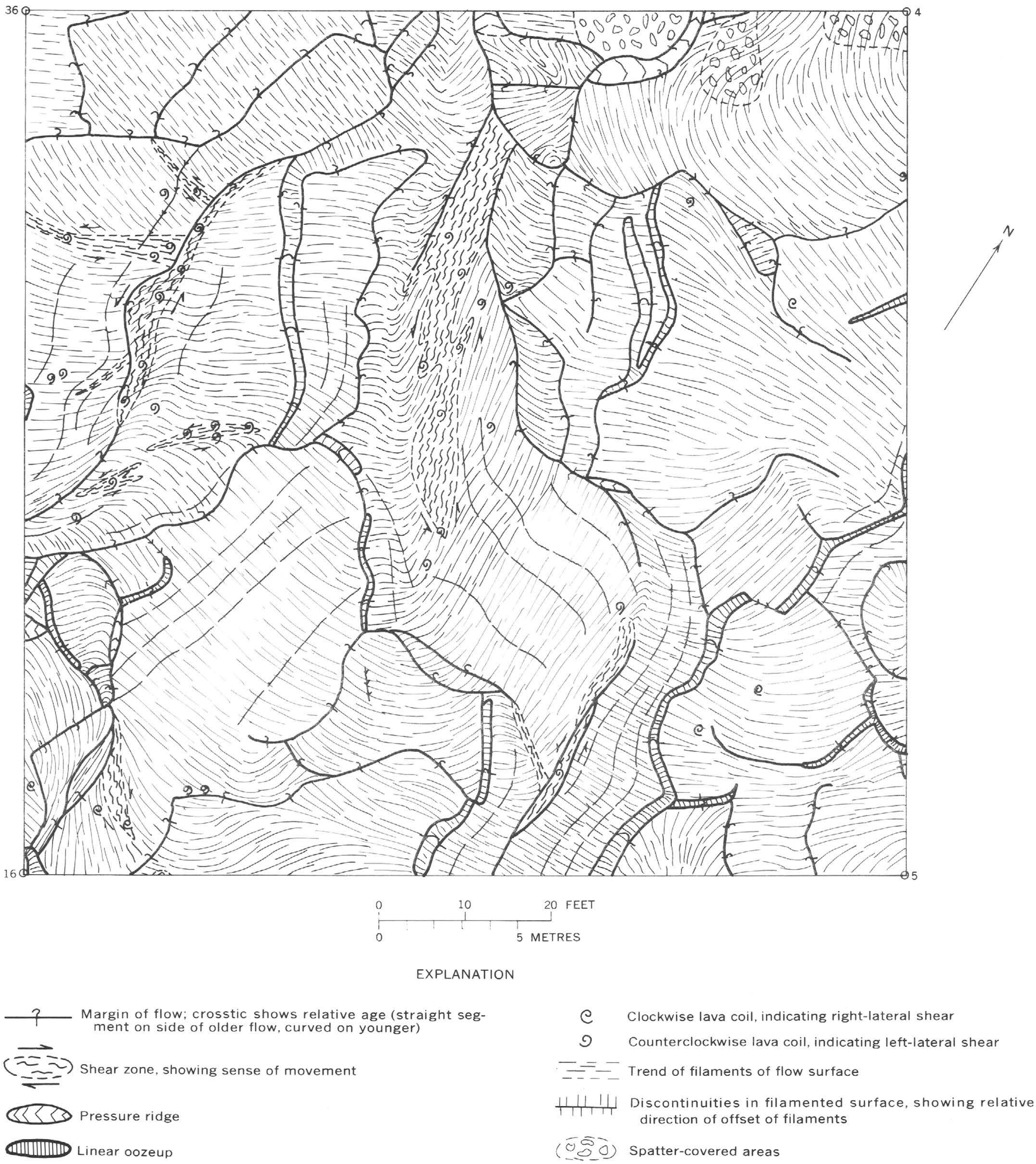

FIGURE 26.—Surface features exclusive of joint cracks on a part of the central part of Alae lava lake. Area of map and location of numbered surveying stations are shown in figure 17.

was so newly formed and thin that cracks in it exposed hot incandescent lava. Crust formed near the vent was destroyed by foundering and covered by overflows in its passage across the lake to be replaced by still newer thinner crust. Lava from the fountains moved outward in diverging streams,

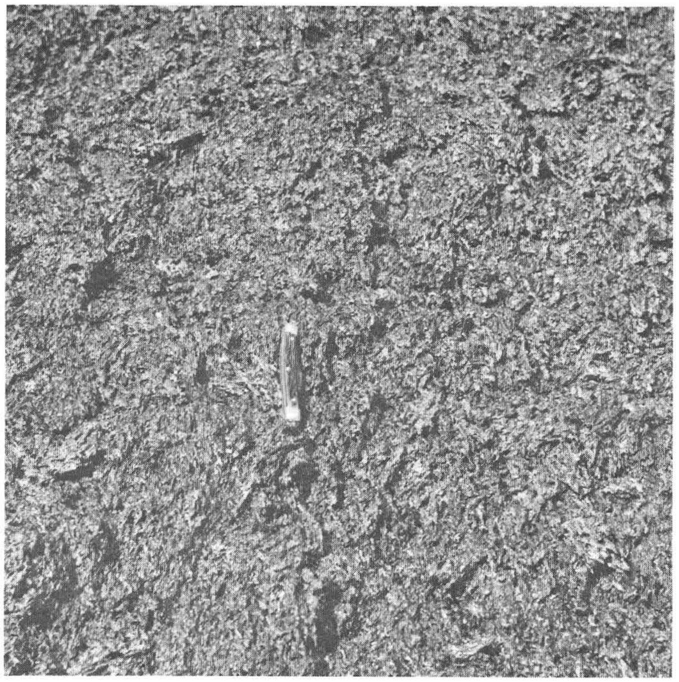

FIGURE 27.—Filamented surface of Alae lava lake. Knife in center of photograph is 10 cm long.

which were bordered at the surface by glowing shear fractures.

The outer margin of the active part of the lake was bounded by breaks where the lake surface stepped down to the lower level of the outer stagnant part of the lake, exposing red-hot lava. These breaks formed conspicuous glowing lines, along which many small flows were extruded, and much foundering of the crust took place.

The crust of the outer stagnant part of the lake was dark. Because the surface had not been renewed by overflows and foundering, the crust had become thicker with time, and cracks no longer penetrated hot, brightly glowing lava. The outward push of lava-rafted crust at the margins of the inner part of the lake caused the crust of the outer part to buckle along lines of weakness, mostly the thin-crusted linear oozeups that occupied cracks along former margins of the inner lake.

The inferred pattern of lava circulation during the evening of August 22 and the margin of the inner active part of the lake at three different times are shown in figure 28, adapted from figure 7 of Peck (1966). Early in the evening, the strongest flow of lava from the fountains was in a stream under the crust northeast of the long axis of the lake. Between 17^h45^m and 22^h45^m, the stream decreased in length and shifted to a position southwest of the major axis. The stream continued to decrease in length, and by 23^h16^m it extended only 100 m from the vent. The flow of lava was deflected each time at the southeast end of the lake, probably by a buttress of static viscous lava. Subsidiary currents split off from the stream towards the margin of the lake, diminishing in vigor with greater distance from the vents.

Because the surface of the lake rose only imperceptibly during the last 26 hours of the eruption, we conclude that the outward flow of lava near the surface was compensated by slow flowage of relatively dense degassed lava downward and backward toward the vents in the main body of the lake, as shown in the cross section in figure 29. Presumedly, this lava was either recirculated in the lake or seeped back down inactive parts of the feeding fissure.

DEVELOPMENT OF JOINT CRACKS

When first traversed 4 days after the eruption, the lake surface was found to be broken by a network of cracks outlining irregular polygons of crust. Some of these cracks had been widened, forming gaping crevasses as much as 30 cm wide and 2 m deep (fig. 30). Many were still glowing red at the bottom on August 30 and yielded temperatures as high as 960° C. The cracks more than 2.5 cm wide at the surface formed an open network in the central part of the lake that radiated outward towards the edge (fig. 31). The pattern is reminiscent of the network of faults over a piercement dome. Presumedly, cracks formed as a result of thermal contraction in the thin crust of the lake during the latter part of the eruption were widened at the end of the eruption because the surface crust was extended by downsagging during drainback of the underlying molten lava.

The formation of joint cracks by thermal contraction of the cooling crust of the lake was studied in detail for 2 years by repeated mapping (at 10 ft to the inch, 1:120) of new cracks and deposits of sublimates in an area approximately 30 m (100 ft) on a side near the center of the lake (fig. 17). Observations and conclusions derived from this study and from studies of Makaopuhi and Kilauea Iki lava lakes have been summarized by Peck and Minakami (1968). Surface features in the area, other than cracks and sublimates, are shown in figure 26.

The cracks were first mapped during late October, November, and early December 1963, when the crust was 3 to 4 m thick. The area was found to be divided by a random orthogonal network (Lachenbruch,

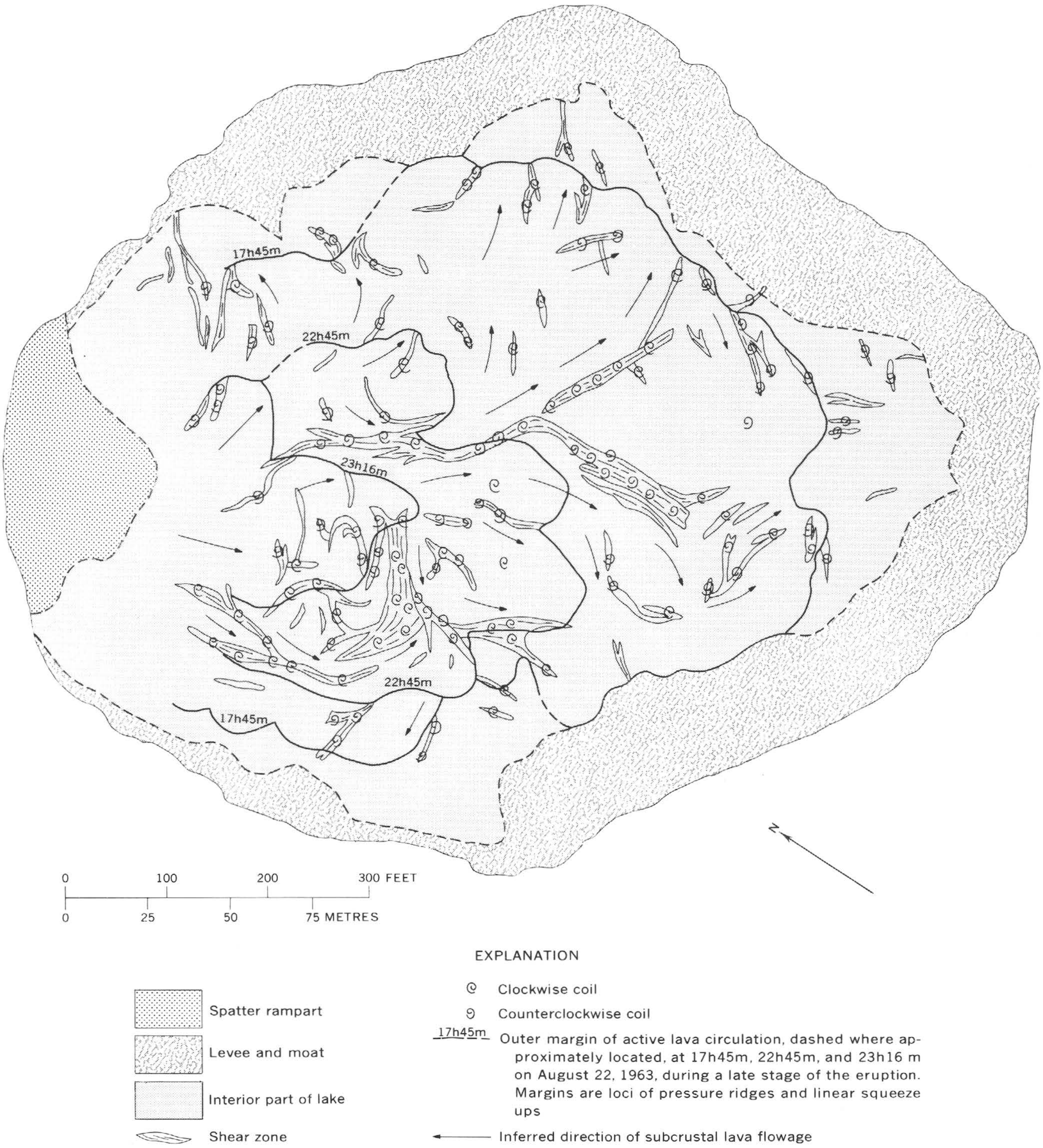

Figure 28.—Outer margins of active lava circulation, shear zones, and inferred directions of lava flowage on August 22, 1963.

1962, p. 48) of straight to gently curving contraction cracks, which ranged from hairline fractures to gaping cracks as wide as 20 cm (fig. 32). The cracks outlined irregular polygons of crust 1.5 to 6 m wide, most of which had 3 to 6 sides. Less abundant were short cracks near the centers of crack polygons and branching off from longer cracks. Many of the cracks follow preexisting flaws in the lava lake, such

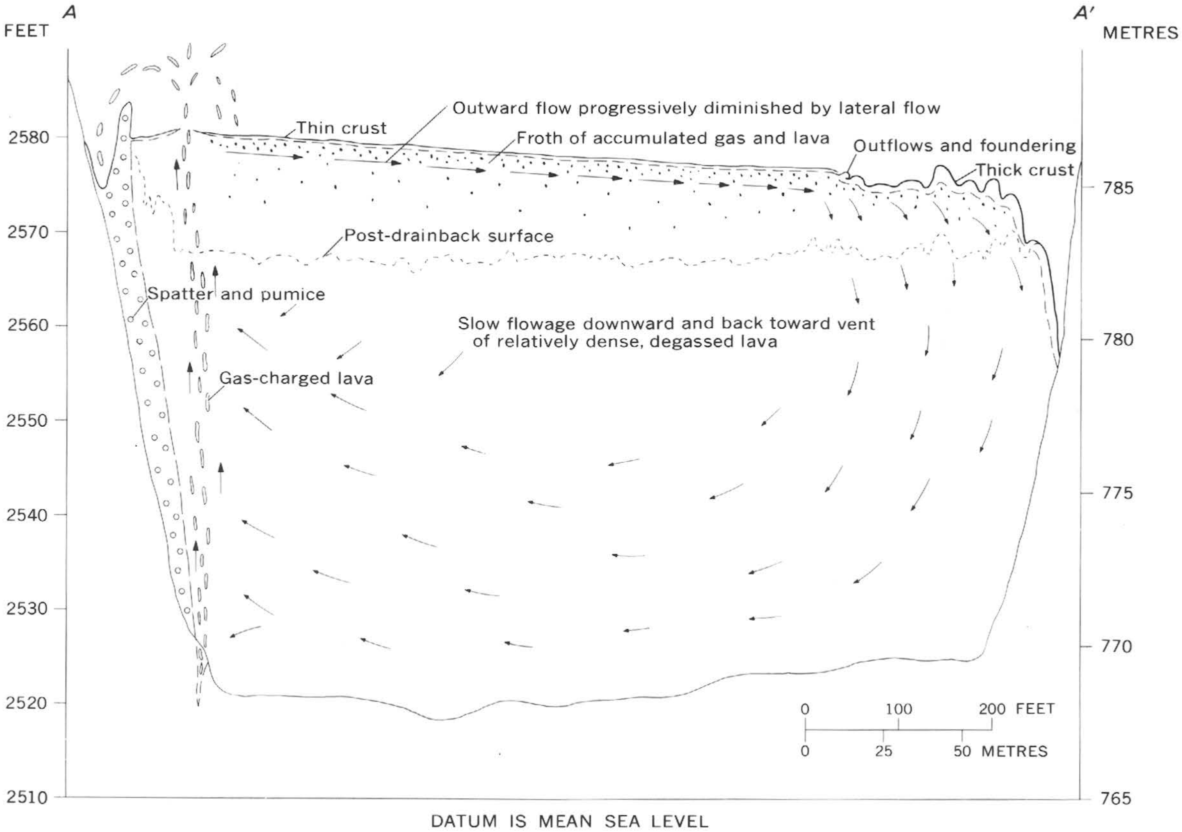

FIGURE 29.—Cross section along the major axis of Alae lava lake (see fig. 17) during the evening of August 22, showing inferred lava circulation. Vertical exaggeration, × 10.

FIGURE 30.—Joint cracks at the surface of Alae lava lake formed during drainback near the close of the eruption. Photograph taken August 11, 1965. Map case for scale.

as the fronts of small flows and shear cracks. Where irregularities in the walls of the cracks or features such as shear zones on the adjacent lake surface permitted correlation across the cracks, no horizontal offset along the crack could be identified. In most places, only displacement normal to the plane of the crack surface was present, although, in a very few areas, one side was displaced vertically as much as 5 cm with respect to the other. More than 90 percent of the crack intersections for which the angle of intersection could be determined were orthogonal (marked by solid dots in fig. 32). In many places, orthogonal intersection was achieved by curvature of one or both of the cracks close to the point of intersection.

Many of the cracks in the area were very inconspicuous, particularly during this early stage of the cooling history of the lake, when few cracks were marked by incrustations of sublimates. Some could be found only by scraping away the filamented surface layer and following the course of the crack on hands and knees. In parts of the area, the cracks were concealed by thin surface flows, in the cracks at the fronts of small flows, or in shallow surface

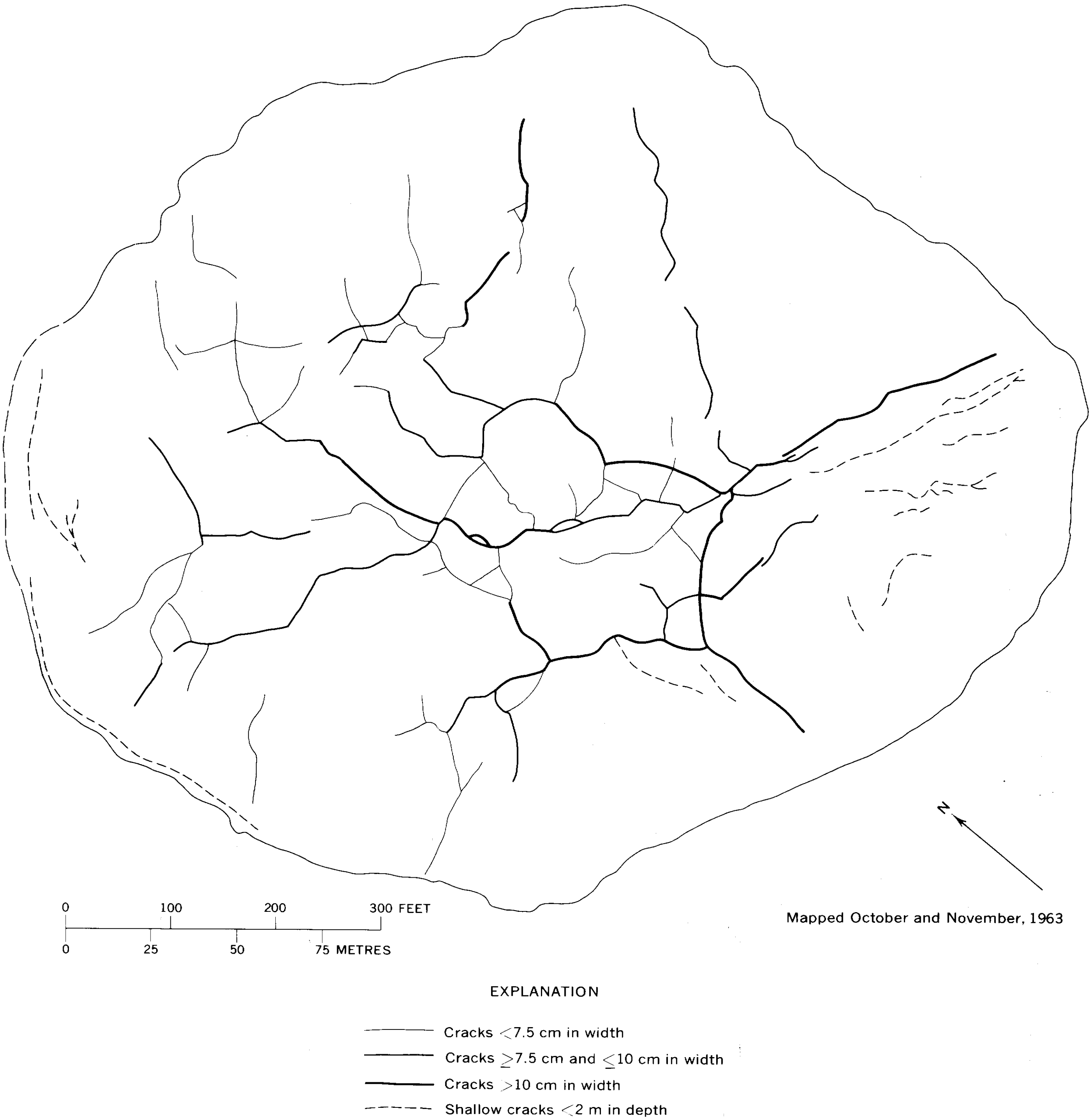

FIGURE 31.—Map of joint cracks on Alae lava lake that formed during drainback near the close of the eruption.

cracks formed during the eruption. No doubt some cracks were missed during the mapping; radiation temperatures in December 1964 along a line near the northwest edge of the area (Decker and Peck, 1967) indicate the presence of several that had been overlooked.

The surface of the area was not flat but was made up of broad hummocks separated by sharp troughs. The surface of each hummock sloped outward with increasing steepness toward the marginal trough, somewhat like an inverted saucer, as shown in the cross section of figure 32. The relief, excluding pressure ridges and oozeups, had a maximum of about 60 cm but averaged less than 30 cm. Each hummock was made up of one or more crack polygons and, with few exceptions, bounded by cracks on all sides.

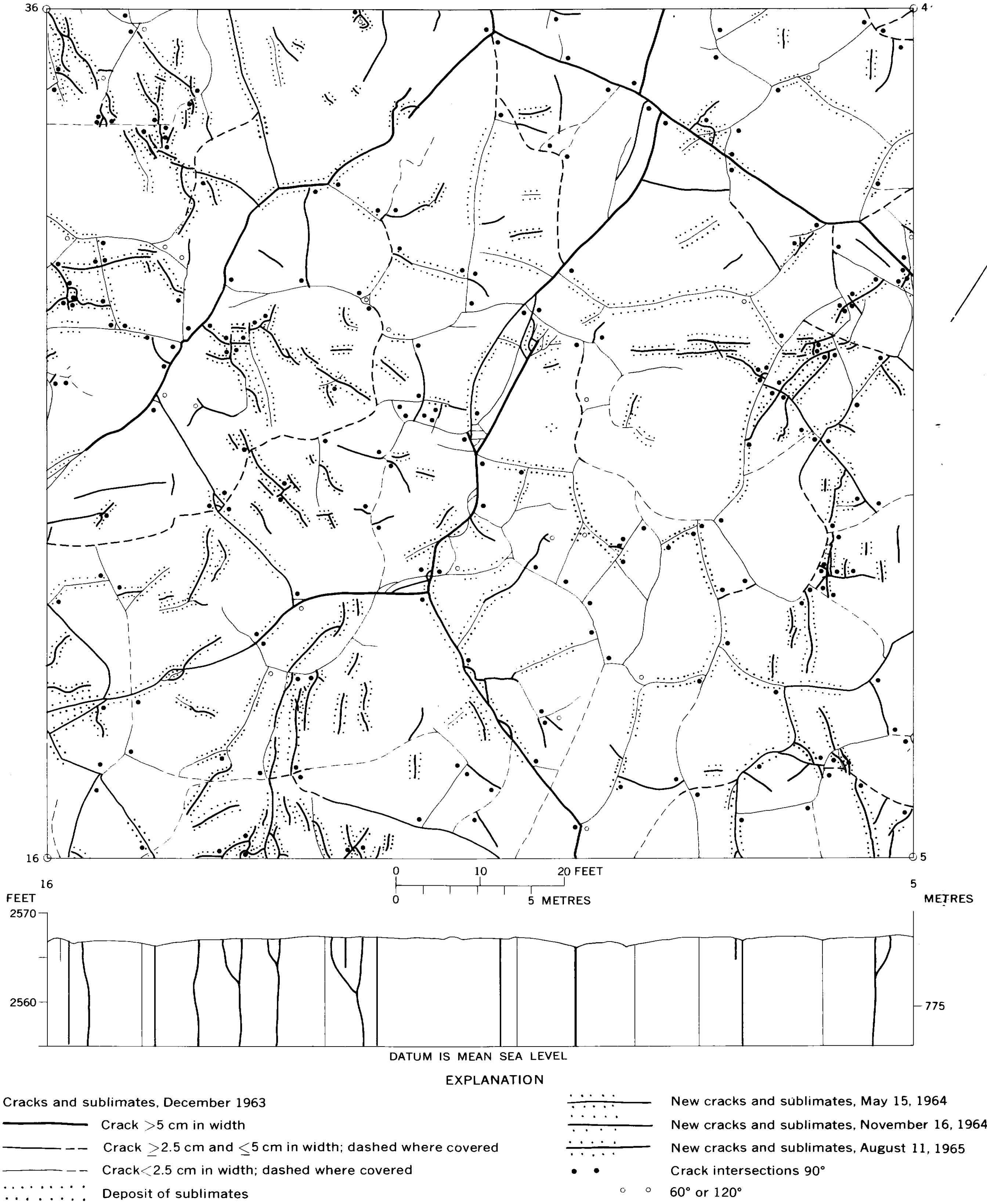

FIGURE 32.—Cracks on part of the August 1963 Alae lava lake. Location of area is shown in figure 17; surface features other than cracks and sublimates are shown in figure 26. Cross section is along the southeast edge of the area. Numbers at corners of the map area refer to tagged nails marking surveyed stations.

Where boundary cracks were not evident, they probably were present at shallow depth but were obscured at the surface by thin overlying flowlets. The troughs delimiting hummocks and the crests of the hummocks are mapped in figure 33. The hummocks ranged from 3 to 6 m in diameter, averaging about $4\frac{1}{2}$ m. Most were roughly equant, but a few were elongate parallel to the long dimension of the lake. Hollow cavities occurred at shallow depths beneath the crests of many of the hummocks (fig. 33) and

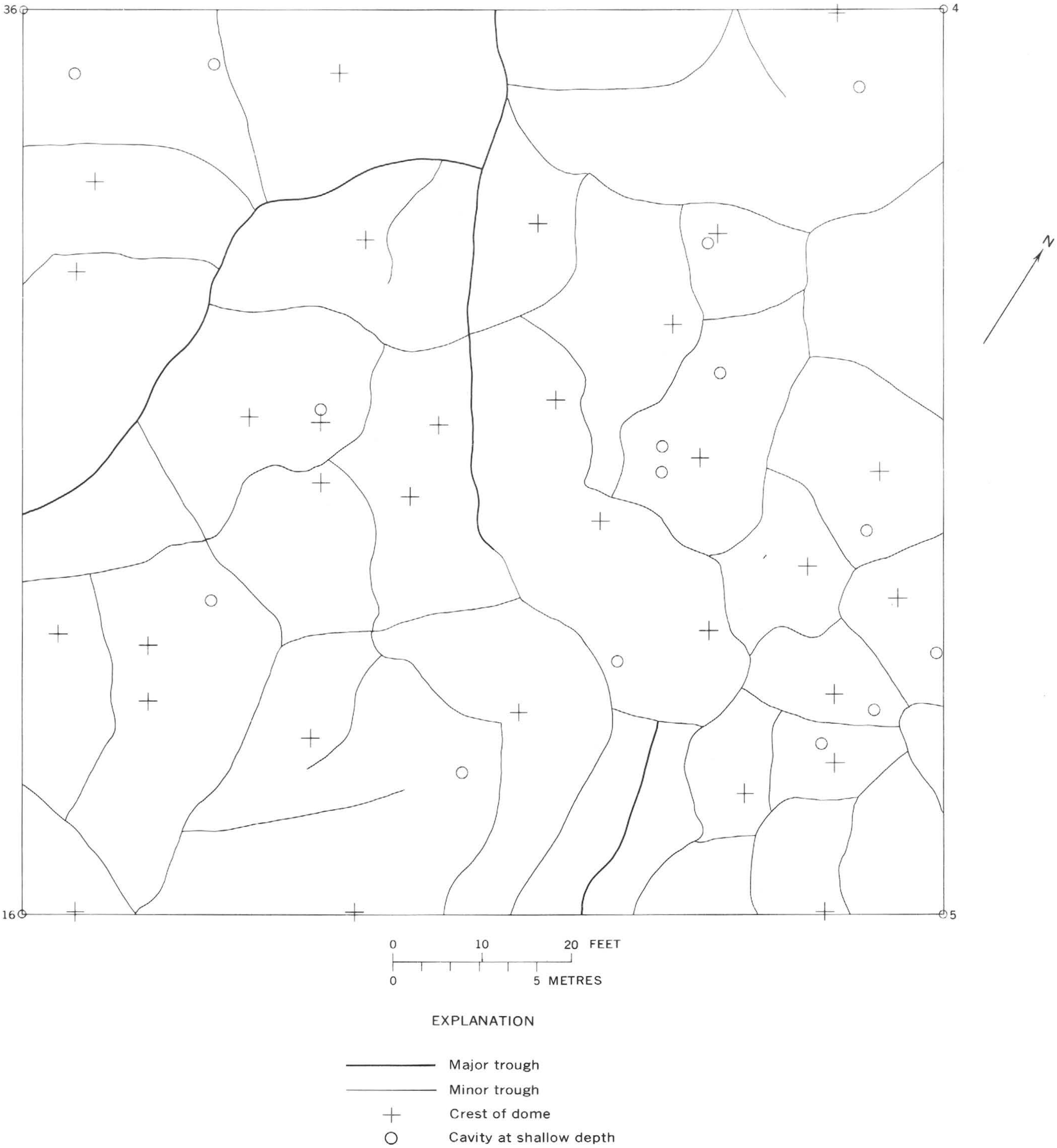

FIGURE 33.—Map showing troughs and crests on part of Alae lava lake. Location of area is shown in figure 17. Crests of domes are marked by crosses. Cavities at shallow depth (located by stamping on the surface and listening for a hollow sound) are marked by circles. Numbers at corners of the map area refer to tagged nails marking surveyed stations.

were encountered in drilling at depths of 0.3 to 1.2 m. The appearance of similar features in flows exposed on the walls of craters and in roadcuts suggests that the cavities in the Alae lake were lensoid openings having convex-upward tops and flat floors. Observations during and after the Makaopuhi eruption indicate that hummocky topography starts forming within a few hours after formation of the crust and is completed within 1 to 4 days (Peck and Minakami, 1968, p. 1154). The uplift of polygon centers and the formation there of lensoid cavities and vesicular zones apparently is caused by the trapping of gas exsolved from the underlying molten lava. Escape of the gas through cracks at polygon boundaries, in contrast, leads to downsagging of the margins.

When detailed mapping was first begun in late October, very few of the cracks had incrustations of sublimates along them. No sublimates are evident on a photograph from the overlook taken October 21, 1963 (fig. 34), and none were noticed during the work on the lake until late October. By the time the mapping was completed on December 17, 1963, the lake surface had cooled sufficiently for sublimates to be deposited. Many of the cracks had incrustations,

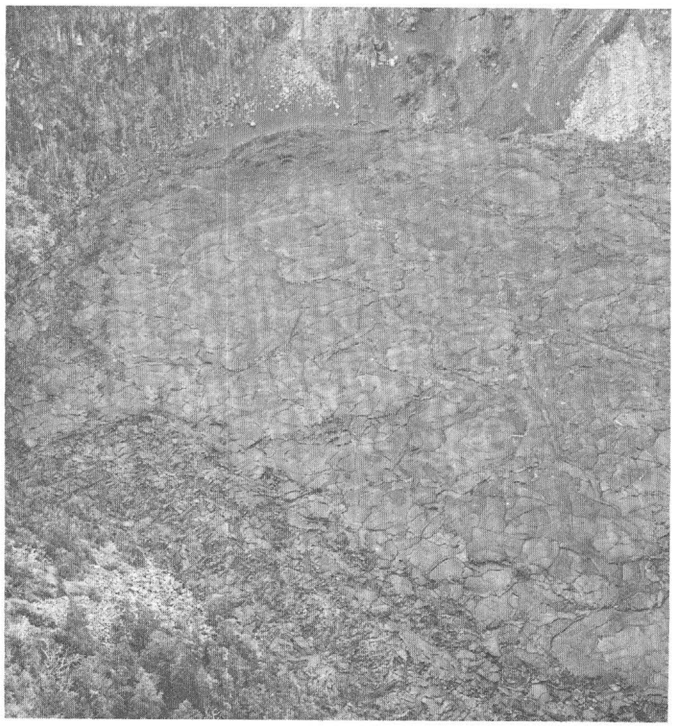

FIGURE 34.—Alae lava lake as viewed from the overlook at the south rim of crater on October 21, 1963. Few sublimates have been deposited on the lake surface as yet because of the relatively high temperatures at shallow depth in the lake. Compare with figure 35.

yellow deposits of sulfur and white deposits of gypsum and anhydrite, along them. The sublimates were particularly noticeable along the short cracks within the polygons, many of which had opened during the course of the mapping. During this period, yellow sublimate-laden gases could be seen rising along some of the cracks. Most of the sublimates were washed away by heavy rains during the next several months, and the areas of incrustation became inconspicuous.

On almost every day of work on the lake during the next several months, cracks could be heard opening in the lake with a sound like that of a sharp distant explosion. New cracks and strips incrusted with sublimates were therefore remapped in the study area on May 15, 1964 (fig. 32), when the crust was 7 m thick. The mapping revealed many new cracks—mostly short cracks near the crests of hummocks but also a few cracks that extended across crack polygons and subdivided them into nearly equal parts. The short cracks at the crests of hummocks probably extended to depths of only a few feet, because of the presence of underlying cavities.

Almost all of the new and many of the preexisting cracks were by now bordered at the surface by incrustations of sublimates. Deposition of sublimates at the surface was accelerated during the first few months of 1964, as shown by the photograph (fig. 35) taken on August 25, 1964, because of drastic cooling of the uppermost part of the crust by heavy rains, which brought 167 cm of rainfall between January 2 and May 28. In late December, only the upper 10 cm was below 100°C; by May, this thickness had increased to 1 m. As a result, gases rich in sulfur and calcium sulfate that were rising along the cracks were cooled sufficiently to deposit the sublimates instead of carrying them into the atmosphere to be blown away by the wind. Heavy rainfall is not a necessary requirement for such deposits; sublimates were deposited on the cooler margins of Alae lava lake and more sparingly on the center before the onset of the heavy rain. During the period from December to May, sublimates were deposited not only along new cracks but also along some preexisting cracks, which suggested renewed downward propagation of at least some of the cracks in the thickening crust of the lake.

The thin filamented surface layer of the lake had now loosened from the underlying lava over much of the lake. This apparently resulted from the widespread formation of small subhorizontal fractures at the base of the layer, presumedly the result of devitrification of the glassy filaments and differential

FIGURE 35.—Alae lava lake as viewed from the head of the aerial tram at the south end of the crater on August 25, 1964. Incrustations of sublimates are apparent along some of the joint cracks as a result of more than 170 cm of rainfall during the preceding 8 months. Compare with figure 34.

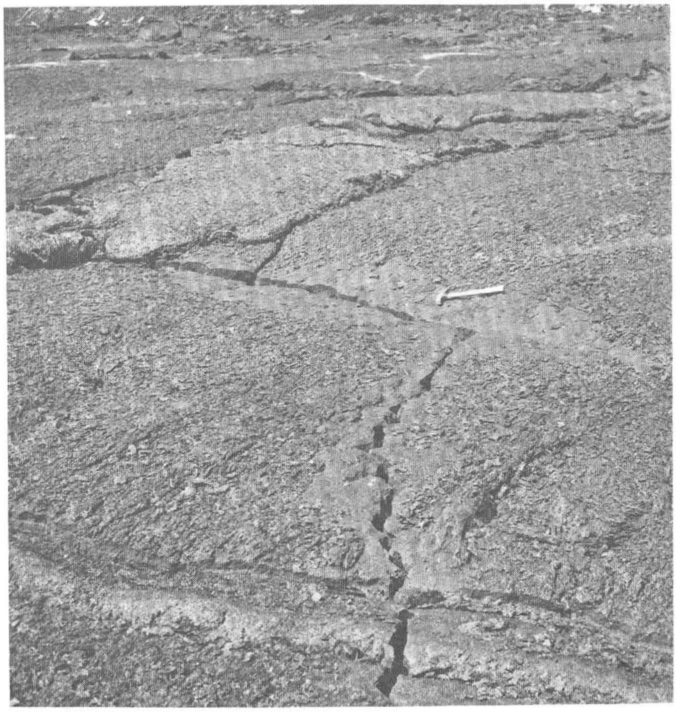

FIGURE 36.—Areas bared of the filamented surface layer near joint cracks in Alae lava lake. Photograph taken March 1965.

thermal contraction of the frothy layer and the relatively dense underlying lava during cooling. Over narrow areas adjacent to some cracks, the loose pieces had been washed by rainwater and blown by wind into the open cracks, leaving a smooth surface of nonfilamented lava exposed (fig. 36).

The rains had chilled the crust of the lake so drastically by the end of May that temperatures in the upper 2 m of the crust did not fall during the following 7 months, but instead stayed approximately constant. When the study area was remapped on November 16, 1964, 15 months after the eruption and 2 months after solidification of the last interstitial melt in the lake, few new cracks or areas incrusted by sublimates were discovered (fig. 32).

When the area was mapped again on August 11, 1965, almost 2 years after the eruption, many new cracks were found (fig. 32). The maximum temperature in the lake by this date had fallen to about 680° C, 300°C below the solidus temperature. The new cracks, which were short and sublimate incrusted, occurred in long swarms that crossed major preexisting cracks (Peck and Minakami, 1968, pl. 1, fig. 2). Newly deposited sublimates were also found along preexisting cracks crossed by the swarms. The alinement and continuity of the swarms of short cracks indicate that they were the surface expression of major continuous cracks at depth in the lake. A few swarms could be seen outside the study area in February 1964. More can be seen in the August 1964 photograph (fig. 35) and even more in the August 1965 photograph (fig. 37). Some of these appear to outline large polygons 30 m or so across. The mapping shows that these did not correspond to preexisting crack polygons but instead cut across them. The swarms probably represent new cracks that originated at depths of 5 to 15 m in the lake and propagated upward to the surface, as suggested by the discontinuous nature of the individual cracks in each swarm, the length of each swarm and its continuity cross major preexisting cracks, and the large dimensions of polygons outlined by some of the swarms. Between May 1964 and August 1965, temperatures in the upper metre of the crust decreased very slightly; thus little stress induced by thermal contraction developed near the surface of the lake. As a result, the upward-propogating cracks feathered out near the surface. In contrast, temperatures deep within the crust continued to fall after May 1964. The maximum change in temperature between May 1964 and August 1965, and hence the maximum accumulated stress, was at a depth of about 10 m, which was slightly below the middle of

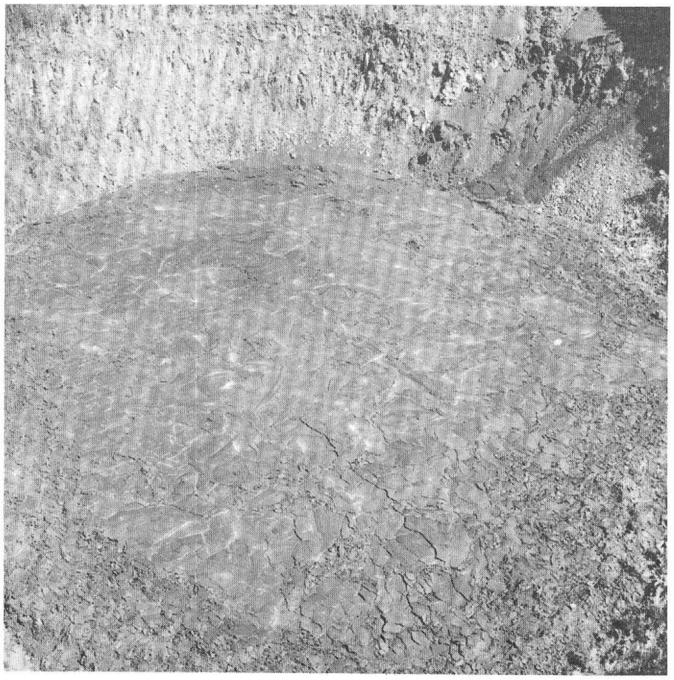

FIGURE 37.—Alae lava lake on August 18, 1965, as viewed from the head of the aerial tram at the south rim of the crater. Swarms of sublimate-incrusted cracks can be seen, some of which outline large crack polygons in the lake.

the lava lake. Apparently the downward growth of preexisting cracks did not adequately release the accumulated stress in this zone so that new cracks opened at points distant from preexisting cracks and propagated upward into the zone of small accumulated stress.

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